Data Acquisition of Photovoltaic Systems Using Wireless Communication – LoRa

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Abstract

The project develops a wireless communication tool based on the LoRa (Long Range) protocol and Internet of Things (IoT) devices for the predictive monitoring of photovoltaic (PV) systems in real-time, prioritizing energy efficiency and data transmission reliability. Utilizing four ESP32 LoRa devices, in addition to sensors and a Raspberry Pi, critical performance data are collected, including the temperature of five PV modules, voltage and current injected into the electrical grid, irradiation, ambient temperature, and relative air humidity. Implemented in a 52.5 kWp power plant, the system forms a robust multi-hop LoRaWAN network with four data collection stations, aiming for the rapid identification of faults and the continuous optimization of system productivity. Wireless radio frequency data transmission enables a scalable and cost-effective network, eliminating the need for cabling infrastructure and allowing system installation in remote and difficult-to-access areas. The automated monitoring and distributed data collection facilitate efficient management and the early detection of inappropriate operational conditions.

Keywords: Photovoltaic Monitoring, Data Acquisition System, LoRa Communication, Wireless Sensor Network, Internet of Things.

1. Introduction

The energy transition has reached a historic milestone: for the first time, global electricity generation from renewable sources has surpassed that generated by coal. This achievement, mainly driven by photovoltaic (PV) and wind power, reinforces the decarbonization trajectory and establishes a new paradigm for the world's electricity matrix (DW, 2024). In this scenario of structural changes, the solar energy market stands out. The global PV market is rapidly expanding, with projections indicating substantial growth in 2025. According to the "Global Market Outlook For Solar Power 2025 – 2029" report, globally added PV capacity is expected to reach approximately 655 GW by the end of 2025 (Solar Power Europe, 2025; Portal Solar, 2025). PV and wind power are expected to meet three-quarters of the growth in global electricity demand between 2024 and 2025 (Portal Solar, 2024).

In such context, PV systems performance optimization is crucial to ensure the operation at the maximum efficiency (Garcia-Valle et al., 2022). However, this efficiency is sensitive and susceptible to reduction due to the influence of environmental variables and electrical parameters. One way to improve the productivity of PV systems is through the implementation of monitoring systems. These systems can have reduced financial costs if their operation is based on IoT devices. Hence, IoT-based PV monitoring systems allow real-time data acquisition, lowering costs and enabling remote analysis of efficiency and fault detection (Dupont et al., 2018), by measuring electrical parameters, module temperature, and environmental data (Costa et al., 2021).

We propose the development of a Real-Time Data Acquisition and Monitoring System for PV Plants utilizing IoT technologies, based on LoRa communication, through a sensor network connected to ESP32 LoRa devices

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that form a multi-hop LoRaWAN network. The proposed system monitors electrical parameters (current, voltage, power), ambient and module temperature, solar irradiance, and relative humidity, and is implemented in a 52.5 kWp PV plant. The main components are shown in Figure 1.

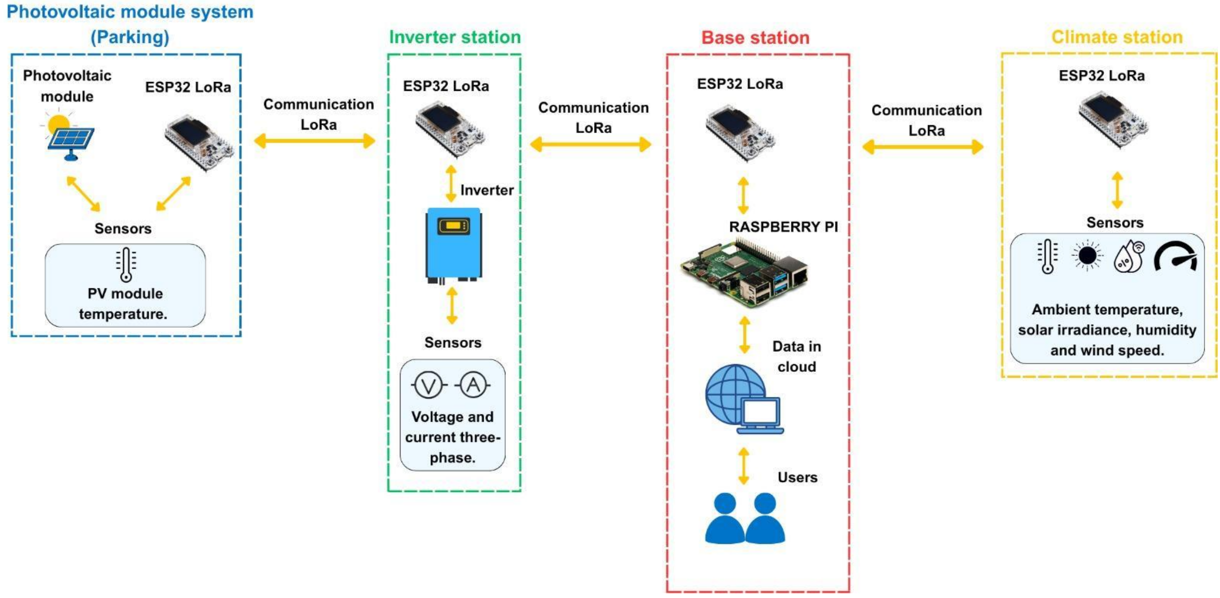


Figure 1: Main components of the LoRa data collection network (Font: Autor,2025).

2. IoT Monitoring System

The monitored plant is installed at the Federal Institute of Education, Science and Technology (IFCE), Limoeiro do Norte Campus (5º8’44” S 38º5’37” W), in the state of Ceará, Brazil. The system is divided into four data collection stations: PV System, Inverter, Weather and Base Station. Due to the equipment layout and structural constraints, wired communication between the stations is unfeasible. Figure 2 shows the location and the distances between the stations.

Figure 2: Data collection stations and distances. (Font: Author, 2025).

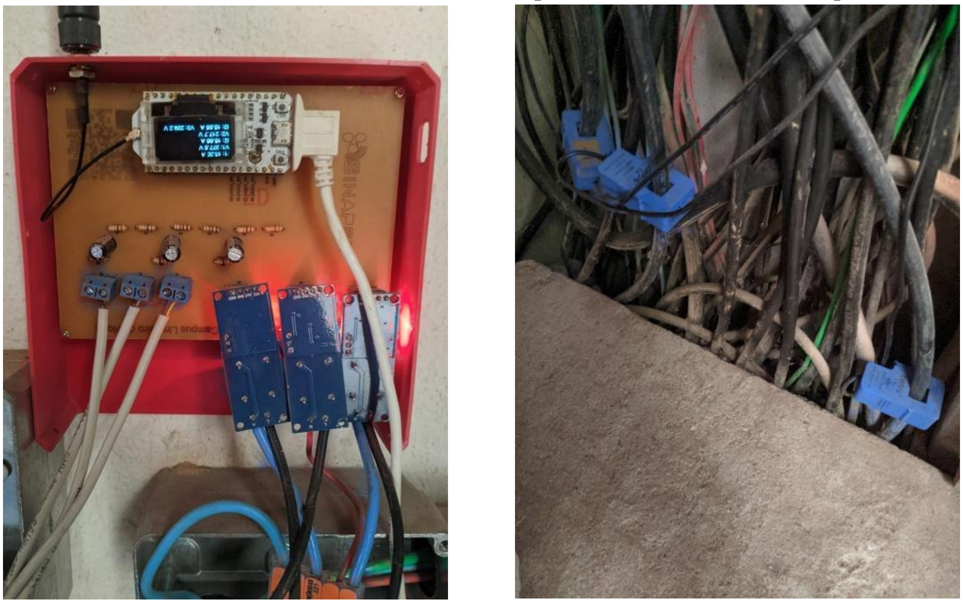
Traditional PV monitoring systems have high costs, proprietary software, and limitations on expansion and long-distance communication (Pereira et al., 2019). By using devices with IoT technology and LoRa wireless communication, a low-financial-cost system can be developed, based on free hardware and software, communication between devices even in remote areas, expansion possibility, and real-time monitoring of collected data. The following items describe the design of each data collection station, highlighting its structure, hardware, and sensors.

2.1 – Base Station

The Base Station has no sensors but is responsible for collecting parameters from the other stations, having an Esp32 LoRa board that communicates with the other devices at all stations and serially with an Rpi (Raspberry Pi). The station's function is to concatenate and process the collected data and send it to an online website where all collected data can be monitored in real time.

2.2 – PV Inverter

The Inverter station collects electrical parameters at the output of a DCWB-SX2-TRIO-TM-50.0-400 three-phase PV inverter connected to a set of strings with a total power of 52 kWp. Monitoring electrical data in grid-connected PV systems is essential to maximize production, ensure safety, maintain grid stability, and extend equipment life, providing valuable insights for ongoing operation and maintenance. The voltages and currents of the three phases (R, S, T) of the inverter output are monitored using three ZMPT101B AC voltage sensors and three SCT-013 non-invasive AC current sensors (both with IoT device connection capabilities). A PCB board is designed to condition the sensor signals and connect to an Esp32 LoRa device (Figure 3a). Figure 3b shows the three SCT-013 current sensors installed in each phase of the PV inverter output.



(a) (b)

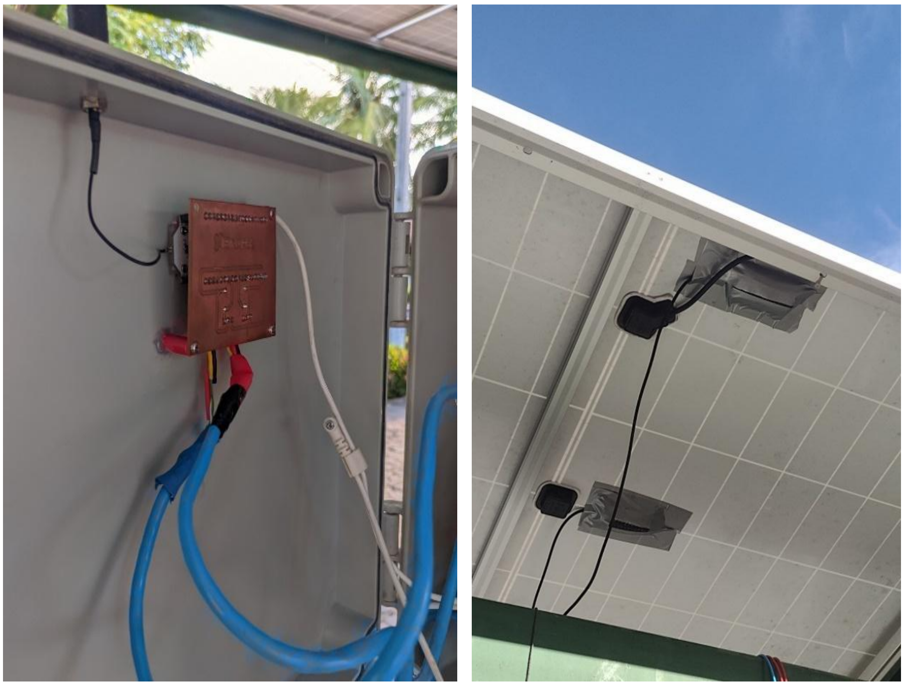
Figure 3. (a) PCB board for connecting the Esp32 LoRa and conditioning the sensors. (b) SCT-013 sensors installed in each phase (R, S, T). (Font: Author, 2025).

2.3 PV System

Temperature monitoring in photovoltaic (PV) modules is crucial, as operating temperature is a critical factor for conversion efficiency and system performance (Pereira et al., 2019; Santos et al., 2024).
The choice of PV panel temperature monitoring strategy significantly influences the analysis and validation of the collected parameters (Santos et al., 2022).

Therefore, it was decided to monitor the central and edge temperatures of five modules using ten DS18B20 digital sensors with IoT connectivity, forming a One-Wire bus. The end of the bus is connected to an ESP32 LoRa device, responsible for sending temperature data. The monitoring layout is shown in Figure 4; Figure 5a shows the PCB board with the sensor conditioning system and the connection to the ESP32 LoRa; Figure 5b shows two DS18B20 sensors installed in a module (central and edge) with thermal protection to prevent disturbances, giving the system greater resistance to environmental variations, humidity and physical damage.

Figure 4: Monitoring layout of modules (Font: Author, 2025).



(a) **(b)**

Figure 5. (a) PCB board for connection to Esp32 LoRa and sensor conditioning. (b) DS18B20 sensors installed on a module. (Font: Author, 2025).

2.4 – Weather Station

To strengthen the credibility of the proposed monitoring system, a Weather Station was implemented aiming to obtain environmental data: irradiance, ambient temperature, and relative humidity. Such monitoring in a PV system is crucial for assessing the local solar potential, predicting failures, verifying project data, and optimizing PV conversion efficiency; additionally, the monitoring allows for a more comprehensive analysis of the variables effect on PV module performance (Dupont et al., 2018), (Pereira et al., 2019). All sensors in the weather station are connected to an Esp32 LoRa module via a signal conditioning PCB.

A SPEKTRON 210 Sensor (Figure 6a) is used to measure irradiance at the modules plane (POA – Plane of Array). Since this sensor lacks IoT connectivity and has a very low output voltage level, calibrated at 76.29 mV for 1000 W/m², a signal conditioning system was developed using an LM358 operational amplifier, increasing the voltage level and thus achieving better accuracy for the Esp32 LoRa ADC input. Ambient temperature and relative humidity are measured by a DHT22 digital sensor (Figure 6b), which has IoT device connectivity and performs temperature measurements in the -40°C to +80°C range, with a typical accuracy of ±0.5°C and a resolution of 0.1°C; for relative humidity, the sensor operates between 0% and 100%, with an accuracy of ±2% and a resolution of 0.1%. To ensure that the data represents real-world environmental conditions as accurately as possible, the sensor is installed inside a weather shelter, isolating it from any interference such as sunlight or heat from the sensor itself.

(a) **(b)**

Figure 6: (a) SPEKTRON 210 sensor; (b) DHT22 sensor inside a weather shelter (Font: Author, 2025).

All sensors comply with the accuracy classes required by the international guideline (IEC 61724-1) that establishes rules for monitoring and calculating the PV performance (IEC, 2021); the sensors underwent a rigorous calibration process, adjusting their presented values with other reference instruments. A summary of the devices at each data collection station is shown in Table 1.

Table 1: Devices at the data collection stations.

Station	Monitored Data	Sensors	IoT devices
PV Station	Temperature of five PV modules (Center and Edge)	10 - DS18B20	1 -Esp32 LoRa V2
PV Inverter	Three-phase voltage and current, Power	3 – ZMPT101B (voltage); 3 – SCT-103 (current)	1 -Esp32 LoRa V2
Weather Station	Solar irradiance, ambient temperature and relative humidity.	1 -Spektron 2010 (irradiance) 1 - DHT22 (ambient temperature and relative humidity)	1 Esp32 LoRa V2
Base Station	Concatenation of data from all stations.	-	1 Esp32 LoRa V2 1 Raspberry Pi 4

The hardware of the developed system has significantly reduced costs due to the use of IoT devices and sensors compatible with these devices. ESP32 LoRa and RPI boards enable the use of open-source hardware and software, wireless communication, connections to low-cost components (sensors), and expansion flexibility.

Factors that influence project cost reduction with the use of IoT technologies compared to traditional systems are summarized in Table 2.

Table 2: Factors influencing costs reduction when using IoT technology in PV monitoring projects.

Feature	IoT Technology	Traditional Systems
Hardware/Software Cost	Low Cost - Use of free (open source) hardware and software	High Cost - Dependence on imported commercial dataloggers and modules and proprietary software
Communication	Wireless (LoRa) - Eliminates the need for communication cables	Usually wired - Unfeasible or expensive over long distances or with obstacles
Network Infrastructure	Reduced - Long range with few gateways	More complex and expensive (traditional mobile networks or Wi-Fi)
Expansion	Ease of network expansion and connectivity	Expansion limitations and sensor connections

3. LoRaWan Network

The network between the monitoring system stations uses the wireless communication technology LoRa, which was chosen due to several factors:

- Good connection with IoT devices.
- No use of cables.
- Some points in the network have no internet access, so data collected at these points is sent to a point that has.
- Due to the buildings physical structure, the network stations are far apart and surrounded by obstacles, requiring wireless communication.

The multi-hop LoRaWAN topology is applied, using relay devices to expand coverage and reduce physical obstacles, especially in dense rural and urban areas. The introduction of relay devices as micro servers also allows for the decentralization of network functions, increasing scalability and reliability (Cotrim & Kleinschmidt, 2023). The multi-hop LoRaWan network is shown in Figure 7; Station 2 – Inverter acts as a relay-device, transmitting not only its information packets, but also retransmitting the packets from 3 (PV Station).

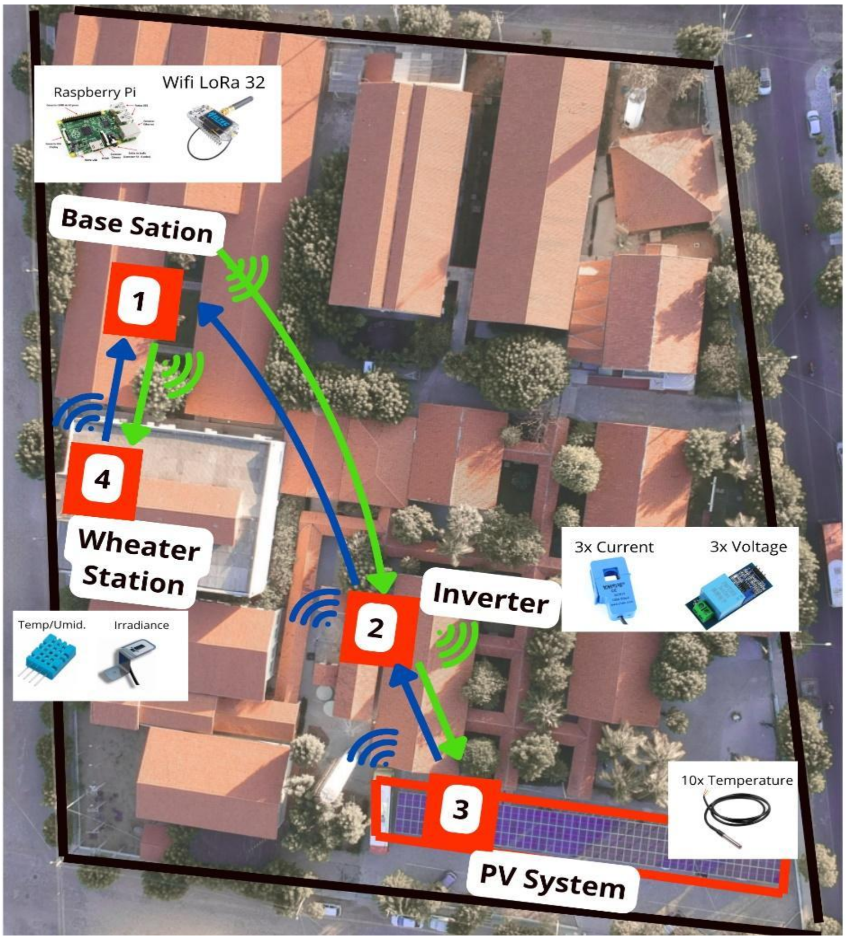


Figure 7: LoRaWan Netwok Multi-hop (Font: Author, 2025).

The PV plant monitoring system consists of four main nodes, each responsible for a stage of data collection and communication: "1 - Base," "2 - PV Inverter," "3 - PV System," and "4 - Weather Station," interconnected via four ESP32 LoRa devices and a Raspberry Pi (RPi) acting as the control center. 1-Base is the network core, consisting of an RPi connected to an ESP32 LoRa that acts as a gateway. This node coordinates communication between the other devices and stores the information in a local and online database. Every 10 minutes, the RPi sends a command to the gateway, which requests data from the other nodes via encrypted packets via a LoRa signal. If there is no response within 10 seconds, further attempts are made, with a limit of 50 retries.

2 - PV Inverter performs the inverter output monitoring, measuring the voltage and current injected into the grid. Between communication intervals (10 minutes), data is continuously collected and averaged. Upon receiving a request from the Base, this node also acts as a repeater, activating the hop function and forwarding the data request to the third node (3 - PV System). 3 - PV System performs thermal sensing of the PV modules using 10 DS18B20 sensors, distributed at strategic points. With each request, it sends the average temperature values collected every 10 minutes to node 2; at node 2, the temperature data is then combined with the voltage and current data before being sent to the gateway. 4 - Weather Station collects environmental data, including irradiance, ambient temperature, and relative humidity. Like the other nodes, it averages data every 10 minutes and sends the data to the gateway upon request.

1 - Base centralizes data acquisition, integrating the module temperature measurements, voltage, current, and weather variables. Transmission is then made via a serial interface to the RPi, which processes the data and saves it to a Google Sheets spreadsheet hosted on the cloud computing architecture. For real-time system monitoring, an interactive dashboard was developed using the Looker Studio tool, which allows instant viewing of operational data through a website monitor. The interface of the website monitor is shown in Figure 8, which can be accessed at www.sinapse.ifce.edu.br.

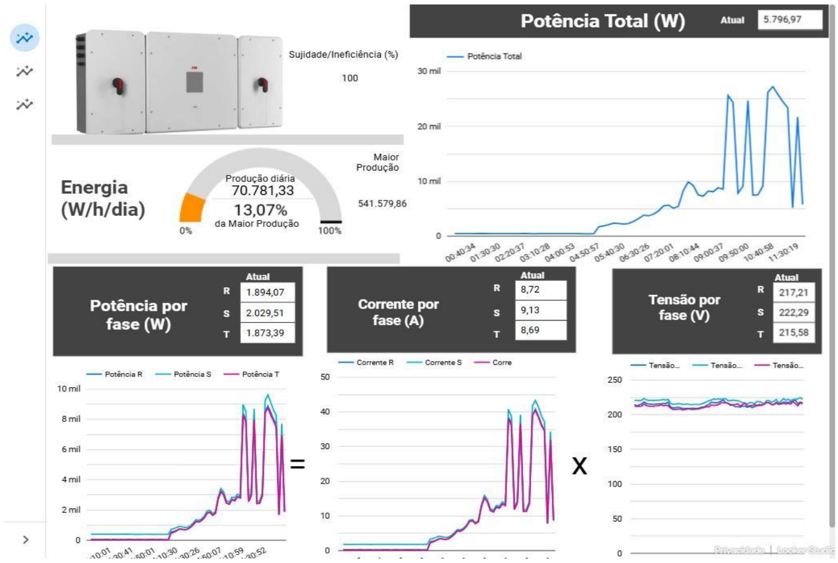


Figure 8: SINAPSE monitoring website interface.

4. Results

According to Ceará Foundation for Meteorology and Water Resources (FUNCEME), the state of Ceará has two distinct seasons: a dry season, usually from July to December, characterized by clear skies, high temperature and irradiation values, and low humidity, causing drought; a rainy season, usually from February to May, bringing rainfall for the state's water recharge (FUNCENE, 2013). To validate and ensure the reliability of the data collected by the proposed monitoring system, two days are chosen for analysis: October 9th 2025, in the dry season, and March 24th 2025, in the rainy season. Figure 9 shows irradiance values for the first day, with an average daily irradiation of 6.2 kWh/m^2 and a maximum irradiance of 1013.6 W/m^2 around 11:30 a.m., characterizing the local dry season.

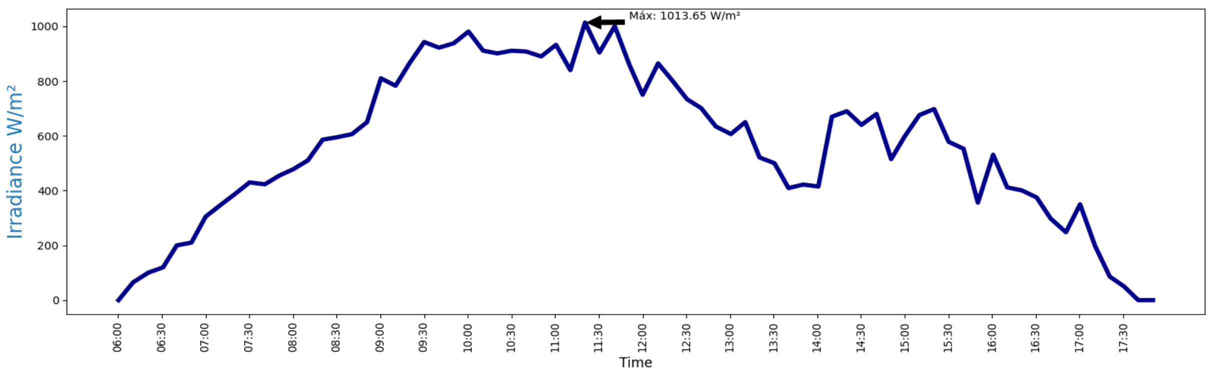


Figure 9: Irradiance data - October 9th (Font: Author, 2025).

PV plant power of October 9th is shown in Figure 10, reflecting the irradiance curve of the day.

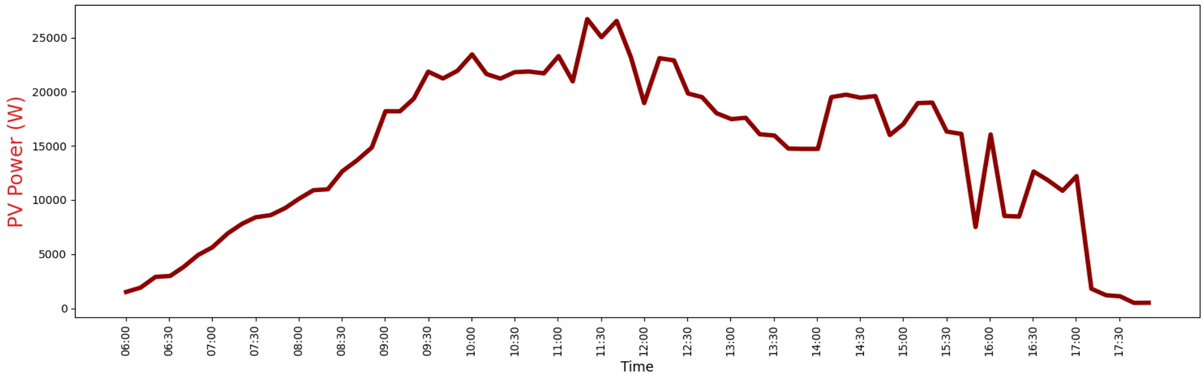


Figure 10: PV plant power - October 9th (Font: Author, 2025).

PV modules center and edge temperatures are shown in Figure 11; edge1 sensor recorded a maximum temperature of 77,8°C.

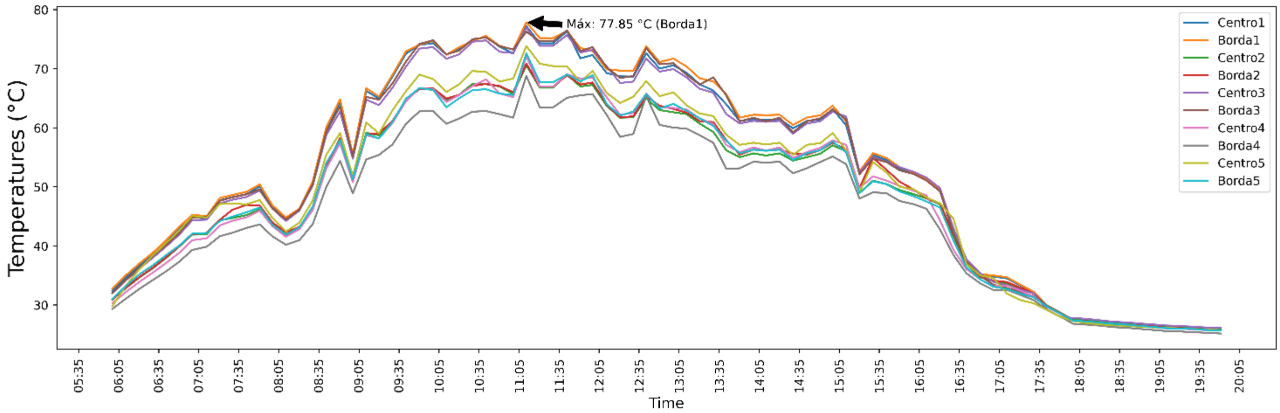


Figure 11. PV modules center and edge temperatures - October 9th (Font: Author, 2025).

Irradiance data of March 24th, 2025 is shown in Figure 12; the average irradiation is 4.1 kWh/m², with a peak value of 887,2 W/m² around 13:00 p.m., confirming the rainy season.

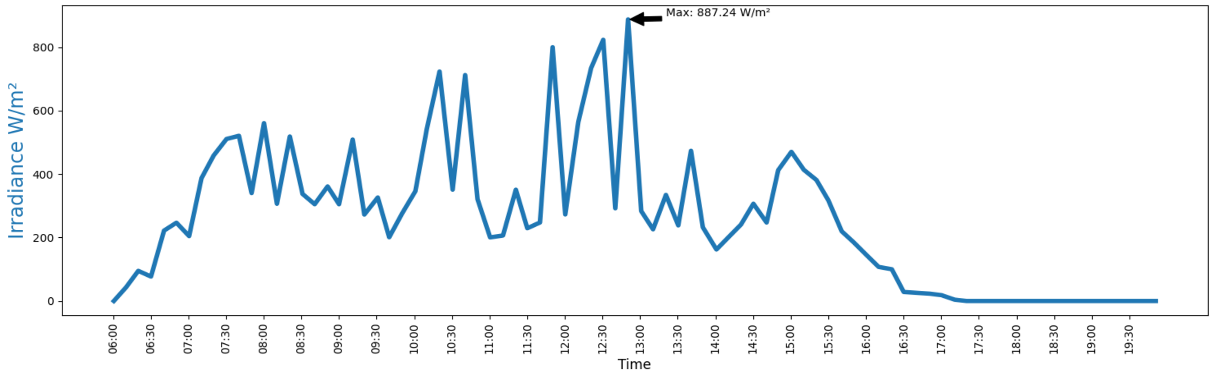


Figure 12: Irradiance data - March 24th (Font: Author, 2025).

PV plant power is shown in Figure 13, reflecting the irradiance data.

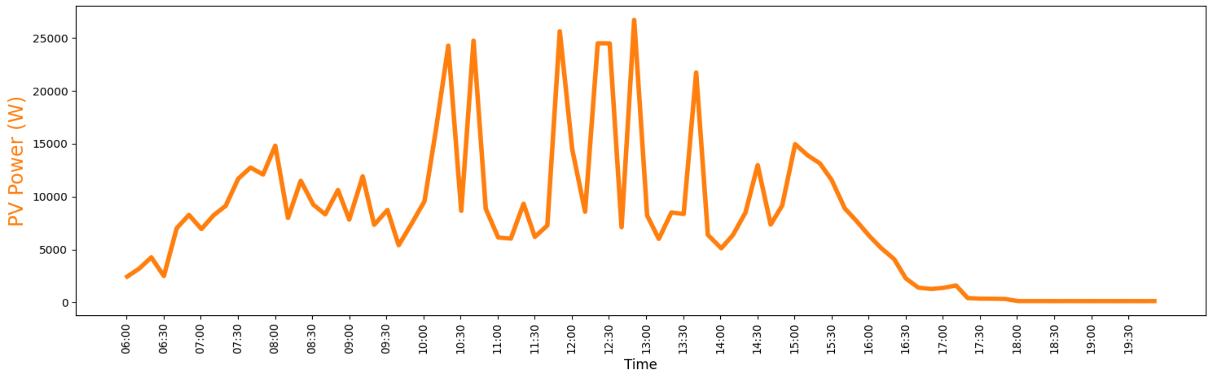


Figure 13: PV plant power - March 24th (Font: Author, 2025).

Center and edge temperatures of the five modules monitored are shown in Figure 14; a peak temperature of around 76.1°C is identified.

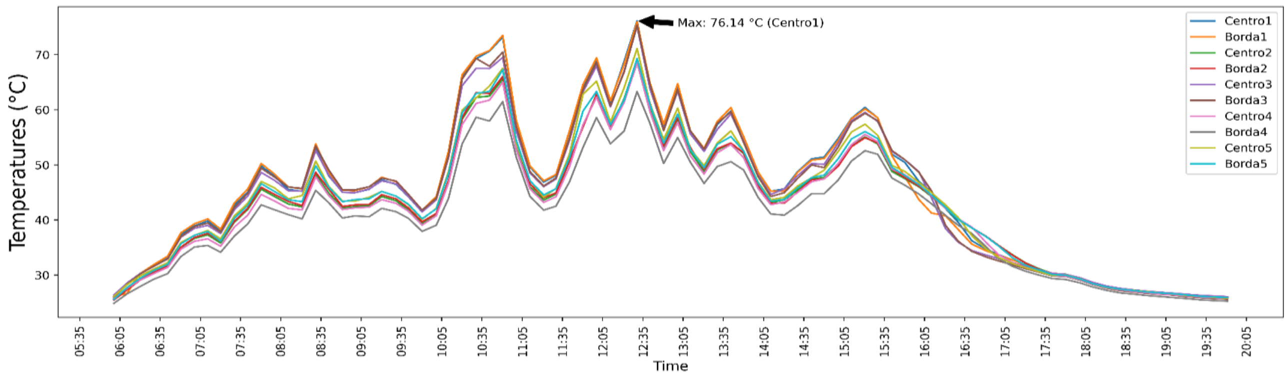


Figure 14: PV modules center and edge temperatures - March 24th (Font: Author, 2025).

Ambient temperature and relative humidity values for the two days are shown in Figure 15. March 24th shows high relative humidity; ambient temperature data is lower compared to data of October 9th.

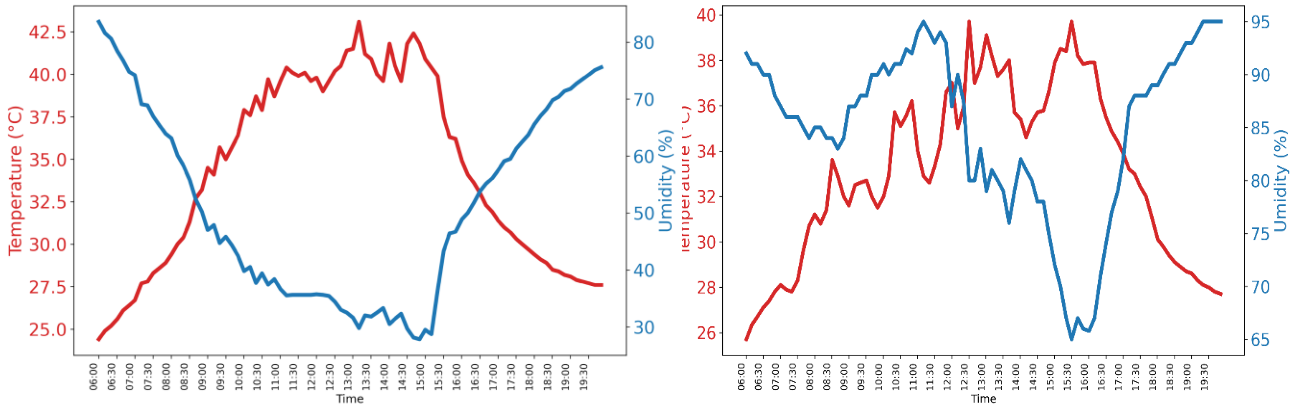


Figure 15: Ambient Temperatures and Relative Humidity - October 9th and March 24th (Font: Author, 2025).

5. Conclusions

The IoT-based monitoring system developed demonstrates good performance and accuracy; the IoT hardware architecture is robust, and the instrumentation shows low error in parameter collection (2% to 5%), in compliance with the IEC 61724-1 standard. The LoRaWAN network operates with high reliability and a very low data loss rate (approximately 5%). A comparative analysis between the parameters collected on October 9th (dry period) and March 24th (rainy period) of 2025 shows a satisfactory performance.

October 9th: characterized by clear skies, low humidity, high temperatures, an irradiance peak of 1013.6 W/m² at 11:30 AM and an average daily irradiation of 6.2 kWh/m². PV power follows the irradiance profile, reaching a peak between 11:00 AM and 12:30 PM. Central and edge temperatures of the five monitored modules show a peak of 77.8°C at module 1 edge sensor around 11:10 am. March 24th: Characterized by cloudy skies, a maximum irradiance peak of 887,2 W/m², an average daily irradiation of 4.1 kWh/m²; PV power is lower compared to October 9th. Central and edge temperatures of the modules average below 60°C, despite the peaks; large temperature differences between modules center and edges are identified, indicating possible peripheral thermal stress and hot spots formation, which can be caused by dirt.

The IoT-based PV monitoring project developed is crucial for optimizing performance; the high reliability of the LoRaWAN network, combined with real-time parameter monitoring, is vital for identifying anomalies, ensuring stability, reducing costs, and providing a database with valuable information for future research on PV monitoring and forecasting.

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