

Design and Implementation of a LORAWAN Network-Based Low-Cost Photovoltaic (PV) Monitoring System

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Abstract- Systems in response to the growing demand for effective monitoring frameworks in the renewable energy sector. The system incorporates sensors to record critical data, such as solar panel output, battery status, and ambient variables, addressing cost-effectiveness, scalability, and remote monitoring concerns in PV installations. Data transfer is supported via a LoRaWAN network, which provides long-range and low-power connectivity, making it ideal for remote and off-grid PV systems. The inclusion of the LoRaWAN technology improves system scalability and efficiency, providing a path for mass adoption in sustainable energy solutions. This low-cost design makes PV systems accessible to a wide range of users, including those in distant or economically challenged locations. The field testing results show that the system provides real-time data on PV system performance, enabling preventive maintenance and informed decision-making. The PZEM-004T V3 module and DC voltage sensor data provided important insights into the dynamic behavior of the monitored electrical system. The steady increase in active power consumption (Pac) from 933 to 2107 Watts implies an increase in the electrical power demand of the system. This study describes a realistic and efficient monitoring approach customized to the unique requirements of PV systems, contributing to the greater adoption of sustainable energy solutions using LoRaWAN technology.

Keywords: Cost-effective technique, monitoring PV system, LoRaWAN network, PZEM-004T V3 module, PV sustainable energy.

1. Introduction

The growing global commitment to sustainable energy solutions has contributed to a substantial rise in the recognition of photovoltaic (PV) systems as pure and renewable energy sources in recent years [1]. The increasing prevalence of solar installations has highlighted the necessity of efficient monitoring and management systems as a crucial element in guaranteeing peak efficiency and energy production. This research offers a novel solution to this requirement by utilizing the possibilities of long-range wide area network (LoRaWAN) technology in the design and implementation of an affordable photovoltaic monitoring system. For defect detection, performance improvement, and real-time assessment, PV systems must be integrated with cutting-edge monitoring systems [2]. However, small-scale

and cost-sensitive applications have faced difficulties owing to the high cost of standard monitoring systems. Our study aims to close this gap by creating a commercially feasible solution that combines the long-range, low-power communication capabilities of LoRaWAN networks with the efficiency of the PV technology.

The capacity of renewable energy sources has increased significantly in the worldwide power generating landscape as of 2019, indicating a major move towards sustainable and environmentally friendly sources. The fact that 200 gigawatts of renewable energy was added to the global energy grid during that year demonstrated how popular clean energy solutions are becoming [3]. Notably, photovoltaic (PV) energy is a significant factor, accounting for 57.5% of this growth. The transformation of sunlight into electricity through the

broad use of photovoltaic technology is a major factor in changing the composition of the world's energy supply. Combinations of these elements define photovoltaic dominance. The persistent reduction in solar panel costs, in conjunction with continuous enhancements in efficiency, has enabled the extensive implementation of photovoltaic systems in various geographical locations. This advancement in technology not only made solar energy more economically viable but also played a major role in the shift to a more robust and sustainable energy infrastructure.

The increasing trend in the use of renewable energy demonstrates the dynamic interaction of market forces, regulatory interventions, and technology breakthroughs. The efficiency and cost-effectiveness of renewable energy systems have steadily improved owing to the ongoing research and development. As a result, 2019 saw a qualitative shift in the global energy landscape toward a future that is more ecologically sensitive and sustainable, in addition to quantitative growth in the capacity for renewable energy. It is advisable to examine studies from respectable organizations, such as the International Energy Agency (IEA) or the International Renewable Energy Agency (IRENA), for the most up-to-date and reliable information on worldwide renewable energy development [4].

To highlight the benefits of solar energy generation and wireless data transmission, a more detailed explanation of the essential elements and intricate details involved in building our monitoring system is required. Through the use of LoRaWAN, a low-power, long-range wireless communication technology, our system can operate in a variety of situations and remains affordable while still being scalable and adaptable. Attempts have also been made to contribute to the development of renewable energy technology by providing an in-depth analysis of the system architecture, sensor integration, and data-processing processes [5]. In addition to addressing cost issues with monitoring options, the proposed low-cost PV monitoring system has opportunities for wider deployment, especially in isolated or resource-constrained places.

The rise of distributed renewable energy promises several advantages beyond environmental energy, and has a significant influence on societal dynamics. Access to electricity is one of the primary social advantages of providing rural areas that are still outside the reach of conventional

power systems. Remote locations that are frequently found in underdeveloped or rural areas may now utilize small-scale solar or wind power plants, negating the requirement for substantial grid infrastructure. Essentially, the growth of distributed renewable energy has become a driving force for good social change in isolated areas [6], providing not only necessary services and jobs, but also a route to a more empowered and sustainable future.

Governments have been instrumental in driving the expansion of renewable energy by encouraging laws and subsidies. These programs have attempted to promote energy security, lower carbon emissions, and accelerate the adoption of renewable energy technology. As nations have realized the importance of diversifying their energy portfolios to address long-term energy sustainability and reduce environmental consequences, the global energy matrix has undergone significant upheaval [7]. The findings of this study provide insight into how LoRaWAN-based solutions might improve the accessibility and efficiency of renewable energy technology, which will eventually help realize the dream of a sustainable and networked energy future.

The Internet of Things (IoT) has significantly improved the reliability, scalability, and real-time data access of photovoltaic (PV) systems. IoT-enabled sensors and communication modules enable informed decision making and proactive maintenance. Remote device management reduces the physical presence, operational costs, and predictive maintenance. IoT also increases the scalability of PV systems, allowing them to grow their capacity and adapt to changing needs. The integration of the IoT (figure 1) enhances the individual PV system performance and the resilience, efficiency, and dependability of the larger energy infrastructure [8].

Hardware development aims to reduce cost and provide flexibility. The proposed system offers scalability, real-time data access, local and cloud storage, remote control, and real-time data access through an IoT cloud system [9]. It is geared towards small and medium-sized operators and researchers owing to its cheap enabling technical framework. It is also interesting for experts in poor nations because of the limited solar technology use due to insufficient finance and research. The system allows for intelligent photovoltaic systems and machine learning algorithms for defect detection and power generation predictions.

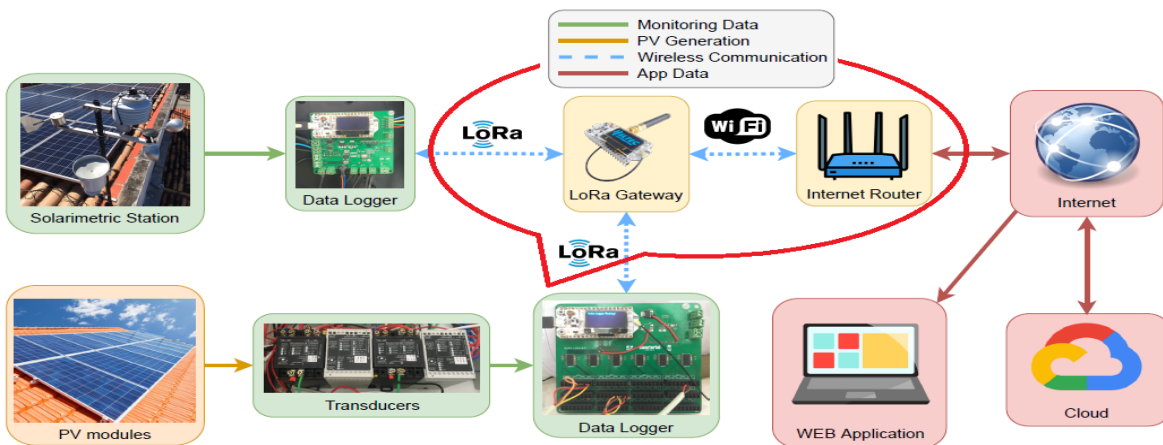


Fig. 1. simplified diagram of the low-cost photovoltaic (PV) monitoring system.

2. Related Works

Researchers and business professionals are exploring low-cost LoRaWAN-based PV monitoring devices to overcome the energy limitations. LoRaWAN, a low-power, wide-area network technology, facilitates long-distance communication and is easy to deploy, thereby accelerating the transition to a decentralized and sustainable energy environment. Mnati et al. (2020) [10] presented the design and Implementation of a Low-Cost PV Monitoring System Using LoRaWAN. This paper presents the design and implementation of a low-cost PV monitoring system that utilizes LoRaWAN for data transmission. The system incorporates low-cost sensors to measure parameters, such as solar irradiance, temperature, and power output.

Zhao et al. (2023) [11] discussed a wireless PV monitoring system based on the LoRa technology. Their work explored the implementation of a wireless PV monitoring system using the LoRa technology. The study discusses the benefits of LoRa in terms of long-range communication and low power consumption for PV system monitoring. This study emphasizes the cost-effectiveness of the proposed solution, which enables easy deployment and scalability. Hamied et al. (2023) [12] offered "A Low-Cost LoRaWAN-Based Photovoltaic Monitoring System for Rural Areas" (2020), which focuses on addressing the challenges of PV monitoring in rural areas with limited infrastructure. It presents a low-cost monitoring system based on LoRaWAN specifically designed for remote and off-grid PV installations. This study highlighted the benefits of long-range communication and low power consumption in such environments.

Teymuri et al. (2023) [13] presented an IoT-Based Low-Cost PV Monitoring System Using LoRaWAN for Energy Efficiency. This work proposes an IoT-based low-cost PV monitoring system that leverages LoRaWAN technology to improve energy efficiency. This study focused on the implementation of low-cost sensors, data transmission using LoRaWAN, and cloud-based data management. This emphasizes the importance of real-time monitoring and data analytics for optimizing PV system performance and energy consumption. Slabicki et al (2018) [14] presented a low-cost monitoring system for Photovoltaic arrays using LoRa technology. This study presents a low-cost monitoring system for photovoltaic arrays that utilizes LoRa technology for wireless data transmission. This research focuses on minimizing the hardware cost by utilizing low-cost sensors and a simplified data acquisition system. Ziyuan et al. (2022) [15] designed and developed a low-cost photovoltaic monitoring system based on LoRaWAN and proposed the design and development of a low-cost PV monitoring system based on LoRaWAN technology. It explores the integration of low-cost sensors for measuring parameters, such as solar irradiance, temperature, and current. This study highlights the use of inexpensive microcontrollers and LoRaWAN gateways to reduce the system costs. The performance of the system is evaluated in terms of data accuracy, reliability, and power consumption.

Melo et al. (2021) [16] presented an evaluation of a low-cost monitoring system for Photovoltaic installations based on

LoRaWAN. This study evaluates the performance and cost-effectiveness of a low-cost monitoring system for photovoltaic installations based on LoRaWAN. This study compares the proposed system with traditional monitoring solutions in terms of data accuracy, reliability, and cost. Wu et al (2021) [17] presented the development of a low-cost wireless photovoltaic monitoring system using LoRaWAN for remote areas. This study focuses on developing a low-cost wireless PV monitoring system using LoRaWAN for remote areas with limited infrastructure.

The monitoring system developed by Hamied et al. 2019 [18] has a straightforward defect detection process. To monitor sun irradiance and cell temperature, we employed more precise sensors with advanced data analytics for performance monitoring and fault detection in photovoltaic systems. In order to monitor PV panels for residential application, a unique LoRa-based technique is developed by Kim, M.S. et al. 2022 [19]. The planned DAQ system can gather various metrics and provide outstanding results. Wireless sensor network-based monitoring system for Photovoltaic panels. This review examines wireless sensor network (WSN)-based monitoring systems for PV panels. They discuss the advantages of WSNs in terms of reduced wiring costs, flexibility, and scalability.

The Intelligent Monitoring System (IMS) for photovoltaic (PV) systems presented by Mehmood et al. 2023 [20] uses lightweight software and inexpensive hardware. This study explored the concept of virtual sensing techniques for performance monitoring in PV systems. It discusses the use of machine learning algorithms and data-driven models to estimate the PV system parameters.

Saleem, M.U. et al (2023) [21] investigates low-cost environmental monitoring solutions for assessing air quality in low-cost environmental monitoring solutions for air quality assessment. It explores the integration of low-cost sensors, wireless communication, and data analytics to monitor parameters, such as particulate matter, temperature, humidity, and air pollutants. Consequently, an overview of related studies on reasonably priced monitoring systems is provided. This highlights the importance of low-cost monitoring techniques to increase the availability of monitoring instruments and promote eco-friendly behavior. A comparison of similar efforts and an investigation of current trends may help identify areas for further research, innovation, and collaboration in the field of low-cost monitoring.

3. Methodology

The LoRaWAN-based low-cost photovoltaic (PV) monitoring system consists of several interconnected components. The design was based on PV sensor nodes that were carefully placed throughout the PV system. These nodes are equipped with sensors that measure vital parameters, including power output, voltage, current, and temperature. To collect and share the collected data wirelessly, they also have microcontrollers and communication modules. The main point of contact for the PV sensor nodes is the LoRaWAN gateway to which they connect. The LoRaWAN network server receives data that the gateway receives from the sensor nodes.

This server manages all functions of the LoRaWAN network, including data decryption, authentication, and routing [22]. This ensures that the data are sent across the network in an efficient and secure manner.

Building a solar photovoltaic (PV) system based on the Internet of Things (IoT) is a significant advancement, particularly with regard to monitoring large-scale PV systems. The device uses the LoRaWAN protocol and an ESP32 microcontroller unit for real-time monitoring, enabling continuous data collection and wireless transfer of information regarding energy generation, system performance, and environmental conditions. This technology is useful for large-scale solar systems, ensuring long-range, low-power communication and reducing operational costs. ESP32 MCU integration allows remote administration and control, eliminating the need for physical site presence for system settings, diagnostics, and firmware updates. A low-cost PV

monitoring system based on the LoRaWAN network architecture provides a high-level overview of the system's components and their interactions. The key elements of the design are determined by a LoRaWAN network server, PV sensor nodes, LoRaWAN gateway, and data storage and display component (figure 2).

3.1. Proposed System Description

A low-cost photovoltaic (PV) monitoring system based on a LoRaWAN network relies heavily on its hardware for data collection, transmission, and processing. PV sensor nodes are essential components of solar energy systems and are equipped with hardware such as wireless communication modules, microcontrollers, and sensors. These sensors record data on variables such as the temperature, voltage, current, and power output. Figure 3 provides an overview of the measurement system.

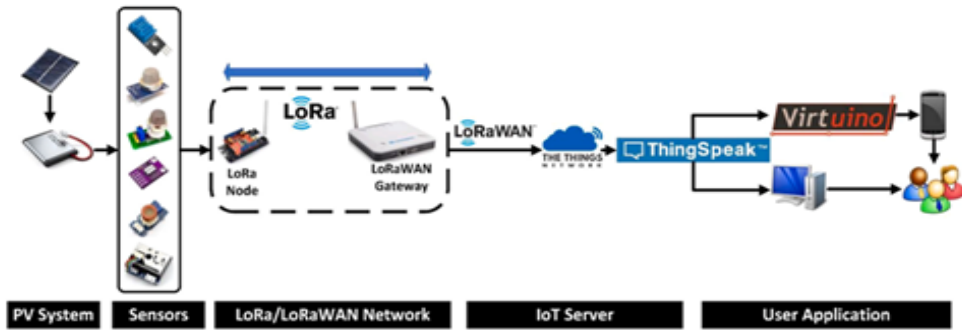


Fig. 2. Complete system architecture.

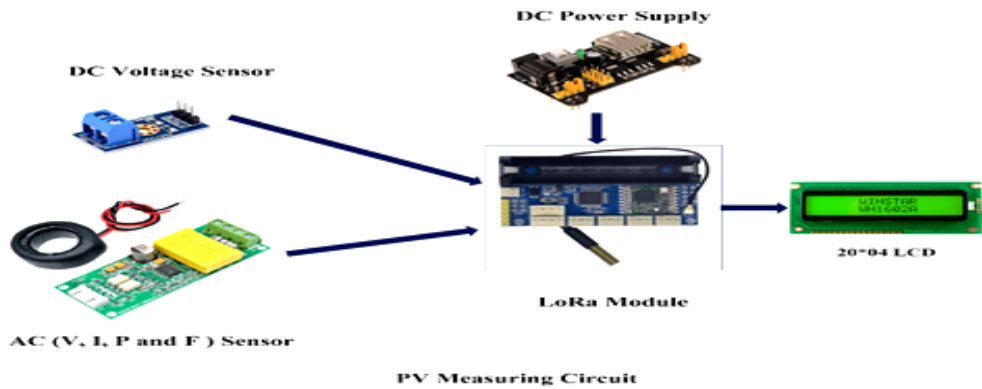


Fig. 3. PV low cost monitoring system.



Fig. 4. Low cost PV monitoring system.

Microcontrollers handle connections with the LoRaWAN network and interpret sensor data. The data were sent to the LoRaWAN gateway via wireless communication modules.

PV sensor nodes require a power supply for functioning and are typically housed in weather-proof enclosures. The choice of hardware depends on monitoring needs, ambient

conditions, power limitations, and cost concerns. The LoRaWAN gateway serves as the communication hub between the nodes and the LoRaWAN network, and consists of antennas and a LoRaWAN module or concentrator. The LoRaWAN network server manages communication and information flow within the network, including hardware such as CPUs, memory, and storage. Data storage may involve a database server or a cloud infrastructure. Users communicate with the PV monitoring system using displays, touchscreens, or input devices with smartphones or tablets serving as the hardware basis for mobile app interactions. Figure 4 shows the PV monitoring system.

3.2. Hardware Components

The components utilized in the proposed system and their experimental manifestations are described in detail in this section. Figure 4 shows the hardware configuration setup. The intended prototype is made up of a Lora radio node as the core of the hardware, PZEM-004T V3 Module for AC measurement, and a DC voltage sensor in addition to the Power Supply Module Board for Arduino and LCD 20*04

3.2.1. Lora radio node v1.0

The ATmega328P and RFM98 433 MHz radio modules are the foundation of LoRa Radio Node v1.0, as shown in figure 5 [23]. The Arduino Pro Mini bootloader, which operates on an 8 MHz 3.3V logic clock, is utilized by the ATmega328P main chip, which is also used by the Arduino Pro Mini. There is a 2 K RAM and a 32 K flash on this chip. It has a built-in 3.7V 14500 battery holder. It can be split into two IIC ports, two analog ports (A0 A1), and two digital ports (D3 D4) with four-pin and three-pin 2510-I type header in the LoRa radio node.

Using the remaining space, this LoRa Radio Node adds an RFM9x LoRa 433 MHz radio module. When the range is longer range than 2.4 GHz, these radios are excellent for broadcasting short data packets (BT, BLE, WiFi, and ZigBee). However, they are not appropriate for delivering music or videos.



Fig. 5. LoRa Radio Node v1.0.



Fig. 6. PZEM-004T V3 module.

3.2.2. PZEM-004T V3 module for AC

An electrical parameter measurement tool frequently used for tracking and measuring different parameters in AC circuits is the PZEM-004T V3 module, as shown in figure 6 [24]. Measurements of voltage, current, frequency, active power, and energy consumption can all be obtained using this flexible module. The PZEM-004T V3 module is extensively utilized in applications such as power distribution panels, home automation, energy monitoring systems, and industrial control systems owing to its adaptability. It is imperative to consult the manufacturer's documentation while utilizing the PZEM-004T V3 module to obtain precise information on its wiring, calibration, and communication protocols.

3.2.3. DC voltage sensor battery

The DC voltage sensor operates based on magnetic modulation, which is intended for use in DC voltage measurement and monitoring. This sensor produces an output signal (DC voltage or current) proportional to the DC voltage input. They can be used in power supply management, DC motor drivers, battery chargers, and other systems. They are also appropriate for measurements and long-term monitoring of DC voltage.

A unique voltage sensor for bidirectional voltage tracking is a DC voltage sensor with a supply voltage of DC 12V/15V/24V shown in figure 7. The input voltage measurement ranges were $\pm 50\text{mV}$, $\pm 50\text{V}$, $\pm 200\text{V}$, $\pm 500\text{V}$, and $\pm 1000\text{V}$. A DC 2.5 ± 2.5 , $5\pm 5\text{V}$, $12\pm 8\text{mA}$, or $10\pm 10\text{mA}$ output signal is possible.



Fig. 7. DC voltage sensor.



Fig. 8. Power Supply Module 3.3V/5V.

3.2.4. LCD 20*04

A typical numeric display seen in many electronic devices, including consumer electronics, digital instrumentation, and applications based on microcontrollers, is a 20x4 LCD as shown in figure 9. The dimensions and arrangement of the display are indicated by the notation “20x4,” which signifies that each of its four lines can show 20 characters. Across four panels of 20 characters each, the 20x4 LCD shows a total of 80 characters. Alphabetic letters, symbols, and user-defined characters can all be displayed at each character location. Usually, an integrated controller processor built around Hitachi HD44780 or a similar controller is in charge of a 20x4 LCD. The controller controlled character creation, display functioning, and host device connectivity.



Fig. 9. 20x4 character LCD display.

4. Results and Discussions

Figure 7 shows a block diagram of the data monitoring process. The process begins with the initialization of the Wi-Fi module ESP-8266 and LCD display if the Wi-Fi module ESP-8266 connects to the router. The monitored parameters are saved as strings and shown on the LCD screen [25]. A block diagram of the transmitter and receiver data monitoring procedures is shown in Figure 10. The transmitter procedure (10 a) starts with initialization, uploading the data, measuring the sensor results, checking the data, and using LoRa for transmitting it. After the received data are uploaded, LoRa is checked on the receiver side. The monitored data parameters were saved as strings along with those shown on the LCD screen.

The design of the proposed system is dependable and works well to show the obtained data in real time. The dynamic behavior of the system is demonstrated via five scenarios that illustrate variances in voltage levels, current draws, and power consumption. It is essential to monitor these features to evaluate the system performance, identify potential issues, and ensure that it runs within its specified parameters.

Active Power Pac (W): This demonstrates how much power the load in the system really uses or produces. Water (W) was used for measurement. Pac shows the actual power that is transformed into productive labor or lost as heat. Active power monitoring is essential to evaluate how well the system uses its electrical energy.

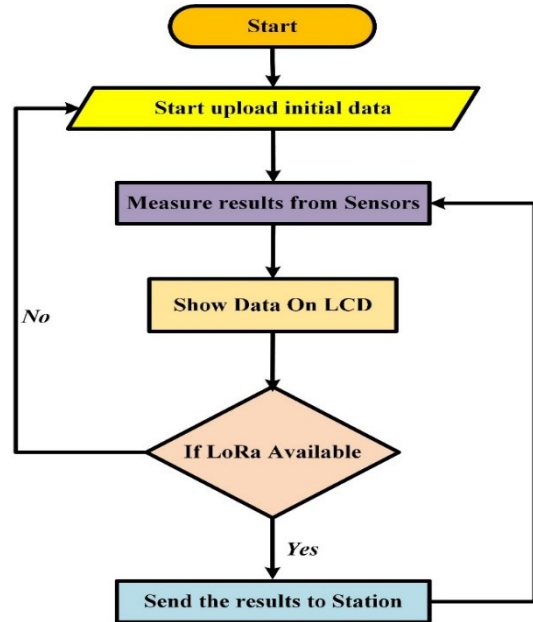


Fig. 10 (a). Block diagram for transmitter.

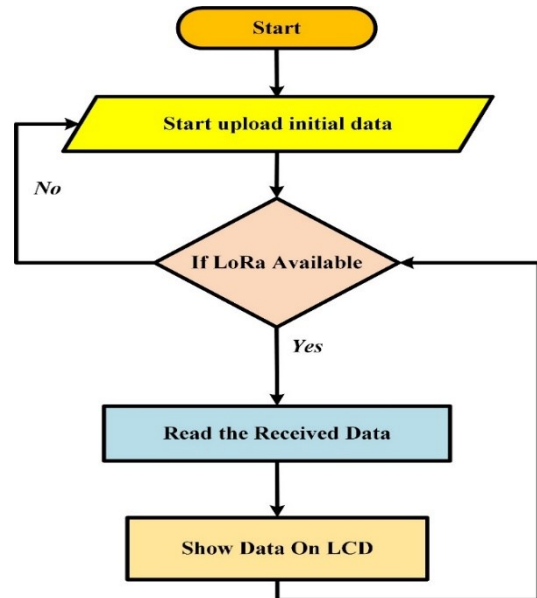


Fig. 10 (b). Block diagram for receiver.

Current Iac (A): The rate at which electric charge flows through the system is represented by Iac. It is critical to monitor the current to verify that the electrical components and conductors can manage the load without exceeding their rated capacities.

V(battery) quantifies the electrical potential difference in the battery and is measured in volts (V). It is critical to determine the charge level and condition of the battery. Monitoring the battery voltage ensures that the energy storage system operates within the recommended voltage range.

AC Voltage V_{ac} (V): It is critical to monitor the AC voltage to guarantee that the electrical appliances and equipment connected to the system receive the necessary voltage to function properly. Deviations from the standard voltage can affect the operation of connected equipment.

These measurements provided an extensive overview of the electrical properties and performance of the system. Operators can examine the efficiency, load circumstances, and general health of an electrical system by monitoring the active power, current, battery voltage, and AC voltage. Table 1 shows the measurement of these parameters, as it enables proactive maintenance, early detection of possible problems, and energy usage management in the monitored environment.

Experiments were carried out, and data were collected at a distance of 1 km in five distinct situations. The system collected data at various times. Figure 11 shows the average active power, current, battery voltage, and AC voltage derived from five data points obtained during an hour.

Table 1. Measurements reading of main parameters from sensors

Scenario	Pac (W)	Iac (A)	$V_{(Battery)}$ (V)	V_{ac} (V)
1	933	4.2	24.8	222.2
2	1209	5.4	24.1	224
3	1401	6.3	24.7	222.4
4	1591	7.1	24.16	224.2
5	2107	9.4	24.66	224.2

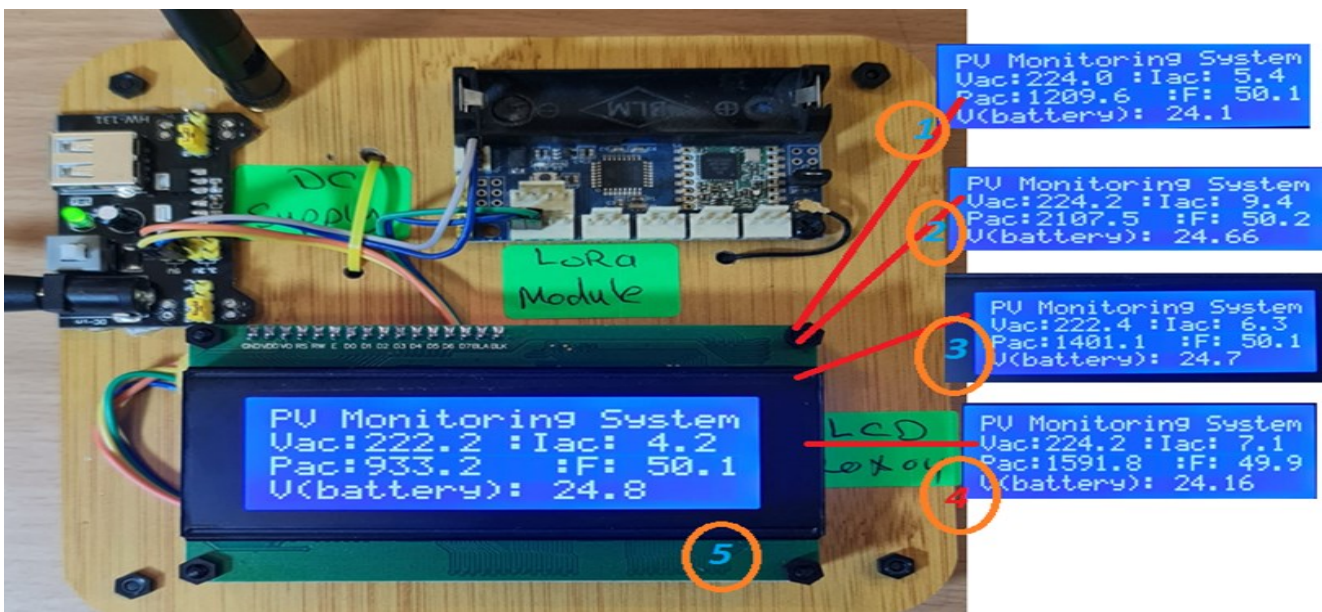


Fig. 11. Experimental results of five scenarios.

Scenario 1: with Pac (W) is 933 Watts, Iac (A) is 4.2 Amperes, $V_{(Battery)}$ (V) is 24.8 Volts, and V_{ac} (V) stands 222.2 Volts. The system consumes 933 Watts of electricity and draws 4.2 Amperes from the power source. The battery voltage was 24.8 volts, whereas the alternating current voltage was 222.2 volts. This scenario implies low power consumption with a balanced relationship between current, voltage, and power.

Scenario 2: Current consumption increased to 5.4 Amperes, and power consumption increased to 1209 Watts. The AC voltage was increased to 224 Volts, whereas the battery voltage was decreased to 24.1 Volts. This scenario suggests that there may be modifications in the operational circumstances and an increase in power demand.

Scenario 3: The power consumption increased to 1401 Watts, accompanied by a comparable increase in current to 6.3 Amperes. The momentary battery voltage was 24.7 Volts, whereas the AC voltage measures 222.4 Volts. This implies an increase in power consumption and the possibility of changing the system.

Scenario 4: There was a power consumption and a 7.1 Ampere current demand. In contrast to the previous situation, both the battery voltage and AC voltage remain constant. This suggests a persistently high power requirement in the steady-state settings.

Scenario 5: The maximum power usage was 2107 Watts, with a current draw of 9.4 Amperes. The battery voltage rises slightly to 24.66 volts, but the alternating current voltage stays at 224.2 volts. In this scenario, the system operates under greater load conditions, indicating a large increase in power consumption.

Based on the readings supplied, some inferences are made from the observed scenarios that deal with mean parameters: increasing power consumption: As scenarios advance, active power consumption (Pac) rises from 933 Watts to 2107 Watts. This indicates that the need for electrical power in the system is increasing. As the active power increased, the current (Iac) increased, suggesting a direct relationship between the power demand and the current.

Stable battery voltage: While the active power and current fluctuate, the battery voltage (V(Battery)) remains largely consistent. This stability indicated that the battery maintained a consistent level of charge and health throughout the observed conditions. Throughout the situations, the AC voltage (Vac) maintains within a very tight range (222.2V to 224.2V). This consistency is critical to ensure that the linked devices receive the voltage required to function properly.

System operating parameters: The measurements indicate that the electrical system is working within permitted limits. A rising trend in power consumption may require system optimization considerations. Investigating possibilities to

improve the energy efficiency, load distribution, or system capacity may be advantageous for long-term performance. Consideration of system dynamics and recognition patterns requires real-time monitoring of electrical characteristics. This will enable prompt intervention, preventive maintenance, and efficient electrical infrastructure management.

These findings were based on the observed patterns and correlations between readings. It is worth noting that more contextual information and a larger dataset would help provide a more detailed analysis of system performance. Also comparative table with already published article is shown in Table 2.

Table 2. A comparative results with already published article

[Reference]	Application	Communication System	Type of Sensors	Microcontroller	Monitoring System
[26], 2014	Monitoring System	ZigBee	pH Probe	Raspberry Pi	PC
[27], 2016	Monitoring System	Cable	Arduino Mega	and PC	PC
[28], 2015	Monitoring System	Wi-Fi	Webcam	Embedded Linux Board and Arduino	Smartphone
[29] 2022	Virtual Real-Time Monitoring	Wi-Fi	sensor board for measuring the variables	Embedded system gateway	efficiency of the PV system
[30] 2020	PV module	Arduino Mega	DC current, DC voltage and solar irradiance	ThingSpeak IoT Wi-Fi module 8266	Real-time monitoring system
[31] 2021	PV module	Wi-Fi	relative humidity, dust density, wind speed and solar irradiance	Blynk App	Senses PV voltage & current
[32] 2023	PV string	Wi-Fi module 8266	DC current and DC voltage	Arduino Mega NodMCU ESP8266	Low-cost Relatively complex
[33]	Internet of things (IoT), artificial intelligence (AI)	mobile application and local web server	sensors data	ESP 32	IoT low-cost monitoring, Web server system
[34] 2023	Tracking PV system	Arduino Mega 2560 Thingier.io cloud	Vmp, Imp. Voc, Isc	NodMCU ESP8266	measuring the V & I on each solar panel.

5. Conclusion

The increasing amount of photovoltaic (PV) systems for the generation of renewable energy has made monitoring solutions more crucial to ensuring peak performance and upkeep. The design and implementation of a low-cost LoRaWAN network-based PV monitoring system are covered in this paper. This highlights how crucial system optimization is in light of the rising power usage. Understanding system dynamics and encouraging proactive management need real-time monitoring of electrical characteristics, especially given the increasing popularity of solar systems.

The measurements from the PZEM-004T V3 module provided useful insights into the dynamic behavior of the monitored electrical system. The constant increase in the active power consumption (Pac) from 933 Watts to 2107 Watts indicates that the system's demand for electrical power is growing. This increase is accompanied by an increase in the

AC current, demonstrating a direct link between the power demand and the rate of electric charge flow in the circuit. Despite changes in the power demand and current, the battery voltage stability indicates a well-maintained state of charge and general health for the energy storage system. The alternating current voltage was maintained within a restricted range, emphasizing the capacity of the system to provide a steady voltage supply to the connected devices, ensuring optimal performance. These data suggest that the electrical system functions within acceptable parameters under reported conditions. The stability of important electrical characteristics, together with the continued health of the battery, demonstrate the resilience of the system under shifting load situations.

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