Design and Implementation of an Accessible Monitoring System for a Wind Energy System in a Power-to-Gas Pilot Plant Located in Middle Guajira

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Resumen

Este estudio presenta el desarrollo e implementación de un sistema de adquisición de datos (SAD.1) de bajo costo para el monitoreo en tiempo real de un sistema eólico instalado en una planta piloto Power to Gas (PtG), ubicada en la media Guajira. Con la finalidad de diseñar una herramienta funcional y económica que permitiera registrar y analizar el desempeño energético del sistema eólico, contribuyendo a la gestión eficiente de la planta piloto PtG. El sistema utiliza comunicación Modbus RTU bajo el estándar RS485, con un microcontrolador Arduino Uno y un módulo MAX485 para la conversión de señales a niveles TTL. Los datos son extraídos del inversor eólico y transmitidos vía puerto serial a una PC, donde un script en Python los procesa, promedia cada cinco minutos y almacena en archivos .CSV. Se lograron establecer perfiles operativos durante un año de monitoreo, identificando una mayor generación entre las 7:00 a.m. y 6:00 p.m., y baja o nula producción en horario nocturno. El SAD.1 permite evaluar el comportamiento del sistema eólico tanto de manera individual como integrado con el sistema fotovoltaico, aportando datos clave para optimizar la planificación y gestión energética de la planta PtG.

Palabras clave
Protocolo Modbus RTU, Estándar RS485, Sistema Eólico, Arduino, Sistema de monitoreo, Energías renovables.

Abstract

This study presents the development and implementation of a low-cost data acquisition system (SAD.1) for real-time monitoring of a wind energy system installed at a Power-to-Gas (PtG) pilot plant located in Middle Guajira. The objective was to design a functional and cost-effective tool capable of recording and analyzing the energy performance of the wind system, thereby contributing to the efficient management of the PtG pilot plant. The system uses Modbus RTU communication under the RS485 standard, with an Arduino Uno microcontroller and a MAX485 module for signal conversion to TTL levels. Data are extracted from the wind inverter and transmitted through a serial port to a PC, where a Python script processes them, computes five-minute averages, and stores them in .CSV files. Operational profiles were established over one year of monitoring, identifying higher generation between 7:00 a.m. and 6:00 p.m. and low or no production during nighttime hours. SAD.1 makes it possible to evaluate the behavior of the wind system both individually and in integration with the photovoltaic system, providing key data to optimize the energy planning and management of the PtG plant.

Keywords
Modbus RTU protocol, RS485 standard, wind energy system, Arduino, monitoring system, renewable energy.

I. INTRODUCTION

The incorporation of instruments for monitoring and controlling variables has become crucial in the analysis of energy systems that exhibit high variability in their operational behavior [1]. In industrial environments, the use of microcontrollers and state-of-the-art controllers has been consolidated as a key strategy for improving process supervision and efficiency [2]. This growth in technological adoption is based on notable technical advantages, such as simple programming architecture, intuitive interfaces, high functional versatility, broad applicability, and affordable cost compared with traditional robust systems [3].

The Modbus RTU communication protocol is a viable and efficient option for establishing data links in industrial applications, with the capability to operate over distances of up to 1200 meters [4]. When it is used in installations with short cabling (~15 m), this protocol can reach transfer speeds of up to 10 Mbps [5]. Its integration with the RS485 standard enables a remote communication architecture under the Master-Slave model through a simple four-conductor configuration (A+, B-, VCC, and GND), where lines A+ and B- correspond to differential data channels in direct and reverse polarity, respectively [6] [7].

As an open-source platform, Arduino represents a key tool for designing this type of accessible system [8]. Its broad development community has generated libraries such as "ModbusMaster," which make it possible to establish communication between Arduino and industrial devices through modules such as MAX485. This module acts as a signal converter from the RS485 protocol (used by the wind inverter) to TTL levels compatible with the Arduino Uno. Communication with the wind inverter is performed by querying Holding Registers and extracting essential parameters such as voltage, current, power, and frequency. Subsequently, these data are transmitted to the computer through the serial port (COM), where a Python script performs reading, statistical processing (averaging), and automatic storage in .csv files generated every 24 hours.

This type of data acquisition system, in which low-cost microcontroller-based arrangements are used, has been widely applied in renewable generation systems, particularly in photovoltaic applications. In general, these systems integrate modules for measuring electrical variables such as voltage, current, frequency, and/or power, together with the corresponding code development that enables reading, processing, and storing the data obtained [9] [10]. In such cases, code design is essential to ensure correct information capture and management, adapting to the characteristics of each energy source and to the needs of the monitored system. Moreover, in scenarios where the monitored system has a Modbus communication line [11], as occurs in some wind and photovoltaic inverters, the process is simplified because it is sufficient to implement a software arrangement that establishes communication and manages data queries. In these cases, adaptive modules such as MAX485 or MAX323 are used for signal conversion and integration with the microcontroller [12]. In the development of SAD.1, the use of these arrangements and the implementation of specialized code were key to achieving a robust and flexible system capable of integrating with renewable technologies and adapting to the particularities of the PtG pilot plant.

One of the main challenges in monitoring renewable energy systems such as wind energy is the lack of accessible and low-cost solutions that make it possible to obtain critical real-time data. Although commercial data acquisition systems with robust capabilities exist, their high cost, licensing requirements, and integration complexity limit their adoption, especially in environments with limited financial resources or in experimental applications [13] [14]. In this sense, it becomes imperative to develop more accessible monitoring solutions, both economically and in terms of technical implementation, that can be easily integrated into existing systems and are compatible with the skills of technical personnel [15].

This research focuses on the design and implementation of SAD.1, a technological solution conceived for the capture, transmission, and automated processing of signals from external operating environments using serial communication through the RS485 protocol [14]. This system was specifically developed to address deficiencies identified in the monitoring process of the wind system of the PtG pilot plant, among which the following stand out: the absence of specialized equipment intended for continuous system monitoring; the impossibility of monitoring during nighttime hours or holidays, which resulted in total data loss during those periods; and the manual nature of the acquisition procedure, which was prone to human error and significant omissions that compromised the reliability of the records [16].

These deficiencies not only affected monitoring continuity, but also prevented the precise establishment of the operational availability profile of the wind system, thereby reducing the analytical value of the collected data. In response to this scenario, SAD.1 offers a viable alternative by fully automating the acquisition process and ensuring record preservation at all times. This solution represents a more economical, flexible, and scalable monitoring strategy, suitable for integration into hybrid projects that combine renewable energies, and enables the construction of reliable operating profiles that are essential for optimizing energy management and decision-making in facilities with limited resources.

A technological gap is identified related to the absence of modular, low-cost data acquisition systems based on open standards, capable of communicating directly with commercial wind inverters through widely used industrial protocols such as Modbus RTU over RS485, while also allowing customized processing, visualization, and storage of information without depending on costly proprietary or licensed solutions. This gap is particularly relevant in academic settings and pilot plants, where specific functionalities are required for operational evaluation but commercial alternatives are often not viable due to their cost and integration limitations. This ultimately affects monitoring continuity and reliability and limits the construction of robust operating profiles. In response, this work addresses this gap through the design and implementation of SAD.1, an accessible architecture based on low-cost microcontrollers, RS485-TTL conversion, and Holding Register queries, which automates the capture and logging of electrical variables from the wind inverter and enables their processing and storage using free software such as Python, thus providing a flexible, reproducible, and scalable solution for energy monitoring and operational support of the PtG pilot plant.

II. METHODOLOGY

This study employs a methodology structured in four phases:

a. First, exhaustive planning and technical review were carried out, focused on the search and analysis of existing prototypes of data acquisition systems that use the Modbus RTU communication protocol under the RS485 standard. This review focused particularly on their integration with low-cost microcontrollers such as Arduino Uno, Raspberry Pi, ESP8266, and ESP32, which are widely used in energy and industrial monitoring applications. Key criteria such as system architecture, serial communication reliability, sampling times, scalability, software library availability, and compatibility with industrial devices were analyzed. Based on this comparative analysis, the design guidelines for the proposed system were established, prioritizing communication stability and adaptability to variable operating conditions.

b. The next phase addressed the definition and configuration of the Modbus RTU communication parameters required to guarantee interoperability between the CTW-5KS wind inverter and the data acquisition system. In this phase, fundamental parameters such as transmission speed (baud rate), data bits, parity, stop bits, and slave addresses were defined in accordance with the inverter manufacturer's specifications. Since the Arduino Uno operates with TTL voltage levels, the inclusion of an RS485-TTL converter module (MAX485) was assumed as a design condition, enabling proper electrical adaptation and differential signal transmission. This technical assumption is key to ensuring data integrity, minimizing electromagnetic interference, and guaranteeing stable communication.

c. The Modbus registers were then analyzed and selected, specifically the "Holding Registers" of the CTW-5KS wind inverter, which contain the operational information required to characterize the wind system. The register addresses associated with relevant electrical variables such as voltage, current, active power, frequency, and other performance parameters were identified and documented. It was assumed that these registers provide reliable, real-time updated measurements according to the manufacturer's specifications, which made it possible to define the logical design of SAD.1 as well as the structure for data acquisition and storage.

d. Finally, the design, programming, and implementation of SAD.1 were carried out, ensuring compatibility between the wind inverter, the Arduino Uno microcontroller, and the required auxiliary devices. Subsequently, the system was commissioned, followed by the processing and analysis of the acquired data, which made it possible to generate behavior plots for the H-5 kW wind turbine. These results, as shown in Figure 1, constitute the basis for evaluating the performance of the wind system under real operating conditions and validating the effectiveness of the developed acquisition system. The methodological sequence is illustrated in the flowchart in Figure 1.

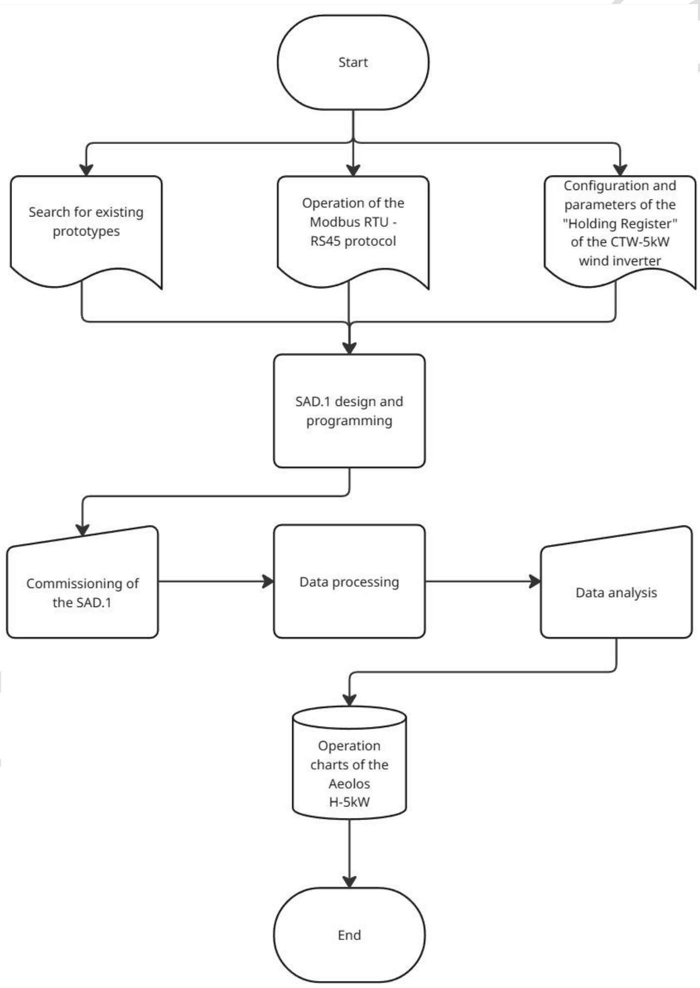

Figure 1: Flowchart of the methodological phases of the research1
Source: Authors' own elaboration

2.1. Study Area

This study was conducted in the Republic of Colombia, in the department of La Guajira, in the city of Riohacha, in the north of the country. The study was carried out in the laboratory block where the Power-to-Gas pilot plant is located at the University of La Guajira, situated at kilometer 3+354 on the Riohacha-Maicao road.

The geographic location of the PtG pilot plant is defined by latitude 11.5103° N and longitude -72.869° W, corresponding to the territorial area of Middle Guajira. This area concentrates the study, monitoring, and evaluation activities associated with the data obtained from SAD.1, as illustrated in Figure 2, which presents the georeferenced location of the pilot plant.

Figure 2: Study area. a) PtG pilot plant at UniGuajira; b) Aeolos H-5 kW wind turbine2
Source: Google Maps

2.2. Equipment Description

This section presents the set of equipment that make up the wind subsystem of the PtG pilot plant and the associated data acquisition solution. The following subsections detail the characteristics of the Aeolos-H wind turbine (5 kW), the CTW-5KS wind inverter, and the communication and monitoring scheme implemented through Modbus RTU over RS485 using Arduino Uno and the MAX485 transceiver for real-time electrical variable reading.

2.2.1. Aeolos-H 5 kWe Wind Turbine

The PtG pilot plant consists of three main subsystems: one subsystem for generating electrical energy from renewable sources (on-grid wind-solar hybrid), a second subsystem dedicated to hydrogen production by electrolysis, and a third aimed at using hydrogen as an energy resource. The electrical energy required for system operation is obtained from a hybrid wind-solar microplant with an installed capacity of 15 kW. This system includes a wind set composed of a 5 kW Aeolos-H wind turbine (see Figure 3), which is connected to the university electrical grid through an independent inverter (CTW-5kW), allowing its integration and controlled operation within the campus energy system. The technical specifications of the wind turbine are presented in Table 1.

Specifications	Values
Rated power	5 kW
Maximum power	6.5 kW
Efficiency	95 %
Cut-in wind speed	2.5 m/s
Cut-out wind speed	11 m/s
Survival wind speed	59.5 m/s
Service life (years)	20
Rotor speed	240 RPM
Tower height	18 m
Rotor diameter	5.6 m
Swept area	24.6 m^2

Table 1: Technical parameters of the Aeolos-H 5 kW wind turbine1
Source: Aeolos CO., Ltd.

Figure 3. Aeolos-H 5 kW wind turbine
Source: Authors' own photograph

2.2.2. CTW-5KS wind inverter

The CTW-5KS wind inverter is a grid-tied device designed to convert the energy generated by wind turbines into energy compatible with the electrical grid; Table 2 presents the technical data of the CTW-5KS. This inverter is responsible for synchronizing and safely and efficiently transferring this energy to the PtG pilot plant.

Input parameters	
Voltage range	(DC) 80V - 600V
Maximum wind system power	5500W
DC voltage ripple VPP	VPP < 10 %
Output parameters	
Power rating	5000W
Grid voltage range	196 -253V AC
Grid frequency	60Hz
Power factor	> 0.99
Maximum efficiency	94%
Standby power loss	< 11 W
Protection	Protection against overintensification, overtemperature, overload, overcurrent, overvoltage
Total harmonic distortion	< 4 %
Communication protocol	RS485

Table 2: Technical data of the CTW-5KS wind inverter
Source: Aeolos CO., Ltd.

The Modbus RTU protocol under the RS485 standard is used for communication, allowing remote supervision of operating parameters. Through its Holding Register, as shown in Table 3, key data such as voltage, current, generated power, and error codes in Table 4 are provided, facilitating integration with control and data acquisition systems.

Address	Parameter	Name	Description
1	RO	Output voltage (GRID)	Voltage value *100 (V)

2	RO	Output current (GRID)	Current value *100 (A)
3	RO	Output frequency (GRID)	Frequency value *100 (Hz)
4	RO	Output power (GRID)	Power value (W)
5	RO	Input voltage (D.C.)	Voltage value *100 (V)
6	RO	Input current (D.C.)	Current value *100 (A)
7	RO	Total generated energy	Energy value (kWh)
8	RO	Energy generated today	Energy value (kWh) *10 (kWh)
9	RO	Error codes	See table "Error Codes"
10	RO	Reserved	
11	RO	Reserved	
12	RO	Software version	Software version
13	RO	Serial number part 1	Lower 16-bit SN
14	RO	Serial number part 2	Upper 16-bit SN
21	WR	Start/Stop	0: Stop; 1: Start

RO: Read Only, WR: Read and Write

Table 3: List of the Holding Registers of the CTW-5KS wind inverter
Source: Aeolos CO., Ltd.

Code	Error
1	Input overvoltage (450VDC)
2	Bus overvoltage (450VDC)
3	Short-period input overcurrent (40A)
4	Average input overcurrent (30A)
5	Short-period output overcurrent (30A)
6	Average output overcurrent (22A)
7	High grid frequency
8	Low grid frequency
9	Low grid voltage
10	High grid voltage
11	IPM failure
12	Inverter overtemperature
13	DSP failure
14	Communication failure

Table 4: Error codes of the CTW-5KS wind inverter
Source: Aeolos CO., Ltd.

2.2.3. Modbus Protocol Communication under the RS485 Standard

Figure 4 shows the communication scheme implemented between the Arduino Uno microcontroller, configured as Master, and the CTW-5KS wind inverter, operating as Slave. Communication is established using the Modbus RTU protocol over an RS485 interface through a MAX485 module, which performs signal conversion between RS485 levels and TTL levels compatible with Arduino. This architecture enables efficient data requests from Holding Registers, guaranteeing reliable acquisition of inverter electrical parameters in real time, such as voltage, current, active power, and frequency, which are essential for monitoring the wind system of the PtG pilot plant.

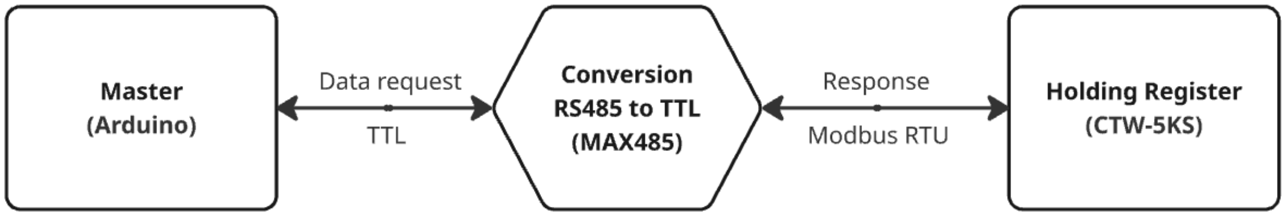

Figure 4: Communication diagram between the CTW-5KS wind inverter and Arduino Uno
Source: Authors' own elaboration

MAX485

Figure 5 shows the MAX485, an essential component for converting RS485 communication signals to TTL levels compatible with microcontrollers such as Arduino. This device adapts the differential signals of the RS485 protocol (±5V) to TTL logic levels (0-5V), allowing Arduino to read and transmit data correctly. Table 5 presents the description of the MAX485 pins. This module is widely used in sensor networks and industrial monitoring systems because of its high reliability in long-distance communications. In this context, MAX485 enables Arduino to request and receive data from the Holding Register of devices such as inverters through the Modbus RTU protocol on an RS485 line.

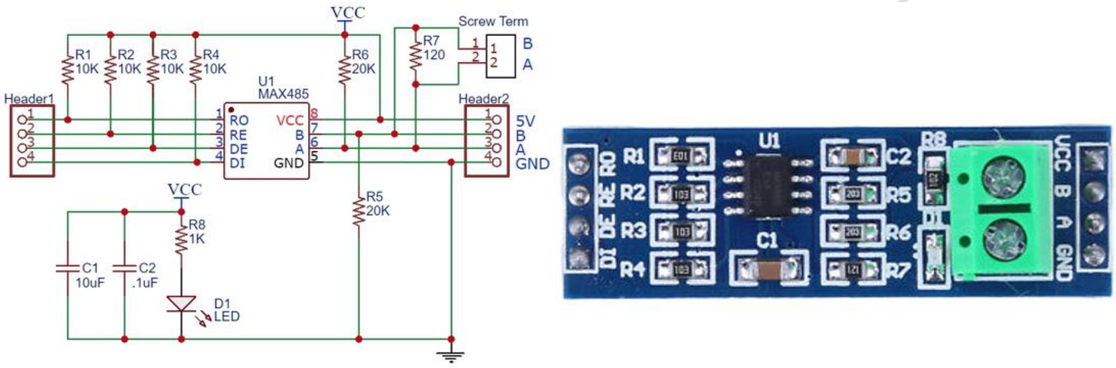

Figure 5: MAX485 transceiver module
Source: Google Images

Pin	Function
VCC	Module power supply, typically 5V
GND	Ground or common circuit reference
A	Differential data line A of the RS485 bus.
B	Differential data line B of the RS485 bus.
RO	Output of data received from the RS485 line to the microcontroller (TTL).
RE	Enables the receiver when low (0V). It must be low to receive data.
DE	Enables the transmitter when high (5V). It must be high to send data.
DI	Data input from the microcontroller to be transmitted through RS485.

Table 5: MAX485 module pins
Source: Authors' own elaboration

Arduino Uno

The Arduino Uno is a development board based on the ATmega328P microcontroller, designed for data acquisition, processing, and transmission in embedded systems, as shown in Figure 6. It is responsible for running programs that interact with sensors, actuators, and communication modules. It is widely used in prototyping and automation. It includes digital pins (0-13), analog pins (A0-A5), power inputs (Vin, 5V, 3.3V, GND), control pins (RESET, IOREF), and serial communication (TX0, RX0). These pins make it possible to establish connections with devices such as MAX485 to receive data via Modbus RTU from registers such as inverter Holding Registers.

Figure 6: Arduino Uno microcontroller

III. RESULTS

The design and programming of SAD.1 were developed for monitoring generation from the wind system of the PtG pilot plant. This system consists of an Arduino Uno microcontroller and an RS485-to-TTL converter module (MAX485), configured under a Master-Slave communication architecture. Programming was carried out using the Arduino IDE environment and a Python script that enables communication with the CTW-5KS wind inverter through the Modbus RTU protocol by accessing "Holding Register" records. The Python code is responsible for collecting the data, computing averages, and generating .csv files containing electrical parameters such as voltage, current, active power, and frequency. This architecture provides a functional and low-cost solution for automating the real-time monitoring and logging of electrical variables.

Design, Processes, and Code of SAD.1 (Connection Diagram)

Figures 7 and 8 illustrate the connections implemented in the design of the SAD.1 data acquisition system to the CTW-5KS wind inverter of the PtG pilot plant, which has an industrial Modbus RTU communication connection under the RS485 standard. The design of SAD.1 consists of an Arduino Uno microcontroller, responsible for data request and reading (Master) through the inverter communication connector under the RS485 standard (A, B, +5V, GND); the CTW-5KS wind inverter data (Slave); a MAX485 module responsible for converting the RS485 standard to TTL so that Arduino can interpret the requested data; and, as a final stage, raw data are sent through serial communication to a PC for subsequent processing, storage, and saving of the wind system inverter data using a Python script.

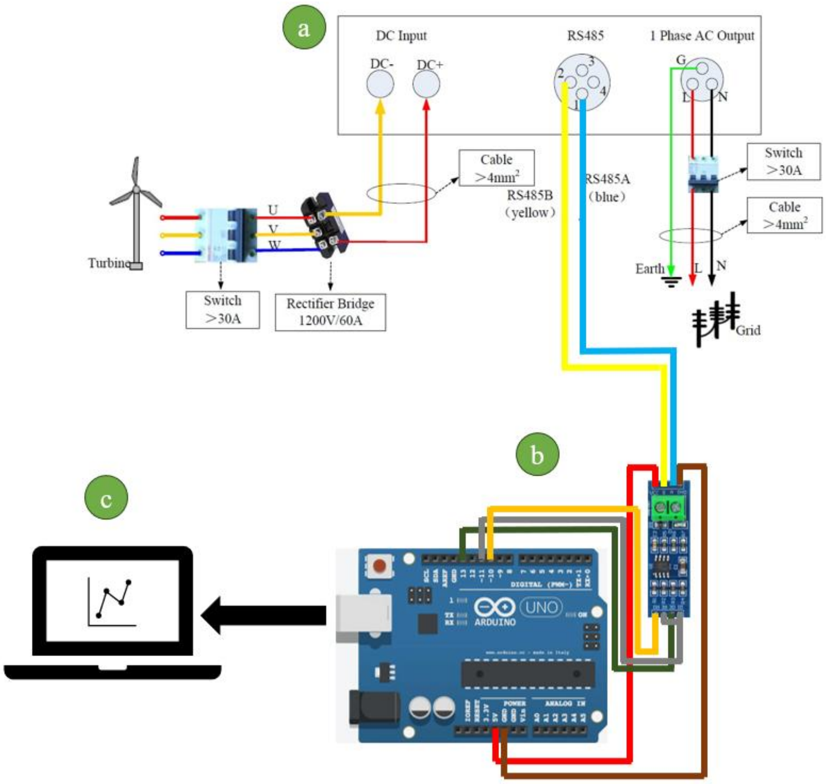

Figure 7: Connection ports of the CTW-5KS wind inverter; b. Connections of SAD.1 to both the inverter and the PC; c. Serial (COM) connection to the PC
Source: Authors' own elaboration

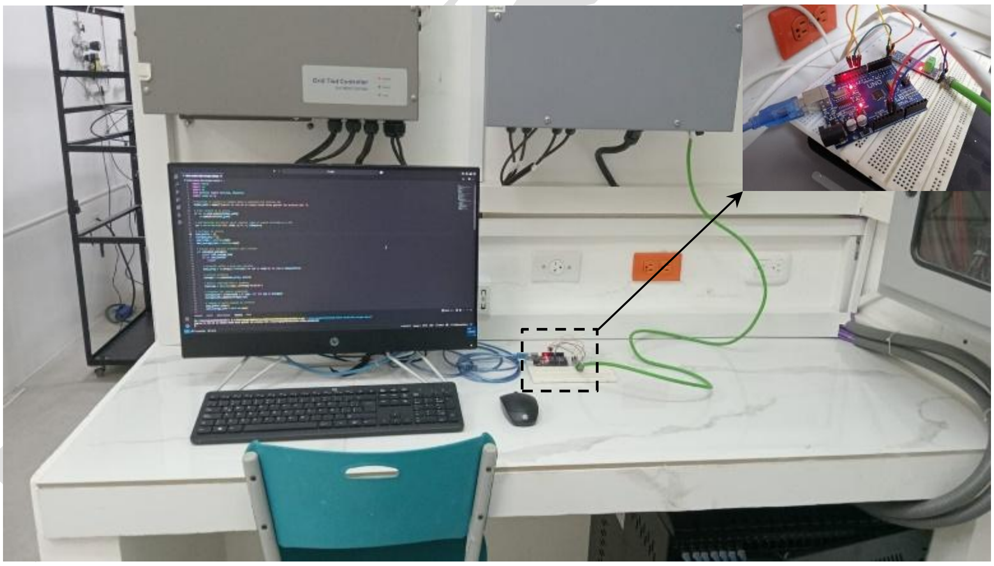

Figure 8: Physical installation of SAD.1
Source: Authors' own elaboration

SAD.1 Process Diagram

The process by which SAD.1 was designed, as shown in Figure 9, spans from data transmission and processing from a CTW-5KS wind inverter to the generation of reports for the wind system. It begins with reading the inverter Holding Register through Modbus RTU communication over the RS485 protocol. This signal is converted by a MAX485 module from RS485 to TTL for subsequent reading by Arduino Uno. Once the data are read, it is verified whether the reading was successful. If not, the physical connections between MAX485 and the inverter are checked in the event of disconnections. If the reading is correct, the data are sent through serial communication to the PC. If transmission is unsuccessful, the connection between Arduino and the PC should be verified. A Python script receives the data, records them, and computes averages. This information is stored as wind system data. It is then verified whether a document containing all the recorded data has been generated. If not, possible errors in the Python code are reviewed. If the document has been generated correctly, wind system reports are produced, thus concluding the process. This flow makes it possible to monitor, store, and analyze system data for evaluation and follow-up.

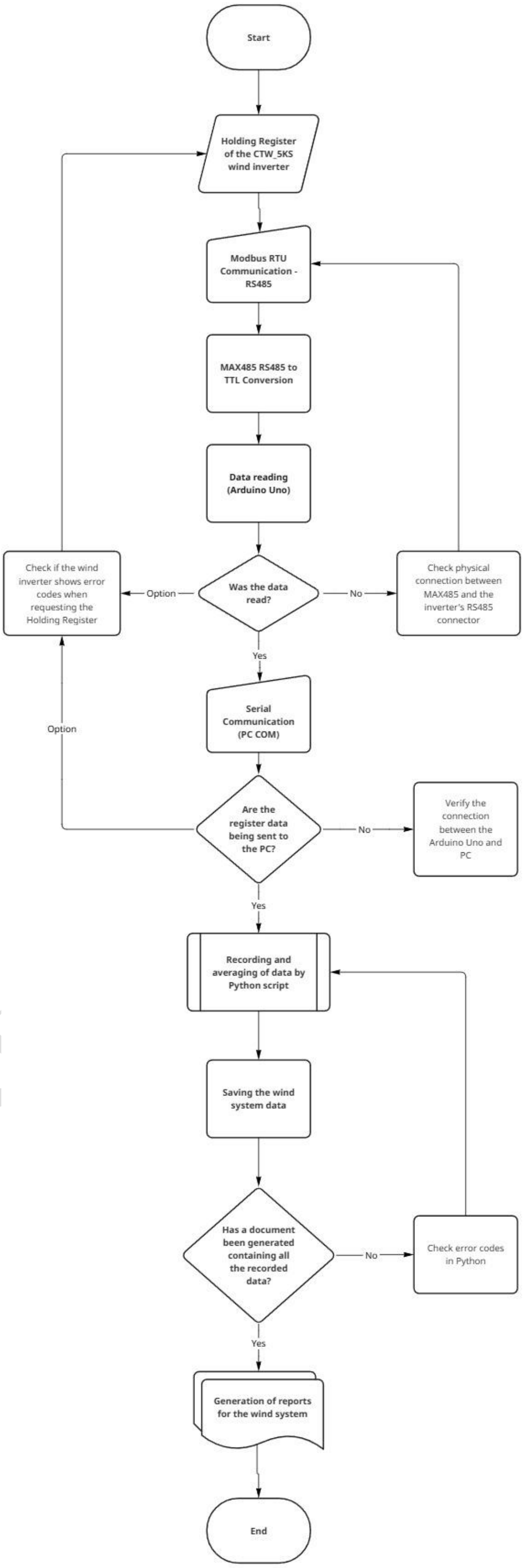

Figure 9: Flowchart of SAD.1 processes

Arduino IDE (Master-Slave Data Reading)

The Arduino Uno code uses the Modbus RTU protocol to read six registers of the CTW-5KS wind inverter (voltage, current, frequency, power, DC voltage, and DC current) and display the values on the serial monitor. First, constants are defined, such as the pins for serial communication, the device ID, and the register addresses. Objects for serial communication and Modbus are created. In the setup function, serial communication is started at 9600 Bd (baud); the system waits until it is ready, and the baud rate is read from the EEPROM. If the speed is 0, it is set to 38400 and saved. Then, Modbus is initialized with that speed, a timeout of 200 ms is configured, and the system waits 500 ms. In the main loop, each Modbus register is read one by one, verifying whether the reading is successful. If so, the value is printed (divided by 100 for most variables, except power), followed by a comma, and at the end of the DC current a new line is added. The system then waits 10 seconds before repeating the process. This code makes it possible to continuously monitor the device variables at a fixed interval; Figure 10 presents the process diagram of the Arduino Uno code.

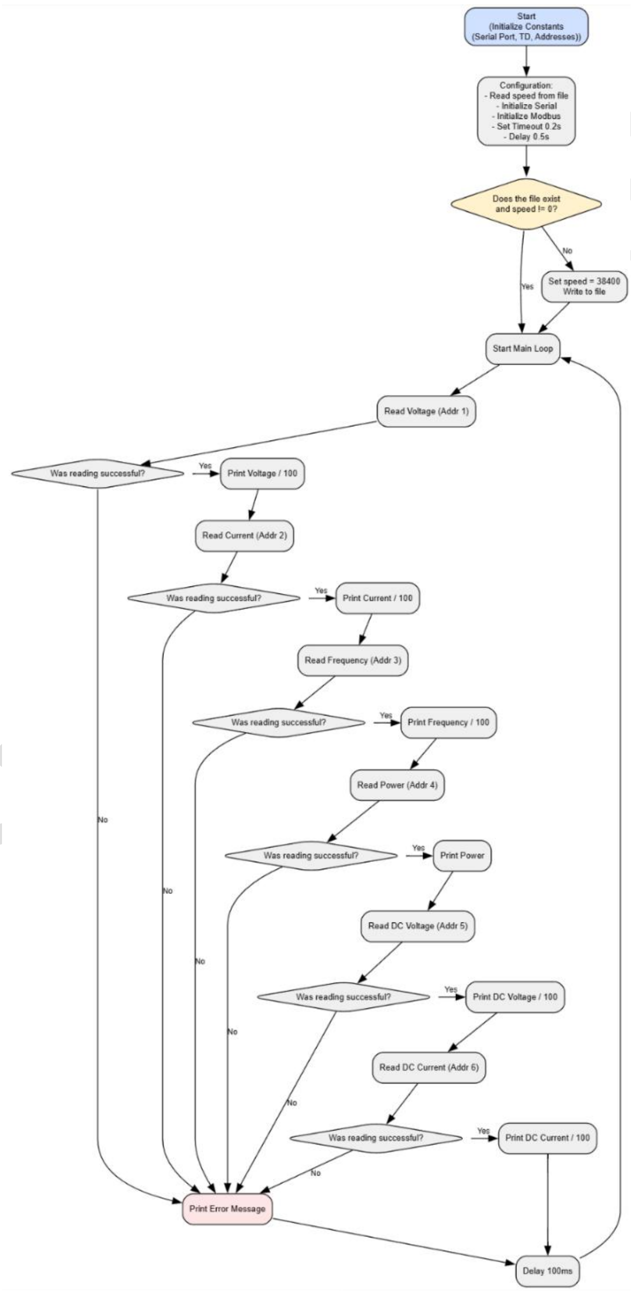

Figure 10: Process diagram of the Arduino Uno code of SAD.1

Python (Data Processing and Storage)

The Python script reads serial data sent by the Arduino Uno, stores them in a buffer, computes averages every 5 minutes, and saves the results to a CSV file every 24 hours. It begins by asking the user for a folder in which to save the CSV files and creates it if it does not exist. It configures serial port COM4 at 9600 baud with a timeout of 1 second and initializes variables for the data buffer, averaged data, and time counters. In an infinite loop, it checks whether data are available on the serial port. If so, it reads a line, decodes it, and splits it by commas. If it contains exactly six variables, it adds a timestamp and the data to the buffer. Every 5 minutes, it computes the average of the buffered data using NumPy, adds it to the averaged dataset, and clears the buffer. Every 24 hours, it computes a final average, saves the averaged data to a .CSV file named according to the date, clears the averaged data, and resets the 24-hour counter. The .CSV file includes headers for the timestamp and the six variables. This code organizes and stores serial data in a structured manner for subsequent analysis. Figure 11 shows the process diagram of the Python script of SAD.1.

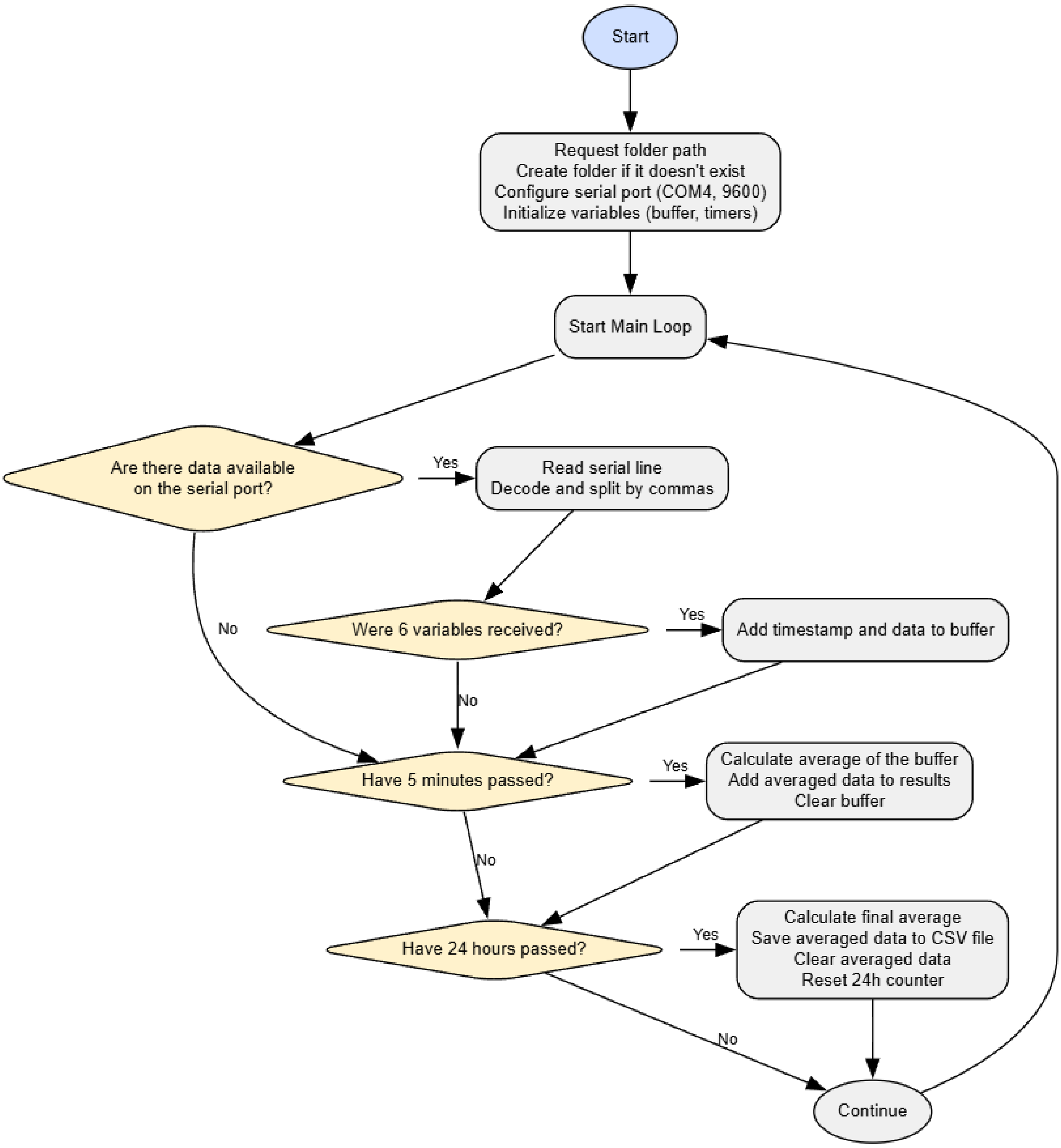

Figure 11: Process diagram of the Python script of SAD.1, responsible for processing, storing, and saving data from the CTW-5KS wind inverter.
Source: Authors' own elaboration

SAD.1 Operating Profiles

After strengthening the structure and functionality of SAD.1, continuous data collection was carried out over a one-year period, generating a real-time database that reflects the behavior of the wind system of the PtG pilot plant. Based on the collected information, it was possible to construct an initial operating profile of the wind system of the PtG pilot plant, focused on power generation, as shown in Figure 12.

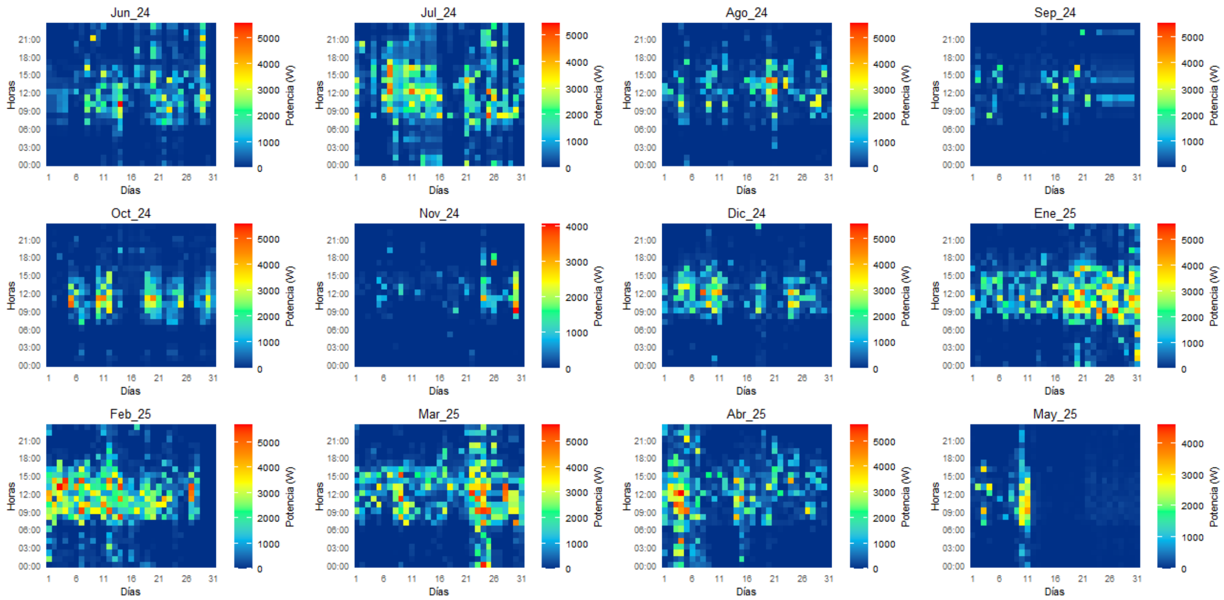

Figure 12: SAD.1 data for the power generation profile
Source: Authors' own elaboration

This profile shows that, during the last months of the year (September to December), system performance decreases notably due to lower wind speeds, which average around 2 m/s [17]. In contrast, the period from June to August presents better conditions, reaching average generation between 2 kW and 3.5 kW, with occasional peaks of up to 4 kW or 5 kW. On the other hand, the months from January to April 2025 reflect the highest production of the wind system, associated with higher wind speeds, with averages between 4 and 6 m/s, as can be seen in Figure 10. In addition, in most operating profiles, the wind system concentrates its power generation mainly during morning and afternoon hours, approximately between 7:00 a.m. and 6:00 p.m., with reduced or no participation during nighttime hours. This behavior is attributed to the environmental conditions characteristic of the PtG pilot plant, where wind density and stability are influenced by temperature variations. These variations directly affect wind turbulence, which impacts the amount of energy that can be extracted from this renewable resource [18] [19].

Based on the identification of variations in the average performance of the wind system at both the hourly scale (see Figure 13) and the monthly scale (see Figure 14), the evolution of electrical power (W) recorded monthly from June 2024 to May of the following year is analyzed. This analysis distinguishes three fundamental parameters: maximum, minimum, and average power. During the period from August to November, a significant reduction in the power generated by the system is evident, attributed to the climatic conditions characteristic of those months at the installation site of the PtG pilot plant. In contrast, the records for the first months of 2025 show marked increases, especially from January to March, with values that reach or exceed 3000 W. The monthly average power maintains a relatively stable trend, although with notable increases between December and March, which suggests a possible improvement in operating conditions or in system efficiency during that period. This type of graphical representation is useful for clearly visualizing fluctuations in the behavior of the electrical system, facilitating comparative analysis between extreme values and monthly averages of generated or consumed power.

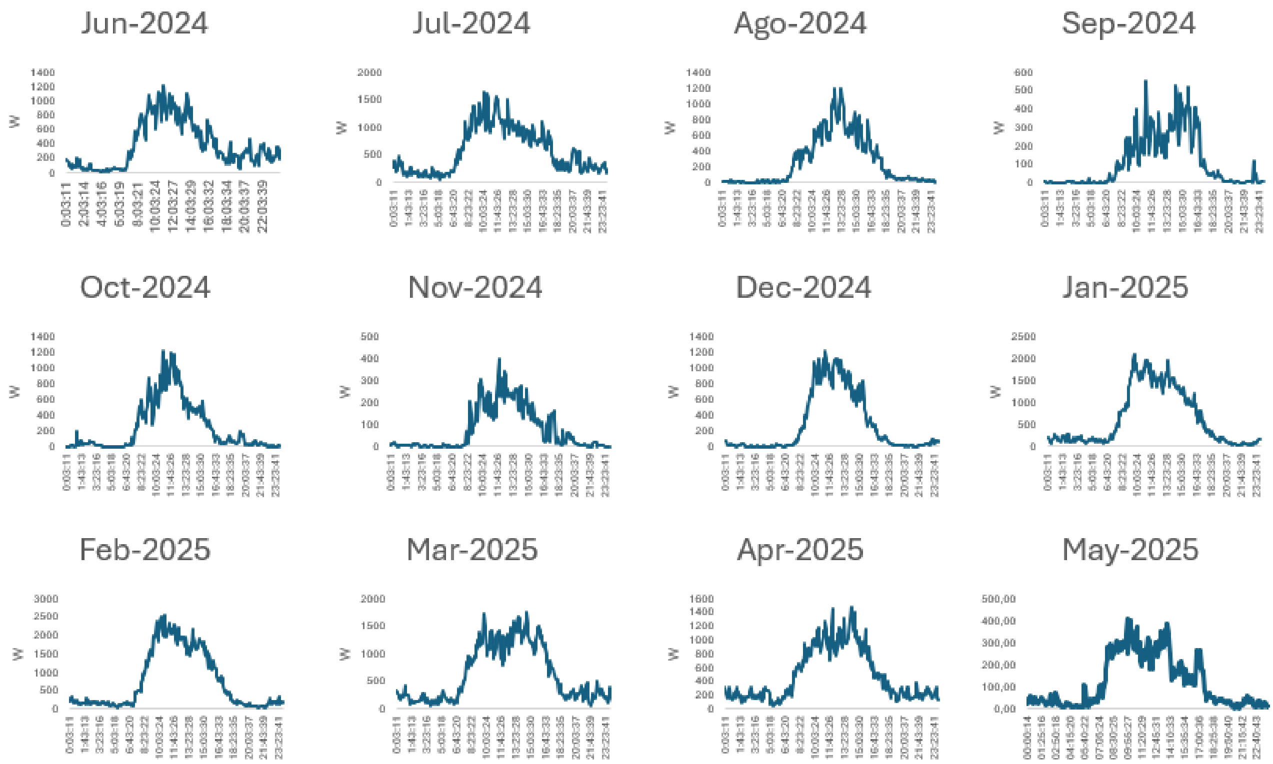

Figure 13: Hour-by-hour average power generation of the wind system using SAD.1.
Source: Authors' own elaboration

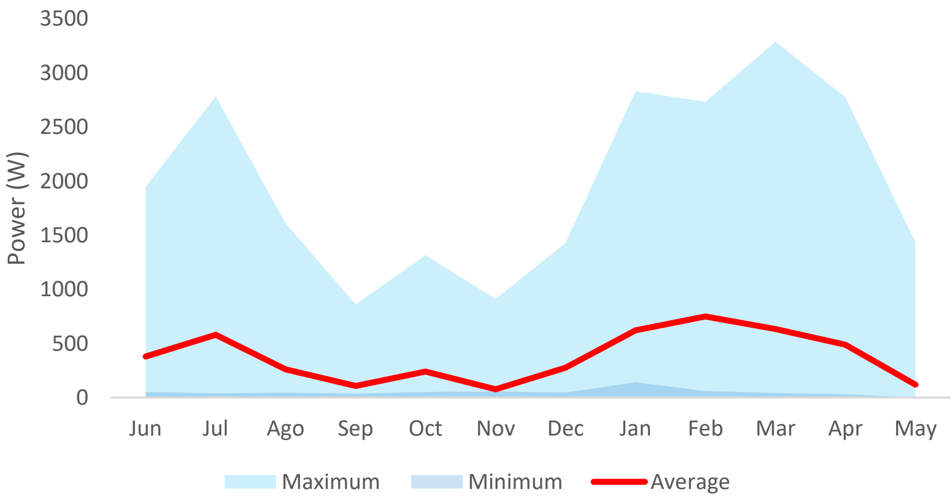

Figure 14: Monthly behavior of the average power of the wind system, based on data obtained by SAD.1
Source: Authors' own elaboration

From the presented data, it is possible to determine more precisely the optimal periods in which the wind system can operate autonomously or in combination with the photovoltaic system to effectively cover the energy demand of the PtG pilot plant (see Figure 15). The graph clearly illustrates the average power generated by each source—wind, solar, and the resulting hybrid system—throughout the day. A phenomenon of simultaneity between both generation systems is evident, especially during the interval between 08:00 and 16:00 hours, when both solar irradiance and wind speed allow significant joint production, reaching peaks above 2500 W in the hybrid system. This complementarity markedly improves energy stability and availability, reducing dependence on external sources and ensuring greater continuity of supply. The commissioning of SAD.1 made it possible to demonstrate this synergy between the renewable generation systems of the PtG pilot plant, confirming that the coordinated integration of both systems not only increases available power, but also optimizes energy management according to local renewable resources, thereby constituting a fundamental tool for the efficient planning and operation of the plant.

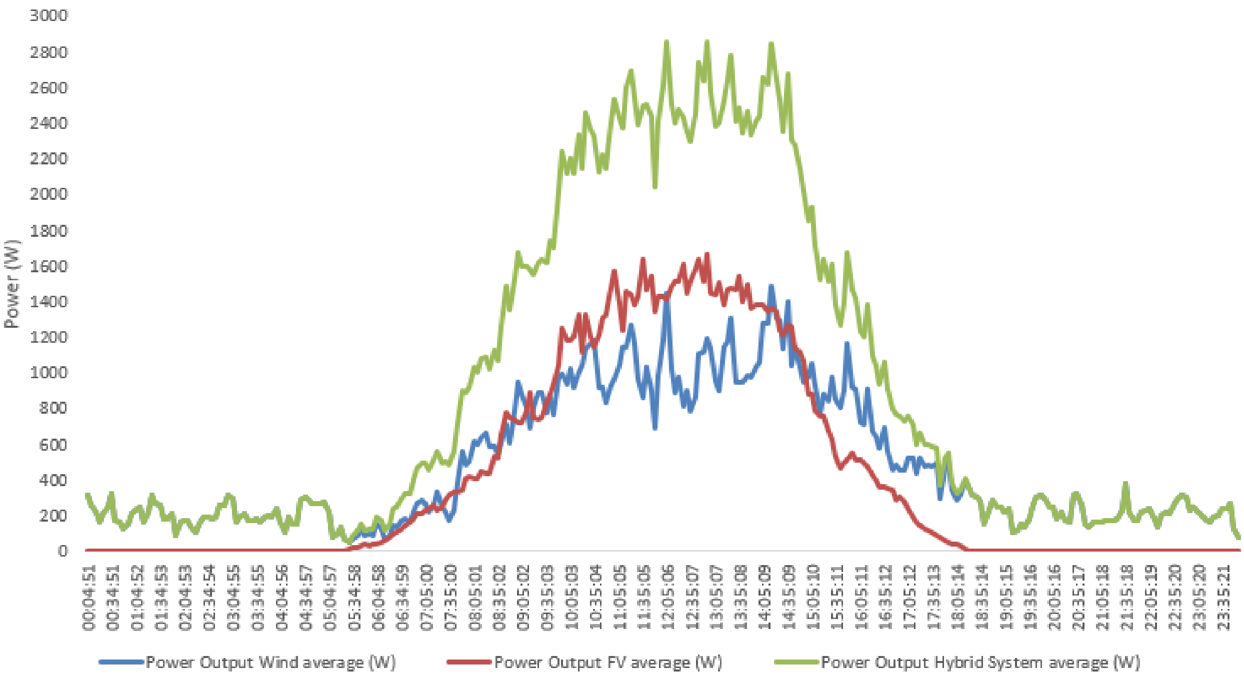

Figure 15: Integration of SAD.1 data for the analysis of the behavior of the wind-solar hybrid system in April.
Source: Authors' own elaboration

Nevertheless, when interpreting these results, some limitations of SAD.1 should be considered: the system relies mainly on the electrical variables reported by the wind inverter, which restricts a more detailed performance analysis, and the absence of direct wind speed and direction measurements prevents comparison of the generated energy with the available wind resource. In addition, the current architecture is oriented toward a local acquisition and processing environment, which limits remote access and advanced real-time analysis. As future work, it is proposed to integrate meteorological sensors to simultaneously record wind speed and direction and enable more robust cross-validation, as well as to evolve toward an IoT-based solution that allows real-time data transmission to the cloud for advanced analytics, thereby strengthening system scalability and reliability.

IV. CONCLUSIONS

The study presented the design and implementation of SAD.1, developed from low-cost microcontrollers and modules and focused on communication through the Modbus RTU protocol under the RS485 standard to interact with the inverter of the wind system of the PtG pilot plant. This system enables real-time data collection, which are processed and stored automatically using a Python script. Thanks to the integration of SAD.1, the limitation arising from the lack of real data from the wind system was overcome, allowing the preparation of operating profiles over a period of eleven months. The results indicate that production peaks are concentrated between January and April, correlated with higher wind speeds, whereas between September and December a significant decrease is observed. In addition, generation was shown to be concentrated mainly between 7:00 a.m. and 6:00 p.m., with little or no nighttime production. The implementation of automated daily reports makes it possible to analyze system behavior both individually and together with the photovoltaic system, facilitating energy planning for the pilot plant. SAD.1 thus constitutes an important tool for consolidating a reliable database on the performance of the wind system of the PtG pilot plant.

CRediT AUTHORSHIP CONTRIBUTION STATEMENT

L. Noriega-De la Cruz: Writing - original draft, formal analysis, methodology, investigation**. M. Cordoba-Ramirez:** Writing - review and editing, conceptualization, methodology. **M. Bastidas-Barranco:** Supervision, writing - review and editing. **D. Serrano-Florez:** Writing - review and editing, formal analysis. **A. Amell-Arrieta:** Funding acquisition, supervision, project administration.

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