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Design and experimentation of an innovative photovoltaic solar cooker with battery storage: A sustainable solution for Africa's future

M. Hmich [a], B. Zoukarh [a], R. Malek [a], S. Chadli [a], O. Deblecker [b], K. Kassmi [a,c,*], N. Bachiri [c]

[a] *Mohamed First University, Faculty of Sciences, Department of Physics, Laboratory of Electromagnetism, Signal Processing and Renewable Energy (LETSER), Team Electronic Materials and Renewable Energy (MEER), Oujda, Morocco*
[b] *University of Mons, Polytechnic Faculty - Electrical Power Engineering Unit, Mons, Belgium*
[c] *Association Humain and Environnement of Berkane (AHEB), Berkane, Morocco*

A R T I C L E I N F O

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A B S T R A C T

In this paper, we present the design, implementation, and experimental results of an innovative, autonomous, and flexible solar cooker integrated with battery storage. This cooker powers two heating elements: the first via 600 Wp photovoltaic panels, and the second via batteries (48 V; 250 Ah), charged by other photovoltaic panels of the same power rating, through a power block (Block 1) and an electronic system (Block 2). The cooker is powered by a total power of 1000 to 1200 W, distributed as follows: 400 to 600 W supplied directly by the photovoltaic panels during daylight, and 200 to 500 W provided by the batteries. Experiments conducted over the course of one year show that the temperature of one heating element reaches 400 °C in 2–4 min of heating by the photovoltaic panels, depending on sunlight, between 10 am and 3 pm. The second heating element reaches 350 °C in 2–5 min when powered by the batteries. The analysis of the results highlights, on one hand, the proper functioning of Blocks 1 and 2, with an efficiency exceeding 90 %, and on the other hand, the effectiveness of Block 1, which optimizes the power supplied by the photovoltaic panels using a "Perturb and Observe" MPPT algorithm. Moreover, this cooker produces 2.5 to 3 kWh of energy over a 5-hour period from the photovoltaic panels, and 2.5 kWh from the batteries during the same period. These performances are more than sufficient to meet the cooking needs of households in both rural and urban areas. Additionally, experimental results show that it is possible to heat 1 L of water to boiling (100 °C) in 10–15 min using either the photovoltaic panels or the batteries. All the results confirm the proper functioning of the solar cooker's Blocks 1 and 2, which efficiently adapt to users' needs (day and night), thus validating the practical feasibility of the cooker. All the results confirm the proper functioning of the solar cooker's Blocks 1 and 2, which efficiently adapt to users' needs (day and night), thus validating the practical feasibility of the cooker. Compared to existing solutions in the literature, these results demonstrate remarkable performance, particularly in the efficient use of energy produced by PV panels and batteries, making this system suitable for both grid-connected and off-grid households.

* Corresponding author.
E-mail addresses: khkassmi@yahoo.fr, k.kassmi@ump.ac.ma (K. Kassmi).

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Introduction

Fossil fuels remain the primary source of greenhouse gas emissions, thus contributing to climate change and environmental degradation [1,2]. Their exploitation also leads to phenomena such as deforestation and air and water pollution [3]. In 2022, Africa accounted for only 3.1 % of global electricity production, with a total of 905,136 GWh, ranking 6th worldwide, far behind countries like China (30.6 %) and the United States (15.4 %). This modest share is reflected in an electricity consumption per capita that is 82 % lower than the global average [4]. This situation highlights the urgency of developing sustainable energy alternatives [5]. At the same time, during this period, the number of people without access to clean cooking solutions continued to rise in sub-Saharan Africa, where initiatives to promote clean cooking have not kept pace with population growth. Today, one billion people on the continent, or about four out of five, still depend on highly polluting cooking fuels used in open fires or rudimentary stoves. These practices exacerbate deforestation and indoor air pollution [6]. They are particularly widespread in rural areas, where access to electricity remains limited or nonexistent, affecting about 80 % of the rural populations in Africa [7]. These conditions have major public health consequences, contributing to respiratory diseases and premature deaths [7]. In response to this reality, the search for alternative solutions, such as solar cookers, is essential to improve living conditions while preserving the environment [8]. These devices, which use solar energy to cook food, are primarily divided into two categories:

- Thermal solar cookers, such as parabolic cookers, box cookers, and solar ovens, use the direct heat of the sun to heat and cook food [9–11]. The parabolic cooker concentrates the sun's rays onto a focal point where a container is placed to heat the food [12]. This type of cooker has the advantage of quickly reaching a high temperature, allowing for rapid and efficient cooking. However, it requires constant orientation towards the sun, which can make its use complicated, and its size and weight may hinder transportation. The box cooker uses the greenhouse effect to trap heat in a glass or plastic box, allowing for slow and even cooking of food [10]. This type of cooker is advantageous because it is simple, affordable, inexpensive to manufacture, and relatively easy to use. However, its performance largely depends on the intensity of the sun, which makes cooking slower, and its capacity is limited, restricting its use for large families [13].
- Photovoltaic solar cookers, which work by converting solar energy into electricity, which is then used to power a heating element. This type of cooker offers greater flexibility and versatility, particularly by allowing the power of other electrical appliances in addition to the cooking system. In these cookers, the management of energy conversion and storage remains a major challenge. Although this technology offers greater versatility and the ability to power multiple devices, the initial cost remains high, and managing energy, particularly in low sunlight conditions, can be complex. Recent studies suggest that suitable insulation materials can play a crucial role in reducing heat loss and improving the efficiency of photovoltaic solar cookers [14,15]. Optimizing these heating elements would not only maximize the temperature reached by the cooker but also increase the system's autonomy by reducing the need for energy. However, this research field is still relatively underdeveloped compared to other technological aspects of photovoltaic solar cookers. It is therefore crucial to continue researching the most suitable insulating materials and their implementation in these systems to improve the efficiency and durability of photovoltaic solar cookers [16].
- Hybrid cookers, which combine photovoltaic and thermal technology, photovoltaic technology with solar batteries, or other configurations. This type of cooker has the advantage of greater autonomy, as it can function even under low sunlight or at night, thanks to the thermal and electrical energy storage capacity. However, it is expensive to purchase and requires more complex maintenance due to the combination of photovoltaic and thermal technologies. Overall, while thermal solar cookers are simpler and cheaper to manufacture, photovoltaic solar cookers offer more flexibility and versatility. However, their successful adoption largely depends on local conditions, such as sunlight intensity, the availability of necessary materials, and installation costs [17–19].Therefore, it is crucial to adapt technologies according to the specific needs of users and environmental conditions, particularly in rural, isolated areas of Africa.

In the face of these challenges, research teams around the world, particularly in Africa, are working to propose solutions. Our *Team Electronic Materials & Renewable Energy EMRE* team at the *Laboratory of Electromagnetic, Signal Processing & Renewable Energy LESPRE* at the University Mohammed Premier (UMP) in Oujda is actively engaged in this approach by developing innovative solutions for cooking with solar energy. The development of technologies such as photovoltaic solar cookers with energy storage addresses the specific needs of local populations while promoting a sustainable approach. The project is part of international cooperation through *Wallonie-Bruxelles-International (Belgium)* WBI and *Long-term Europe Africa Partnership on Renewable Energy* LEAP-RE programs, aimed at promoting renewable energy in Africa. The proposed solar cooker uses photovoltaic energy, and includes an energy storage battery, allowing continuous use even during cloudy days or at night. Our system is based on heating thermal resistances via a system composed of power blocks, DC-DC converters, and electronics managed by a microcontroller. This system aims to improve the heating performance by optimizing heat management. Moreover, the thermal resistance insulation is enhanced through the use of specific techniques and materials. The intelligent management system, which integrates electronic control and real-time monitoring of electrical parameters, allows monitoring both locally and remotely via the Internet.

In this article, we present an innovative solar cooker using photovoltaic energy with a power of 600 W, coupled with an energy storage battery (48V/250 Ah/600 W), allowing continuous use even on days with low sunlight or at night. The system relies on heating thermal resistances via a setup consisting of power blocks, DC-DC converters, and electronics managed by a microcontroller. Compared to existing solutions in the literature, the proposed system offers a significant improvement in terms of flexibility, autonomy, and efficient use of photovoltaic and stored energy, making it suitable for both grid-connected and off-grid environments. This approach aims to improve the heating performance of the thermal resistances by strengthening their insulation using specific materials and advanced techniques. We will experiment with the system by recording both electrical parameters (voltage, current, power) at the input and output of the converters, associated efficiencies, and the heating temperatures of each thermal resistance powered by both energy sources. Additionally, we will measure meteorological parameters, such as light intensity and ambient temperature, to analyze their impact on the overall operation of the cooker. This monitoring will help optimize the solar cooker's performance and verify the efficiency of its management system, including electronic control and electrical data acquisition, both locally and remotely via the Internet.

Structure and operation

Prototype specifications

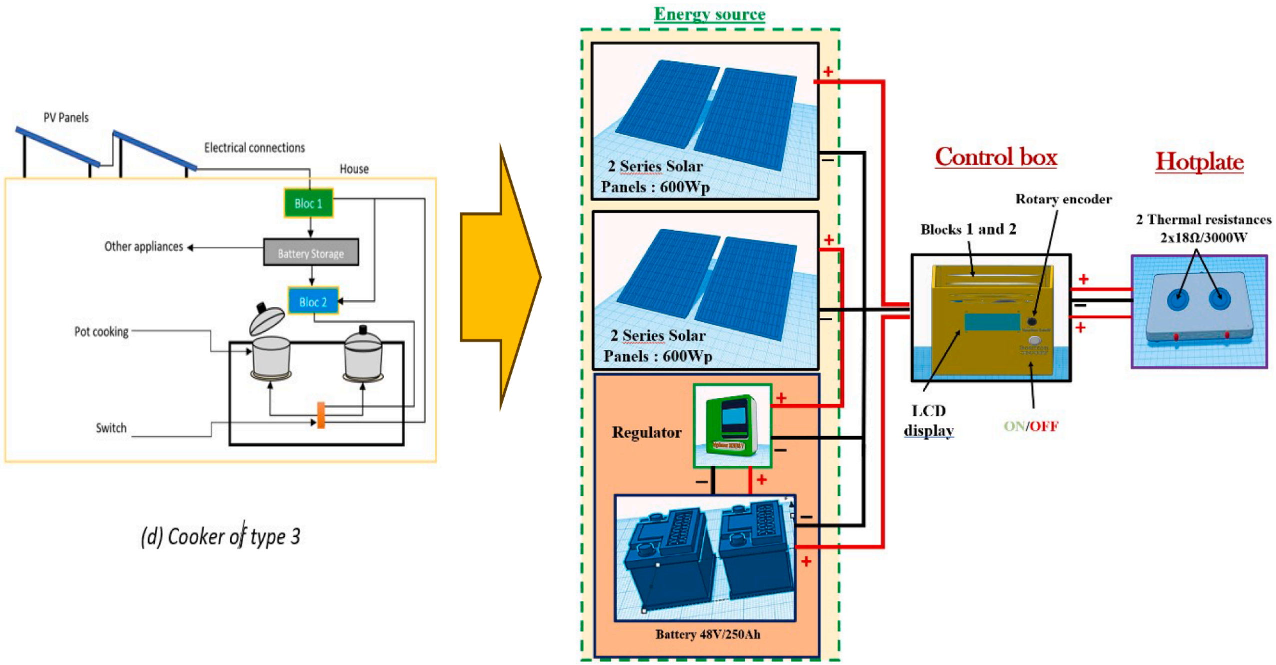
The proposed cooker prototype, of the cooking plate type (Fig. 1), allows cooking with photovoltaic (PV) panels during sunny days and solar batteries during poorly sunny and nighttime conditions. The operation of the cooker is based on the use of a power board (Block 1) and a digital electrical board (Block 2). This digital board uses a microcontroller (Raspberry) to manage all the functions of the cooker through the PV panels and batteries: acquisition and display of electrical quantities, malfunction detection, manual or automatic operation of the cooker. Based on fieldwork, we propose the cooker prototype (Fig. 1), which is designed considering the daily energy needs of users, which range from 3–4.5 kWh/day. The proposed cooker must therefore comply with the specifications, which consist of producing daily cooking electrical energy (Day and Night):

- By the PV panels (600 Wp), which produce, throughout the day, an energy of 3.5–4.2 kWh/day, with a cooking power of 400 W - 450 W for 5 h (equivalent to an energy of 2–2.25 kWh/day).
- By the batteries during the night and on poorly sunny days (48V/250Ah/12 kWh). We have chosen lead-acid batteries due to their cost-effectiveness, availability, and proven reliability in off-grid energy systems. They are charged by two other PV panels of the same power as the previous ones, to produce a cooking power, depending on user needs, of 200 - 450 W for 5 h (equivalent to an energy of 1–2.25 kWh/day). The total battery charge (12 kWh/day) ensures cooking autonomy for 5 to 8 days without sunlight.
- A total cooking energy from the PV panels and the batteries of 3–4.5 kWh/day.
- Cooker that performs the following operations:
  ü Operation 1: Cooking throughout the day with 600 Wp photovoltaic panels,
  ü Operation 2: Cooking with solar batteries day and night,
  ü Operation 3: Cooking with both PV panels (Operation 1) and solar batteries (Operation 2).

Synoptic diagram

Fig. 2 represents the schematic diagram of the cooker as well as the structure of the heating system (Blocks 1 and 2) powered by photovoltaic energy, proposed in this project. The different blocks of this cooker are:

- Energy source that powers the cooker system. It consists of:
  - 2 PV panels with a total power of 600 Wp.
  - A 48 V/250 Ah solar battery (4 batteries of 12V/250Ah in series), charged by two other 600 Wp PV panels during sunny days. These batteries ensure the storage of 12 kWh/day of energy and the continuous powering of various active components (Raspberry board, power switches, etc.) via +5 V and +15 V voltages, using a charge-discharge regulator.
- Heating plate, with dimensions 50 cm in length, 32 cm in width, and 10 cm in height. It is formed by two thermal resistors of 18 Ω value (Fig. 2). One resistor is powered by the electrical energy produced by the PV panels during sunny days. The second resistor is powered by the solar batteries during poorly sunlit days or at night.
- Power block (Block 1) consists of two DC/DC Boost converters, each capable of operating at a power of 1 kW. Converter 1 is powered by the PV panels during sunny periods, while Converter 2 is powered by the solar batteries during periods of low sunlight or nighttime. The power switches of both converters are controlled by a periodic signal with a frequency of 20 kHz and a variable duty cycle α (ranging from 0 to 1). The duty cycle refers to the fraction of time the switch is in the "on" state during each switching cycle, determining the amount of power delivered to the load and ensuring that the output voltage is maintained at the desired level.
- Electronic block (Block 2), which consists of analog and digital circuits, powered by the batteries via a polarization circuit (+5 V and +15 V). The overall operation of the cooker is managed by the microcontroller 'Raspberry', which performs the following tasks:
  - Task 1: Operation of the cooker under the sun, by heating a thermal resistor. In this case, two modes of operation are ensured:
    - Optimal operation of the PV panels (automatic mode) via an MPPT (Maximum Power Point Tracking) command (Perturb and Observe). This is achieved by activating relay 1 and controlling the 'MOSFET' power switch of the DC/DC converter, through a 20 kHz frequency PWM signal with a variable duty cycle α.
    - Manual operation of the cooker (manual mode) by activating relay 1 and adjusting the operating point of the PV panels. This is achieved by varying the duty cycle α of the PWM signal generated by the microcontroller to control the 'MOSFET' power switch of the DC/DC converter.



. **1.** Schematic of the Cooker Prototype to Design and Build.

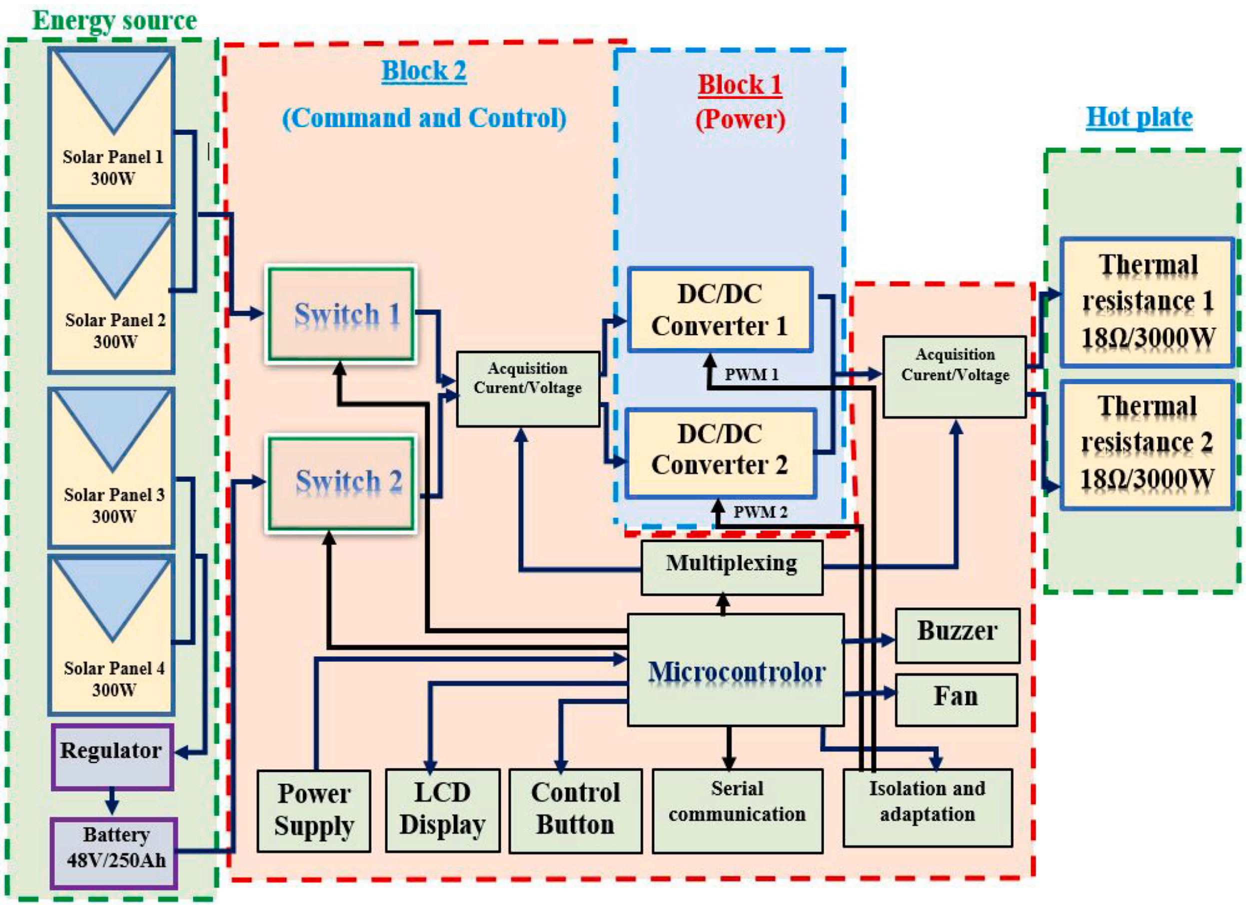


Fig. 2. The block diagram of the cooker as well as the structure of the system (Blocks 1 and 2) powered by photovoltaic energy.

  - Task 2: Operation of the cooker by the solar batteries during poorly sunlit or nocturnal periods, by heating the second thermal resistor. The microcontroller activates relay 2 and generates a PWM signal with a frequency of 20 kHz and a duty cycle α, varying between 0.1 and 0.5.
  - Task 3: Acquisition and display on LCD, local and remote control of the electrical parameters of the DC/DC converters (Voltage, current, and efficiency). The acquisition of these parameters is carried out through a digital multiplexer.
  - Task 4: Detection of any malfunction (overvoltage, overcurrent, disconnection of thermal resistors from the DC/DC converter outputs). To do this, the microcontroller deactivates relays 1 and 2 to disconnect the energy sources from the two DC/DC converters.
- Computer (Optional), for which an interface (Application) is set up to store, process, and display the various electrical parameters acquired. This application also allows local and remote monitoring (via the Internet). It also enables remote control of certain functions (ON/OFF of the system). This is achieved by activating/deactivating the various power relays, allowing the cooker to be turned on/off.

Cooker control

The flowchart in Fig. 3 illustrates our solar cooking system, capable of using PV panels, batteries, or a combination of both to power stoves. This flowchart describes a flexible, secure solar cooking system that adapts to variations in energy availability. With its various modes and alerts, it ensures efficient resource use while providing precise control, either manually or automatically. Upon starting, the user selects a cooking mode via an LCD screen that offers three options:

1. Cooking with photovoltaic panels only (resistance 1): In this mode, energy is provided exclusively by the PV panels. The system collects electrical data (voltage, current, input and output power) to monitor the heating of the heating plate. Two sub-modes are available:
∘ Automatic mode: A MPPT (Maximum Power Point Tracking) algorithm optimizes the conversion of solar energy.
∘ Manual mode: The user directly adjusts the duty cycle to control the power. The data is transmitted via a serial port and wirelessly for remote monitoring.
2. Cooking with batteries only (resistance 2): In this case, the energy comes from the batteries. The system collects and monitors the same electrical data (voltage, current, power). Only manual mode is available, allowing the user to adjust the duty cycle of the PWM signal controlling the power switch of the DC/DC converter 2 (Fig. 2) to adjust the power. As in the previous mode, the data is transmitted via a serial port and wirelessly for remote monitoring.
3. Combined cooking with photovoltaic panels and batteries (resistances 1 and 2): This mode combines the PV panels and batteries to simultaneously power both resistances. The electrical data from both sources are collected and transmitted. Both automatic (MPPT) and manual modes are also available to adjust cooking power.

Additionally, safety conditions and alerts apply to all modes:

- In the case of low solar irradiation, the user is prompted to switch to battery power.
- If the battery level is low, an alert will prompt the user to recharge the batteries before continuing.
- To confirm and proceed after each alert, the user must intervene by pressing a button, ensuring that all safety checks have been performed.

Experimental results

Measurement bench

The Fig. 4 presents all the measurement equipment set up in our LETER laboratory to experiment with the complete solar stove designed during this work. The different blocks composing this test bench are as follows:

- PV panels with a total power of 1200 Wp that power the stove. In this prototype, they are used as follows:
  - Two PV panels (1) connected in series for a total power of 600 Wp, directly powering the control box (11).
  - Two other PV panels (2) also connected in series for a power of 600 Wp, charging the solar batteries (5) via a charge/discharge regulator (4).
- Four 12 V/250 Ah batteries (5) connected in series to form a global battery of 48 V/250 Ah. These batteries are charged by PV panels (2) through the charge/discharge regulator (4).
- Control and energy management box (11) that regulates the energy supplied by the PV panels (1) and the solar batteries (5). This box controls the heating of the heating plate (10) via two DC/DC converters and an electronic board that controls the entire solar cooking system.
- The heating plate (10) includes two resistive elements (left and right), each capable of supporting up to 2 kW of power and withstanding temperatures up to 1000 °C. In the context of this work, however, these resistors were operated under reduced power, either directly from the PV panels or via battery storage, with a maximum input power limited to approximately 600 W.

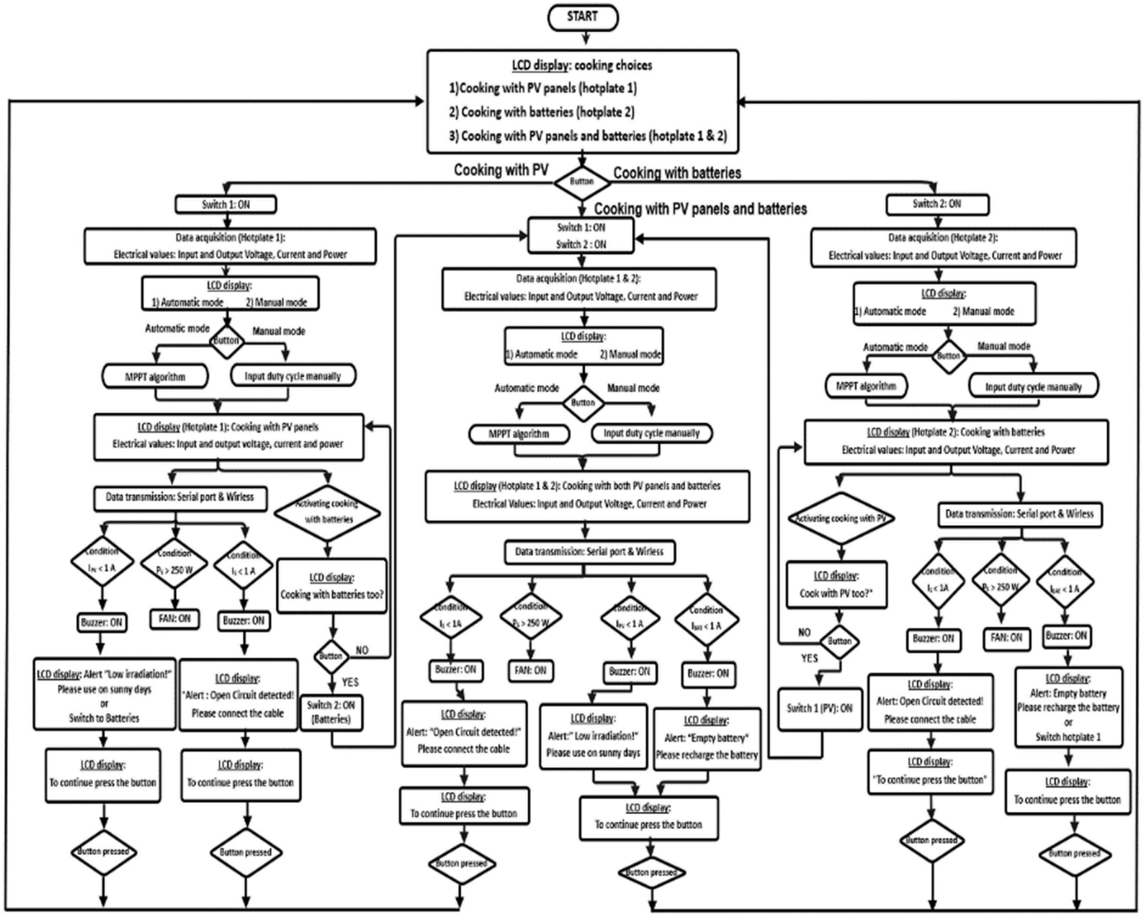


Fig. 3. Flowchart of the control of the cooker by the Raspberry microcontroller.

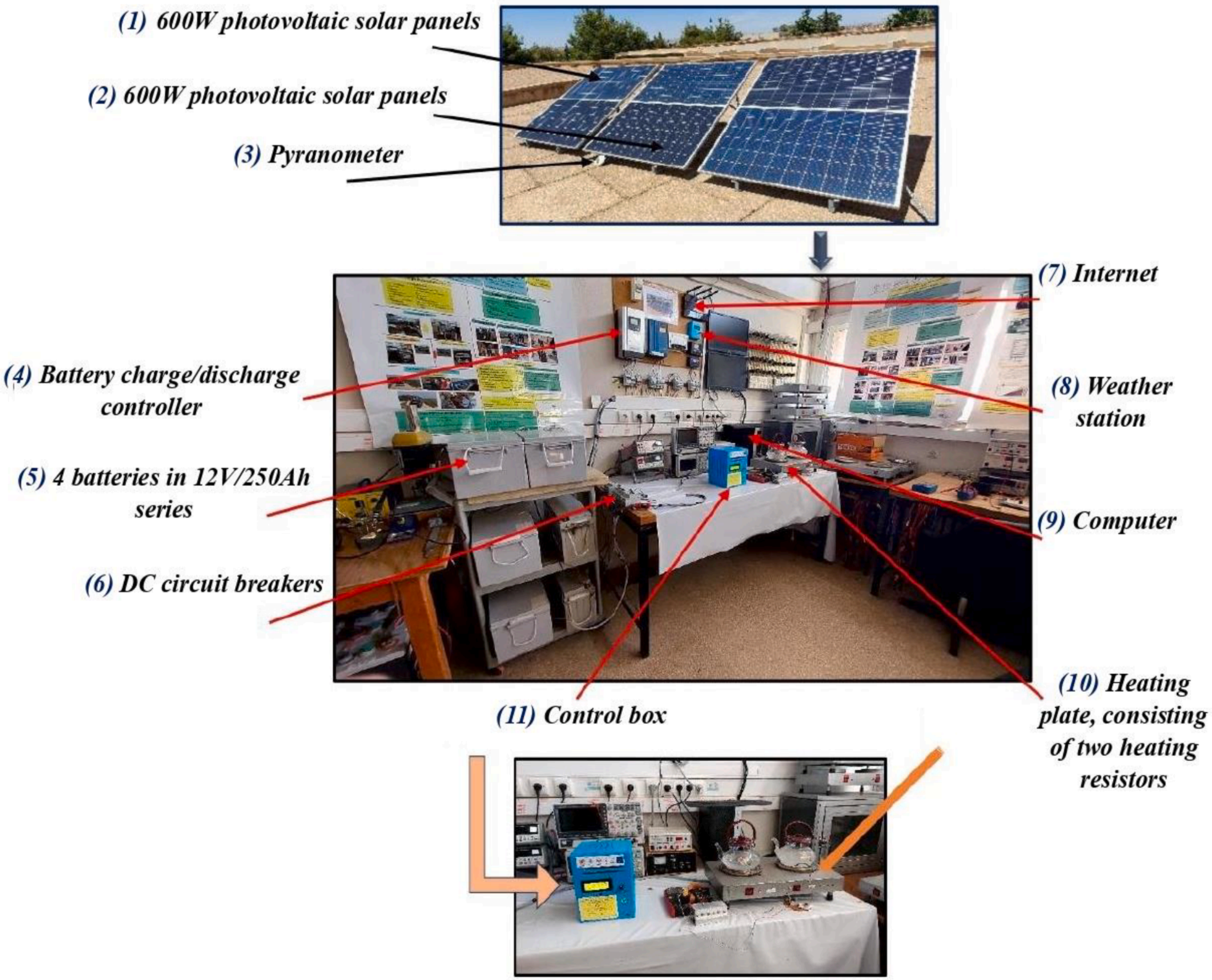


Fig. 4. Measurement bench and **cooker** set up in the laboratory of the University of Oujda.

- Weather station (8), equipped with a pyranometer (3) and a thermal sensor to measure the solar irradiance and ambient temperature.
- Monitoring and control equipment (9), consisting of a computer and two screens used to program the control board (Raspberry microcontroller). It also allows monitoring and regulating the stove's operation, locally or remotely via the internet (7).

Characterization of photovoltaic panels

We experimented with the electrical performance of a photovoltaic panel under three different irradiance intensities (Le): 700 W/ m^2, 540 W/m^2, and 462 W/m^2. The typical current-voltage and voltage-power characteristics obtained at 25 °C are shown in Fig. 5. From these characteristics, we plotted the evolution of the short-circuit current (ICC) as a function of irradiance (Fig. 6). In the context of our experiment, the power of the photovoltaic panels reached a maximum of 230 W at a solar intensity of 750 W/m^2, based on the measurements from that day. However, given the linear behavior of the photovoltaic panel performance with respect to irradiance intensity, it is possible to extract the same parameters from the PV panels if the power reaches 600 W. This linear behavior allows us to predict the panel characteristics even at higher power levels, up to their nominal capacity, while maintaining the validity of the analyses performed.

Using the electrical model of a photovoltaic panel with a single diode, given by the relation:

$$I_{PV} = I_{CC} - I_S\left(exp\left(\frac{qV_{PV}}{N_p\ Fac\ k_bT}\right) - 1\right) \tag{1}$$

Where:

I_S:Saturation current of the photovoltaic cell diode,
Np: Number of photovoltaic cells (36 cells in our case),
Fac: Ideality factor,
q: Charge of an electron (-1.6×10^{-19} C),
k_b: Boltzmann constant (1.381×10^{-23} J/K),
T: Temperature,

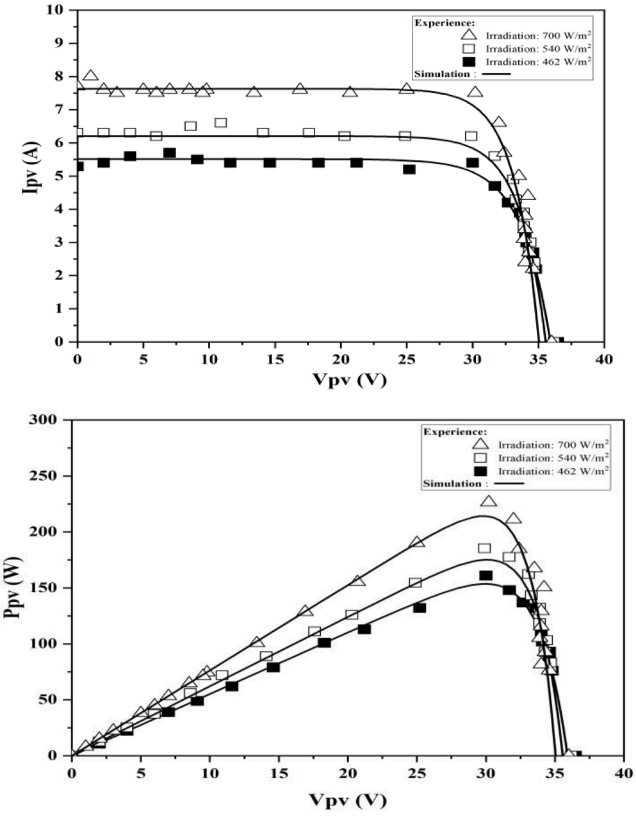


Fig. 5. Current-Voltage and Power-Voltage Characteristics of Photovoltaic Panels at a Temperature of 25 °C and Three Light Intensities: 700 W/m^2, 540 W/m^2, and 462 W/m^2.

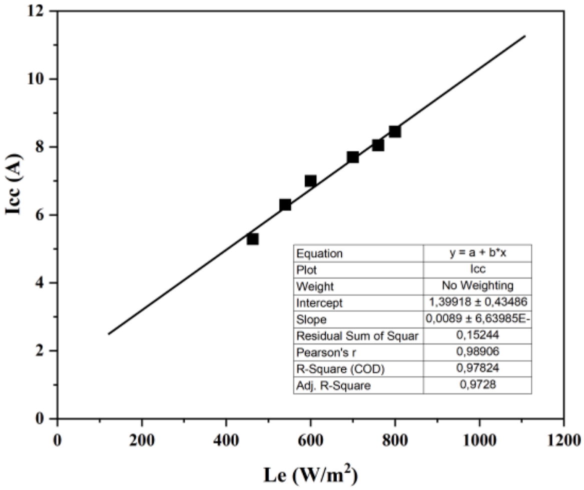


Fig. 6. Short-circuit current (Isc) as a function of irradiance.

We plotted the evolution of $\ln(I_{CC}-I_{PV})$ as a function $V_{PV}/(Np*k_bT/q)$ in Fig. 7. The results allowed us to deduce:

- The short-circuit current increases linearly with irradiance from 4.5 A to 7.5 A, following the relation:

$$I_{CC} = 1.399 + 8.9\ 10^{-3} \cdot Le \tag{2}$$

- A linear behavior of Ln (I_{CC}-I_{PV}) with respect to $V_{PV}/(Np*k_bT/q)$, for the current-voltage characteristic in Fig. 5. From the slope of this characteristic, we deduced the ideality factor Fac to be between 1.225 and 1.488, and from the y-intercept, we deduced the saturation current of the diode to be between 0.398×10^{-7} A and $5.68 \times 10^{-}A$.
- The open-circuit voltage and optimal voltage of the PV panel are very little dependent on irradiance. They are approximately 35 V and 32 V, respectively.
- The optimal current and power increase with irradiance. In our case, they range from 5.5 A to 7.6 A and 150 W to 240 W, respectively.
- The optimal resistance of the photovoltaic panel varies from 6.4 Ω to 4.6 Ω.
- A very good agreement was found between the experimentally obtained current-voltage and power-voltage characteristics and the calculated ones using relation 1, considering the parameters ISI_SIS and Fac.

Based on these results, we deduced the electrical characteristics of the two photovoltaic panels in our installation (Fig. 4), when irradiance varies from 462 W/m² to 700 W/m²:

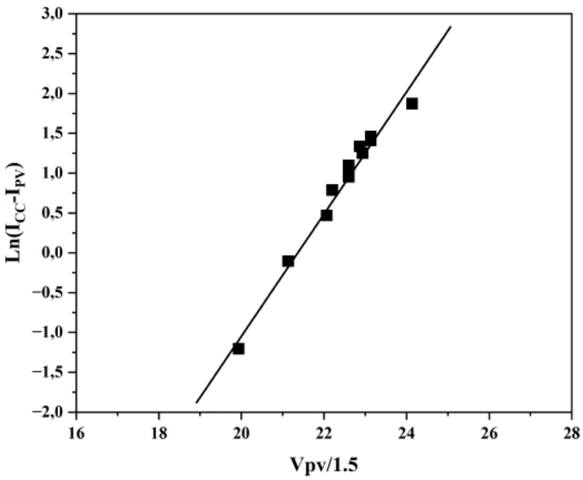
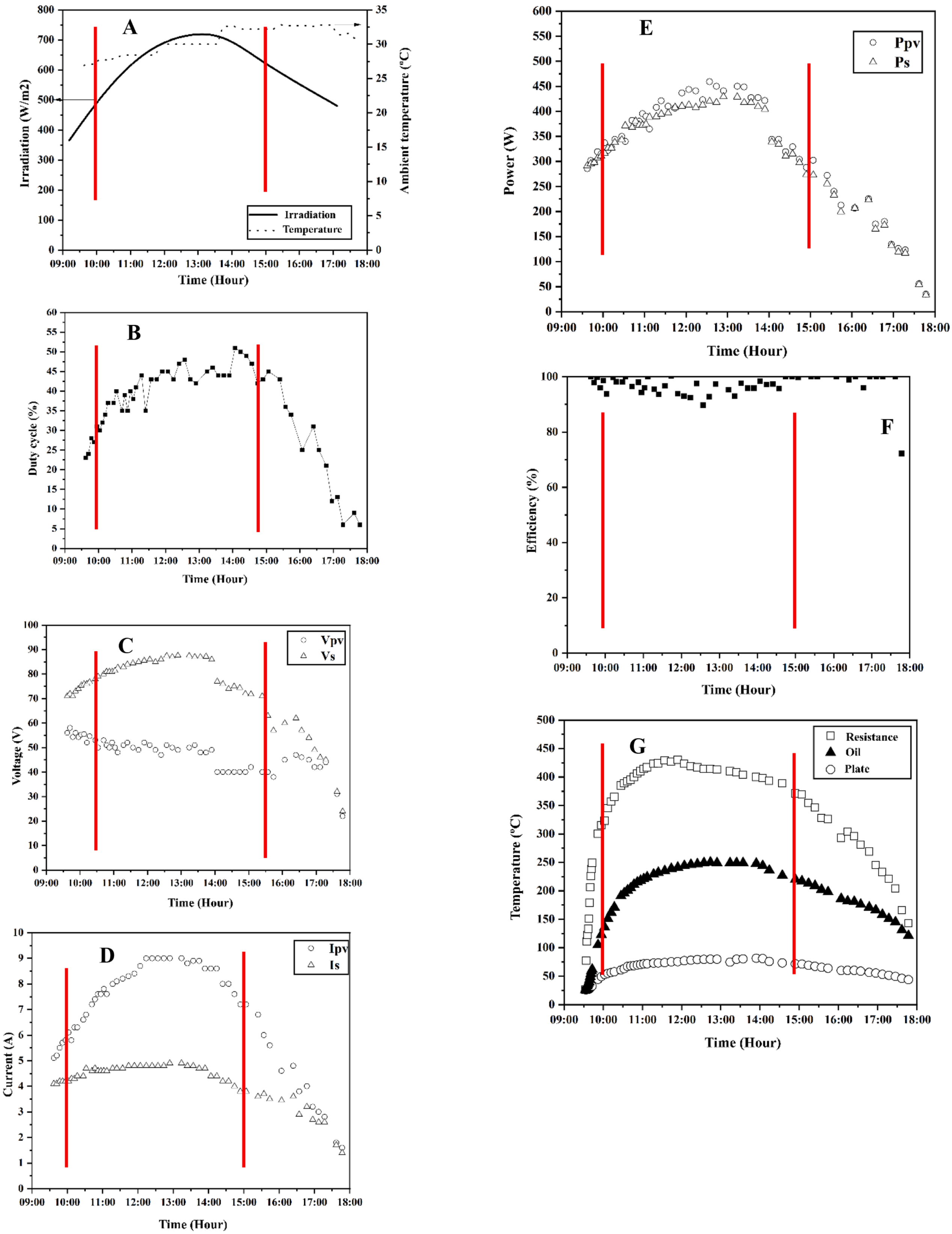


Fig. 7. Typical Plot of Ln(Icc - Ipv) as a Function of V_{PV} / (Np * kbT/q) for a Current-Voltage Characteristic from Fig. 5.



(caption on next page)

Fig. 8. Typical operation of the cooker with PV panels in automatic mode (October 26, 2023).
A: Illumination and ambient temperature, B: Duty cycle, C: Voltage, D: Current, E: Power, F: Efficiency, G: Temperature of the heating plate metal sheet, oil, and heating resistor

- The short-circuit current varies from 4.5 A to 7.5 A.
- The circuit voltage is around 70 V.
- The voltage, current, power, and optimal resistance are around: 64 V, 5.5 A to 7.6 A, 300 W to 480 W, and 12.8 Ω to 9.2 Ω.

The results demonstrated the validity of the photovoltaic panel's electrical performance for dimensioning and selecting the electrical components of Blocks 1 and 2 of the electronic box (Fig. 1), which powers the cooker developed in this work

Cooker experimentation

We experimented with the cooker from Fig. 1 by heating 1 L of oil following three scenarios: heating by the PV panels, batteries, and PV panels plus batteries. For each scenario, we recorded:

- Meteorological conditions: Solar irradiance and ambient temperature.
- Electrical quantities: Duty cycle of the DC/DC converter control signal, voltages, currents, and power at the input and output of these DC/DC converters.
- Efficiency of the DC/DC converters, calculated as the ratio of output power to input power, considering the energy losses in the system.
- Temperature of the heating plate (sheet), oil, and heating resistors.

Next, we present the typical results obtained when the cooker is powered by the PV panels and batteries (Scenarios 1 and 2). The operation following Scenario 3 is almost identical to that of Scenarios 1 and 2.

Operation with photovoltaic panels (Scenario 1)

Automatic operation. Fig. 8 shows the different measurements obtained during the heating of the cooker, over the course of a whole day, by the photovoltaic panels in automatic mode. From this, we can deduce:

- The maximum illumination intensity reaches 700 W/m^2 around 1 PM, and the ambient temperature varies from 26 °C to 33 °C.
- The maximum power provided by the PV panels is 480 W, achieved around 1 PM with a duty cycle of 0.45. Under these conditions, the voltage and current at the input of the DC/DC1 converter are 50 V and 9A, respectively, and at the output, they are 90 V and 5A.
- During the day, the energy produced by the PV panels is about 2659 Wh/day, with 2564 Wh/day produced at the heating plate.
- Between 10 AM and 3 PM (5 h of operation), the duty cycle varies from 0.25 to 0.53, the voltage, current, and power at the input of the DC/DC1 converter range from 40–60 V, 5–9A, and 260–450 W, respectively, and at the output, from 70–90 V, 3.5–4.5A, and 300–440 W. In these conditions, the energy supplied by the PV panels (produced at the heating plate) is about 1957 Wh/day (1833 Wh/day). In these conditions, the energy supplied by the PV panels is about 1957 Wh/day, with 1833 Wh/day produced at the heating plate. This energy represents over 73 % of the total energy produced throughout the day.
- Between 11 AM and 2 PM (3 h of operation), the duty cycle varies from 0.40 to 50, the voltage, current, and power at the input of the DC/DC1 converter range from 40–50 V, 7.5–9A, and 375–475 W, respectively, and at the output, from 80–90 V, 4.5–4.4A, and 370–350 W. In these conditions, the energy supplied by the PV panels (produced at the heating plate) is about 1595.6 Wh (1557.5 Wh). This energy represents over 60 % of the total energy produced throughout the day.
- The efficiency of the DC/DC1 converter is practically constant throughout the day, remaining above 90 %.
- The maximum temperatures for heating the resistor and oil are around 430 °C and 250 °C, respectively, achieved around 1 PM. However, the temperature of the heating plate does not exceed 60 °C. These temperatures remain almost constant between 11 AM and 2 PM.

The results obtained show, between 10 AM and 3 PM, when the illumination varies from 500 W/m^2 to 700 W/m^2, a good efficiency of the DC/DC1 converter ($>$ 90 %), with electrical power production ranging from 350–450 W (which means the energy supplied by the PV panels (produced at the heating plate) is around 1.8–2 kWh/day). These energies are in good agreement with the cooker's specifications 3: cooking power of 400 W - 450 W, energy of 2–2.25 kWh/day. Under these conditions, the temperatures of the heating resistor (390–450 °C) and the oil (220–240 °C) are very high for daily cooking in households. Furthermore, during this heating period, the produced energies represent over 73 % of the total energy produced throughout the day. This demonstrates the proper functioning of the cooker's heating system: Power Block 2 (DC/DC1 converter) and Electronics Block 1 (cooker control).

All the results obtained show the feasibility of operating the cooker with the photovoltaic panels, following scenario 1 in automatic

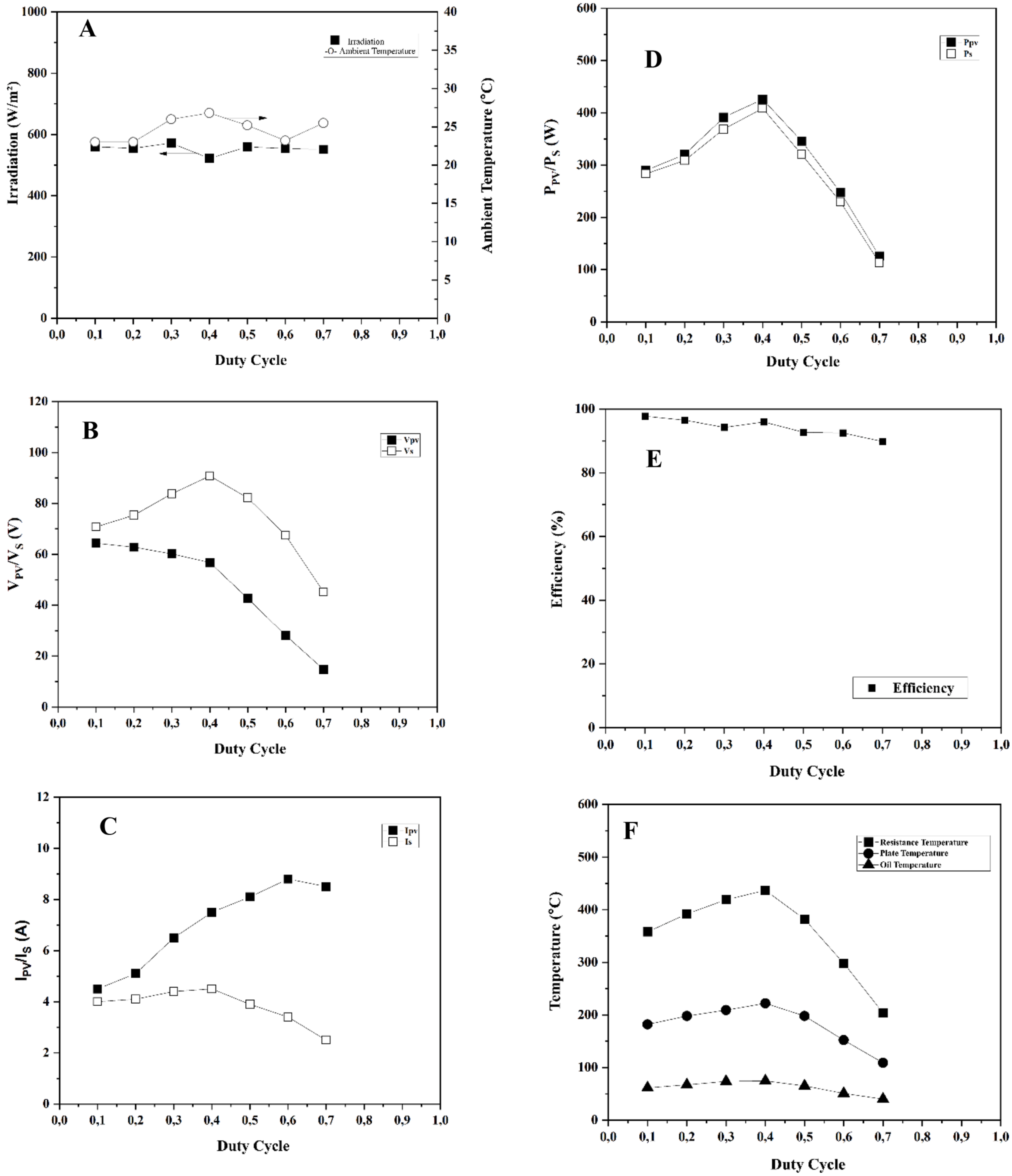


Fig. 9. Typical operation of Cooker with PV panels (5) in Manual Mode (October 26, 2023), when the illumination is 600 W/m^2 and the ambient temperature is 22–26 °C.
A: Illumination and ambient temperature, B: Voltage, C: Current, D: Power, E: Efficiency, F: Temperature of the heating plate sheet, oil, and heating resistance.

mode. In Fig. 8, we have highlighted in red the proposed period for using the cooker during a sunny day with PV panels, as well as the period when the power from the PV panels exceeds 250 W, which allows for the necessary electrical energy and heating temperature to reach cooking temperatures above 300 °C, ensuring optimal cooking performance.

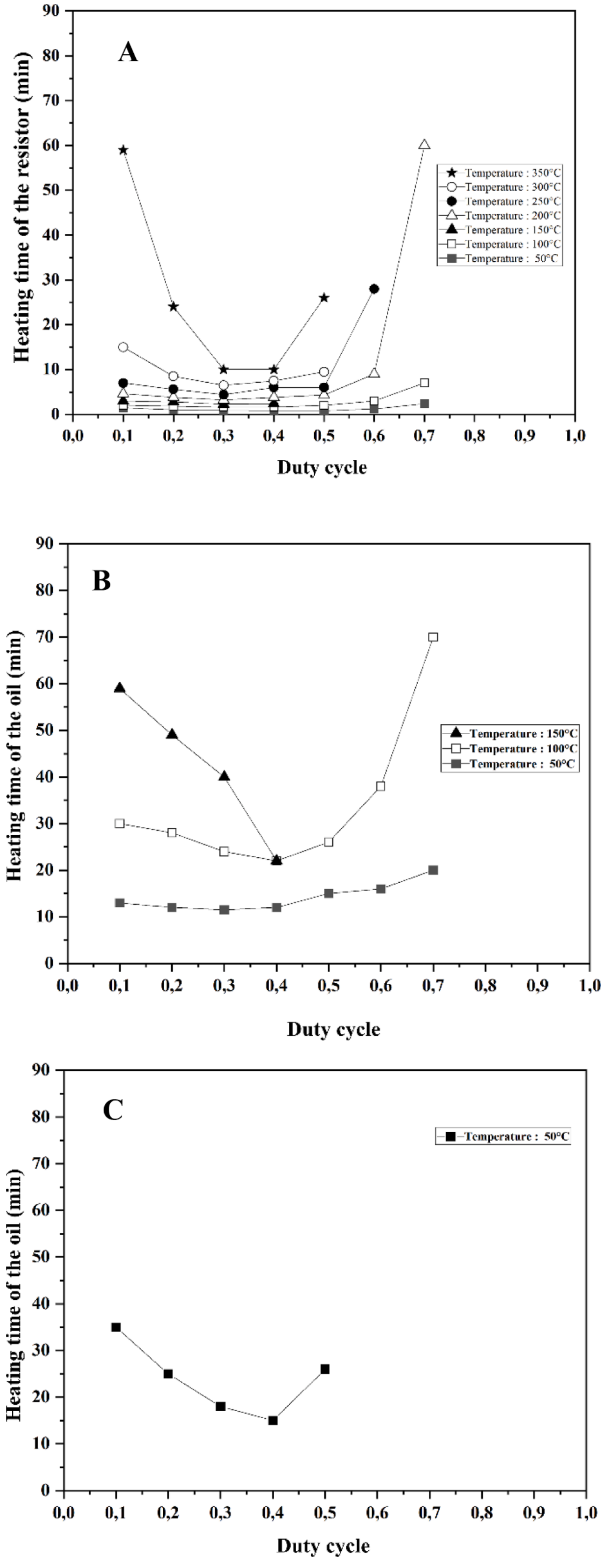


Fig. 10. Heating times of Cooker 3 (Heating Element (A), Oil (B), Plate (C)) as a function of the duty cycle of the DC/DC converter control signal for a lighting of 600 W/m².

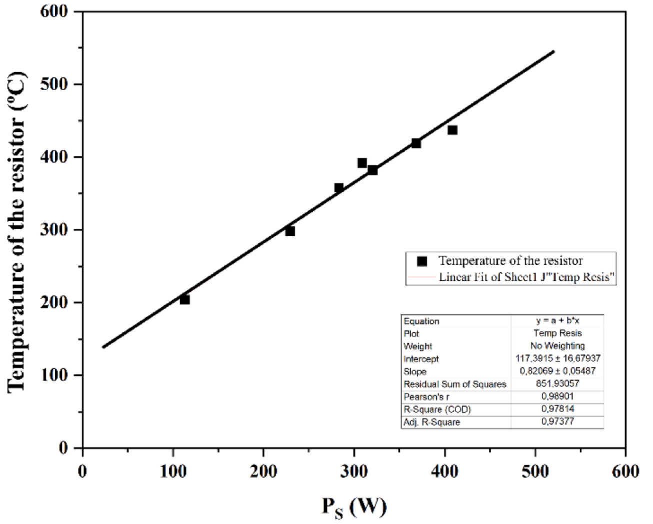


Fig. 11. Dependence of the heating temperature of the resistor on the output power of the DC/DC converter 1.

Manual operation. The Fig. 9 represents the various measurements obtained during the heating by PV panels in Manual Mode (Scenario 1). These measurements were carried out by varying the duty cycle of the DC/DC1 converter's control when the illumination intensity was 600 W/m^2 and the ambient temperature ranged from 22–26 °C. We can deduce the following:

- The operation and heating of the heating plate are strongly dependent on the duty cycle. When the duty cycle increases or decreases, the cooker's performance (power and temperature of the resistance) reaches a maximum. Under optimal conditions, the duty cycle is 0.40, and the voltage, current, and power are 58 V, 8 A, and 420 W at the input of the DC/DC1 converter, and 90 V, 4.2 A, and 400 W at its output.
- For each measurement, the efficiency of the DC/DC1 converter is greater than 90 %.
- When the duty cycle varies from 0.10 to 40, at the input of the DC/DC1 converter (PV panels), the voltage remains nearly constant (around 60 V), the current increases from 4.2 A to 8 A, and the power increases from 300 W to 420 W (a 40 % increase). Under these conditions, the temperature of the plate remains at 60 °C, while the temperatures of the resistances and the oil increase from 350 °C to 450 °C (a 28 % increase), and from 180 °C to 220 °C (a 22 % increase).
- When the duty cycle varies from 0.40 to 0.70, at the input of the DC/DC1 converter (PV panels), the voltage decreases from 60 V to 18 V (a 70 % decrease), the current remains almost constant at 8–8.5 A, and the power decreases from 420 W to 100 W (a 73 % decrease). Under these conditions, the temperature of the plate stays at 60 °C, while the temperatures of the resistances and the oil decrease from 450 °C to 250 °C (a 44 % decrease), and from 220 °C to 140 °C (a 37 % decrease).

The overall results show that in Manual Mode, the operation strongly depends on the duty cycle. The values and variations obtained are in good agreement with the simulations and the cooker's specification sheet. Compared to Automatic Mode, in Manual Mode, the user can vary the duty cycle to decrease the power supplied by the PV panels and thus the heating temperature. These results demonstrate the feasibility of the cooker's operation according to Scenario 1 in Manual Mode.

Cooker performance: heating time. In this paragraph, we analyzed the performance of the cooker by estimating the heating time of the heating element, oil, and plate as a function of the duty cycle for a lighting of 600 W/m^2. For the heating element, we plotted the dependency of the maximum temperature with the heating power. The results obtained are represented in Figs. 10 and 11. These results show that:

- The minimal heating time is achieved with a duty cycle of around 40 %, which maximizes the power of the panels for this lighting of 600 W/m^2. Under these conditions, we deduced:
  - For the heating element, temperatures of 100 °C, 200 °C, and 350 °C are reached after 2 min, 4 min, and 10 min.
  - For the oil, temperatures of 100 °C and 150 °C are reached after 24 min.
  - For the plate, a temperature of 50 °C is reached after 15 min.
- If the duty cycle is varied around the optimum, the power of the PV panels decreases, and the heating time increases. A significant increase in this time is observed for high temperatures if the duty cycle is decreased or increased by 20 %:
  - For the heating element, the temperature of 350 °C is reached after 25 min.
  - For the oil, temperatures of 100 °C and 150 °C are reached after 28 min and 45 min.
  - For the plate, a temperature of 50 °C is reached after 22 min.
- The heating temperature of the heating element varies linearly with the output power of the DC/DC converter:

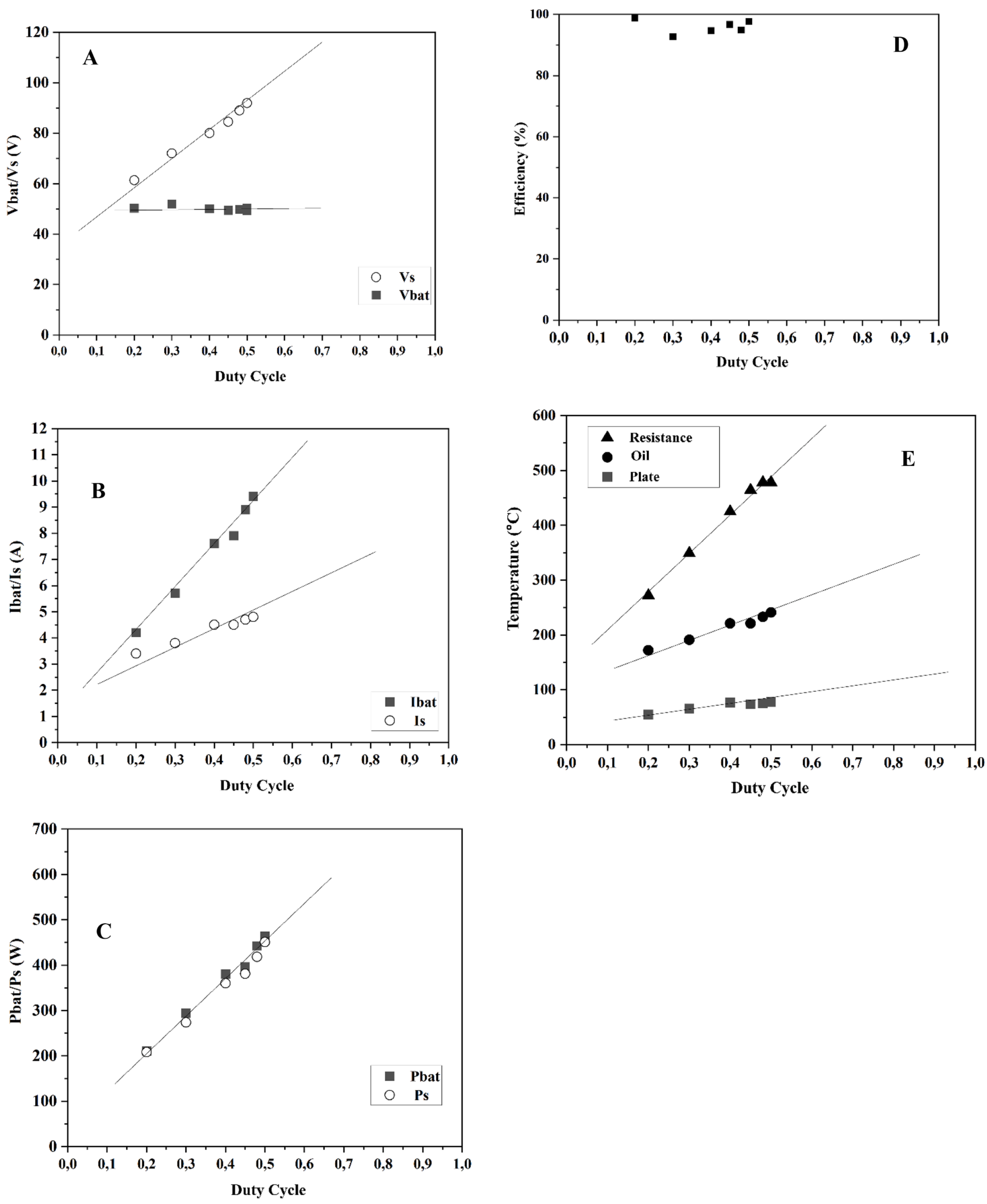


Fig. 12. Typical operation of the cooker 3 with solar batteries. A: Voltages, B: Currents, C: Powers, D: Efficiencies, E: Temperature of the heating plate sheet, oil, and the heating plate resistance.

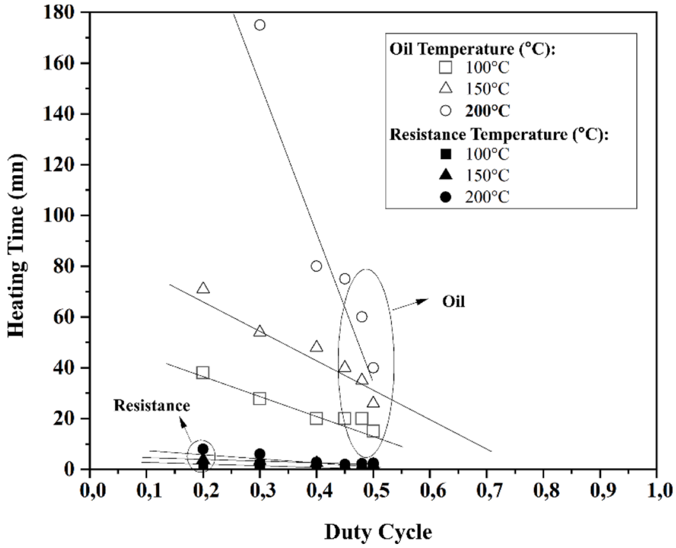


Fig. 13. Heating time of Cooker (resistor and oil) by solar batteries as a function of the duty cycle.

$$\mathbf{T_R} = 117.3915 + 0.8206 \textbf{ x PS} \tag{3}$$

This equation is valid under conditions where the heating element receives a minimum power input, typically greater than 50 W, ensuring that the system is able to generate and maintain heat. In practical scenarios, if the output power of the DC/DC converter drops to zero, the heating element would not sustain the temperature of 117 °C, as the energy supply would be insufficient to maintain such temperatures. The relationship holds primarily when there is an active energy source, such as the PV panels or the batteries, providing power to the heating element.

Overall, the results show that for a lighting of 600 W/m^2, under optimal conditions (400 W), heating times for the heating element are <5 min (10 min) at temperatures of 200 °C (350 °C). This demonstrates, on one hand, the good performance of the type of heating element used, and on the other hand, the feasibility of the cooker, which is proposed for cooking in households.

Operation with solar batteries (Scenario 2)

Manual operation. The Fig. 12 shows the different measurements obtained during heating by the batteries in manual mode (Scenario 2). We can deduce the following:

Fig. 14. Demonstration of the prototype's use (Fig. 4) by women in rural Morocco.

- The operation and heating of the heating plate strongly depend on the duty cycle. The electrical energy production by the batteries increases linearly with the duty cycle.
- When the duty cycle increases from 0.20 to 0.50, the battery voltage remains practically constant at 48 V, while the battery current, output voltage, and output current of Converter 2 increase linearly by 4–10A (a 150 % increase), 60–90 V (a 50 % increase), and 3.2–4.5A (a 40 % increase), respectively. As a result, the input power increases from 200 W to 450 W (a 125 % increase).
- For each measurement, the efficiency of the DC/DC converter 2 is greater than 90 %.
- Under these conditions (varying the duty cycle from 0.20 to 0.50), the temperature of the plate remains almost constant around 60 °C, while the temperatures of the resistances and oil increase from 250 °C to 500 °C (a 100 % increase) and from 150 °C to 200 °C (a 33 % increase), respectively.

The overall results show that the heating of the plate strongly depends on the duty cycle. Since the various components of the power and electronic blocks have been sized to operate below voltages, currents, and power of 12A, 120 V, and 500 W, we have limited the duty cycle variations to 0.55. Regarding the variations in the maximum heating temperature of the resistance with the output power of Converter 2, we have verified that it follows the law obtained for Converter DC/DC1 (relation −3-), powered by the PV panels.

Cooker performance: heating time. As with the PV panels, we estimated the heating time of the heating resistor and the oil based on the duty cycle ratio. The temperatures of the plate sheet are not represented since their values do not exceed 60 °C. The results obtained are shown in Fig. 13. The following conclusions can be drawn:

- Heating time decreases with the duty cycle ratio.
- In the case of the resistor:
  - For a duty cycle of 0.20 (Power of 200 W), temperatures of 100 °C, 200 °C, and 350 °C are reached within times <2 min, 5 min, and 8 min.
  - For duty cycles greater than 0.40 (Power of 400W-450 W), temperatures of 100 °C, 200 °C, and 350 °C are reached within times <2 min.
- In the case of the oil:
  - For a duty cycle of 0.40 (Power of 400 W), temperatures of 100 °C, 150 °C, and 200 °C are reached within 20 min, 45 min, and 80 min, respectively.
  - For a duty cycle of 0.50 (Power of 450 W), temperatures of 100 °C, 150 °C, and 200 °C are reached within 18 min, 22 min, and 40 min, respectively.

The overall results show heating times for the resistor and the oil (cooking) comparable to those obtained with traditional heating methods (gas). This indicates the proper functioning of both the power unit (DC/DC Converter 2) and the regulation electronics (Block 2). As a result, Cooker 3 can be used in households for cooking day and night.

Analysis of results and feasibility of the prototype

The analysis of the results obtained in this work, compared to the solar cooking systems described in the literature, highlights several key aspects regarding the performance of each technology, particularly those using solar panels and batteries. Based on the literature review of these cookers, we can conclude that thermal box cookers using phase change materials (PCMs) stand out for their ability to store heat and provide stable cooking. However, their performance is limited, particularly in terms of temperature and cooking duration. Indeed, these systems do not reach temperatures higher than 250 °C, and their cooking duration is around 50 min [20]. In comparison, our photovoltaic cooker far exceeds these limits, with maximum temperatures reaching 430 °C for the resistor and 250 °C for the oil, providing faster and more versatile cooking.

Regarding photovoltaic cookers that incorporate solar panels and batteries, their performance varies depending on their design and components used. For instance, a system using a 100 Ah AGM battery and a 450 W solar panel generates a stable power output of around 200 W. While this system benefits from thermal management through the insulation of the Wonderbag, it is limited by its low power output [21]. In contrast, our photovoltaic system surpasses this model by reaching a maximum power output of 480 W and an energy production of 2659 Wh/day. The efficiency of our DC/DC converter, which exceeds 90 %, ensures optimized energy management and stable temperatures between 11:00 AM and 2:00 PM, with maximum values of 500 °C for the resistor and 200 °C for the oil, thus guaranteeing rapid and efficient cooking throughout the day.

Another system, using a 300 W solar panel and materials optimized for heat transfer (such as a stainless steel pot), demonstrates an energy efficiency of 44 % to 61 %, heating water in 5 to 15 min [22]. Although this system improves heat transfer, it remains inferior to our cooker in several aspects. In fact, our system generates 1957 Wh/day during its optimal operating range (from 10:00 AM to 3:00 PM), which is far superior to the 300 W system. Additionally, the maximum temperatures reached by our cooker (430 °C for the resistor and 250 °C for the oil) are much higher, enabling faster and more versatile cooking. These results clearly position our system ahead of current photovoltaic cookers discussed in the literature, both in terms of thermal performance and energy production. The combination of high power output, stable operation over extended hours, and ease of use makes this prototype a strong candidate for large-scale deployment in both connected and off-grid households.

This image (Fig. 14) shows the installation of our prototype (Figs. 1 and 4) in a rural household, with a woman using it in the presence of the Association Homme et Environnement. Feedback from the users, particularly this woman, was very positive, highlighting both the ease of use and satisfaction with the system's performance. The simplicity of the system's operation, requiring only the activation of two buttons—one for the solar panels and another for the battery—was appreciated, demonstrating its user-friendliness for rural households. Currently, the Association is working with local decision-makers on a project to acquire a hundred prototypes to address cooking challenges in the region, targeting a hundred families and improving their living conditions through the adoption of this innovative technology.

In summary, our hybrid photovoltaic cooker stands out for its power, efficiency, and versatility, far surpassing other solar cooking technologies using photovoltaic panels and batteries. With a significantly higher energy production (2659 Wh/day), a power block efficiency exceeding 90 %, and much higher cooking temperatures (500 °C for the resistor and 200 °C for the oil), our system represents a high-performance and innovative solution for modern solar cooking. These features meet the growing demand for fast, stable, and versatile cooking, positioning our cooker as the benchmark among available photovoltaic solutions.

Regarding the cost of the proposed solar cooker, we have filed a patent with the Moroccan Office of Industrial and Commercial Property (OMPIC), patent number MA62943, filed on November 7, 2023. A positive report is expected by April 17, 2024, and its publication is currently underway. Additionally, we have initiated advanced discussions with an international manufacturer to assess the commercial viability of this prototype in Morocco and Africa. Currently, the estimated cost of the prototype is as follows: photovoltaic panels ($200–300), batteries ($800–1500), control box, and dual-zone heating plate ($80–150), giving a total cost ranging from $1080 to $1950. These figures are subject to change based on the optimization of the production process and negotiations with suppliers. We acknowledge that the initial cost of the system, ranging from $1080 to $1950, may seem high compared to the average annual cooking expenses of African households (approximately $180 per year). However, it is important to consider that the solar cooker represents a long-term investment with significant benefits. The system is designed to reduce dependence on traditional fuels (such as firewood, charcoal, and gas), which are costly and often pose environmental and health risks. By utilizing solar energy, households can significantly reduce their fuel costs over time, making the system economically viable in the long term, especially in rural areas where access to fuels can be limited or expensive. Moreover, the payback period of 8.3 years can be further reduced with ongoing research and technological improvements aimed at lowering production costs. Additionally, partnerships and grant programs, in collaboration with governments or non-governmental organizations, could help subsidize the initial cost and make the system more accessible to low-income households. We plan to conduct further evaluations, including pilot programs in both rural and urban environments, to gather real-world data on the economic impact of the system and optimize its cost-effectiveness ratio.

As part of our discussions with the manufacturer, we are conducting a thorough market study to make this prototype accessible and feasible for rural communities. The goal is to optimize the product cost while maintaining high performance. We foresee that the commercialization of this solar cooker will meet the growing demand for sustainable and affordable cooking solutions in Africa. This analysis and the related efforts for commercialization are integral parts of the funding projects that support our work (LEAP-RE, WBI, ARICA). We are confident that once industrialization begins, the manufacturing cost can be significantly reduced through economies of scale and optimized supply chain.

Conclusions

In this publication, we presented and experimented with the solar cooker system, powered by photovoltaic panels (600 Wp) and batteries (48 V, 250Ah). The cooker powers a heating plate, formed by two thermal resistors, through a control box, consisting of a power block 1 (two DC/DC Boost converters) and an electrical block 2 that regulates the operation of the cooker (power supply from the two energy sources, optimization, display of electrical quantities). Based on its experimentation over entire sunny, partially sunny, and sunless days, we concluded:

- The PV panels produce, during 5 h of operation in sunlight, powers of 300–600 Wp and energies of 2.6–2.7 kWh. The heating temperatures of the resistors reach 400–450 °C after 10 min of heating.
- The solar batteries produce powers of 200–450 W and energy of 1000–2250 Wh/day during 5 h of operation. This energy represents 8.3–19 % of the battery charge. The heating temperatures of the resistors reach 300–400 °C after 10 min of heating.
- The PV panels and solar batteries together provide energy of 4.85–4.95 kWh/day.

The results obtained show the proper functioning of the different components of the cooker (photovoltaic panels, batteries, power blocks, electronics, heating plate). The various powers and energies produced (1000 W, 8 kWh) and the heating temperatures (above 400 °C) are in line with the cooker's specifications. The cooker's experimentation over entire days throughout the year validates its operation and demonstrates its potential for use in rural and urban households for daily cooking.

All the results demonstrate the good functioning of all the cooker's components (photovoltaic panels, batteries, power blocks, electronics, heating plate). The performance achieved, with powers around 1000 W, energy up to 8 kWh, and heating temperatures above 400 °C, fully meet the requirements defined in the specifications. Prolonged experimentation confirms the reliability and performance of the solar cooker. This system is suitable for daily use in both rural and urban households, providing an ecological and efficient solution for cooking. The results and analysis of the new prototype demonstrate its superior performance in terms of energy efficiency and cooking capabilities. The integration of photovoltaic panels and battery storage ensures continuous operation, even on days with low sunlight, offering a versatile and reliable solution for both rural and urban households.

An interesting future perspective would be to monitor the performance of the cooker in the kitchens of two families, collecting data on daily usage, energy consumption and storage in the batteries, as well as the utilization of the photovoltaic panels. This phase of experimentation will help refine our understanding of the real needs of users and identify areas for improvement. Based on the results obtained, we can consider optimizing the system, particularly by using more suitable converters and adjusting components to maximize energy efficiency and the durability of the cooker.

Credit author statement

In the framework of international cooperation, the work was planned and carried out by the following co-authors, with each contributing as outlined below:

- **M. Hmich**: Design of the cooker system, simulation of operation, wiring, and experimentation.
- **B. Zoukarh**: Wiring and testing with photovoltaic panels and batteries.
- **R. Malek**: Simulation and remote control.
- **S. Chadli**: Local control and implementation of operating software.
- **O. Deblecker**: Supervision, monitoring of operation, interpretation of results, and writing.
- **K. Kassmi**: Project coordination with international and national partners, supervision, monitoring of design and operation, and writing.
- **N. Bachiri**: Experimentation in rural households: scheduling, obtaining authorizations from the commune and the province of Berkane for the researchers' fieldwork.

Declaration of competing interest

The authors declare that they have no conflict of interest, whether financial, personal, or otherwise, with any individuals or organizations.

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National Centre for Scientific and Technical Research (CNRST), Rabat, Morocco

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