

Chapter 6

Digitization of an Innovative Solar Cooker Using Photovoltaic Solar Energy with Battery Storage

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Abstract

The work presented in this chapter concerns the digitization of the operation of a photovoltaic (PV) solar cooker, in order to maximize its efficiency, monitor its use and make it more reliable. In this context, we have developed an innovative solar cooker powered by PV panels (600 Wp) and batteries (48/250Ah) via an electronic box, consisting of power

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blocks (DC/DC converter) and control electronics. The operation of the cooker is ensured by a digital code, which ensures optimal operation by the PV panels, manual operation by the PV panels and batteries, monitoring of electrical (input and output of the DC/DC converters) and thermal (temperature of the thermal resistors) quantities. Experimentation with the cooker on sunny, poorly sunny and nocturnal days has demonstrated the digital capacity of the implemented code to monitor in real time the operation of the cooker and therefore the electrical energy required by users, while ensuring an efficiency of over 95% of the power block's DC/DC converters. In addition, the system for regulating and controlling the energy sources (PV panels and batteries) allows cooking for 6-8 hours a day at cooking temperatures in excess of 400°C, with battery autonomy of 8-10 days. All these results show that the numerical code in place works well and can therefore be used to digitize the solar photovoltaic cooker application developed in the course of this work.

Keywords: photovoltaic solar energy, electrical energy, high-temperature (>400°C) photovoltaic cooker, digitization, data transmission, database storage, displays and management, DC/DC converter, electronic control system

1. Introduction

Traditionally, cooking has relied mainly on coal, wood and natural gas, both in the home and in catering [1-3]. According to the International Energy Agency [4-7], global coal consumption is set to increase by 3.3% in 2022, reaching a record 8.3 billion tones. A study of energy consumption in Kisangani shows that coal accounts for 81.4% of consumption and firewood for 31%. Faced with the challenges posed by the production of greenhouse gases and climate change [8-9], it is becoming imperative to turn to non-polluting renewable energy sources [10-11], such as solar energy. Solar cookers, which use electricity generated by photovoltaic panels, are an ideal solution [12-15]. They enable daily cooking without the need for fossil fuels, wood or coal, thus helping to preserve forests and improve air quality. By promoting the development and adoption of these technologies, we're increasingly moving towards a more sustainable future, where energy needs are in harmony with environmental protection [16-17].

Although they offer high efficiency, continuous availability and easy storage, current solar cookers have major drawbacks: operation and efficiency do not meet users' requirements, random operation, uncontrolled monitoring, etc. Furthermore, the solar cookers that exist in the literature (parabolic or Fresnel reflector cookers [18-21], box cookers [22-24], photovoltaic cookers [25-27], etc.) are neither reliable nor used in households. Consequently, their Digitization is crucial to improving efficiency and user-friendliness. Currently, solar cookers suffer from regulation and optimization problems, with uncontrolled performance and insufficient monitoring. By integrating digital technologies, we can optimize their operation and monitor their electrical parameters (voltages, currents, power and DC/DC converter duty cycles) in real time. This digitization will make it possible to identify recurring problems, develop customized solutions and improve design and use in homes, rural and urban communities. To this end, since 2022, we have been carrying out applied research on solar cookers powered by photovoltaic solar energy, as part of European projects (WBI 3.3, LEAP- RE 'SoCoNexGen) to digitize the operation of innovative cookers powered by photovoltaic energy, with a view to their use in African households where there is a large solar deposit throughout the year.

Within this framework, we propose in this chapter the design and digitization of an innovative solar cooker using photovoltaic solar energy, with battery storage, 1.2 kWp power, and heating temperatures in excess of 400°C. Our work has been extended to include setting up and digitizing a meteorological station to measure meteorological parameters such as illuminance intensity and ambient temperature. These approaches enable precise regulation and continuous optimization of the efficiency of these cookers for a given amount of sunshine. Our work focuses on the implementation of a numerical code to optimize operation, and the acquisition of operating data for these cookers and the meteorological station. By experimenting with the code, we are able to demonstrate how well the proposed solar cooker works, and to acquire data that will enable us to improve the technology of these cookers, in line with users' needs.

2. Cooker Design and Digital Heating System Using PV Panels and Batteries

2.1. Structure and Specifications of the Digitized Solar Cooker

Figure 1 shows the structure of the prototype solar cooker to be digitized in the course of this work. The cooker is powered by photovoltaic panels and solar batteries. Its operation is based on the use of a power board (Block 1) and a digital electronic board (Block 2). In our case, to digitize its operation, we used a recent Raspberry Pi Pico microcontroller [28]. The digital system implemented manages all the functions of the cooker, from the acquisition of electrical quantities to the detection of malfunctions, as well as the choice between manual or automatic operating modes.

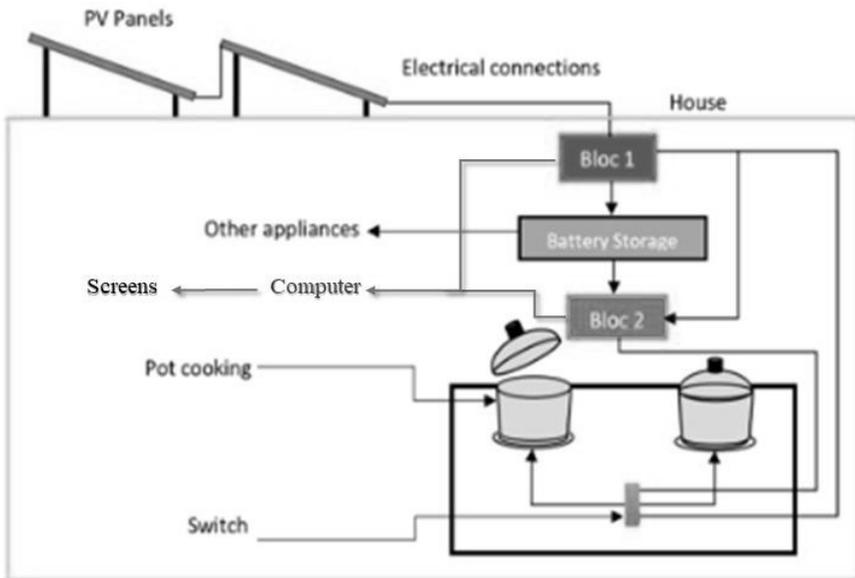


Figure 1. Structure of the innovative solar cooker to be digitized.

Taking into account studies carried out in the field, in terms of household cooking, we propose a solar cooker that meets the daily energy needs of users: energy of 1.2 kWp and energy production of 8 to 10 kWh per day. To make the proposed cooker reliable and ensure year-round production of electrical

energy for cooking, we propose a digital, computer-controlled system (Figure 1), which performs the following functions:

- *Operation 1:* Use of 600 Wp photovoltaic panels to produce 4 to 5 kWh of energy per day.
- *Operation 2:* Use of solar batteries (48V/250Ah) to provide 4-5 kWh of energy per day, with an autonomy of 8-10 days. These batteries are charged by an additional 600 Wp photovoltaic panels.
- *Operation 3:* Cooker powered by PV panels (Operation 1, 600 Wp) and solar batteries (Operation 2, 600 Wp). In this case, the cooker is powered by a total of 1.2 kWp, producing a total energy output of 8 to 10 kWh per day.

2.2. Block Diagram of the Digitized Solar Cooker

Figure 2 shows a detailed synoptic diagram of the digitized solar cooker proposed in this work. This computer-controlled cooker is designed to optimize the use of solar-generated electrical energy through advanced digitization of its main components:

- *Photovoltaic solar power source:* Consisting of PV panels with a total output of 600 Wp and 48V/250Ah batteries. This configuration not only powers the cooker directly, but also stores excess energy for up to 8-10 days' autonomy. The batteries ensure continuous polarization of active components, including the Raspberry Pi Pico board and power switches.
- *Heating plate:* Equipped with two thermal resistors of 18 Ω each (Figure 2), one resistor is powered by energy from the photovoltaic panels on sunny days, while the second is powered by solar batteries during periods of low sunlight or at night.
- *Power block (Block 1):* Consisting of two Boost DC/DC converters operating at a frequency of 20 kHz, with a maximum power rating of 1 kW each. The first converter is powered by the PV panels, while the second is powered by solar batteries.

- *Command and control block (Block 2)*: Incorporating analog and digital circuits powered by the batteries via a bias circuit, this block is essentially driven by a Raspberry Pi Pico microcontroller. This microcontroller plays a central role, managing the overall operation of the cooker according to three main tasks:
 - *Task 1*: Manage the heating of the thermal resistor using directly collected solar energy.
 - *Task 2*: Activation of heating by the second thermal resistor using the energy stored in the solar batteries during periods of low sunlight or at night.
 - *Task 3*: Acquisition, LCD display and remote control of the various electrical quantities of the DC/DC converters, such as voltages, currents and efficiencies. This feature enables precise monitoring and continuous optimization of the cooker's operation, maximizing its energy efficiency and user-friendliness.

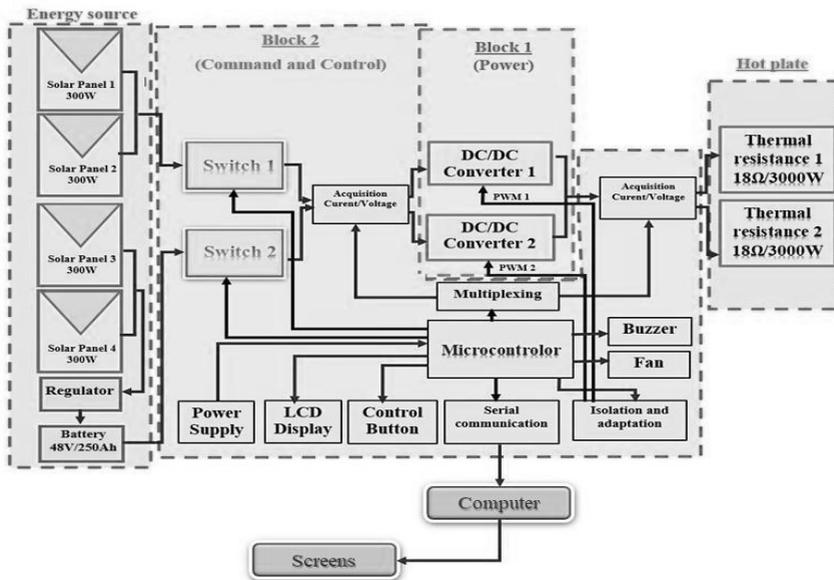


Figure 2. Block diagram of the digitized solar cooker.

2.3. Weather Station

In order to monitor the operation of the solar cooker digitized in the course of this work, we have set up a metrological station, whose digitization makes it possible to track the acquisition, in real time, of illumination intensity and ambient temperature. Figure 3 shows the synoptic diagram of this meteorological station and the digital system for acquiring, controlling and displaying meteorological quantities. It comprises:

- A pyranometer to measure light intensity.
- A DS18B20 digital sensor for ambient temperature acquisition
- A ‘Raspberry Pi Pico’ microcontroller to perform the following tasks:
 - Ambient temperature acquisition.
 - Acquisition of illumination intensity, using the pyranometer and an ADS1115 analog-to-digital converter.
 - Transmission of measured values from the microcontroller to the local computer via FTDI 232 level converter.
 - LCD display of acquired values.
 - Use a Rotary Encoder to scroll and select the type of quantities to be displayed: Illuminance intensity, Ambient temperature, or both simultaneously.

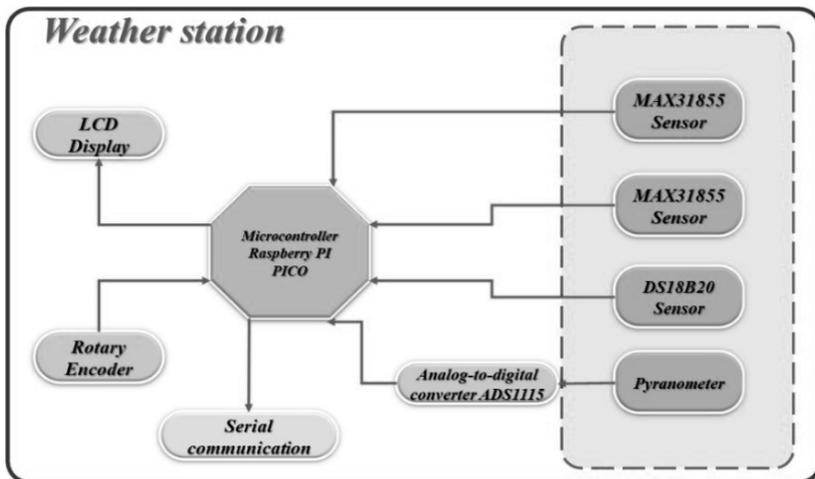


Figure 3. Block diagram of the meteorological station digitized in the course of this work.

3. Code Set up to Digitize the Cooker and the Metrological Station

Based on research into current software used in renewable energy applications, we have chosen the following software for digitizing the cooker and weather station:

- On the Raspberry Pi Pico microcontroller, we used Thonny software and the MicroPython language to send and transmit data.
- For data reception and visualization on the mainframe, we used the Python language, and PyCharm software for code development, compilation and execution.
- For data storage, we used MySQL Workbench and SQL language to efficiently manage the information collected.

In what follows, we present the software and the flowchart of the code used to digitize the operation of the cooker and the weather station.

3.1. Software and Languages Used

The software used are:

- Thonny and Micropython, an integrated development environment (IDE) specially designed for Python programming [29]. With its user-friendly interface and features such as a code editor and integrated debugger. It is widely used to program microcontrollers such as the Raspberry Pi Pico using the MicroPython language, offering a practical and efficient platform for the development of embedded projects. In our case, we used Thonny to write and test our MicroPython programs. Once the code had been developed, we transferred it to the Raspberry Pi Pico and ran it to implement our embedded projects.
- PyCharm and Python [29-30] which is a comprehensive integrated development environment (IDE) offering extensive support for several languages and frameworks, including Python, Django [31], Flask [32], FastAPI [33], JavaScript [34], TypeScript [35] and various databases right from the start. It allows you to work on your projects

locally or remotely, guaranteeing an exceptional development experience right from the start. PyCharm brings together all the Python tools needed for Web development and data science in one place. In our case, we used PyCharm, in particular Community Edition 2023.2.2. We configured Python 3.12 as the interpreter for our projects. We used PyCharm in the same way as Thonny Python: to write and test our programs in Python. Once our codes are developed, we run them on our computer to implement our projects. The choice of the PyCharm environment is justified by its advantages:

- Code completion: helps you write code more quickly and correctly.
 - Advanced debugging: makes it easy to find and correct errors.
 - Web support: compatible with frameworks such as Django and Flask.
 - Code completion: PyCharm offers automatic suggestions for embedded code and external packages.
 - SQL debugging, described in the next paragraph, which lets you view SQL code when stopping at a debug point.
 - Git visualization: shows the differences between the last commit and the current code.
 - Code coverage: can execute files outside PyCharm and display code coverage.
 - Package management: displays all installed packages and makes it easy to add new ones.
 - Local history: keeps track of modifications to facilitate rollbacks.
 - Refactoring: simplify file renaming with practical shortcuts.
- MySQL Workbench and SQL are of crucial importance for our prototype and meteorological station, providing a database for storing electrical (voltages, currents, power, duty cycles), thermal (cooker temperatures) and meteorological (illuminance and ambient temperatures) data [36, 37, 38]. In addition, the use of MySQL Workbench, renowned for its reliability, performance and ease of use, offers an effective solution for managing this data in an organized and accessible way.

3.2. Code Flowchart and Functionalities

3.2.1. Control of Cooker Power Supply via Photovoltaic Panels and Batteries

Figure 4 shows the flowchart of the digital code that drives the operation of the cooker in Figure 1 via photovoltaic (PV) panels (in Optimum (Automatic) and Manual modes) and batteries (in Manual mode). The code execution steps are:

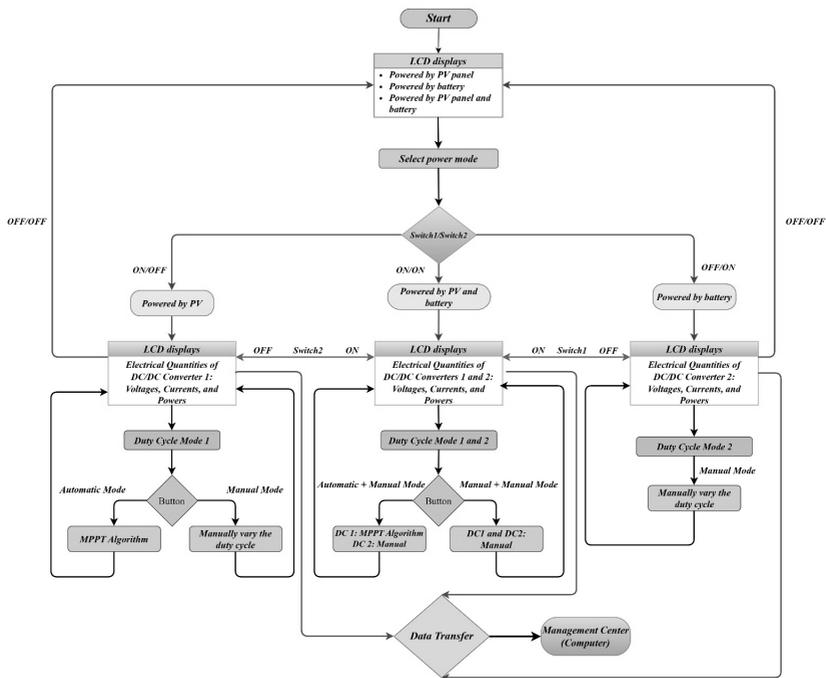


Figure 4. Flowchart of a power supply management system (solar cooker).

- Start the cooker,
- Display on the cooker's LCD screen: power from PV panels, power from batteries, and power from PV panels and battery.
- Selection of PV power supply (ON/OFF): the code displays the electrical quantities of DC/DC converter 1 on the LCD screen, including voltages, currents and powers. It then proposes two operating modes: automatic mode, which uses the MPPT algorithm

from Figure 5 [39, 40] to optimize the power supply, and manual mode, which allows the user to manually vary the duty cycle (Power).

- Selection of battery supply (OFF/ON): the code displays the electrical values of the DC/DC converter 2. Here, only one mode is offered, manual mode, where the user can manually vary the duty cycle (Power).
- Selection of power supply from PV panels and batteries (ON/ON): the code displays the electrical values of the two DC/DC converters 1 and 2. The code then provides two combinations of operating modes: automatic mode for the PV panels, using the MPPT algorithm shown in Figure 5, and manual mode for the batteries.
- Storage of acquired data in the computer.

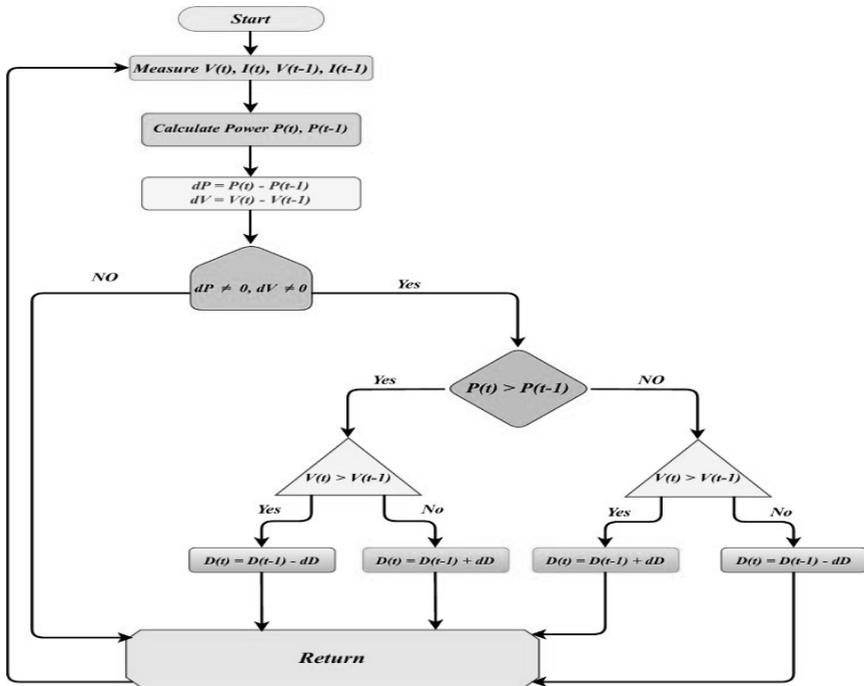


Figure 5. Maximum power point tracking algorithm (MPPT) [39-40].

3.2.2. Data Acquisition, Display and Storage Interface

Figure 6 shows the flowchart of the interface code implemented for data acquisition, display and storage on the computer. This code, executed in Python, is developed using the PyCharm editor on the computer and the

Thonny MicroPython software for the microcontroller. It uses the Tkinter library for the graphical interface and the PySerial library for serial communication. Code execution activates the links between the computer and the equipment to be digitized: the cooker and the weather station. Data is acquired via the FTDI 232 module, transferred and displayed on an LCD screen for the cooker and weather station. The steps involved in executing this code are:

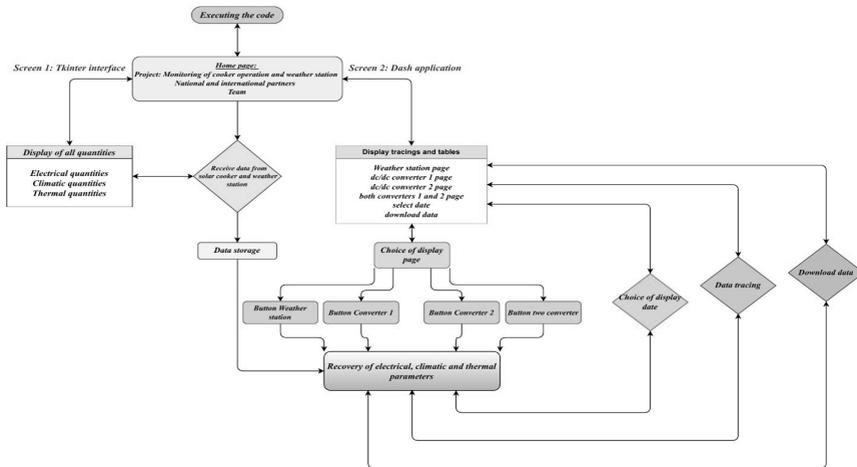


Figure 6. Graphic interface code flowchart.

- Home page providing general information on the project, national and international partners, and code tasks, including electrical, thermal and meteorological acquisitions.
- Acquisition and storage of all electrical quantities from the cooker and meteorological quantities from the metrological station.
- *Display on “Screen 1”* using the Tkinter interface. The code displays the instantaneous values:
 - Meteorological: light intensity and ambient temperature.
 - Electrics of the cooker: voltages, currents and power at the inputs and outputs of the cooker’s two converters, control duty cycles and efficiencies of these two DC/DC converters.
 - Thermal: temperatures of the cooker’s two thermal resistors.
- *Display on “Screen 2”* where the user can select the monitoring of the operation of various equipment, via an interactive interface:

- Meteorological station: By default, the code plots light intensity and ambient temperature for the day of code execution. It also plots daily and monthly average values for these variables throughout the year.
- Tracing of electrical quantities (voltages, currents, power) and controls (duty cycles) of DC/DC 1 and DC/DC 2 converters, as well as thermal data (temperature of cooker heaters) for each day of operation.
- Trace the quantities of a single converter (DC/DC 1 or DC/DC 2) or both simultaneously.
- Plotting of daily and monthly average values of all acquired quantities.
- Download data acquired from the cooker and weather station on previous days for in-depth analysis.

4. Realization and Operation of the Cooker Controlled by the Digital Codes Set up

4.1. Structure of the Steering System in Place

Figure 7 shows the structure of the electronic system used to control the cooker and the interface for acquiring, displaying and storing the cooker's electrical, thermal and meteorological parameters. This system consists of:

- Computer which is the management center of our system via a wired UART link using FTDI 232. This computer is equipped with two screens to display the electrical and meteorological data acquired and stored.
- Solar cooker powered by PV panels, in automatic mode (MPPT algorithm) and manual mode, and solar battery in manual mode. Electrical values are displayed on an LCD screen and transmitted to a computer for further processing and analysis.
- Weather station equipped with a temperature sensor to measure ambient temperature, and a pyranometer to measure light intensity. Meteorological values are displayed on an LCD screen and transmitted to a computer for further processing and analysis.

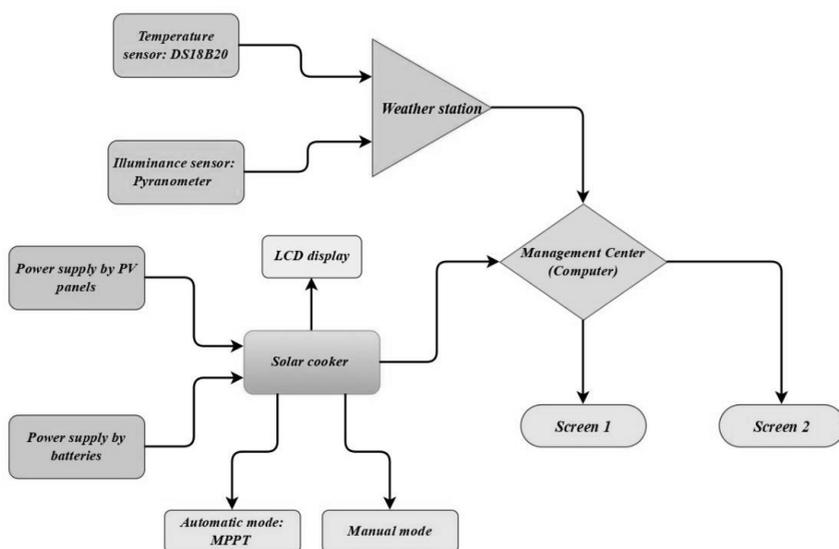


Figure 7. Block diagram of the complete system.

4.2. Complete Measurement Bench for the Cooker System and Weather Station

Figure 8 shows the equipment of the cooker (Prototype P3) set up at the LETER laboratory of the University of Oujda (Morocco). The equipment of the cooker and the various pieces of equipment required for its experimentation are:

- Photovoltaic (PV) panels with a total power of 1200 Wp :
 - PV panels (5) in series with a total output of 600 Wp , connected directly to the control box (9).
 - PV panels (6) in series, rated at 600 Wp , connected to the solar batteries (8) via a charge/discharge controller (7).
- Charge/discharge controller (7) for charging batteries (8) via PV panels (600 Wp).
- 4 Solar Batteries (8), each rated at $12 \text{ V}/250 \text{ Ah}$, connected in series to form a $48 \text{ V}/250 \text{ Ah}$ battery. They are charged by the 600 Wp PV panels (6) via the charge/discharge regulator (7).

- Energy management and control box (9) supplied by 600 W_p PV panels (5) and solar batteries (8). It regulates the heating of the hotplate (4), powered by the two energy sources (PV panels (5) and solar batteries (8)), via two DC/DC converters, and an electronic board that controls the operation of the complete cooker system. It has been designed for connection and operation of:
 - A heating plate (4) consisting of two heating resistors (left and right), with a power rating of 2 kW and a temperature of 1000°C.
 - A weather station (15) consisting of a pyranometer (16) and thermal sensor for measuring the intensity of ambient temperature illumination.
 - A computer and two screens (17) to program the control board (Raspberry Pi Pico microcontroller), control, regulate and monitor the operation of the cooker, locally and remotely via the Internet (18).

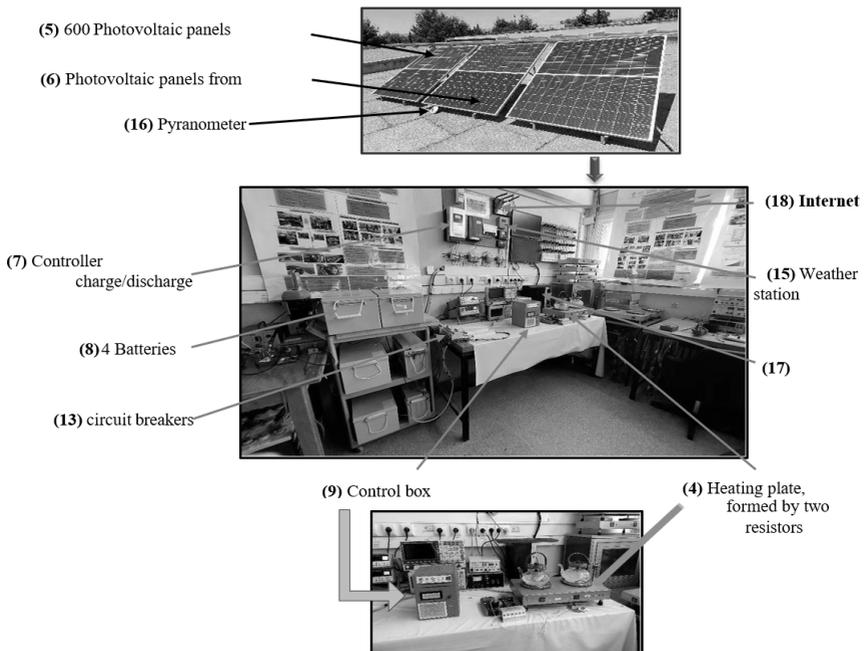


Figure 8. Broaching of cooker 3 produced in this LAEP-RE ‘SoCoNexGen’ project.

4.3. Installation and Execution of Digitizing Codes

We installed the various cooker software programs (section III.1) and the code developed in the course of this work on the computer shown in Figure 8. We then experimented with the computer-controlled operation of the cooker over a period of several days. Typical operation of the code-driven cooker (Figures 4-6) is as follows:

- *Screen 1:*
 - The main window in Figure 9 appears, showing all the necessary information about the team, the project and our partners.
 - Real-time display of climatic, electrical and thermal data from the cooker's hotplates. As shown in Figure 10, during the day July 3, 2024, we can see:
 - The ambient temperature is 31.0°C and the illuminance 452.5 W/m².
 - The electrical values of converter 1 where the PV panels supply the cooker in automatic mode (MPPT): voltage, current and power are respectively 62.57 V, 4.63 A and 289.7 W at input; and 73.29 V, 3.75 A, 274.84 W at output. The control duty cycle and converter efficiency are 15.45% and 94.87%.



Figure 9. Welcome window after code execution.

- The electrical values of converter 2, where the batteries supply the cooker in manual mode: voltage, current and power are respectively 49.3 V, 4.19 A, 206 W at the input; and 70.3 V, 3.77 A, 264 W at the output. The control duty cycle and converter efficiency are of the order of 30% 95%.
- The temperature of the cooker's hotplates is 362.0°C and 52.8°C.

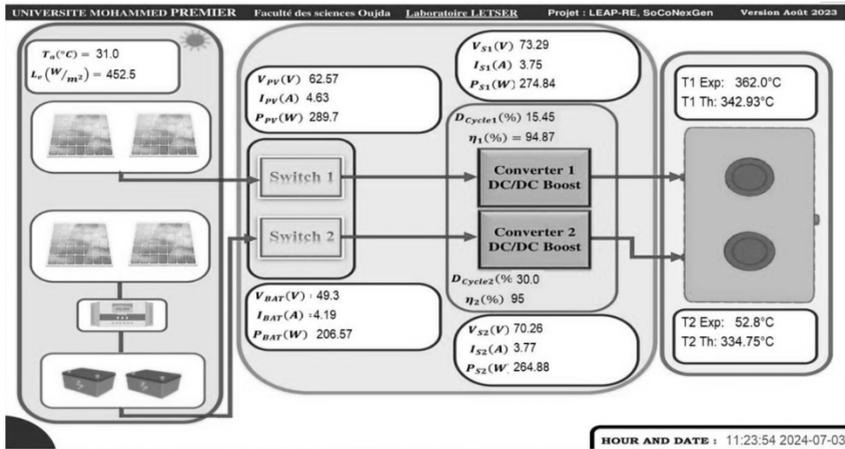


Figure 10. Screen 1 display.

- *Screen 2:*
 - *The weather station” button* displays daily graphs of temperature and irradiance, including their averages, as well as annual graphs showing monthly averages of these parameters (Figure 11).
 - *Converter 1” button:* plots electrical quantities at the input and output of converter 1 (Figure 12). During this phase, the interface displays:
 - The duty cycle is of the order of 0.58.
 - BOOST converter input voltage varies from 57V to 68V.
 - BOOST converter output voltage varies from 65V to 88V.
 - The converter input current ranges from 3.5A to 7.7A.
 - The current at the converter output is of the order of 3.6A.
 - The inverter’s input and output powers are 300W and 280W. This represents an efficiency of 93%.

- The plate temperature reaches 375°C during 35 minutes of heating.

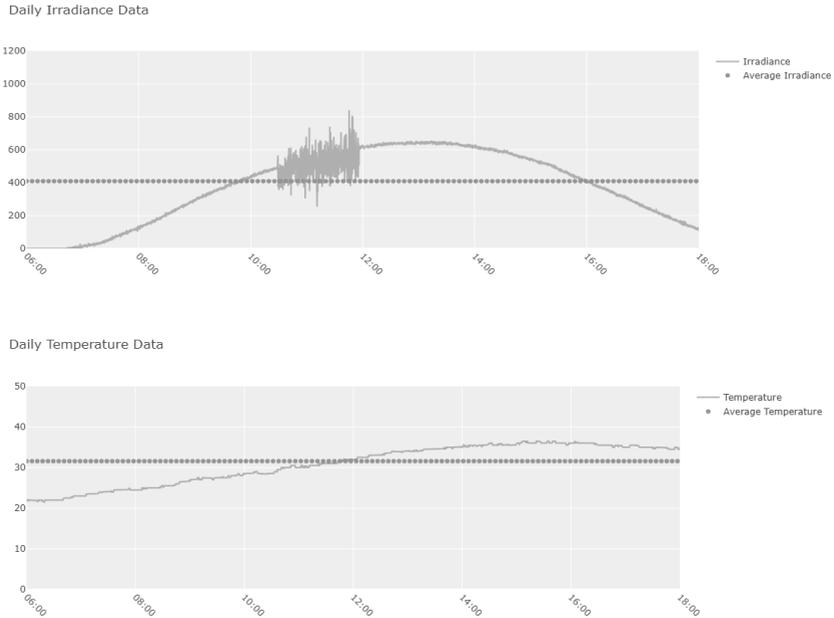


Figure 11. Plot of ambient temperature and daily irradiance.

- *Converter 2'' button:* plots electrical quantities at the input and output of converter 2 (Figure 13). During this phase, the interface displays:
 - The duty cycle is of the order of 30.
 - BOOST converter input voltage varies from 48V to 50V.
 - BOOST converter output voltage varies from 69V to 73V.
 - The converter input current ranges from 6A to 6.2A.
 - The current at the converter output is of the order of 3.8A.
 - The converter's input and output powers are of the order of 300W and 270W. That's 93% efficiency.
 - The plate temperature reaches 230°C.

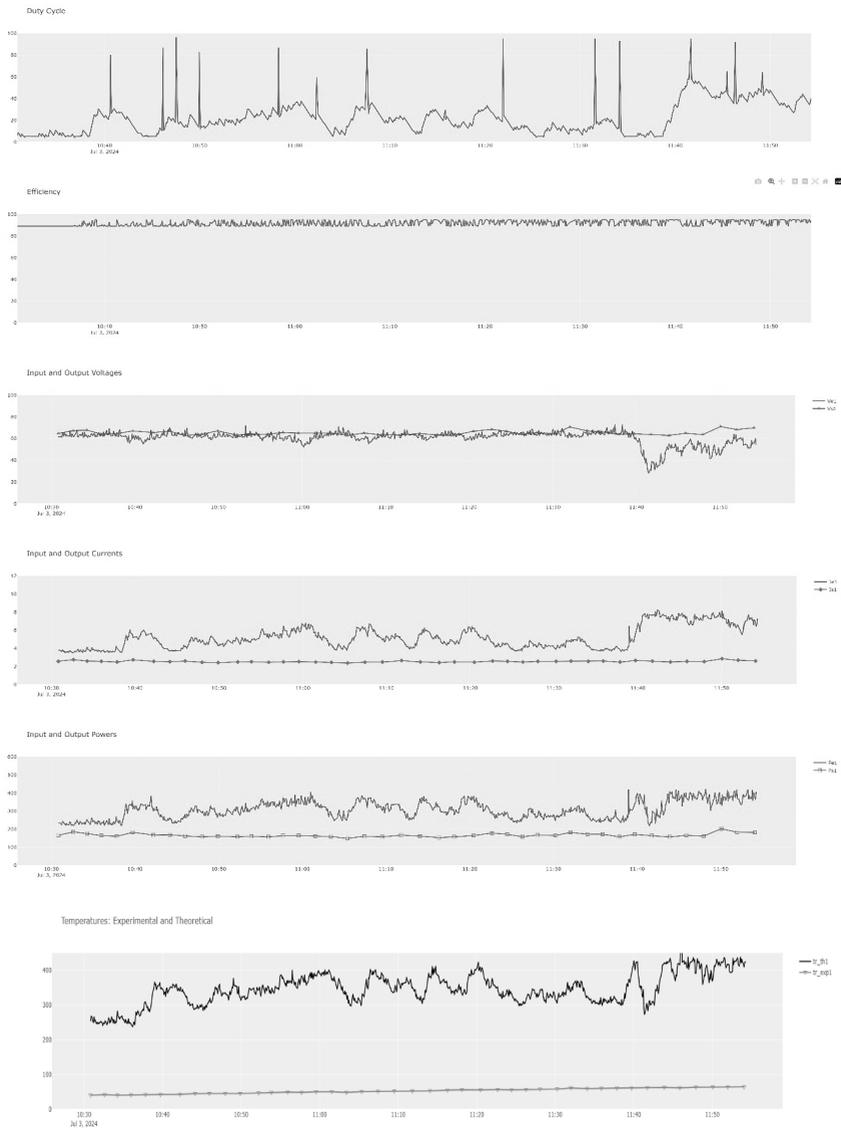


Figure 12. Electrical quantities of DC/DC Converter 1.

- *Converters 1 and 2* button: This code plots the electrical and thermal values of converters 1 and 2 (Figure 14).

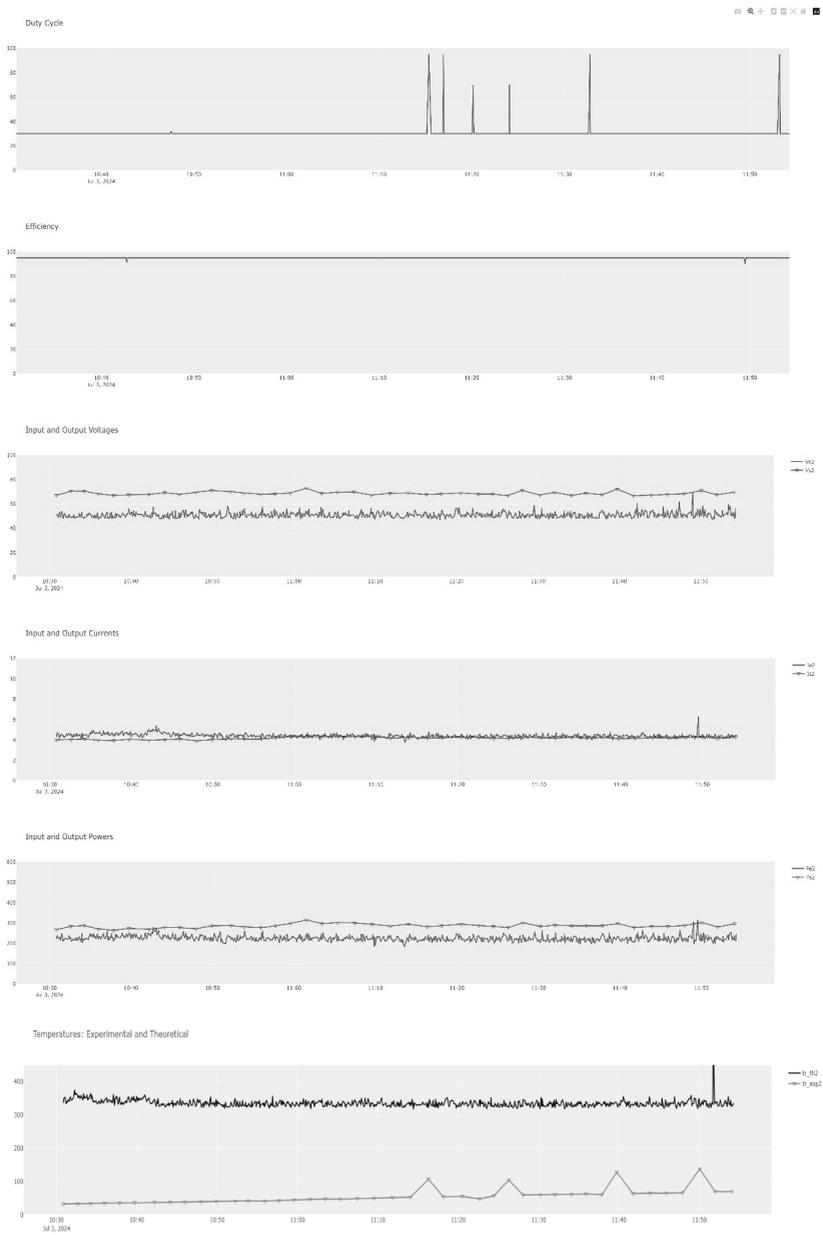


Figure 13. Electrical quantities of DC/DC Converter 2.

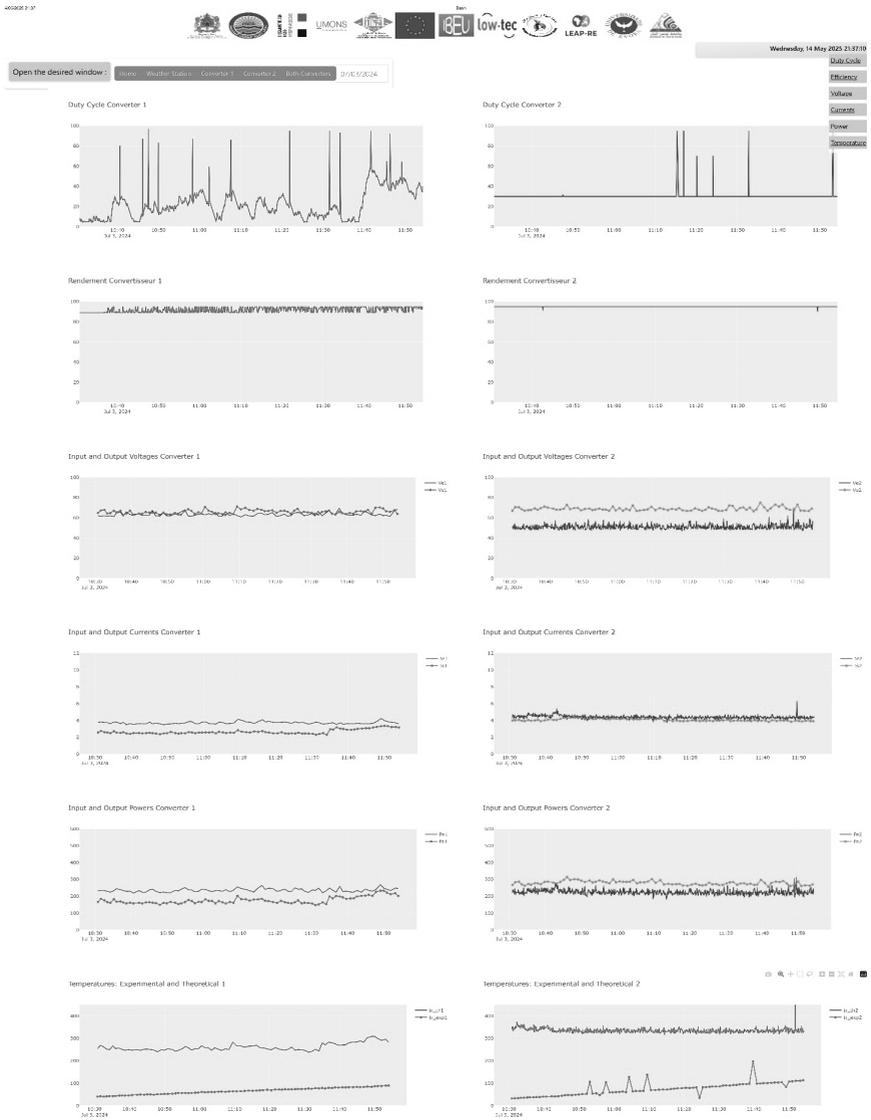


Figure 14. Electrical quantities of the two DC/DC converters 1 and 2.

- *Data download:* In this case, with the code in place, you can download the data stored in Excel format from the station and the two DC/DC converters 1 and 2 (Figures 15 and 16).

	A	B	C	D	E	F	G
1	Heure	température	(W/m ²)				
2	00:00:01	28.5	0				
3	00:00:06	28.5	0				
4	00:00:11	28.5	0				
5	00:00:16	28.5	0				
6	00:00:21	28.5	0				
7	00:00:26	28.5	0				
8	00:00:31	28.5	0				
9	00:00:36	28.5	0				
10	00:00:41	28.5	0				
11	00:00:46	28.5	0				
12	00:00:51	28.5	0				
13	00:00:56	28.5	0				
14	00:01:01	28.5	0				
15	00:01:06	28.5	0				
16	00:01:11	28.5	0				
17	00:01:16	28.5	0				
18	00:01:21	28.5	0				

Figure 15. Downloading station data.

	A	B	C	D	E	F	G	H	I	J	K	L	M
1	Date	Alpha1	endement	Ve1	Vs1	Ie1	IS1	Pe1	P _{s1}	tr th1	tr exp1		
2	09:46:54	8	93.89	31.13	33.27	2.14	1.88	66.62	62.55	168.72	25.8		
3	09:46:58	11	89	31.2	34.23	2.37	1.92	73.94	65.72	171.32	26.3		
4	09:47:03	10	89.62	31.32	33.74	2.32	1.93	72.66	65.12	170.83	25.3		
5	09:47:07	9	90.29	31.73	34.04	2.21	1.86	70.12	63.31	169.34	25.3		
6	09:47:12	8	89.69	31.71	33.13	2.19	1.88	69.44	62.28	168.5	26.5		
7	09:47:16	8.15	89	31.97	33.18	2.23	1.87	71.29	62.05	168.31	26		
8	09:47:21	7.15	89	31.56	32.75	2.15	1.84	67.85	60.26	166.84	26.5		
9	09:47:25	6.15	89	31.31	32.55	2.16	1.83	67.63	59.57	166.27	26.8		
10	09:47:30	5.15	89	31.3	32.37	2.1	1.8	65.73	58.27	165.21	27.3		
11	09:47:34	6.71	91.08	31.21	32.88	2.14	1.85	66.79	60.83	167.31	27.5		
12	09:47:39	5.71	91.16	31.23	33.01	2.18	1.88	68.08	62.06	168.32	27.5		
13	09:47:43	4.71	90.11	31.33	32.13	2.06	1.81	64.54	58.16	165.12	27.5		
14	09:47:48	5.84	92.33	31.4	32.91	2.1	1.85	65.94	60.88	167.35	27.8		
15	09:47:51	8.84	89	31.53	33.51	2.26	1.87	71.26	62.66	168.81	27.5		
16	09:47:57	11.84	92.69	31.3	34.61	2.35	1.97	73.56	68.18	173.34	28.3		
17	09:48:00	14.84	89.69	31.53	35.78	2.48	1.96	78.19	70.13	174.94	28.3		
18	09:48:05	13.84	92.97	31.09	35.36	2.41	1.97	74.93	69.66	174.55	28		
19	09:48:09	12.84	89	31.25	34.73	2.41	1.91	75.31	66.33	171.82	27.8		
20	09:48:14	14.76	90.51	31.22	35.39	2.53	2.02	78.99	71.49	176.06	28.5		
21	09:48:18	14.09	95	31.31	35.75	2.46	2.05	77.02	73.29	177.53	28.5		
22	09:48:23	13.09	94.48	31.08	35.59	2.4	1.98	74.59	70.47	175.22	32.5		
23	09:48:27	12.09	91.26	32.46	34.51	2.33	2	75.63	69.02	174.03	32.5		
24	09:48:32	11.09	91.46	31.4	34.14	2.33	1.96	73.16	66.91	172.3	32.3		
25	09:48:36	10.09	90.64	31.64	33.8	2.31	1.96	73.09	66.25	171.76	32.5		

Figure 16. Downloading data from the two converters DC/D 1 and 2.

Conclusion

In this chapter, we have presented the algorithms and the execution of the numerical codes for the control of a photovoltaic solar cooker, and of the interface that allows the acquisition, display and storage of the electrical, thermal and meteorological quantities of this cooker.

Experimentation with these codes over a period of several days on the prototype set up during the course of this work has shown, on the one hand, that the cooker operates correctly according to user requirements (Optimum and manual), and, on the other hand, that all acquired values are tracked and stored. These results show that digitizing the operation of stand-alone applications (cookers, etc.) makes it possible to acquire data throughout the year, which can be used to improve the technology of these applications.

This work is continued with a particular focus on the implementation of a numerical code to monitor the operation of this cooker and the meteorological station set up in the course of this work.

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