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CONFERENCE PROCEEDING

Innovative electric heating system for a hybrid solar cooker (photovoltaic/thermal) using photovoltaic energy with battery storage

M. Hmich[1] · H. Chadli[1] · S. Chadli[1] · K. Salmi[1] · R. Malek[1] · O. Deblecker[2] · K. Kassmi[1,3] · N. Bachiri[3]

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Abstract
In this paper we present the structure and operation of an electric heating system, using energy supplied by photovoltaic panels with storage in batteries, for a hybrid solar cooker (600 Wp). This innovative cooker is a sustainable alternative to domestic cooking and helps reduce dependence on fossil fuels. The system uses a 300 Wp photovoltaic panel and 24 V/180Ah batteries to heat by heating resistance, via a boost-type DC/DC converter (power block) controlled by a local and remote regulation (control and regulation block). Typical testing of the complete system over sunny days by photovoltaic panels, and batteries during night periods and lack of sun, showed stable operation at around 225–250 W, a DC/DC converter efficiency of 90% and heating temperatures of 350–400 °C. All the results obtained respect the needs of inhabitants and the specifications of the projects undertaken during this work. As a result, the use of this innovative solar cooker in rural and urban homes.

Keywords Photovoltaic/thermal solar energy · Electrical energy · Photovoltaic/thermal cooker · Energy storage in batteries · DC/DC converter · Electronic control system · High-temperature heating (>200 C°)

✉ K. Kassmi
Khkassmi@yahoo.fr

1 Faculty of Science, Department of Physics, Laboratory of Electromagnetic, Signal Processing & Renewable Energy LESPRE, Mohamed First University, Team Electronic Materials & Renewable Energy EMRE, Oujda, Morocco

2 Polytech. Mons - Electrical Power Engineering Unit, University of Mons, Mons, Belgium

3 Association Humain and Environnement of Berkane (AHEB), Berkane, Morocco

1 Introduction

Today, the production of greenhouse gases and climate change require the use of non-polluting renewable energy sources, such as solar power [1, 2]. The electrical energy produced by photovoltaic panels is used for lighting homes and public spaces [3] water pumping [4] powering desalination systems [5, 6] and solar cookers [7]. This last application is very topical, as it enables daily cooking without recourse to fossil fuels (gas), wood or coal. This helps preserve forests and improves air quality [8, 9]. The development of these technologies thus contributes to more sustainable development, by harmonizing energy needs with environmental protection.

When it comes to cooking, coal, wood and natural gas are the sources most commonly used in households, particularly in the catering trade [10, 11]. Moreover, the International Energy Agency illustrates that global coal consumption is set to increase by 3.3% in 2022, reaching a record 8.3 billion tones [12]. Furthermore, a study of energy consumption in the city of Kisangani (Democratic Republic of Congo (DRC)), shows that coal accounts for a large 81.4%, firewood for 31% [13]. In Africa, where the climate is sunny practically all year round, solar cookers are an ideal solution for cooking. However, with the abundance of solar energy, these cookers can provide an economical and environmentally-friendly cooking alternative.

In the literature, several solar cooking techniques can be found, mainly divided into three categories. Each technique has its own specific characteristics:

- Parabolic or Fresnel reflector solar cookers, which concentrate the sun's rays at a focal point, generating ideal very high temperatures [14–17]. This cooking technique depends on direct sunlight during operation, and cookers must constantly follow the sun's position. Because of their size and bulk, and their very limited effectiveness during cloudy periods and particularly in winter, users tend not to use these cookers.
- Thermal box cookers retain solar heat in an insulated enclosure. They enable slow, even cooking, suitable for simmering, baking and roasting [18, 19]. Their efficiency is highly dependent on weather conditions, and on the sun's tracking during operation, as is the case with concentration cookers.
- Photovoltaic (PV) solar cookers, based on heating a thermal resistor with electrical energy supplied by photovoltaic panels [20, 21]. This method is highly flexible, enabling cooking even on cloudy days and at night, with the use of batteries that store electrical energy. The cookers proposed in the literature are unstable and only work when the sun is shining, when sunshine is at its maximum (around 12 h). This is due to problems of dimensioning and operation of the cooker's regulation and control system [22].

Despite significant advances in the field of photovoltaic (PV) panels, several challenges and gaps persist in the literature, particularly regarding the optimization of energy production and storage. First, the variability of sunlight poses a major problem, making it difficult to predict electricity production, especially in regions where the climate is unpredictable. Furthermore, current storage systems, while effective, still require improvements in terms of durability, cost, and long-term storage capacity [23–26].

To optimize and maximize the efficiency and versatility of solar cooking, projects and research are currently being carried out on the combination of two different technologies

[27]. Hybrid cookers include thermal and photovoltaic (PV) cookers, with/without electrical energy storage in batteries [8, 28]. The main advantage of these cookers lies in their ability to supply both thermal and electrical energy during cloudy periods and at night. In this context, we propose to design a photovoltaic system, consisting of a power unit and electronics, to heat the oil that heats a hybrid solar thermal/photovoltaic cooker, via a thermal resistor. This work is part of the international LEAP-RE 'SoCoNex Gen' [29] and WBI 3.3 [30] projects, carried out within the framework of international cooperation with European partners (Germany, Belgium, etc.).

In this paper, we present the structure and operation of the electric heating system of the thermal resistance, of the hybrid cooker (Thermal/Photovoltaic: Cooker 2) by the PV panels of 300 Wp and the batteries of 180Ah. These batteries are charged by other 300 Wp panels via a charge/discharge controller. Particular attention is paid to resistance temperatures on sunny days, in poor sunlight or at night.

1.1 Schematic diagram of PV panel and battery heating system

Figure 1 shows the synoptic diagram of the hydropower (photovoltaic/thermal) cooker proposed in this project. The various components of this cooker are:

1. Thermal oil heating block that heats two pots. This block is heated by concentrating mirrors that reflect and concentrate solar heat onto a panel containing a fluid. This heat heats the fluid circulating in the cooker's two pots.
2. Photovoltaic electric heating block, consisting of:

✓ A photovoltaic (PV) panel with a total output of 300 Wp, providing a daily energy output of 2-2.5 kW.

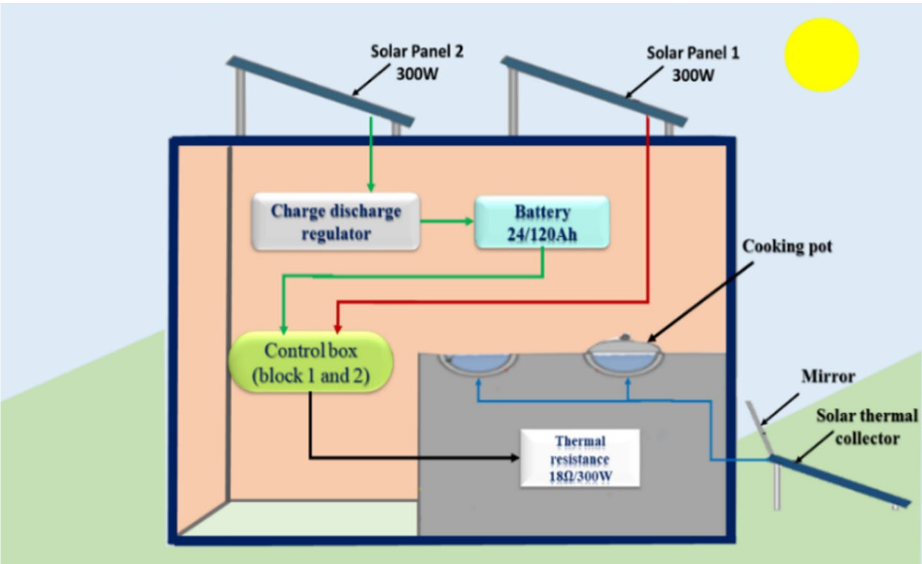

Fig. 1 Block diagram of the photovoltaic/thermal water cooker to be built

✓ A 24 V/180 Ah solar battery (2 × 12 V/250 Ah batteries in series), charged by another 300 Wp PV panel on sunny days. These batteries store energy of 2-2.5 kW per day.
✓ Thermal resistance of 18 Ω.
✓ Power block (Block 1), consisting of a Boost DC/DC converter, operating at a frequency of 20 kHz and a power of 500 W.
✓ Electronic block (Block 2), comprising analog and digital circuits powered by the batteries via a polarization circuit (+ 5V and + 15V). The overall operation of the cooker is managed by a 'Raspberry Pi Pico' microcontroller.

The photovoltaic and battery heating block (Fig. 2) is designed to perform the following tasks:

- Task 1: Operating the cooker with the sun, by heating a thermal resistor. It can operate optimally with MPPT [31, 32] control in automatic mode, or manually by varying the PV panel operating point.
- Task 2: Operating the cooker with solar batteries on less sunny days or at night.
- Task 3: Acquisition and display of electrical data on an LCD screen.
- Task 4: Detect malfunctions (overvoltage, overcurrent, disconnection of thermal resistors).

It should be noted that to monitor the operation of this block, depending on weather conditions, we set up a weather station, consisting of a Pyranometer and thermal sensor, to measure the intensity of illumination and ambient temperature.

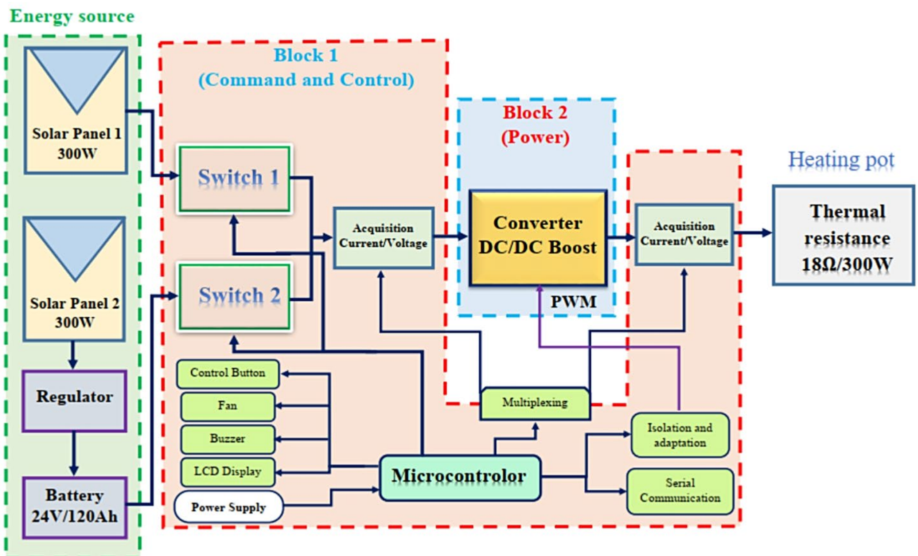

Fig. 2 Block diagram for electric heating using PV panels and solar batteries

1.2 Photovoltaic electric heating system trials and discussions

1.2.1 Heating system and measurement bench

Figure 3 shows the Photovoltaic (PV) cooker heating system installed at the LETSER laboratory at the University of Oujda (Morocco). The equipment consists of:

- 600 Wp PV panels:

  ✓ A 300 Wp PV panel, connected directly to the control box. It produces **900–1250 kWh/day** of energy, which can be used for cooking on sunny days. This panel produces a daily energy output of around **2.1 kWh/day.**

  ✓ A 300 Wp PV panel, which charges the solar batteries (24 V/180Ah) via a charge/discharge regulator. This panel produces a daily energy output of around **2.1 kWh/day**, enough to charge the batteries on a sunny day. It should be noted that due to the use of our prototype in hot countries (Africa, etc.), we used polycrystalline silicon photovoltaic panels with an efficiency of around 15 to 17%, resistant to extreme temperatures.

- Charge/discharge controller for battery charging by the 300 Wp PV panel.
- 2 Solar Batteries, 12 V/180 Ah each, connected in series to form a 24 V/180Ah battery. They are charged by the 300 Wp panel, via the charge/discharge regulator, to store a total energy of **4300 kWh/day**. Over the course of a day, they produce **625–1150 Wh/d** (i.e. 14.5–27% of the total battery charge, and an autonomy of 4–7 days).

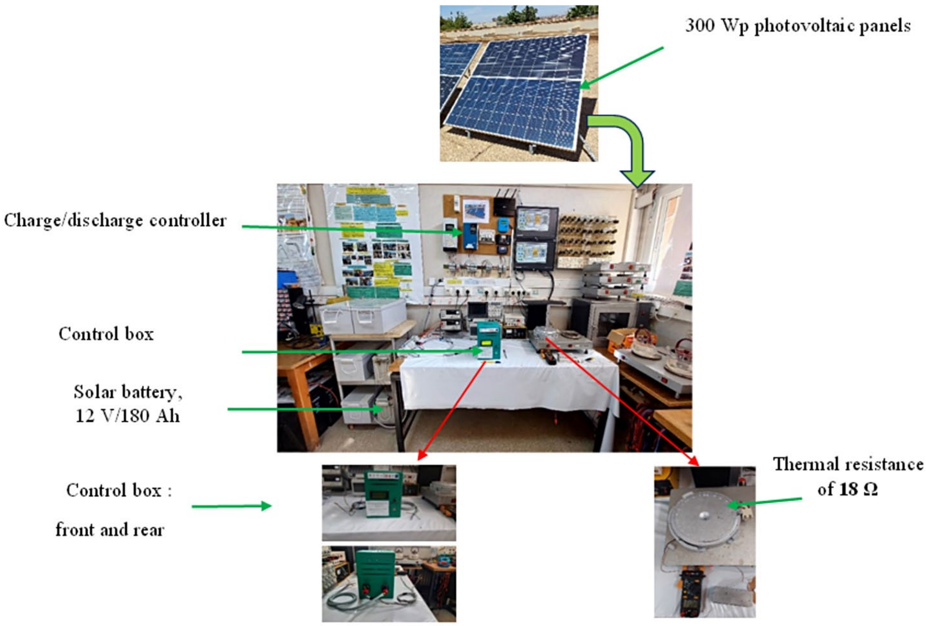

Fig. 3 Installation of the electric heating system for the hybrid cooker used in this project

– Control and management box for the energy supplied by the 300 Wp PV panel and solar batteries. It regulates the heating of the cooker's heating resistor, powered by the two energy sources (PV panel and solar batteries), via a DC/DC converter and an electronic board. It has been designed for connection and operation:

✓ Front panel: Start/stop of the cooker's electric heating system, LCD display, scrolling through parameters and operation (panel, batteries) via encoder.
✓ Rear panel, which is formed by two inputs/outputs:

- Input: connection of the 300 Wp PV panel and batteries (24/180 Ah) to heat the cooker's heating resistor. The batteries also power the electronic board components.
- Output: heating of the cooker resistor by the PV panel or batteries.

Thermal resistance of **18 Ω**, withstanding power ratings of 2 kW and temperatures of 1000 °C.

1.3 System operation results

In this section, we present the typical results of tests carried out on the cooker shown in Fig. 3. We analyzed the metrological (illumination intensity and ambient temperature) and electrical (duty cycle, voltages, current, power, efficiency) quantities and the temperature of the thermal resistance according to two scenarios:

– Powered by Photovoltaic panels in automatic mode,
– Powered by Battery in manual mode.

1.3.1 PV panel operation (scenario 1)

Figure 4 shows the various measurements obtained during a full day of heating by the PV panel in Automatic mode (Scenario 1). We can thus deduce:

– Illuminance levels reach a maximum of 950 W/m^2 at around 2 pm, and ambient temperatures range from 15 °C to 24 °C,
– The maximum power supplied by the PV panel is 250 W. This is achieved at around 1 p.m., with a duty cycle of 60%. Under these conditions, voltages and currents at the DC/DC converter input are respectively 26 V and 9 A, and at the output 65 V and 3 A.
– During the day (7.6 h of operation), the energy produced by the PV panel (**5)** and the heating resistor (**4)** is of the order of 1336.4 Wh and 1248 Wh.
– Between **10 and 15 h** (5 h of operation), the duty cycle varies from 40 to 60%, voltage, current and power vary at the DC/DC converter input from 30 to 26 V, 5–6 A and 125–250 W respectively, and at its output from 45 to 65 V, 2.5–3 A and 125–245 W. Under these conditions, the energy supplied by the panel and the heating resistor are of

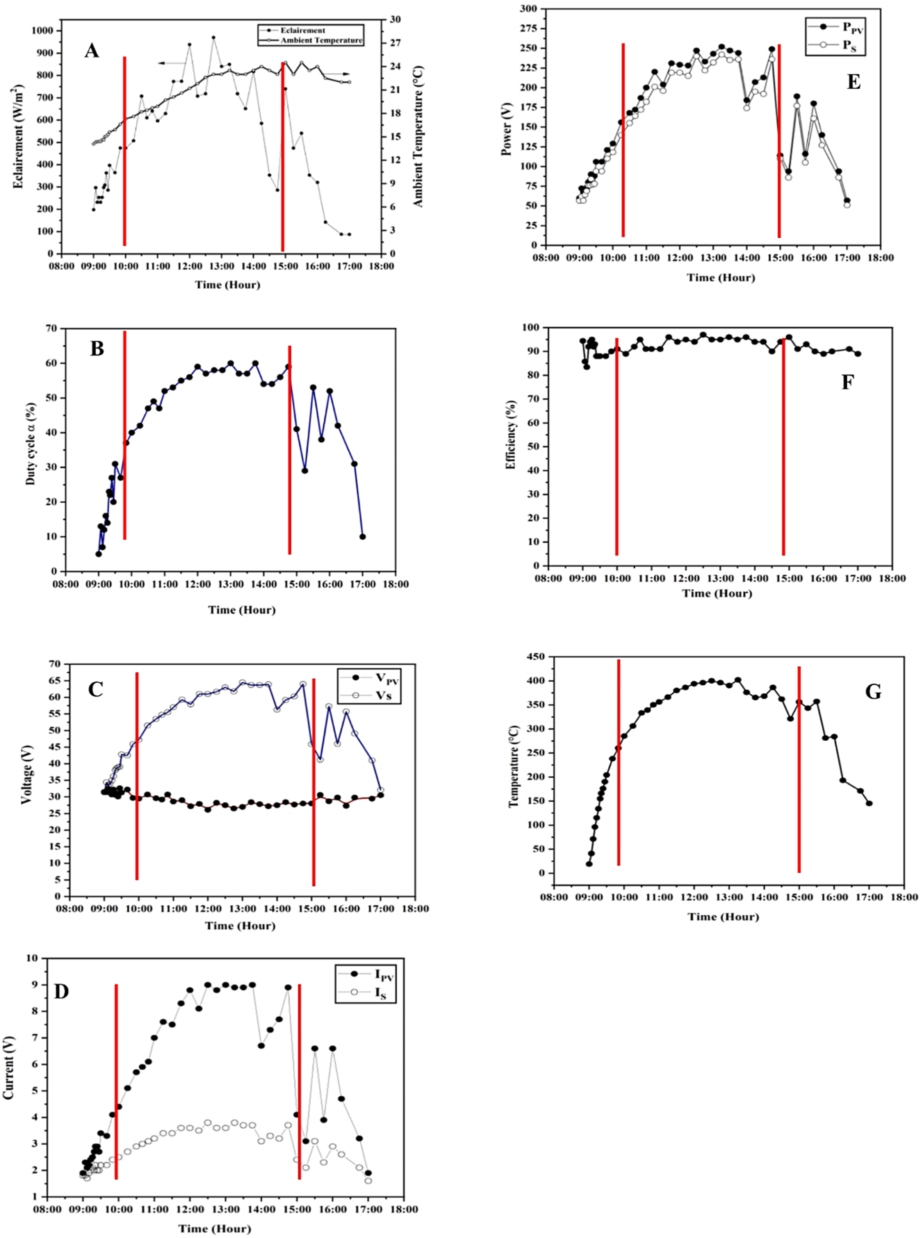

Fig. 4 Typical operation of the cooker 2 heating system with the PV panel in Automatic mode (October 26, 2024). **A**: Illumination and ambient temperature, **B**: Duty cycle **C**: Voltages, **D**: Currents, **E**: Powers,**F**: Efficiency, **G**: Resistor temperature

the order of 995 Wh and 946.3 Wh. These energies represent over 74% of the energy produced throughout the day.
- The efficiency of the DC/DC converter is constant throughout the day. It exceeds 90%.
- The maximum heating temperature of the resistor is around 400 °C. Between 10 a.m. and 3 p.m., the heating temperature varies from 250 to 400 °C.

The results obtained between **10 a.m. and 3 p.m.**, when maximum illuminance is around 800 W/m^2, show good efficiency of the DC/DC converter (>90%), producing electrical outputs of 125–245 W and resistance heating temperatures ranging from 250 to 400 °C. This testifies to the smooth operation of the cooker's heating system: power block 2 (DC/DC converter) and electronic block 1 (cooker control). In addition, the energy produced (around 950 kWh) is in good agreement with that set in the specifications for the cooker 2 system (around 900–1250 kWh). These results demonstrate the feasibility of operating the PV panel heating system for cooker 2 in scenario 1 in automatic mode. In Fig. 4, we have shown in red the proposed period of use for this system, for heating cooker 2 on a sunny day using the PV panel.

1.3.2 Battery operation (scenario 2)

Figure 5 shows the various measurements obtained during battery heating in Manual mode (Scenario 2). We can thus deduce:

- Heater resistance operation are highly dependent on duty cycle. The production of electrical energy by the batteries increases linearly with the duty cycle.
- As the duty cycle increases from 20 to 65%, the battery voltage remains constant (21–24 V), but the battery current, voltage and converter output current increase linearly by 1.8–10 A (a factor of 5.5%), 28–58 V (a factor of 107%) and 1.8–3 A (a factor of 66.6%) respectively. The result is an increase in input power from 30 W to 220 W (an increase by a factor of 7.33).
- For each measurement, the DC/DC converter efficiency is over 90%.
- Under these conditions (variation of the duty cycle from 20 to 65%), the resistor temperature varies from 50 to 370 °C (an increase by a factor of 7.5).

The overall results show that resistance heating is highly dependent on duty cycle. Since the various components of the power and electronics blocks have been dimensioned to operate below the voltages, currents and power ratings of 12 A, 120 V and 300 W, we have limited variations in the duty cycle to 65%.

When the duty cycle varies from 50 to 65%, the power supplied by the batteries and the load is of the order of 120–225 W. During 5-hour operation, the energy supplied is 600–1125 Wh/d. These powers and energies comply with the specifications: **625–1150 Wh/d.** Furthermore, the heating temperatures of the resistor range from 250 to 350 °C. These results show that the heating system designed in the course of this work works well, and that it is therefore feasible to use it to heat the cooker 2 using photovoltaic energy.

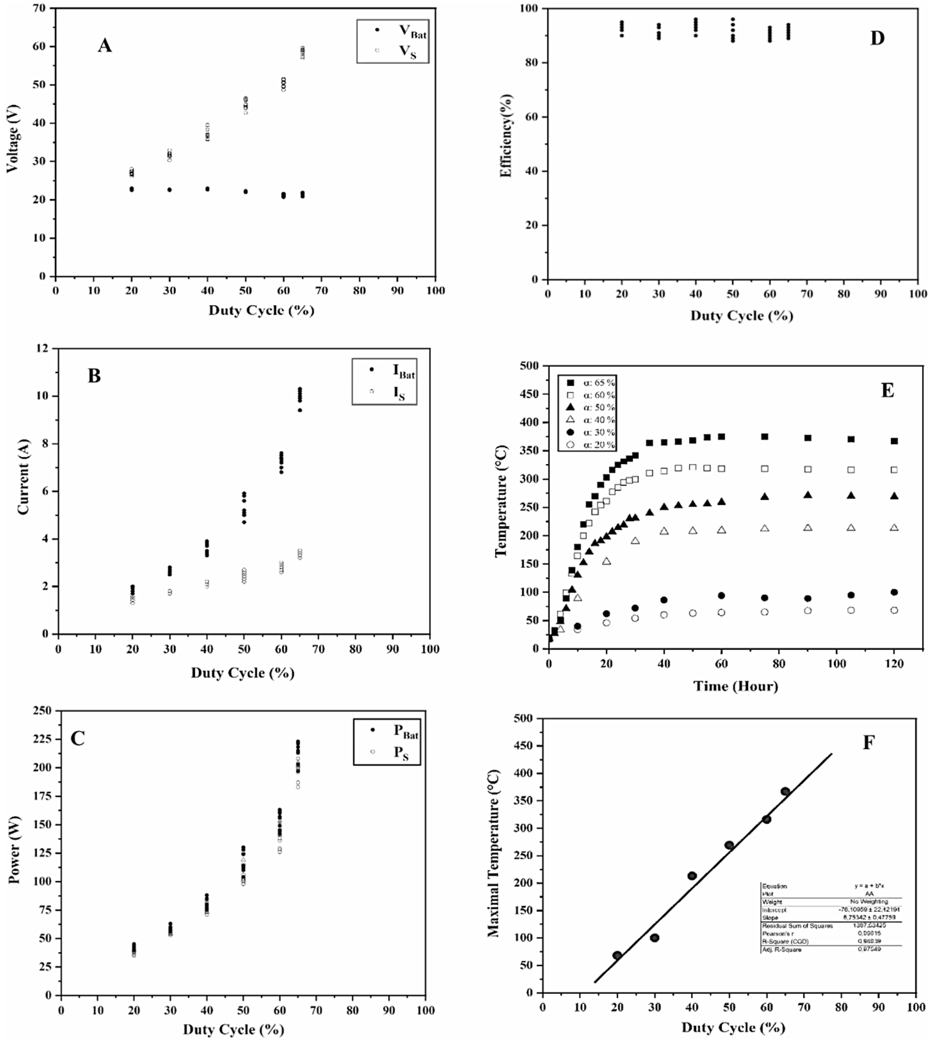

Fig. 5 Typical operation of cooker 2 heating system with Solar Batteries as a function of the duty cycle of the DC/DC converter control. February 10, 2024. **A**: Voltages, **B**: **Currents**, **C**: Powers, **D**: Efficiency, **E**: Resistance temperature, **F**: Maximum resistor temperature

1.4 Resistor heating temperature analysis

Based on the results of Figs. 4 and 5, we have plotted in Fig. 6 the variation of the maximum heating temperature of the thermal resistor as a function of the power of the panels or batteries. We can deduce that from a power of 80 W, the temperature varies linearly with power according to the equation:

$$T_R = 124 + 1.125\ xPs \tag{1}$$

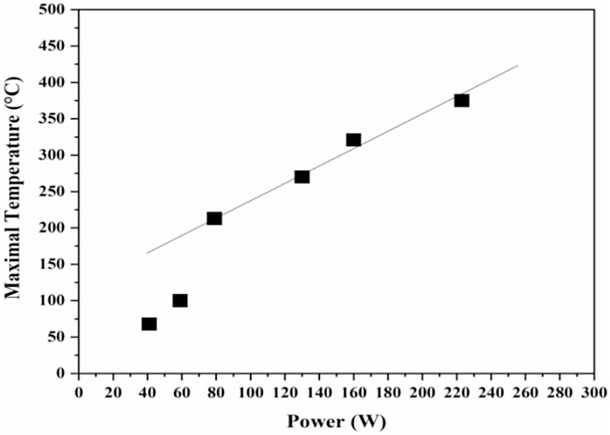

Fig. 6 Variation of maximum resistor temperature with PV panel or battery output

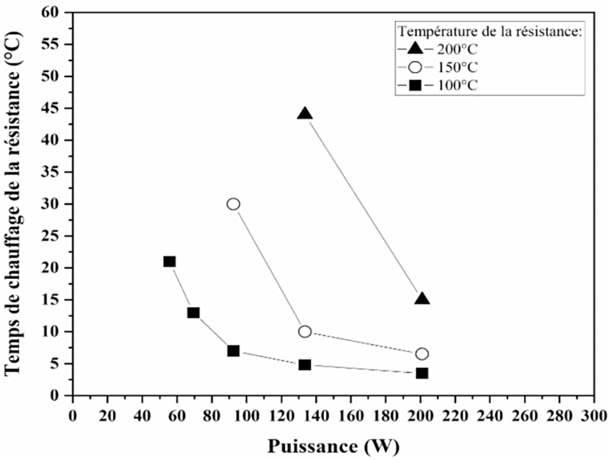

Fig. 7 Resistor heating time as a function of PV panel or battery power and resistor temperature

Figure 7 shows the dependence of thermal resistor heating time on panel or battery power for various resistor temperatures. These results show:

- As power increases by a factor of 2, heating time decreases by a factor of 3–4,
- For power ratings above 140–200 W, temperatures of 100–200 °C are reached after times of around 5–45 min,
- For power ratings of over 200 W, temperatures of 100–200 °C are reached in the order of 2.5–15 min.

Taken together, these results show heating times and temperatures for the heating resistor comparable to those obtained on conventional gas-fired cookers. We can therefore conclude that the electric heating system using PV panels and batteries is feasible, and can therefore be used to heat the hybrid cooker developed in the course of this work (Fig. 1).

Regarding the economic side of our innovative solar cooker prototype, the cost mainly depends on the prices of the photovoltaic panels, batteries, electrical components and thermal resistances used. At present, the price of photovoltaic panels is decreasing, the overall cost of our prototype is estimated at 500–550 $.

2 Conclusion

In this paper we have presented the power electronics system for heating a Thermal/Photovoltaic cooker using photovoltaic (PV) energy. We analyzed its operation when powered by a 300 Wp PV panel (Scenario 1), 24/180Ah batteries (Scenario 2). Based on laboratory tests, we deduced:

- In the case of heating by the PV panel (scenario 1), between 10 a.m. and 3 p.m., maximum illuminance is around 800 W/m^2, good efficiency of the DC/DC converter (> 90%), production of electrical powers 125–245 W, energy supplied by the panel and to the heating resistor around 995 Wh and 946.3 Wh, and heating temperatures of the resistor varying from 250 to 400 °C.
- In the case of heating by solar batteries (scenario 2), when the duty cycle varies from 50 to 65%, the power supplied by the batteries and at load is of the order of 120–225 W. During 5-hour operation, the energy supplied is 600–1125 Wh/d. Resistor heating temperatures range from 250 to 350 °C.
- In the case of panel or battery heating, temperature varies linearly with power (60–300 W), and heating time at a given temperature depends on power: for power ratings above 140–200 W, temperatures of 100–200 °C are reached after times of the order of 5–45 min. For wattages above 200 W, temperatures of 100–200 °C are reached after times of the order of 2.5–15 min.

These results show on the one hand, the proper functioning of the different blocks of the electric heating system of the hybrid cooker, and on the other, that the energy required to heat the cooker (PV/Thermal) is being produced in accordance with the specifications.

- In the case of PV panels: 900–1250 kWh/day.
- In the case of batteries: 625–1150 Wh/d.

All the results obtained show that the heating system of cooker 2 has been validated and can be integrated into the complete cooker (PV/Thermal).

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Author contributions The authors contributed to the completion of this work:- M. HMICH, H. CHADLI, K. KASSMI: System design,- S. CHADLI, R. MALEK: Simulation of operation,- M. HMICH, H. CHADLI: System cabling,- M. HMICH, K. SALMI: Experimentation in the Laboratory,- N. BACHIRI, K. KASSMI: Data collection in rural areas,- M. HMICH, K. KASSMI: Writing the paper.

Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

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