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Realization of autonomous heating plates operating with photovoltaic energy and solar batteries

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A B S T R A C T

The work presented in this paper shows the feasibility of an innovative stand-alone solar cooker (hot-plate) powered by renewable photovoltaic (PV) energy. This cooker is formed by PV panels (600 W), two DC/DC energy converters, two thermal resistors and a digital control unit. The role of the latter is to manage locally and remotely the operation of the cooker, according to the needs of the users, and to acquire and display the meteorological (lighting and ambient temperature), thermal (temperature of the resistance) and electrical quantities of the system (currents, voltages, powers, yields …). Experimentation of the system during whole days shows that, for an illumination intensity of 1115 W/m^2 and an ambient temperature of about 22 °C, the global electrical power supplied by the PV panels reaches 464 W/peak. The temperature of the thermal resistance reaches 700 °C (70 °C/s) after 10 s, the efficiency of the converters is 87%, the boiling of one liter of water (temperature 90 °C) and the heating of 0.5 L of oil (temperature 270 °C) took place after 20 min. and 60 min respectively. In addition, the study on energy storage in solar batteries shows that the energy produced throughout the day can be stored in 160 Ah batteries (i.e. two 75 Ah batteries). All these results show the feasibility of the proposed cooker, and consequently its use in rural as well as urban households for cooking during sunny days and nights.

1. Introduction

Currently, in some parts of the world, thousands of people have limited access to cooking fuels. Electricity and gas are not always available, and people rely on charcoal and wood from forests to meet their cooking energy needs [1,2]. This cooking method is harmful to health and the environment. Prolonged exposure to cooking fires leads to respiratory infections, eye damage and lung cancer. Also, according to the FAO [3], about 16 million hectares of forests are destroyed every year. To remedy this, several organizations and associations have mobilized to propose an ecological alternative, using solar energy. Currently, solar cookers, powered by solar radiation, are proposed and tested in several countries [4,5] (Africa, Latin America, …). These cookers help to solve, on the one hand, health problems by preserving human health against poisoning caused by wood fire, and on the other hand, environmental problems by helping to limit deforestation.

In the literature, several types of cookers have been proposed and tested. There are box-type solar cookers, operating, outside the home. These cookers are based on the phenomenon of the greenhouse effect which confines the direct and diffuse radiation of the sun (thermal energy) [6,7]. These types of furnaces have the capacity to reach, in 4 h of use, under an illumination of 858.11 W/m^2 and an ambient temperature of 37.9 °C, a temperature ranging from 140 to 150 °C, with a maximum thermal efficiency that does not exceed 54% [6]. This type of furnace requires, during its use, the intervention of the user to orientate it and move it along the sun. Other **parabolic solar cookers** are based on the concentration of the sun's rays, using parabolic shapes, on a focused area [8]. This type of cooker has, when used optimally, high cooking temperatures between 200 °C and 300 °C

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[9] and thermal efficiencies ranging from 43.45% to 77% [10]. In spite of its high temperature, this type of oven is not widely used because of its high cost, its large space requirement, its uncontrollable temperature and the risk of burning food and even users (hands, eyes …)..

Recently in [15], we proposed, in collaboration with the Solar Institute of Julich (Germany) and the IBEU Company (Germany), the feasibility of a solar furnace (Marmite) whose heating is based on the concentration of solar rays, by mirrors, on a heat transfer fluid. The experimentation of this thermal cooker shows that it could, under an illumination of 800 W/m^2 and an ambient temperature of 25 °C, reach a temperature of 200 °C after 60 min. In spite of the encouraging performances of this type of furnace, particularly with regard to thermal storage, the duration of the rise in heating temperature is important and its use is limited to the outside of the hearths in the course of the sun.

In order to innovate in the field of cooking and to offer innovative equipment, new types of autonomous solar box ovens based on the use of photovoltaic solar energy have been experimented. These ovens are heated by heating resistors, which are powered by electrical energy produced by photovoltaic panels and stored in 24 V- 45Ah batteries [13]. In this proposal, the use of batteries increases the cost of the cooker and its maintenance. Despite the use of PV energy, performance is very limited due to the lack of regulation and control of the power supplied by the PV panels [11,12]. Under a lighting of 950 W/m^2 and an ambient temperature of 20 °C, a battery power of 76.9 W, the temperatures inside the furnace and the heating element do not exceed 124 °C [13]. Moreover, for a water quantity of 0.385 g, the thermal efficiency does not exceed 43.6% [14].

In this context, our objective, within the framework of the Wallonia-Brussels International WBI program (Project N°4. 2) and project INDH/2019–17, in collaboration with the Polytechnic Faculty of Mons (University of Mons, Belgium), the socio-economic sectors of the Oriental region of Morocco (INDH, Province of Berkane (Morocco), Association Man and Environment of Berkane (Morocco)), is the development of innovative solar cookers with renewable photovoltaic energy (box and hot plate ovens), adaptable to the needs of household cooking. The expected goal is to offer cookers (Oven and Hot Plate) efficient, reliable, and capable of reaching cooking temperatures of around 300° C with a very high temperature rise, low cost and usable inside and outside homes. This equipment has been patented by the Moroccan Industrial and Commercial Property Office OMPIC in 2019 [16].

In this paper, we propose the feasibility of an autonomous solar cooker running on the electrical energy produced by the photovoltaic (PV) panels during the day, and by the solar batteries at night. The batteries are charged during the day by the photovoltaic panels. The proposed system is formed by PV panels, with a power of 600 W/peak, two DC/DC converters (Power Block) and a remote acquisition, control and supervision block. After describing the structure of the cooker, we present the first results obtained in the laboratory, concerning its operation during a whole day. Particular attention will be paid to the monitoring of the heating speed, the maximum temperature, the heating times of 1 L of water and 0.5 L of oil, and the dimensioning of the solar batteries that store the energy produced during the day. The performances obtained will be compared with those of conventional solar thermal cookers.

2. Synoptic diagram

2.1. Synoptic diagram and operation

Fig. 1 shows the synoptic diagram of the different blocks of the solar photovoltaic cooker, which was the subject of our work. This prototype is formed by:

- **Block A**: Photovoltaic generator, formed by PV Panels providing an overall power of 600 W/peak,
- **Block B**: Power block composed by:
  - o Two power switches (S1 and S2) to control the on/off of the system,
  - o Two Boost type DC/DC converters to supply the thermal resistors according to the user's needs. These converters are controlled by two PWM signals with frequency f = 10 kHz and variable duty cycle α_1 and α_2. This topology is used to increase the reliability of the system and improve the efficiency [17].
- **Block C**: Heating plate made up of two thermal resistances, withstanding temperatures above 800 °C. These resistors are manually controllable via switches (S3 and S4) to allow the user to use one or two heating resistors at the same time.
- **Block D**: Autonomous power supply for the system's electronic boards. It consists of a 50 W PV panel, a charge/discharge regulator, a small battery (12 V, 10 Ah) and an electronic circuit designed to supply the different supply voltages of the electronic components of the boards (+12 V, −12 V, 5 V and ground).
- **Block E**: Formed by a control and supervision circuit. It consists essentially of a microcontroller which is used to :
  - o Acquire electrical quantities and display them on an LCD screen,
  - o Generate the PWM 1 and PWM 2 signals required to control the power switches of the converters used,
  - o Transmit the acquired data to a user interface, installed in a PC, via a USB connection.
- **Block F**: Management and supervision interface. Its role is to:
  - o Present the real-time animation of the operation of the entire system, displaying the different electrical quantities (Voltage, Current, Power, Duty Cycle) of each block, the energy efficiency, the lighting intensity and the temperature of the heating resistor,
  - o Graphically represent the acquired data in real time,
  - o Store the various data acquired on a database that can be consulted remotely via the Internet.

2.2. Power block

The use of an adaptation stage between the PV generators (Block A) and the heating resistor (Block C) is essential to guarantee optimal operation of the photovoltaic panels. We have therefore used two discretized Boost type DC/DC converters with efficiencies higher than 80% (Block B). We propose this multi-stage topology to guarantee the maximum power supplied to the heating resistor and to avoid any problem related to the photovoltaic panels (shading, failure, malfunction…). DC/DC converters are designed and dimensioned [18] to:

- Operate in continuous mode,
- Support two PWM signals, controlling the power switches of the converters, frequency of 10 kHz and variable duty cycle $\alpha 1$, $\alpha 2$,
- Support input and output currents below 12 A and 5 A, and input and output voltages below 80 V and 100 V, respectively,
- Set input and output voltage ripples to values below 200 mV,
- Set current ripples in the inductance to values below 0.2 A.

2.3. Command and control block

The control of the operation of the photovoltaic solar cooker, proposed in this work, is carried out by two electronic boards, designed and developed in our laboratory. They are constituted by a PIC18f4550 microcontroller [19], in order to perform the tasks

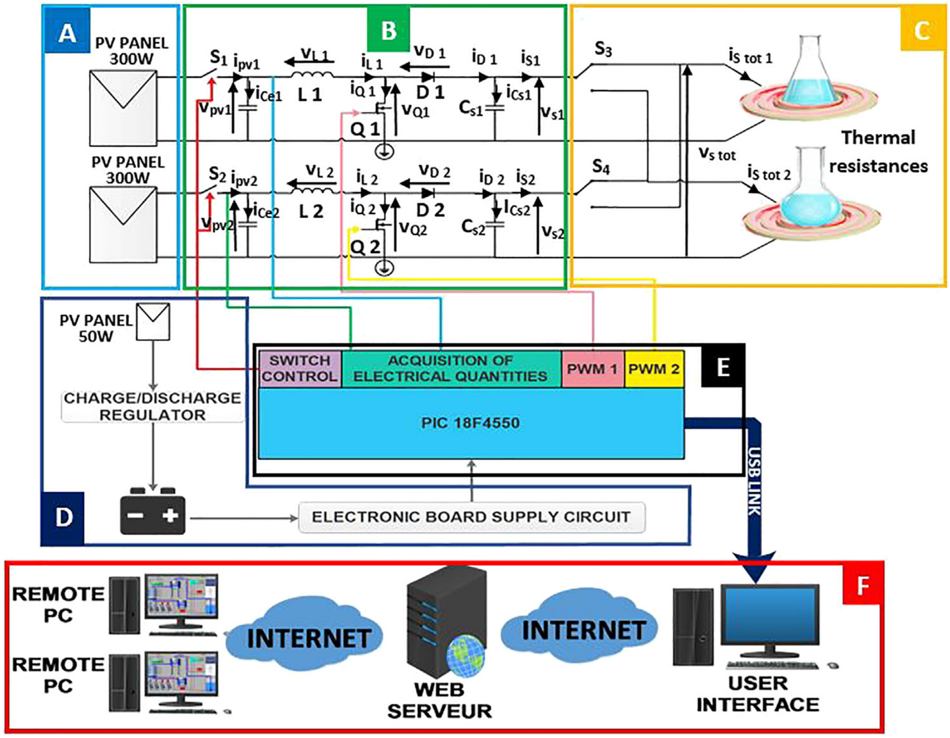

Fig. 1. Synoptic diagram of the autonomous solar cooker with photovoltaic energy.

of acquisition of the electrical and thermal quantities, execution of the MPPT algorithm, and creation and sending of the frame to the computer, via a serial communication (USB) for processing. These tasks are carried out by a program, in C language, developed and injected into the microcontroller. The execution of this program is carried out in the following:

- The initialization of the duty cycles α_1 and α_2 to the value **0.5** and the variable **TEMPO** to 0. The latter is responsible for the frequency of sending the frame to the supervision and control interface,
- The acquisition of meteorological conditions (Ambient temperature and irradiation),
- Activation of the control relays **S1** and **S2** and verification of the existence of a problem or anomaly in the operation of the PV system. If a problem exists, the system automatically deactivates relays **S1** and **S2** and sends an error message to the control and supervision system,
- The acquisition of the electrical and thermal quantities when all the verifications of the correct operation of the system are done,
- The generation of PWM signals, by the microcontroller, of variable duty cycle α_1 and α_2 in order to control each power stage separately. The regulation of the operation of DC/DC converters is based on the processing of the powers of each stage, using the Hill Climbing method, to converge to the maximum power point (PPM) (MPPT control) [13]. This processing is done as follows:
  - o If $dP1/dt > 0$ ($dP2/dt > 0$) and the α_1 (α_2) duty cycle does not reach the value **0.9**, the α_1 (α_2) duty cycle of the first (Second) converter is incremented by one step $\alpha_1 = 0.01$ ($\alpha 2 = 0.01$). If not $\alpha_1 = 0.9$ ($\alpha_2 = 0.9$).
  - o If $dP1/dt < 0$ ($dP2/dt < 0$) and the α_1 (α_2) duty cycle does not reach the value **0.1**, the α_1 (α_2) duty cycle of the first (Second) converter is decremented by one step $\alpha 1 = 0.01$ ($\alpha 2 = 0.01$). If not $\alpha_1 = 0.1$ ($\alpha_2 = 0.1$).
  - o Incrementing the variable **TEMPO**.
- Calculation of the frame sending frequency: after a time T set by the user, the program compares the variable TEMPO to ΔT :
  - o If TEMPO > T, the variable TEMPO is initialized and a frame containing all the electrical, thermal and meteorological system status (on, off, faulty) quantities is sent to the control interface via a USB link.
  - o If not, the program checks the status of the PV system and resumes the acquisition of the electrical and thermal quantities again.

2.4. Hot plate

The hot plate used in our heating system is composed by:

- Two heating resistors of 13 Ω each, housed in two temperature-resistant ceramics, with diameters of 16 cm and 20 cm. On these ceramics are placed the receptacles containing the water to be heated,
- Two contactors, equipped with indicator lights, to connect or disconnect the two resistors independently,
- Two inputs connected directly to the two outputs of the DC/DC converters to supply one or two heating resistors.

2.5. Four interface

During the operation of the cooker, data acquisition is necessary to ensure the supervision, storage and processing of data from the electrical system via a computer. For this purpose, we have developed and realized a management and supervision application (such as those created in previous works [19,20]) capable of acquiring data, processing it, recording it in a database and visualizing it in real time. The software allows:

- To retrieve the information from the control and supervision board presenting the different electrical quantities acquired, using the different sensors. The communication is done using

the USB link to facilitate the use and make our electronic board compatible with all new PCs. The software then allows to process and store the acquired data on a database. These data are then transferred to a web server installed in our laboratory. This server shares the data with all users who connect to the server. This option allows remote control, supervision and monitoring of the solar cooker in order to follow the performance and operation of the system in real time, and to act faster in case of failure.
- Present a real-time animation of the entire system, displaying the different electrical quantities (voltage, current and power) of each block, energy efficiency, lighting, ambient temperature, and the temperatures of the heating elements and the cooking process.

3. Results and discussions

3.1. Experimental procedure

The PV heating system designed and built in our laboratory is shown in Fig. 2. This system is composed of:

- PV generators (A) formed by PV panels generating 600 W/peak power. This block also has a meteorological station formed by a NTC thermistor probe to measure the ambient temperature, and a 50 W PV panel. The latter charges the battery, which powers the system's boards, and allows the measurement of direct illumination after its calibration. This station is connected to an acquisition board that transfers all data to the acquisition interface.
- Power block (B) formed by :
  - o Two Boost type DC/DC converters. Each converter is designed to operate at a chopping frequency of 10 kHz, a power of 500 W and a maximum current of 12 A.
  - o Two acquisition and control cards using a microcontroller (PIC 18F) that performs the following tasks :
    - ■ The acquisition of the electrical quantities of the PV panels, meteorological (illumination and ambient temperature) and thermal (temperature of the thermal and cooking resistors).
    - ■ The display of the acquired data on the LCD display,
    - ■ The transfer of the acquired data to the graphical interface,
    - ■ Automatic generation of two PWM signals, 10 kHz frequency and duty cycles α1 and α2, by executing the MPPT algorithm (Fig. 3) to extract the maximum electrical power from the PV panels, and thus power the thermal resistors under optimal conditions.
  - o A power supply card that generates the voltages (+12 V, −12 V, +5V, GND) necessary for the proper functioning of the system. This card is powered by a small battery (50 Ah) which is charged by the 50 W panel via a charge/discharge regulator. This card makes our system autonomous and only works with photovoltaic solar energy.
- Hot plate made of two heating resistors (C), 13 Ohm each. They are chosen to support currents of 10 A and temperatures above 1000 °C. It produces the warmth to heat and cook food using photovoltaic solar energy.
- A computer (D) connected to the control and data acquisition board, via a USB link. It runs an application in LabVIEW language for data acquisition and storage in a SQL database. It also allows local and remote monitoring [19,20] of the operation and performance of the heating system.

3.2. Operation of photovoltaic panels

Optimal operation of the proposed heating system requires the dimensioning of thermal resistors and DC/DC converters, and knowledge of the electrical characteristics of the PV panels used. We have therefore taken the current–voltage and power-voltage characteristics of the PV panels used during a sunny day. Based on the typical electrical characteristics obtained on a PV panel, for illuminances ranging from 300 W/m^2 to 900 W/m^2, we have determined and represented the optimal electrical quantities in table 1. We can therefore deduce:

- The optimal characteristics of the panels used are in accordance with those provided by the supplier [21],
- When illuminance ranges from 300 W/m^2 to 900 W/m^2, the optimal voltage, current, power and resistance range is 22.4 to 25.4 V (13.4% increase), 2.87 to 8.61 A (3-fold increase), 64 to 218 W (3.4-fold increase) and 2.95 to 7.8 Ω (increase by a factor of 2.65) respectively.
- To ensure continuous operation of both DC/DC Boost converters [18], the thermal resistance values must be>8 Ω. In our case, for this purpose, we used thermal resistances with values of 13 Ω.

3.3. Typical hotplate experimentation during one day

In the city of Oujda (which is located in northeastern Morocco on an altitude of 450 m), we experimented with the system in Fig. 2 in a sunny day of July, using a single converter (One PV panel) and then two converters (Two PV panels). In both situations, we recorded the illumination intensity, the ambient temperature, the electrical power supplied by the PV panels, the electrical power output of the DC/DC converters, and the temperature of the thermal resistance. The results obtained, presented in Fig. 3, show that:

- During the day of the measurements, the illumination intensity and the ambient temperature reach their maximum values around 13 h30 mn. They are of the order of 1,115 W/m2 and 22 °C,

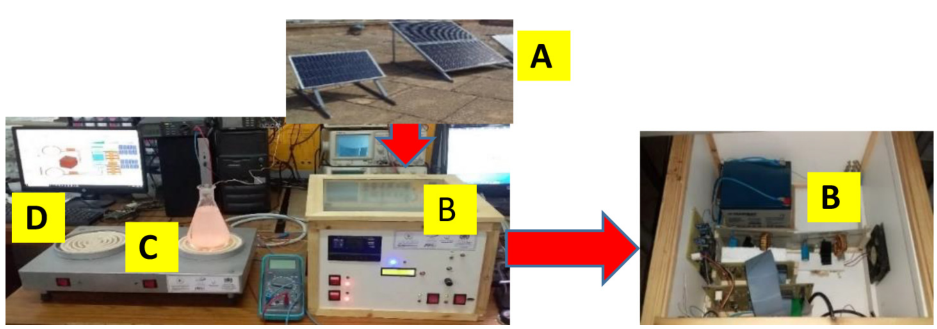

Fig. 2. Photovoltaic solar energy cooker proposed in this work.

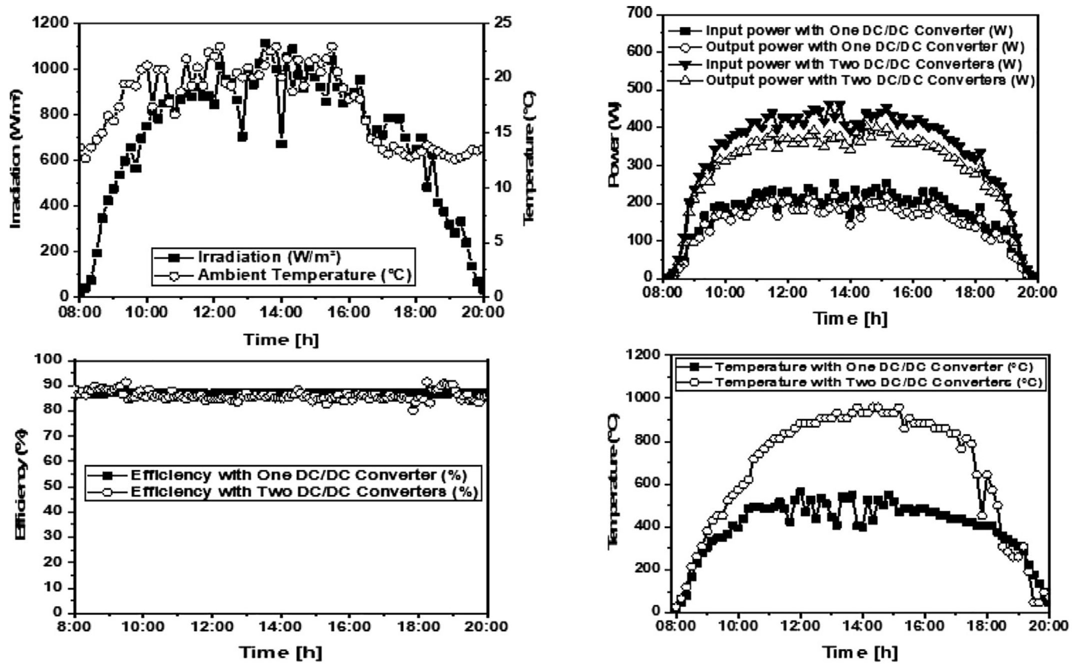

Fig. 3. Illuminance intensity and ambient temperature, Total electrical input and output power, Overall DC/DC converter efficiency, Temperature of heating resistor using one converter and two DC/DC converters.

- At about 1:30 pm, the system in Fig. 2 shows the best energy performance. Using a single converter, the input and output powers are of the order of 252 W and 219 W respectively. Using two converters, the input and output powers are about 464 W and 404 W, respectively.
- By using one or two converters, the overall efficiency of the converters is 87–90%.
- During the operating period 11 h −18 h, under the output powers, 180 W in the case of one converter and 360 W in the case of two converters, the temperatures of the thermal resistance are respectively of the order of 528 °C and 958 °C.

Moreover, from the power plot, we have deduced the electrical energy (Win) supplied by the PV panels and that (Wout) supplied to the thermal resistance (output of the DC/DC converters). During 10 to 11 h of operation, in the case of a single converter, the energy produced by the PV panel Win = 2.07 kWh and the energy supplied Wout = 1.78 kWh. In the case of two converters, the energy produced Win = 4.024 kWh and the energy supplied Wout = 3.5 kWh. From these produced energies (Wout), the dimensioning of the capacities of the batteries shows that we can store them in a 75 Ah battery in the case of a single DC/DC converter, and in a 160 Ah battery in the case of two DC/DC converters.

The comparison of all the electrical quantities obtained (voltages, currents and powers), at the input and output of the converters, compared to the optimal ones, simulated in the Orcad Pspice environment, shows a very good agreement. As a result, during one day of operation, the system in Fig. 1 is operating practically under optimal conditions, and the MPPT control in Fig. 2 has performed well. In addition, the temperature values of the thermal resistors (528 °C and 958 °C) and the efficiencies, which are close to 90%, testify to the very encouraging energy performance. The good functioning of the heating plate in Fig. 1 during the day, and the reasonable number of batteries dimensioned, show the possibility of using this plate both during the day and at night using solar batteries.

Table 1
The optimal electrical quantities of the PV panels used.

Le (W/m^2)	Vopt (V)	Iopt (A)	Ropt (Ω)	Popt (W)
300	22.4	2.87	7.8	64.3
500	23.9	4.78	5	114.32
900	25.4	8.61	2.95	218.7

3.4. Application: Water and oil heating with photovoltaic solar energy

In this paragraph, we have experimented with the hotplate in Fig. 2 under the conditions of its use in kitchens. To do so, we heated 1 L of water and 0.5 L of oil for one hour under almost the same lighting and ambient temperature. As before, using one DC/DC converter (one PV panel) and two DC/DC converters (2 PV panels), we took the illuminance, ambient temperature, input and output powers, yields, temperatures of the thermal resistance, water and oil. In each case, the energy produced at the input and output of the DC/DC converters is deducted. The results obtained, presented in Fig. 4, show:

- Water heating:
  - o Illumination intensity and ambient temperature are respectively around 1100 W/m^2 and 23 °C,
  - o The initial temperature of the water is around 23 °C,
  - o When using a single converter, the input and output power of the converter are about 213 W and 185 W respectively. The temperature of the resistor is of the order of 580 °C, and that of the water reaches its boiling point (90 °C) after 50 min of heating (i.e. 1.2 °C/min). In this case, the energy supplied by the PV panel and the converter are respectively of the order of Win = 212.64 Wh and Wout = 185 Wh. During this time, the heating energy is 11% of the energy produced by the DC/DC converter all day long,
  - o Using two converters, the input and output power of the converter are in the order of 428 W and 372 W respectively. The temperature of the resistor is in the order of 930 °C, and that of the water reaches its boiling point after 17 min of heating (i.e. 3.3 °C/min). In this case, the energy

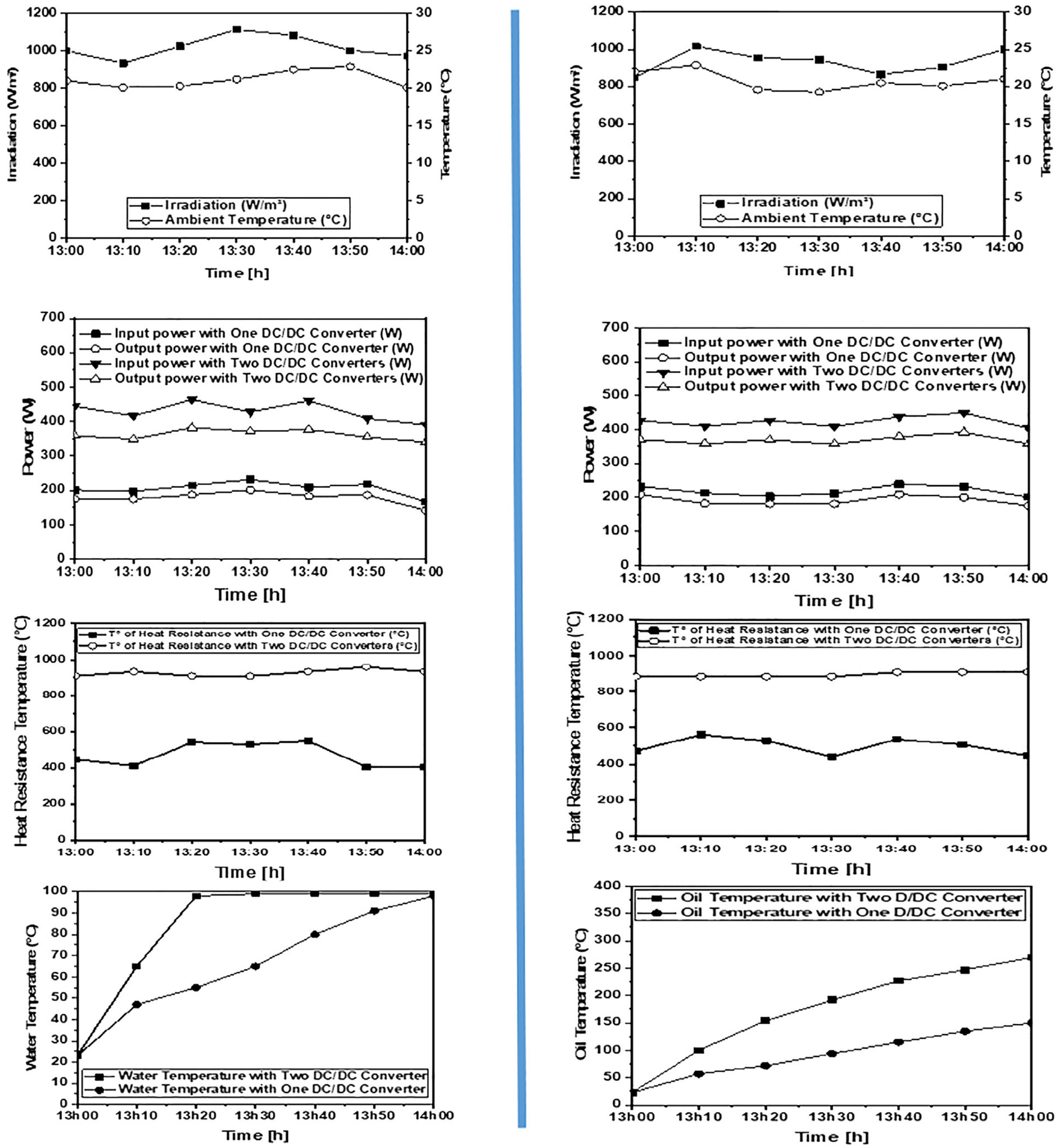

Fig. 4. Intensity of illumination and ambient temperature, Total electrical input and output power, Total converter efficiency, Temperature of heating resistor using one converter and two DC/DC converters, in the case of water and oil heating.

supplied by the PV panels and the inverter are respectively of the order of Win = 432.75 Wh and Wout = 364.06 Wh. Meanwhile, the heating energy represents 11% of the energy produced by the two DC/DC converters during the whole day,

- o Converter efficiencies are in the range of 87–90 %.

- Oil heating
  - o Illumination intensity and ambient temperature are about 1000 W/m^2 and 23 °C respectively,
  - o The initial temperature of the oil is around 23 °C,
  - o Using a single converter, the input and output power of the converter are about 231 W and 201 W respectively. The temperature of the resistor is of the order of 563 °C, and that of the oil reaches the value 150 °C after 60 min of heating (i.e. 2.5 °C/min). In this case, the energy supplied by the PV panel and the converter are respectively of the order of Win = 230.15 Wh and Wout = 200 Wh. During this time, the heating energy is 10% of the energy produced by the DC/DC converter all day long,
  - o By using two converters, the input and output power of the converter are about 438 W and 380 W respectively. The temperature of the resistor is of the order of 880 °C, and that of the oil reaches the value 270 °C after 60 min of heating (i.e. 4.4 °C/min). In this case, the energy supplied by the PV panels and the converter are respectively of the order of Win = 438.3 Wh and Wout = 379.8 Wh. Meanwhile, the heating energy represents 10.4% of the energy produced by the two DC/DC converters during the whole day,
  - o Converter efficiencies are in the range of 87 – 90 %.

The analysis of the results obtained in this paragraph, shows the dependence of the temperature and the heating time of water and oil with the power of the PV panels. When doubling the power of the panels, during a 60 min heating period, the temperature of the thermal resistance, water and oil heating temperature increases by 60%, 175% and 76% respectively. Under household cooking conditions (Time < 2 h, with water and oil), using two PV panels, the energy required, in the order of 800 Wh, represents 20% of the energy produced by the DC/DC converters all day long. Consequently, the batteries dimensioned in the previous paragraph can withstand overnight cooking.

Also, by comparing these results with those obtained on solar cooking systems (box ovens, parabolic ovens ...) [6,22], we can deduce the best heating performances on the photovoltaic heating pack developed in the course of this work: improvements in temperature, heating speed and heating time by a factor of 5.5, 2 and 3 respectively. These performances and the autonomous cooking mode, inside and outside of the houses, allow us to conclude that the prototype developed and realized in the framework of the projects, engaged during this work, is efficient.

4. Conclusion

In this work, we showed the study, design and realization of an autonomous cooking system using photovoltaic energy. This system is made up of photovoltaic panels, adaptation blocks (DC/DC converters) and controls, and thermal resistors that can withstand temperatures of up to 1000 °C. The experiment of this system, for a power of 470 W, in the case of heating one liter of water and 500 ml of oil, using two DC/DC converters, shows:

- The system provides an output power of 404 W with an efficiency of 87%,
- The temperature of the thermal resistance reaches the value 958 °C,
- During 12 h of operation, the total electrical energy produced at the input and output of the converters is 4,024 kWh and 3.5 kWh respectively,
- One liter of water, reaches the temperature of 90 °C after 20 min of heating (i.e 3.3 °C/min),
- 4.1 Liter of oil, reaches the temperature of 270 °C after a heating time of 60 min (i.e. 4 °C/min),
- The electrical energy produced, of the order of 3.5 kWh, requires its storage in 160 Ah solar batteries (i.e. two 75 Ah batteries).

Comparison of these results with those in the literature, obtained on conventional thermal solar cookers, shows better performance on the photovoltaic solar cookers developed during this work:

- Improvement of the heating temperature by a factor of 5.5,
- Improves heating speed by a factor of 2,
- Improves heating time by a factor of 3.

All the results obtained show the feasibility of photovoltaic heating plates, with very interesting performances. During the day, the heating took place directly by the photovoltaic panels, equipped with the appropriate control system. During the night, the heating is carried out by the energy stored in the batteries. This energy is supplied by the photovoltaic panels during the day.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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