Chapter 3

Innovation and Digitization of Solar Cookers Towards Sustainable Energy Management

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ABSTRACT

This chapter presents the digitization and supervision of a photovoltaic solar cooker using a Raspberry Pi Pico W microcontroller. The system collects meteorological and electrical parameters (voltage, current, power, efficiency, temperatures) in

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real time and automatically regulates the cooker's operation. Data, transmitted via the MQTT protocol, are instantly displayed on a Tkinter interface and archived in MySQL databases to ensure full traceability. The results show that the developed architecture enables: Real-time reception and display of data, Timestamped storage for individualized monitoring, Deferred visualization through an interactive web application based on Dash. This centralized and scalable solution provides a reliable tool for supervision, performance analysis, and adaptation of solar cookers to various contexts.

This chapter presents the digitization and supervision of a photovoltaic solar cooker using a Raspberry Pi Pico W microcontroller. The system collects meteorological and electrical parameters (voltage, current, power, efficiency, temperatures) in real time and automatically regulates the cooker's operation. Data, transmitted via the MQTT protocol, are instantly displayed on a Tkinter interface and archived in MySQL databases to ensure full traceability. The results show that the developed architecture enables: Real-time reception and display of data, Timestamped storage for individualized monitoring, Deferred visualization through an interactive web application based on Dash. This centralized and scalable solution provides a reliable tool for supervision, performance analysis, and adaptation of solar cookers to various contexts.

I INTRODUCTION

The energy transition still faces many shortcomings, particularly in key sectors such as cooking. Indeed, many communities continue to rely on fossil fuels (gas, oil, etc.), while others use cooking methods that lead to uncontrolled forest degradation (Imani & Moore-Delate, n.d.; Marín et al., 2021; Yolcan, 2023). Against this backdrop, our project aims to introduce a sustainable and environmentally friendly solution, harnessing photovoltaic solar energy and battery storage. This approach presents itself as a reliable alternative, particularly suited to tropical countries, which benefit from high solar intensity (Mawire et al., 2024; Simon Prabu et al., 2023; Aquilanti et al., 2023; Lecuona-Neumann et al., 2024). To validate the efficiency of our cooker, laboratory tests are essential. However, to ensure full validation and daily performance monitoring, it is crucial to install these cookers in households. These installations will enable the technology to be tested in real-life conditions, allowing performance to be monitored remotely, regardless of geographical location. This field deployment is also a key step towards reducing the ecological impact of using wood as an energy source for cooking. The Raspberry Pi Pico W plays a central role in the operation of our cooker, acting as the device's brain. It manages all the tasks involved in controlling the system, such as choosing the cooking mode, calculating electrical and thermal parameters, and displaying data on the LCD screen. In addition, we need to add an essential functionality: sending data via a communication protocol.

The MQTT (Message Queuing Telemetry Transport) protocol was chosen for this purpose. Very popular in the field of the Internet of Things (IoT), MQTT is a lightweight messaging protocol designed to facilitate communication between devices connected over low-bandwidth or unreliable networks (Rodríguez-Muñoz et al., 2025; Zeghida et al., 2024; Lakshminarayana & Santhi Thilagam, 2025; Das & Jain, 2025; Zeghida et al., 2025). This solution is ideal for our project, given that we will be installing the cookers in a village where network quality could be variable. MQTT also enables us to manage several cookers, each with its own "topic" (string used to identify messages and organize communication). This feature will enable us to monitor and control each cooker independently, while guaranteeing reliable and efficient data exchange. The data collected is sent to the management center in our laboratory, where it is stored in an organized database. An application has already been set up to display the various cookers and their associated electrical and thermal data. This application enables real-time monitoring, providing an overview of the status of each cooker and facilitating management of the information needed to optimize performance and continuously improve the technology.

In the framework of the international cooperation projects WBI 3.3 and LEAP-RE 'SoCoNexGen', we propose the digitalization of an innovative solar cooker powered by photovoltaic solar energy, with the objective of enhancing its reliability, enabling real-time monitoring (both locally and remotely), and collecting instantaneous usage data from household deployment. This data-driven approach will support continuous optimization and cost reduction, facilitating broader dissemination.

This chapter describes the various methods and strategies we have put in place to test how remote data transfer works. This includes the practical steps and techniques we used to check whether the cooker can correctly and reliably send the electrical and thermal data collected to our management center located in the laboratory, using the MQTT communication protocol. We will also detail the tests carried out to ensure that the communication system operates effectively, even in environments with limited network connectivity, as may be the case in rural areas.

II SOLAR PHOTOVOLTAIC COOKER WITH BATTERY STORAGE

II.1 Cooker Overview

As illustrated in the block diagram in Figure 1, prototype no. 4 of our photovoltaic solar cooker — with a total power output of 1.2 kW — is based on a dual power supply architecture, offering flexible and autonomous operation under varying solar conditions. Each power source is managed by an optimized DC/DC boost converter, and the system is composed of the following main functional blocks:

- The first heating element is powered directly by two 600 W photovoltaic panels via a dedicated DC/DC boost converter. This converter is designed to maximize the energy drawn from the solar panels and operates in two distinct modes:

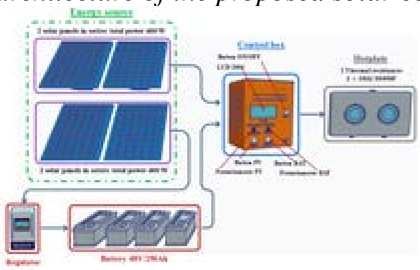
    1. Automatic mode, where the duty cycle is dynamically regulated using the Perturb and Observe (P&O) algorithm to track the maximum power point;
    2. Manual mode, where the user can adjust the duty cycle manually based on specific requirements.

- The second heating element is supplied by a 48 V battery pack, composed of four batteries connected in series, through a second DC/DC boost converter. This converter is optimized to minimize energy losses and functions exclusively in manual mode. The battery pack is independently recharged by another set of two 600 W photovoltaic panels, ensuring continuous operation during low irradiance periods or at night.
- The entire power flow and operational logic are coordinated by a central control box, which plays a critical role in regulating energy distribution. It ensures smooth switching between power sources (solar panels and batteries), manages the boost converters, and maintains overall system stability and safety.

At the heart of the control system is a Raspberry Pi Pico W microcontroller, which supports the digitalization of the cooker. Its main functions include real-time monitoring of electrical and thermal parameters, automatic or manual control of the heating resistors, data display on an integrated LCD screen, and local and remote supervision using the MQTT communication protocol developed as part of this work.

This digital layer enables continuous performance tracking both on-site and remotely through the transmission of data to a centralized monitoring platform. This functionality is essential for evaluating real-world usage, optimizing the system, and supporting broader deployment strategies.

Figure 1. Functional architecture of the proposed solar cooking system



II.2 Digital Control and Languages Used

The solar cooker is controlled by a two-level digital architecture: the on-board microcontroller (Raspberry Pi Pico W) and the LETSER laboratory supervision center. Each level uses a programming language adapted to its constraints and objectives:

- **Raspberry Pi Pico W level:** The Raspberry Pi Pico W acts as the core of the embedded system and is programmed in MicroPython a lightweight version of Python designed specifically for microcontrollers. This choice offers simplicity, hardware compatibility, and low resource consumption. MicroPython efficiently handles sensor readings (voltage, current, temperature), controls relays and heating elements, and manages data transmission via Wi-Fi or temporary access points. Its integrated libraries simplify communication with peripherals using protocols such as I2C, SPI, and UART, enabling rapid integration of devices like LCD displays, digital sensors, and diagnostic interfaces. This makes MicroPython an ideal environment for the on-board development of our solar cooker.
- **Supervision center (LETSER laboratory) level:** Data transmitted through the MQTT protocol is received by a computer running a Python program. Python's readability, modularity, and rich ecosystem make it well suited for this role. The program's responsibilities include receiving MQTT messages, processing data in real time through filtering, conversion, and validation, and dynamically visualizing the information using powerful libraries such as Plotly and Dash. Simultaneously, the data is stored in a structured way within a relational database.

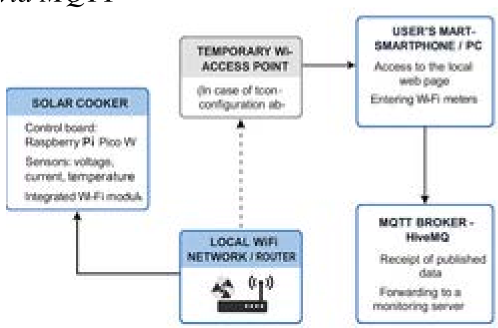
- **Database management:** We chose MySQL due to its robustness and broad compatibility with analysis tools. Using the MySQL Workbench interface, we designed relational schemas and managed tables corresponding to families, weather stations, and cookers, enabling flexible querying of the data. This centralized system provides sustainable and scalable management of the data collected from the solar cookers.

II.3 Overall Operating Diagram and Data Transmission

The overall operation of the system (**Figure 2**), including initial configuration, network connection and data transmission, is shown in the figures below. These illustrate both the local operation of the solar cooker and its integration into a large-scale cloud architecture. When first commissioned, or if no Wi-Fi configuration is available, the Raspberry Pi Pico W automatically activates a temporary Wi-Fi access point. The user can then connect to it via a smartphone or computer, access a local web interface and enter the Wi-Fi network parameters. These settings are then saved in a JSON file.

At each subsequent start-up, if this configuration file is present and valid, the Pico W automatically connects to the Wi-Fi network without user intervention. Once the connection is established, it publishes the collected measurements (voltage, current, temperature) in real time via the MQTT protocol to a remote broker (HiveMQ). This architecture enables autonomous, reliable and secure operation, while offering a simple, intuitive user interface suitable for both local and remote use.

Figure 2. Wi-Fi communication diagram between the smart solar cooker and the supervision server via MQTT



On a larger scale, several photovoltaic cookers installed in families (Family 1 to Family *n*) are connected to the Internet and transmit their data via MQTT to the

HiveMQ broker in the cloud (**Figure 3**). The LETSER laboratory supervision center receives this data in real time, then stores it in a MySQL database.

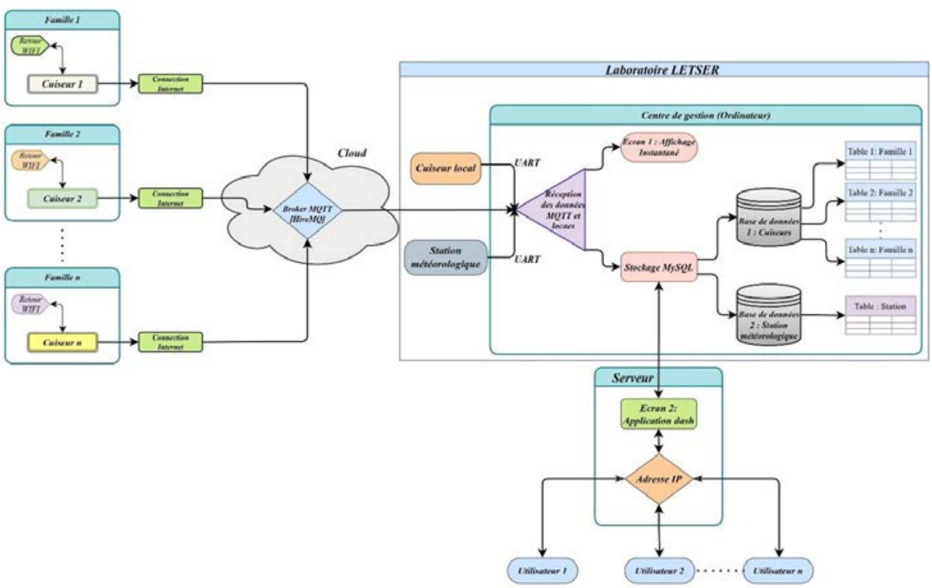
Two separate databases are maintained:

- One for the cookers, with one table per family,
- The other for the weather station, integrated into the same supervision system.

The data is then displayed in real time on a local screen, and also made accessible via a Dash application hosted on a server. This interface enables several authorized users to consult the performance of the cookers via their web browser, from the server's IP address.

This modular system enables extensive, scalable and interactive supervision, with precise traceability of the energy and thermal performance of each installation.

Figure 3. Communication diagram between domestic solar cookers and the supervision center



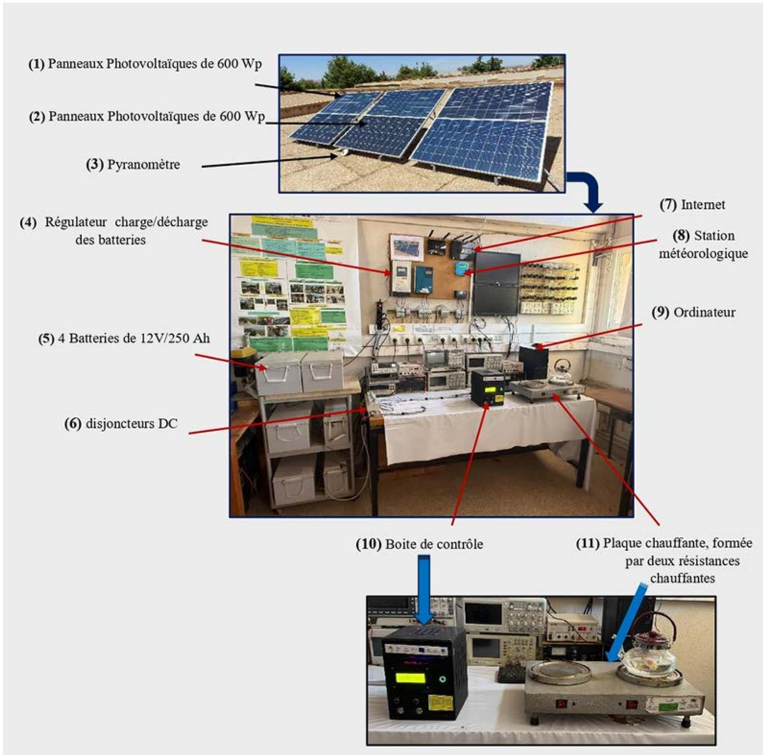
III EXPERIMENTAL VALIDATION OF A SOLAR COOKER DATA COLLECTION AND TRANSMISSION SYSTEM

III.1 Connecting and Starting Up the Solar Cooker

Figure 4 shows the equipment package for cooker 3 (Prototype P4) set up in the LETER laboratory at the University of Oujda (Morocco). The proposed cooker is designed to produce a total energy output of 2-4.5 kWh/d. The cooker's equipment and the various items of equipment required for its testing are:

- Photovoltaic (PV) panels with a total power of 1200 Wp:
  - ✓ Two PV panels **(1)** in series with a total output of 600 Wp, connected directly to the control box **(10)**. They produce energy of 500-600Wp) x7h=3.5-4.2 kWh/day, and cooking energy of (200-450W)x5h = 1-2.5 kWh/d.
  - ✓ Two PV panels **(2)** in series, rated at 600 Wp, connected to the solar batteries **(5)** via a charge/discharge controller **(4)**. These panels produce energy of 500-600Wpx7h=3.5-4.2 kWh/day, and cooking energy of (200-400W)x5h = 1-2 kWh/d.
- Charge/discharge controller **(4)** for charging the batteries **(5)** by the PV panels (600 Wp).
- 4 Solar Batteries **(5)**, 12V/250Ah each, connected in series to form a 48V/250Ah battery. They are charged by the 600 Wp PV panels **(2)** via the charge/discharge regulator **(4)**. They can store a total energy of 12 kWh, and produce, depending on user requirements, cooking energy of (200-400W) x5h=1-1.2 kWh/d.
- Energy management and control box **(10)** supplied by **600 Wp** PV panels **(1)** and solar batteries **(5)**. It regulates the heating of the hot plate **(11)**, powered by the two energy sources (PV panels **(1)** and solar batteries **(5)**), via two DC/DC converters, and an electronic board that controls the operation of the complete cooker system.
- Heating plate **(11)** consisting of two heating resistors (left and right), with a power rating of 2 kW and a temperature of 1000°C.
- Meteorological station **(8)** consisting of a Pyranometer **(3)** and thermal sensor to measure ambient temperature illuminance intensity.
- A computer and two screens **(9)** to program the control board (Raspberry Pi microcontroller), control, regulate and monitor the operation of the cooker, both locally and remotely via the Internet **(7)**.

Figure 4. Broaching of the cooker 4 produced in this LAEP-RE 'SoCoNextGen' project.



III.2 Internet Connection via Wi-Fi

The **Raspberry Pi Pico W** built into our cooker is equipped with a Wi-Fi module for connection to a local network (home or mobile Wi-Fi). Once connected, the microcontroller can transmit and receive data in real time.

The Wi-Fi connection is configured automatically at start-up via a configuration file stored in the microcontroller's internal memory. This file contains the Wi-Fi network identifiers (**Figure 5**).

If no network configuration is detected at start-up, the cooker automatically activates a temporary Wi-Fi access point ("Access Point" mode) (**Figure 6**). This local network allows the user to connect directly to the cooker via a smartphone, tablet or computer. An embedded web interface then appears, offering a simple form for entering Wi-Fi network parameters (SSID and password) **(Figure 7**). Once the information has been entered, the device reboots and automatically attempts to connect to the configured network.

Figure 5. Successful Wi-Fi connection between cooker and local router

Figure 6. Automatically activates a temporary Wi-Fi access point

Figure 7. Screenshot of Wi-Fi configuration web page displayed on smartphone

This solution makes the system fully autonomous and easy to deploy, even in environments without technical support, while avoiding the need for manual code modification or physical access to the microcontroller board. What's more, it enhances the device's flexibility by enabling rapid, secure remote configuration, thus reducing the risk of human error and the costs associated with on-site intervention. This approach also enhances system scalability, facilitating the integration of future upgrades without service interruption.

III.3 Data Transmission via MQTT Protocol

Once connected to the Internet, the cooker uses the MQTT (Message Queuing Telemetry Transport) protocol to transmit data to a remote server called a broker **(Figure 8)**. For our system, we chose **HiveMQ**, a free, public MQTT broker that enables fast, lightweight and reliable message exchange (**Figure 9**).

Figure 8. MQTT communication between the cooker and the HiveMO broker

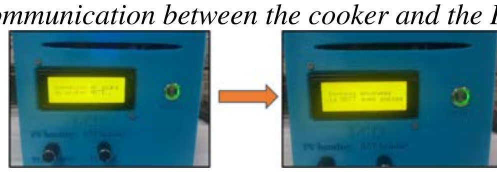
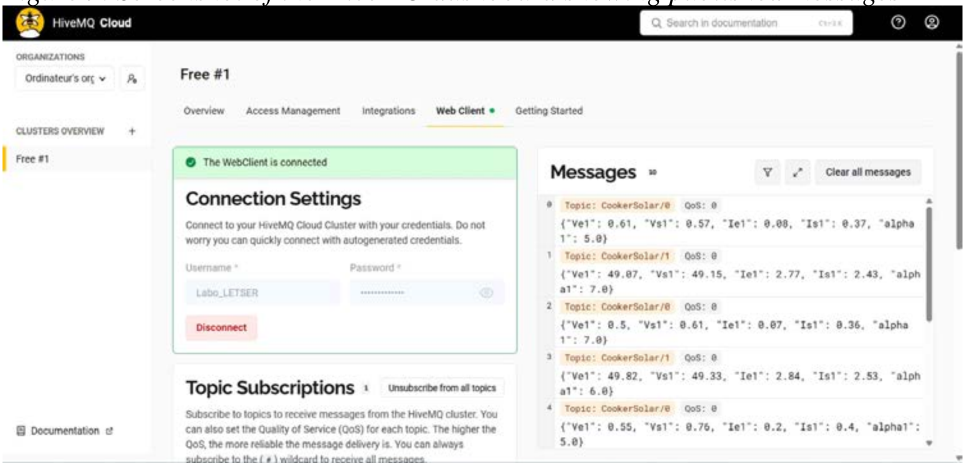


Figure 9. Screenshot of the HiveMQ dashboard showing published messages



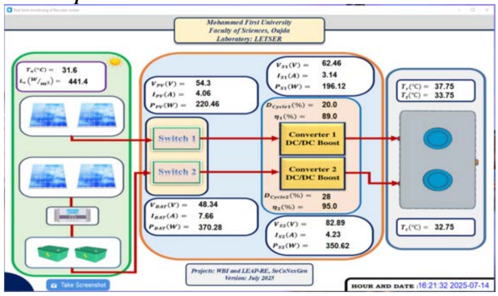
Each cooker publishes its data (power, voltage, temperature, etc.) on a specific, uniquely identified **MQTT topic**. This makes it possible to individually track several cookers in different households.

IV SOLAR COOKER SUPERVISION ARCHITECTURE: RECEPTION, STORAGE AND VISUALIZATION

IV.1 Real-Time Reception and Local Display via Tkinter

Data from the solar cookers, transmitted via the MQTT protocol, are received in real time by our main program. These are immediately displayed on a local graphical interface developed with Tkinter, installed on the laboratory's supervision workstation. This interface enables live monitoring of electrical quantities (voltage, current, power, efficiency) as well as heater plate temperatures (see **Figure 10**).

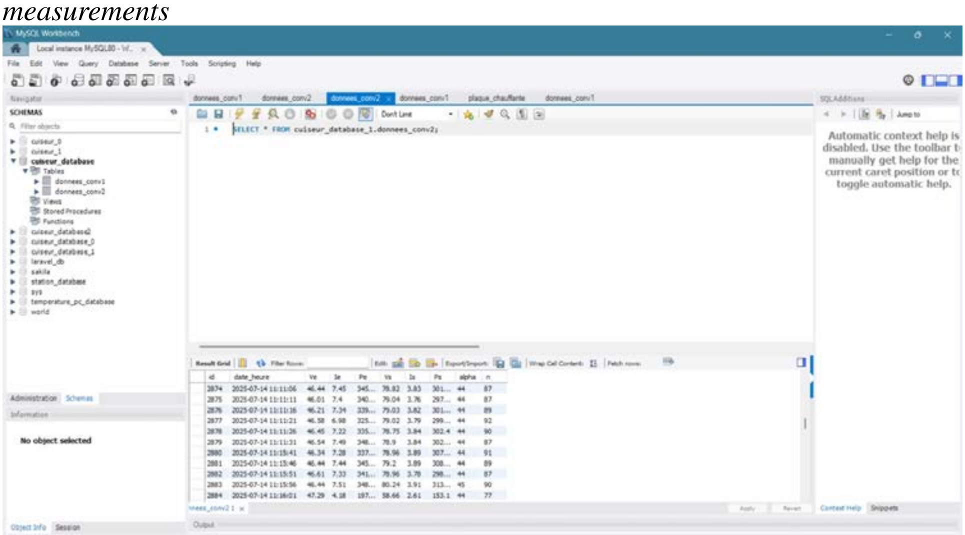
Figure 10. Photo of the supervision station installed in the laboratory



IV.2 Centralized Storage in MySQL Workbench

In parallel with the real-time display, all data received is automatically stored in several MySQL Workbench databases (**Figure 11**), each dedicated to a solar cooker and hosted in our laboratory. Each measurement is recorded with its timestamp, ensuring complete, individualized traceability of each system's operation. This distributed architecture enables fine-tuned, targeted use of the data, whether for analysis, specific reports or maintenance actions.

Figure 11. Screenshot of MySQL databases containing thermal and electrical measurements



IV.3 Deferred Visualization via Dash Web Application

The web application was developed using the Dash framework to enable deferred viewing of electrical and thermal data stored in MySQL databases. It offers an interactive user interface, structured into several pages accessible via navigation buttons. The following figures illustrate the different views available.

IV.3.1 Dash Home Page: Corporate Presentation and Partnerships

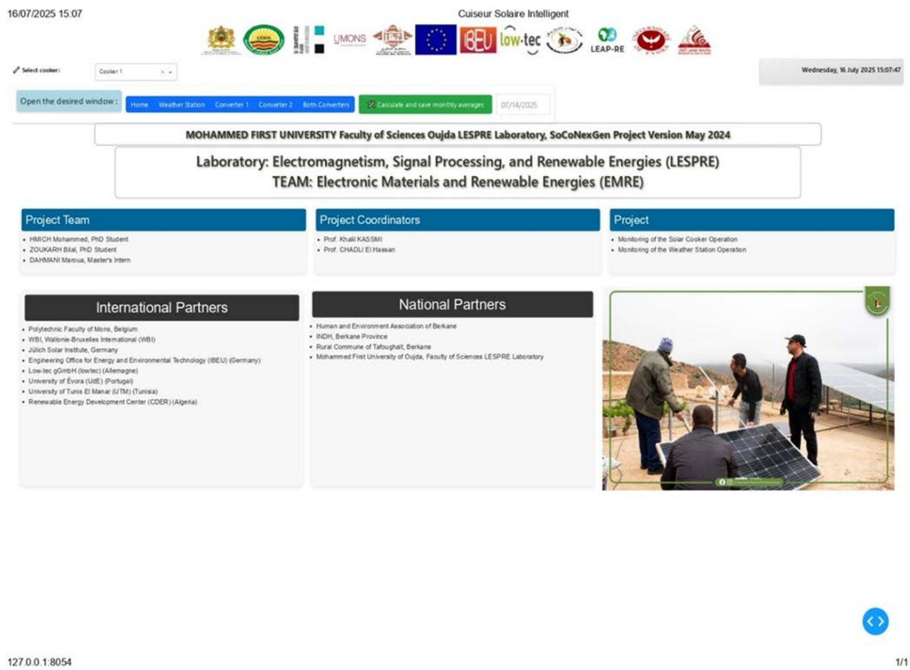
The home page of the Dash web application (**Figure 12**) has been designed to present institutional information related to the project, the scientific context, and the national and international partners involved. It does not yet contain technical graphics, but serves as an explanatory gateway for the user.

Elements displayed include

- Project name, laboratory (LESPRE) and host university (UMP - Oujda);
- Team composition: PhD students, trainees, supervisors;
- Academic and technical partnerships, divided into two categories:
    - o *International partners*: European and North African universities and research centers;
    - o *National partners*: local institutions, local authorities and associations.
- An image carousel highlights project logos or photos.

This page, accessible via the home-button, serves as an introduction to the entire supervision system. It provides a first institutional view before navigating to the technical pages (weather station, converters, etc.).

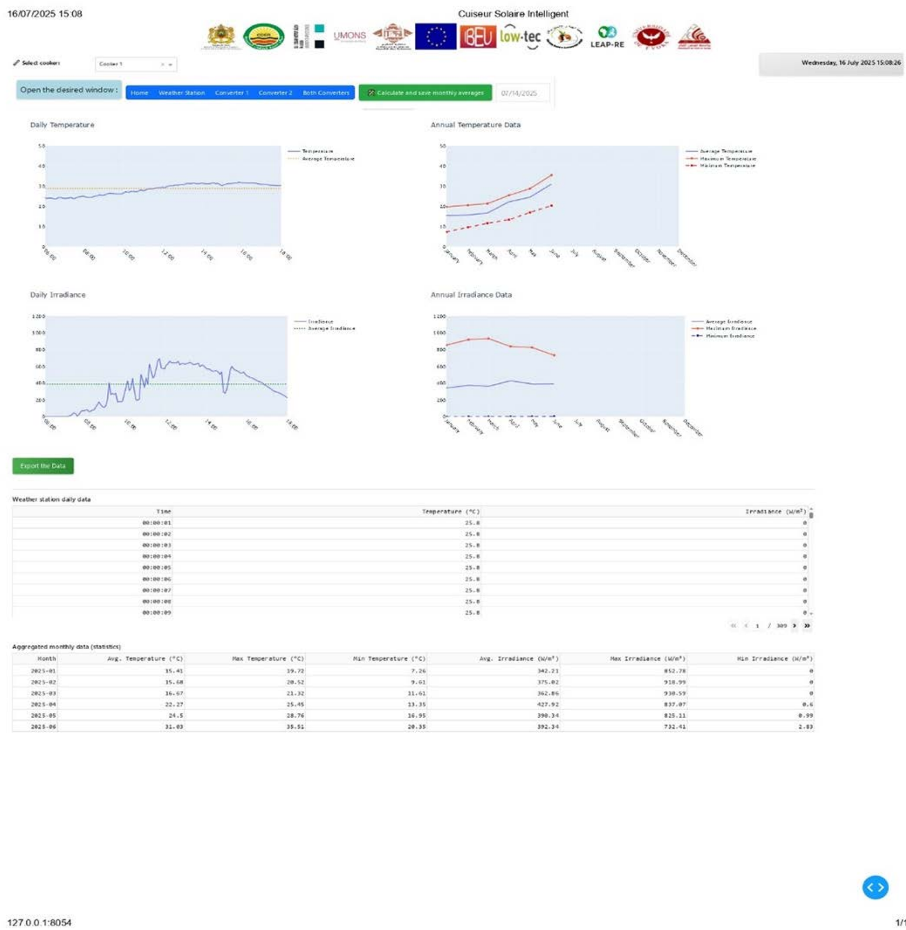
Figure 12. Dash home page interface showing project teams and partners.



IV.3.2 Weather Station Page: Temperature and Irradiance

The weather station page (**Figure 13**) displays interactive graphs showing the evolution of ambient temperature and solar irradiance over time. These data come from the UART module connected to the environmental sensors, and are retrieved from the MySQL database dedicated to the station.

Figure 13. Display of weather data via Dash application (temperature and irradiance)



IV.3.3 Converter Page: Delayed Performance Monitoring

This section of the Dash application allows you to view the temporal evolution of electrical and thermal data recorded for a specific converter, based on data stored in MySQL databases.

Interactive Features

The page dedicated to each converter (**Figure 14**) is accessed via buttons (converter1, converter2, two converters) in the navigation menu. It offers the following functions:

- Delayed display of measured quantities: input/output voltage (Ve, Vs), input/output current (Ie, Is), power (Pe, Ps), efficiency η, and duty cycle α ;
- Simultaneous display of associated hotplate temperatures (Tr, Tt, Tc) to analyze the thermal-electrical relationship;
- Interactive graphs grouped by data type (voltage, current, power, etc.) with quick anchor links;
- Dynamic tables for viewing measurements in tabular form;
- Data export in Excel format (Export the Data) for external analysis or archiving.

Figure 14. Delayed monitoring interface for Converter 1: graphical display and measurement table.

V CONCLUSION

The work presented in this chapter illustrates the relevance of an innovative energy solution, combining photovoltaic solar energy, battery storage and remote digital supervision. By combining efficient hardware technologies (converters, sensors, Raspberry Pi Pico W microcontroller) with lightweight but robust software solutions (MicroPython, MQTT, MySQL, Dash), the solar cooking system developed meets the real needs of rural households, while offering a scalable and adaptable infrastructure. Laboratory tests validated the cooker's thermal performance, while field experiments demonstrated the system's ability to operate reliably in constrained environments, where connectivity and access to electricity are sometimes limited. The choice of the MQTT protocol, combined with an intuitive visualization interface, made it possible to set up real-time data tracking, guaranteeing complete traceability and optimized management of the energy produced and consumed.

This holistic approach shows that it is now possible to design energy systems that are autonomous, intelligent and environmentally friendly. The proposed solar cooker is thus a concrete solution to the challenges of energy transition in rural areas, providing comfort, safety and reduced ecological impact.

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