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Design and validation of IoT measurement system for photovoltaic generation

Diseño IoT y validación de sistema de medida para generación fotovoltaica

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Abstract

Use photovoltaic (PV) systems for electricity generation is constantly growing in Brazil. With the reduction in the price of PV modules and the implementation of the electric power compensation system by the power distributor, the consumer is investing in PV microgeneration to reduce the power bill. This article aims to develop an embedded system in the context of the Internet of Things (IoT). Having an IoT monitoring system applied to a grid-connected PV system in an educational institution helps teach IoT and PV generation concepts. The system is based on the ESP32 development board for acquiring DC voltage and current generated by a 1.35 kWp photovoltaic system connected to the grid and installed at the IFCE. This proposal offers a low-cost educational solution using open source and programmable hardware, which sends the data to a database in the cloud, allowing remote access worldwide. Then, using the data analysis methodology, it was possible to validate the values measured with the inverter installed with an error of less than 1% for the voltage and current acquired during one day. With this result, it is concluded that the designed IoT system can be used for measurement in PV systems.

Keywords: ESP32, IoT, measurement, photovoltaic, energy, generation

Resumen

El uso de sistemas fotovoltaicos (FV) para la generación de electricidad está en constante crecimiento en Brasil. Con la reducción del precio de los módulos FV la implementación del sistema de compensación de energía eléctrica por parte del distribuidor de energía, el consumidor está invirtiendo en microgeneración FV para reducir la factura de energía. El objetivo del presente artículo es desarrollar un sistema embebido en el contexto de Internet de las cosas (IoT). Tener un sistema de monitoreo IoT aplicado a un sistema FV conectado a la red en una institución educativa ayuda a enseñar conceptos tanto de IoT como de generación FV. El sistema se basa en la placa de desarrollo ESP32 para la adquisición de tensión y corriente continua generada por un sistema FV de 1,35 kWp conectado a la red e instalado en el IFCE. Esta propuesta ofrece una solución educativa de bajo costo, utilizando código abierto y hardware programable, que envían los datos a una base de datos en la nube, lo que permite el acceso remoto en todo el mundo. Utilizando metodología de análisis de datos, fue posible validar los valores medidos con el inversor instalado con un error inferior al 1% para la tensión y la corriente adquiridas durante un día. Con este resultado se concluye que el sistema IoT diseñado puede ser utilizado para la medición en sistemas FV.

Palabras clave: ESP32, IoT, medida, fotovoltaica, energía, generación

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1. Introduction

The first modern solar cell, measuring just two square centimeters in area, was introduced in 1954 with 6% efficiency and five mW of power, as described in [1]. A significant advance in the development of the PV market, identified in [2], was observed from the increase in Chinese production. For the eighth consecutive year, Asia eclipsed all other regions for new installations, accounting for nearly 58% of global additions; even excluding China, Asia was responsible for around 23% of new capacity in 2020. Asia was followed by the Americas (18%), which moved ahead of Europe (16%). China continued to dominate the global market (and solar PV manufacturing), with a share of nearly 35% (up from 27% in 2019). In 2021 the estimated global capacity was 760 Gigawatts, as shown in [3].

In addition to reducing the cost of PV modules, distributed generation in Brazil has become an attractive investment in solar energy. Currently, the consumer can generate electricity and use the compensation system to reduce the cost of energy consumed directly on the bill. Compensation allows the energy exceeding consumption for that month to be used within a maximum period of up to five years. The conditions for connection to the conventional electricity distribution structure were established on April 17, 2012, by the National Electric Energy Agency [4].

Knowing how much the PV system will generate per month is one of the first concerns of the final consumer. The engineer designs the system, but external factors such as dirt, system failures, material wear, and weather conditions can alter the energy generation estimated in the original design. With a monitoring system applied to the PV generation system, it can monitor the production and consumption of electricity. This way, it is possible to identify non-standard behaviors for that system: the faster this identification, the minor damage to the final consumer.

Regarding data monitoring via the Internet, the number of devices connected to the cloud is increasing, and, consequently, the volume of data has grown substantially. Our daily lives are surrounded by constantly updated information. When a status on a social network is changed, there is an information feed, which generates updates to the user's database. This dynamic way to get information quickly, accessible, and up-to-date does not just apply to social media or journalism. Considered the fourth industrial revolution, Industry 4.0 has been gaining prominence and promises to have a more profound and exponential impact than previous industrial revolutions. One of the industry's pillars 4.0, according to Vitalli [5] is the Internet of Things (IoT, English Internet of Things). Among the devices available on the market for IoT applications are the ESP32 and ESP-WROOM (model used in this work), which are constantly used in academic research because of their easy programming.

IoT systems are applied to facilitate communication between equipment and human beings in various areas, such as hospitals [6], manufacturing processes [7], waste management [8], as well as renewable energies [9] - [10].

The ESP32 development platform has been used in IoT projects around the world. Then, to enable multimedia data transmission via Wi-Fi, this device was used to compose a hybrid communication system and data transmission system in IoT networks [11]. In addition to Wi-Fi communication, the ESP32 also features Bluetooth communication. A vehicle window control system was developed in [12] using Bluetooth communication.

ESP32 was also used in a data center's temperature, humidity, and air quality monitoring network to automate the activation and deactivation of the cooling, ventilation, and air filtration system [13].

1.1. Related Works

The ESP32 and ESP8266 were used to build an IoT network to measure weather data and the temperature of PV modules in [14]. The communication used between the ESP32 and the ESP8266 was Wi-Fi.

A comparative analysis and practical application of the ESP32 microcontroller module for IoT was illustrated in [15]. The article demonstrated that ESP32 is an excellent option for IoT systems, as it presents advantages in performance and price compared to the others analyzed. Its performance reflects its reliability, ensuring the system is always up and running. Thus, they can be used in critical systems such as the one proposed in [16] for monitoring liquefied petroleum gas (LPG) leakage.

In PV systems, ESP32 was used in a water pumping control system powered by a solar generator [17]. A web server using ESP32 was developed in [18] to monitor and collect data from a PV system. Data was stored in a text file and saved directly to the SD memory card. The data can be retrieved, and the text file downloaded onto a web page.

It was possible to verify the real behavior of the PV modules using low-cost components, as can be seen in the tracking system of IV (Current-Voltage) and PV (Power-Voltage) curves built-in [19]. It is also possible to monitor the PV system using low-cost equipment [20] - [21]. This work proposed the development and validation of IoT system didactic with programmable and open-source hardware, aiming at greater flexibility in data collection and submission to a database. Validation was done from a commercial inverter with IoT technology. Just as the software was used in [22] to support teaching, the system designed in this research can be used in the classroom to teach embedded systems, the internet of things, or renewable energy as an example of a didactic monitoring system.

Some articles that used monitoring systems, applied or not to PV generation, were gathered in Table 1. The use of internet connection through different devices for data communication, processing, and sending was observed. Most of the articles presented (67%) did not use a validation system for the data collected, especially in systems for measuring electrical variables (voltage and current, for example), as in the case of this work, showing the contribution of this paper in this area.

Table 1. Comparison of monitoring articles similar to this

Article	Device	Validation method
[23]	SamD21G	Not applicable
[24]	Arduino Mega 2560 + ESP8266	Not applicable
[25]	ESP32	By commercial equipment
[26]	34970A	Not applicable
[20]	Raspberry Pi	Not applicable
[21]	SanUSB + Wi-Fi modem	VA6510 temperature sensor

Alves et al. [27] analyzed a situation using Didactic Training Engineering (DTE) and found that this structure facilitates didactic mediation and learning. The proposal system can be used for DTE in renewable energy, programming, or embedded system. Another application for this project is in Professional Didactics (PD). Alves [28] accentuated the use of technology to provide an understanding of the notions discussed in the class. Similarly, the teachers could iterate with the students using the proposed system in this work.

This research aims to design, develop and validate a didactic IoT system for monitoring the voltage and current generated by the PV modules. The focus of this research is to develop a didactic system, easy to reproduce to disseminate knowledge in this area of research, facilitating the acquisition of data in photovoltaic solar generation plants. Low-cost sensors for measuring PV system current and voltage are applied. The data obtained were compared with the data collected by the installed PV inverter, checking the error between the systems to validate the developed system.

The system developed in this research can be applied to verify the real power generated for PV plants in [29], for example.

2. Materials and methods

2.1. Problem and Methodology

This section presents the project development stages, exposing the materials and methods used. The proposed system can be divided into 5 (five) parts:

1. Embedded system with Wi-Fi connection
2. Cloud data storage
3. Sensing
4. Data provided by the inverter
5. Embedded system programming.

2.1.1. Embedded system with Wi-Fi connection

Several low-cost devices can provide internet connection and perform pre-programmed actions. With these devices, it is possible to transform a local data acquisition system into an IoT system that constantly feeds a cloud database.

The Raspberry Pi family of devices, developed in the UK by the Raspberry Pi Foundation, has hardware built into a single card and card slot memory, USB interface, HDMI, input/output pins, serial interface, and built-in Wi-Fi modem [30]. These devices can be easily integrated into an IoT network. A Raspberry was used in [31] to monitor current and voltage in a PV pumping plant.

Some devices from the Arduino platform [32], such as the ARDUINO UNO Wi-Fi REV2, are specially designed for IoT applications. These devices have a user-friendly programming platform (Arduino IDE) in C ++ with minor modifications.

Other devices widely used due to their low cost are the microcontrollers manufactured by Espressif [33]. These controllers, like the ESP32, allow microcontrollers to connect to a wireless network. The manufacturer provides some hardware versions for use as needed.

A comparison between ESP32 and a previous version of Espressif IoT modules (2014) ESP8266 is shown in Table 2.

Table 2. Comparison between ESP32 and ESP8266

ITEM	ESP32	ESP8266
Clock	160 MHz	80 MHz
Wi-Fi	Yes	Yes
Bluetooth	Yes	No
RAM	512 KB	160 KB
FLASH	16 Mb	16 Mb
ADC	18	1
DAC	2	0

ADC – Analog/Digital
DAC – Digital/Analog Converter

Note that ESP32 has more excellent processing and storage power compared to ESP8266. So, in this research, ESP32 was used for the proposed monitoring system in order to connect the monitoring system the Internet.

2.1.2. Cloud data storage

Some solutions available on the market are AWS IoT Services (Amazon Web Services), CloudMQTT, and Ubidots. AWS IoT is a specialized service, from the edge to the cloud, in IoT technology offered by the company Amazon [34].

CloudMQTT is a service that aims to facilitate sending messages through the MQTT protocol between devices in an IoT system. 24/7 support offers free connection for five users at a speed of 10 Kbit/s [35].

Ubidots is a platform that allows it to connect hardware and/or digital data services to the cloud with its easy-to-integrate API. It has an editable platform for the project's needs and a free mobile application. It has an educational license with the right to connect up to twenty devices with up to ten sensors each [36].

This work, however, proposes the creation of a system like the one used in [7]. But without the use of local storage on an SD card. All data is sent to a cloud server for comparison with data provided by the inverter installed in the PV system.

ThingSpeak™ [37] is a free and configurable analytics platform service often used for prototyping IoT systems that allow you to aggregate, visualize and analyze real-time data streams with cloud storage. ThingSpeak provides instant views of data posted by its devices in ThingSpeak's database through a web platform made available to users. Therefore, this work used the ThingSpeak platform for data storage in the cloud.

2.1.3. Sensing

For power analysis, two variables are essential: voltage and current. The PV system used in this work comprises a set (string) of five PV modules in series, totaling 1.35 kWp. Some technical characteristics of the Jinkosolar PV modules (2019) used can be seen in Table 3.

Table 3. Electrical characteristics of the PV module used in this work

ITEM	STC	NOCT
Maximum Power ()	270 Wp	200 Wp
Maximum power voltage (Vmp)	31.7 V	29.4 V
Maximum power current	8.52 A	6.80 A
Open circuit voltage (Voc)	38.8 V	35.4 V
Current short circuit current	9.09 A	7.38 A
Maximum Series Fuse Rating	15 A	15 A

STC - Standard Test Conditions
NOCT - Nominal Operating Cell Temperature

The voltage measurement of the modules was made at the DC input of the inverter. The open-circuit voltage, the highest voltage supplied by the system, can be calculated by Equation (1):

$$V_{OUTPUT}(max) = 5 * 38.8 = 194V \quad (1)$$

The voltage difference generated by the string in the PV panel (V_{FV}) is measured by the voltage divider. Knowing that the analog input ESP32 is up to 3.3 V (V_{OUT}), we can calculate the resistors for voltage divider using Equation (2):

$$R_1 = \frac{(V_{FV} V_{OUT})}{V_{OUTPUT}(max)} R_2 \quad (2)$$

For this case, $R_1 = 57.78 * R_2$. R_1 and R_2 are resistors for the voltage divider shown in Figure 1.

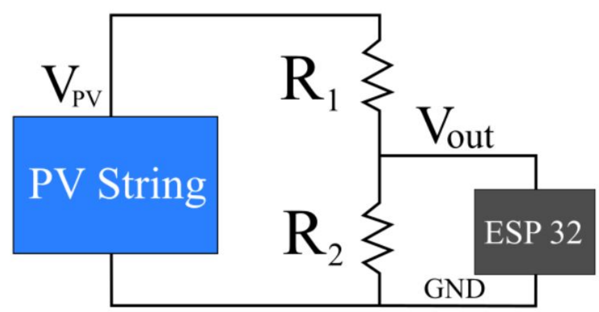

Figure 1. Schematic of the voltage divider used in the system for reading PV voltage

The V_{out} is connected directly to the ESP32 pin to measure a voltage proportional to the voltage of the PV module's string. The ratio between them is $V_{PV} = 58.79 * V_{out}$.

The current measurement is made with the 20A ACS712 current sensor module. This module is shown in Figure 2, highlighting the pin connections. The arrangement chosen for the sensor is between the inverter's DC input and the circuit-breaker box so that the measurement is made parallel to the inverter and as close as possible. Therefore, the proposed project's sensing system measures the power that the PV string provides, comparing it with that registered by the inverter for system validation.

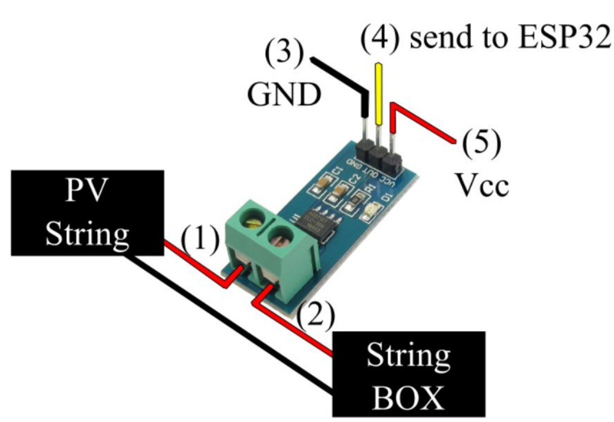

Figure 2. Installation schematic of the 20 A ACS712 current sensor module

This sensor has a 66 mV/A proportional analog output that can be read from the module output pin indicated by number four (4) in Figure 2. The operating voltage of the module is 5VDC (5). Pins one (1) and two (2) correspond to the inverter's DC input and the string box circuit breaker. Pin three (3) corresponds to the source's zero references (gnd) that supply the sensor.

2.1.4. Data provided by the inverter

The inverter used for comparing and validating the system with hardware in this work is model PHB1500-NS from the manufacturer PHB (2020). This equipment has a Wi-Fi monitoring system with real-time data available to users on the manufacturer's page via login and password. Some characteristics of this inverter grid-tie are shown in Table 4.

Table 4. PHB1500-NS inversor characteristics

DESCRIPTION	VALUE
Maximum Power	1950 W
Maximum Voltage	450 V
Generation Start Voltage (DC)	80 V
Current (DC) maximum	10 A
MPPT	1/1
AC power	1500 W
AC output voltage	60 Hz; 220 V
interface	Wi-Fi, USB and RS485

Note that this model has, in addition to interfaces for operation configuration, a Wi-Fi interface used in the monitoring system, which sends the collected data to the manufacturer's server. The manufacturer provides a page web for accessing the generation data collected by the inverter.

With the system proposed in this work, it is possible to program the protocol of how data is collected and sent to the cloud, enabling integration of this data with the user's preferred server. In this way, the user can program the time interval he/she wants and send this data to any server, for example, to research fault detection with intelligent algorithms or any research where data acquisition is necessary.

2.1.5. Embedded system programming

The use of programmable hardware (ESP32) allows the choice of this time according to the user's need and the server for sending the data, enabling future research. The firmware developed and recorded in ESP32 consists of a routine to send the average of the measurements every minute. It is shown in the diagram in Figure 3.

It can be seen from the flowchart in Figure 3 that the program starts by connecting the device to the internet via Wi-Fi to access the NTP server where they have access to local time and later sends the average value of the measurements to a server in the cloud, which in this case is the Thing Speak, every one minute.

The use of ESP32 also makes it possible to report information about the generation and eventual failures in real-time in a customized way. However, this work focuses on validating the system through comparison with the inverter data, leaving this functionality for future work.

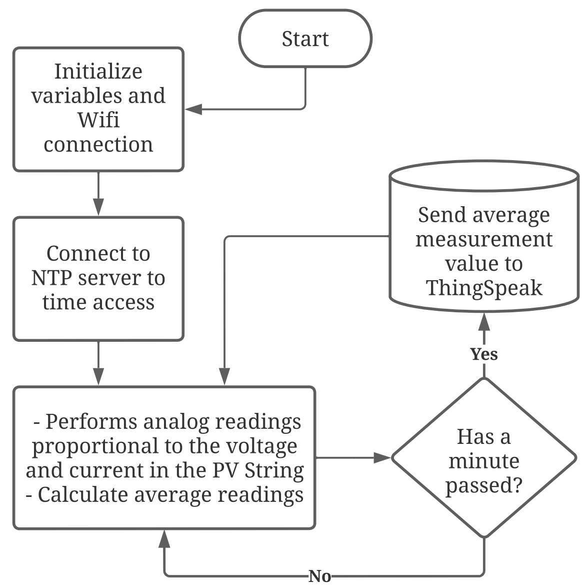

Figure 3. Flowchart of source code (firmware)

3. Results and discussion

In order to ensure the correct measurement of electrical variables, voltage, and current, tests were carried out to calibrate the sensors with the ESP32 with a digital multimeter, as seen in Figure 4.

The current sensor and the divider voltages generate voltages proportional to the current and voltage value of the string PV, respectively. The tests aim to calibrate the current sensor and voltage divider with resistors to ensure the correct proportionality between the value sent to the ESP32 and the value of current and voltage generated by the string PV. Once calibrated, this data is compared with the voltage and current values read and stored by the commercial Inverter of the PV system.

The assembly recorded in Figure 4 shows the current sensor (3) in series with a multimeter (5) between the DC input (2) of the Inverter (1) and the protection box (4), containing circuit breakers and main switch. The current, generated by the string PV, passes through the protective box and is read by the sensor, which, in turn, sends a voltage proportional to the current to one of the analog input ports of the

ESP-WROOM-32 development board (6). It will be installed in a protection frame fixed to the wall (7) to house the system developed in this work. This assembly consists of an initial prototype for laboratory testing. Subsequently, a plate was assembled to extend the ESP-WROOM-32 connections to the voltage divider and current sensor, as seen in Figure 5.

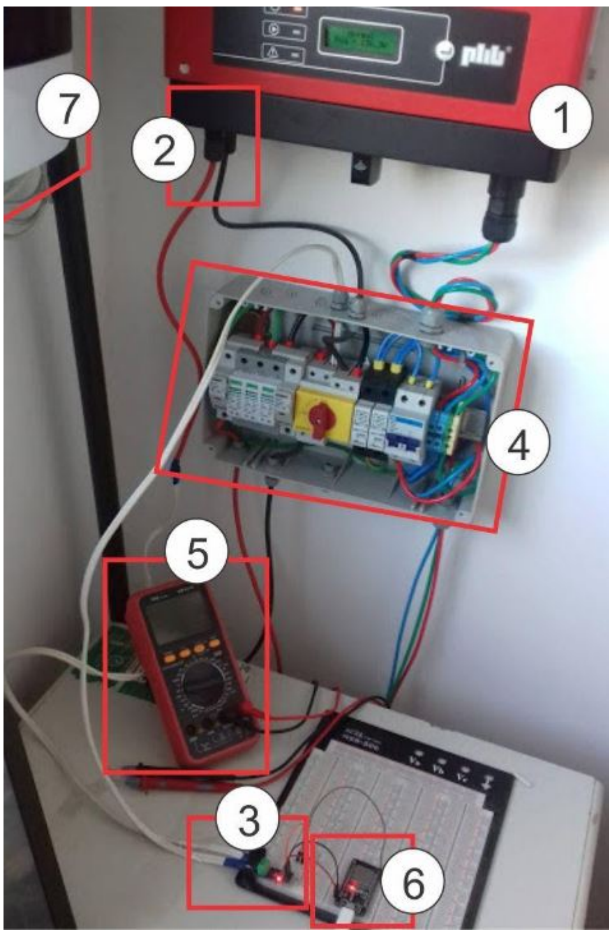

Figure 4. Installation schematic of the 20 A ACS712 current sensor module

This extension board (Figure 5 (b)) was developed to connect the voltage divider to acquire the voltage string PV and the current sensor to acquire the current generated by the string PV to the ESP32. The power to the board comes from an external 5V source (Figure 5 (a)) connected to the ESP-WROOM-32 development board. The voltage divider and the current sensor were installed inside the protection box and the main switch presented in item 4 of Figure 4 and connected to the connection board with ESP32 via network cable (Figure 5 (b)).

With the low-cost IoT system developed in this work, it is possible to obtain current and voltage data generated by the string of five PV modules in series for comparison with the data sent to the cloud by the Inverter installed in the PV plant. The comparative graph between the current values acquired by the Inverter and the IoT system developed in this work can be seen in Figure 6.

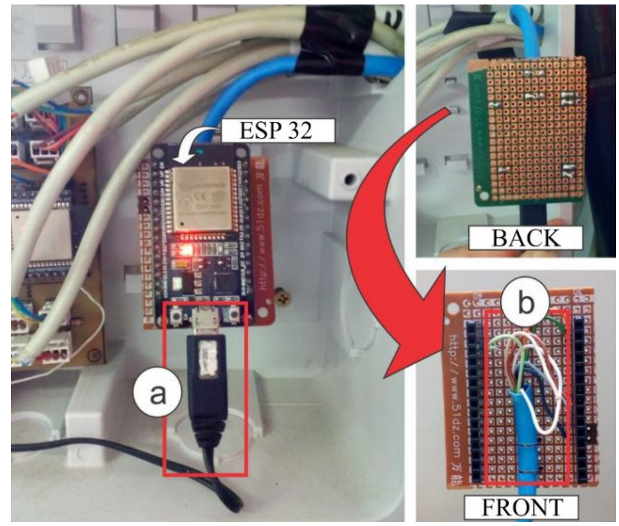

Figure 5. ESP32 and extender plate

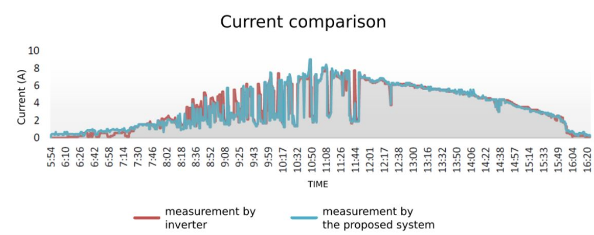

Figure 6. Comparison of current between the inverter and the proposed system

Similarly to the current, the voltage comparison can be seen in Figure 7.

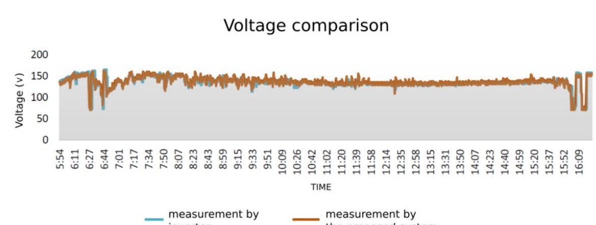

Figure 7. Comparison of voltage between the inverter and the proposed system

From the data collection by the Inverter and the low-cost system, in addition to generating the graphs shown in Figure 6 and Figure 7, the error was calculated by the sum of a defined amount of data collected by each system in the same time interval. A percent error throughout the day of less than 1% for current and voltage was obtained. On the day shown in the graphs in Figure 6 and Figure 7, an error of 0.26% for voltage and 0.56% for the current was observed.

4. Conclusions

IoT monitoring systems applied to PV microgeneration are being increasingly researched and applied, and their development is needed as PV systems continue to become a viable form of electricity generation. Modern PV inverters have IoT technology to send generation data to the manufacturer's server. However, with the system proposed in this work, it is possible to configure how this information is collected and where it is published in the cloud, generating flexibility in data collection for future research.

A low-cost didactic system using the ESP32 microcontroller development board, the ACS712 20A current sensor, and the voltage divider resistors was implemented in this work. With the system in operation, the collected data were compared with the data provided by the PV inverter, enabling the validation of the proposed system.

From the results obtained, considering that the validation showed an error was less than 1%, it can be concluded that the low-cost didactic system using ESP32 can be used to measure PV plants similar to this one. This proposed system helps teach concepts of both IoT and PV generation and encourages the academic community to research renewable energies in technical and university courses.

For future works, artificial intelligence can be applied to the data to detect failures. In addition, the proposed project can help measure and report to users and maintainers, in real-time and customized ways, the performance and any failures in the electrical generation of the analyzed PV systems.

Finally, it can be concluded that it is possible to develop and apply a didactic monitoring system with proper calibration and validation to assist academic research and teaching purposes related to IoT monitoring systems applied to installed PV plants.

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