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DEVELOPMENT OF AN INNOVATIVE COOKER (HOT PLATE) WITH PHOTOVOLTAIC SOLAR ENERGY

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ABSTRACT

In this paper, we present the feasibility of an innovative autonomous solar cooker (hot plate) running on renewable photovoltaic (PV) energy. The proposed equipment is based on the sizing, design and construction of a PV system, adapted to the needs of users in the rural and especially urban world. It is formed by PV panels, DC / DC energy converters, thermal resistors and a digital block for control, supervision, acquisition and displays of meteorological, thermal and electrical quantities of the system (lighting, PWM signals, currents, voltages, powers, efficiency, temperatures, etc.). Experimentation with the system for whole days shows, for an intensity of illumination varying from 400 W/m^2 to 900 W/m^2 and an ambient temperature of the order of 22°C, the overall electrical power supplied by the panels PV of 430 W/peak, and the temperature of the thermal resistance, reaches after 15 s, the value of 580°C (i.e. 38.66°C/s). Under these conditions, the boiling of one liter of water and the cooking of 2 Kg of food (fries) took place after 25 minutes of cooker operation. Comparison with conventional thermal cookers shows a marked improvement in the cooking temperature, boiling times and heating speed of 178% (a factor of 2.79), 83.3% and 943% (a factor of 10.43) respectively. In addition, the thermal efficiency of the cooker is estimated at 86%, an improvement of 59.2% compared to conventional cookers. All the results obtained clearly show remarkable performances, consequently the feasibility of the innovative photovoltaic cooker, proposed during this work, inside and outside the homes.

1. Inttroduction

Human activities such as the use of fossil fuels, the exploitation of tropical forests and the raising of livestock are increasingly influencing the climate and temperature of the earth. These activities cause the release of huge quantities of greenhouse gases, which are in addition to those naturally present in the atmosphere, thereby reinforcing the greenhouse effect and global warming [1]. In addition, the increase in the use of wood, because of its low cost, intensifies the problem of deforestation and environmental degradation. To remedy this, several national and international organizations have mobilized to find an alternative [2,5]. Among the most supported and encouraged solutions are renewable energy applications, such as innovative solar ovens. In the literature, several types of cookers have been proposed:

- Box-type solar ovens, operating outside homes, directly to the sun's rays (thermal energy) [3,4,6,7]. These types of ovens were able to reach, in 4 hours of use, under an illumination of 858.11 W/m^2 and an ambient temperature of 37.9°C, a maximum baking temperature of the order of 140°C, with maximum thermal efficiency which does not exceed 54 % [3]. This type of oven requires, during its use, its orientation and movement over the sun.
- Parabolic solar ovens based on the concentration and focusing of the sun's rays by the parabolic reflectors on the bottom of the container (Pot, ...) [8]. This type of cooker has, when optimally used, high cooking temperatures between 200°C and 300°C [9] and thermal efficiency which vary from 43.45 % to 77 % [10]. The drawbacks of this type of system are its size, orientation of the reflectors over the sun, expensive and presenting risks of burns for users (hands, face, eyes, etc.).

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- In addition, other work on solar ovens running on electricity and thermal energy from the sun [11], or on photovoltaic energy [12] show heating temperatures and yields that do not respectively exceed 140°C and 40 %. In addition, in this work and in all of the literature [12–14], the cooking heating time is not presented and analyzed.
- Currently, hardly any cooker running on photovoltaic solar energy, equipped with the systems for regulating the electrical power of photovoltaic panels, is presented in the literature. The proposed cookers [19] with a power of less than 80 W, heat the thermal resistances using solar batteries (45 Ah). The heating temperatures and yields obtained are not satisfactory (less than 124°C. and 43.6 %). The power (DC/DC converter) and regulation units (Analog and Digital Circuits)[17], developed and adapted to the cookers offered, offer greater reliability, autonomy, and functionality guaranteeing cooking at temperatures set by the user.
- Recently [21] we proposed, in collaboration with the Solar Institute of Julich (Germany) and the Company IBEU (Germany), the feasibility of a solar oven (Marmite) whose heating is based on the concentration of the rays solar, by mirrors, on a heat transfer fluid. Experiments with this thermal cooker show 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 minutes. Despite the encouraging performance of this type of oven, particularly with regard to thermal storage, the duration of the heating temperature rise is important and its use is limited outside the homes over the sun.

In this context, our objective, within the framework of the Wallonie - Brusselles International WBI program (Project N°4.2) and INDH/2019-17 project, in collaboration with the Polytechnic Faculty of Mons (University of Mons, Belgium), the socioeconomic sectors of the Oriental region of Morocco (INDH, Province of Berkane (Morocco), Man and Environment Association of Berkane (Morocco)), is the development of innovative solar cookers with renewable photovoltaic energy (Box ovens and hotplate). The expected goal is to offer efficient, reliable cookers (Oven and Hot Plate), capable of reaching cooking temperatures of around 300°C with a very high temperature rise, low cost and usable indoors and outside homes. This equipment was patented at the Moroccan Office of Industrial and Commercial Property OMPIC in 2019 [22].

In this paper, we propose the feasibility of the innovative autonomous solar cooker, of the hot plate type, operating on renewable photovoltaic (PV) energy. This cooker is powered by PV panels, with a power of 430 W/peak, fitted with power and control blocks, adaptable to the cooking needs of households. After describing the structure and sizing of the solar oven, we present the first results obtained in the laboratory, concerning its operation during the day: heating speed, maximum temperature, water heating and cooking of food (Frits) and efficiency thermal. The performance obtained will be compared with that of conventional solar cookers (boxes).

2. Structure of the solar cooker with photovoltaic energy

2.1. Specifications

Within the framework of the work undertaken in the two projects, INDH/ 2019-17 and WBI N°4.2, the essential object is to supply innovative cookers, with photovoltaic energy (PV), for households, mainly, inside homes. After studies in the field, the needs of families in terms of cooking require electrical power supplied by the PV panels below 500 W. Taking into account this power (500 W) and the electrical characteristics of the PV panels available on the market and in the laboratory (paragraph II.2), we proposed the development of an innovative prototype respecting the specifications:

- Heating plate formed by two thermal resistors with RTherm value = 12-14 Ω. In order to offer a reliable cooker, ensuring the production of energy all day long and taking our previous studies [15,17], these thermal resistances are supplied by two DC/DC discretized Boost converters, with satisfactory efficiency (> 80%).
- Two DC / DC converters operating in continuous mode [26] (Figure 1). Each converter meets the conditions:
- 400 W power, PWM signal which controls the power switch with frequency f = 10 kHz and variable duty cycles α, input current less than 10 A, output current less than that, input voltage lower than 80V, output voltage greater than that of input and less than 100 V.
- Undulations of the input voltage ΔVPV less than 100 mV and that of the output ΔVS less than 50 mV,
- Current undulations in the inductance ΔIL less than 1.5 A,
- Taking into account the previous conditions, the values of the induction L and of the capacitors at the input and at the output are estimated at [24]:
- L = 100 μH, CE= 1 000 μF, CS = 400 μF.
- The switch (Q) and the power diode (D) have been chosen to support the different voltages, currents and variations at 10 kHz.
- Electric power source is a photovoltaic generator formed by two types of PV panels (Type 1: 2 PV panels of 100 W each, Type 2: 1 PV panel of 230 W). Each PV panel type is connected to the input of one of the two DC / DC converters.

2.2. Synoptic diagram

Figure 2 shows the block diagram of the different blocks of the 'Hot Plate' cooker using photovoltaic solar energy, which is the subject of our work. In accordance with the previous specifications, this prototype is formed by:

- Bloc A : Photovoltaic generator, formed by the two types of PV panels (type 1 and type 2), with an overall power of 430 W/peak,
- Bloc B: Heating plate constituted by two thermal resistances, supporting temperatures higher than 800°C. Via the two switches, the user could use one resistor or both at the same time.
- Bloc C : Power block. It is composed by:
- Two power switches to control system on/off,
- Two Boost type DC / DC converters to supply the two thermal resistors according to user needs. These converters are controlled by two PWM signals of frequency f = 10 kHz and of variable duty cycle α_1 and α_2. This topology is used to make the system more reliable and improve performance [24,26]. To do this, two modes are available: Automatic mode where the maximum electric power is extracted by the PV generator (MPPT command), Manual mode where the variable electric power extracted by the PVgenerator is set by the user.
- Bloc D: Autonomous power supply for the system's electronic cards. It is formed by a 50 W PV panel, a charge/discharge regulator, a small battery (12 V, 10 Ah) and an electronic circuit made to supply the different supply voltages of the cards electronic components (+12 V, -12 V and 5 V).
- Bloc E: Control and supervision circuit for the entire electronic system. It is formed of a microcontroller which performs the following tasks :
- Control the power switches to allow the user to choose the power stage to use, according to his needs (Converter 1, or converter 2 or both at the same time),
- Transmit the acquired data, from the entire system, to a user interface, installed in a PC, via a USB link.
- Bloc F: Management and supervision interface. Its role is to :
- Present the real-time animation of the operation of the entire system, displaying the different electrical quantities (Voltage, Current, Power, Duty cycles) of each block, energy efficiency, lighting intensity and temperatures heating and cooking resistors.
- Graph the data acquired in real time,

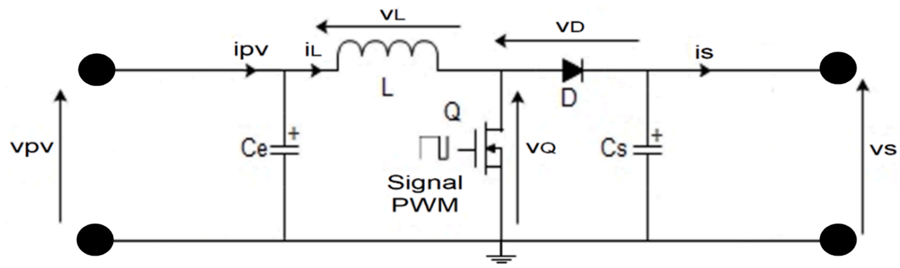

Figure 1. Convertisseur DC/DC de type Boost.

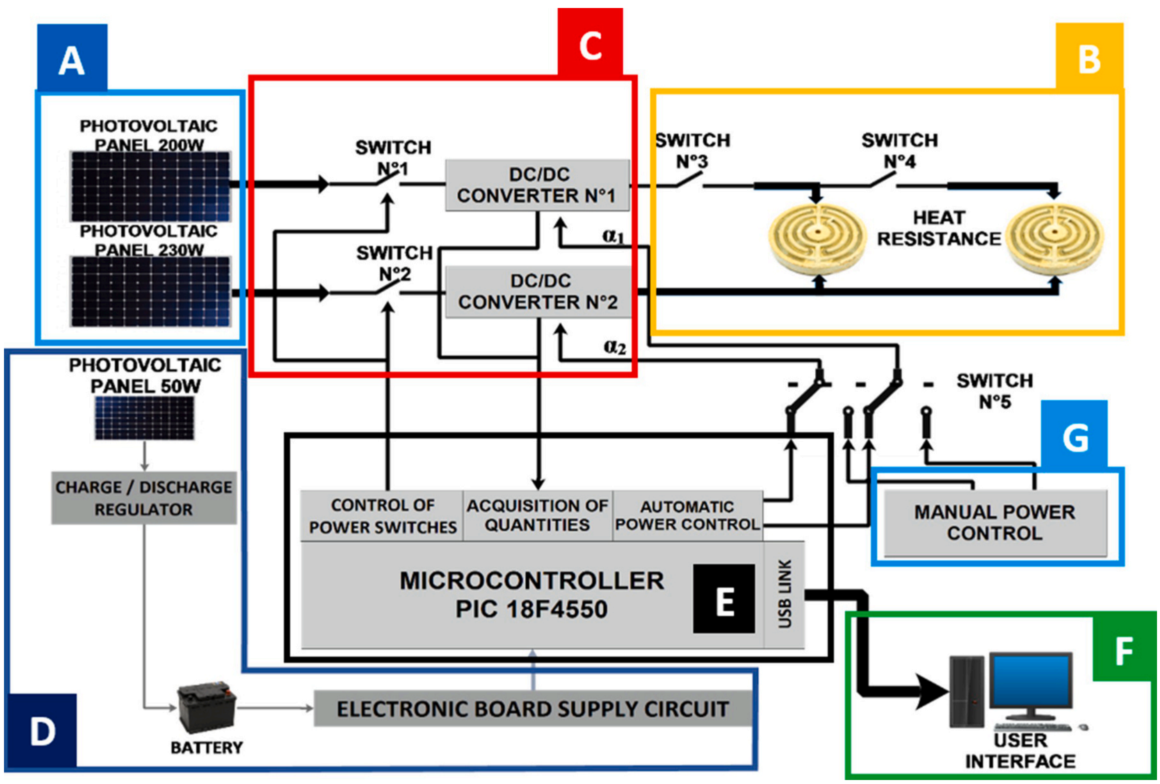

Figure 2. Synoptic diagram of the solar cooker with photovoltaic energy developed during this work.

- Store the various data acquired on a database that can be consulted remotely by internet.

- Bloc G: Analog circuit, which allows manual variation of PV generator power by varying the duty cycles (α_1 and α_2) of the PWM signals generated by this block.

It should be noted that in this prototype, our proposal lies in the integration into the cooker, the power unit (C) and that of acquisition and regulation of the power supplied by the Photovoltaic panels. In the presence of these blocks, the user regulates the appropriate temperature for his cooking on a sunny day.

2.3. Structure and operation of each block

2.3.1. Control blocks

The operation of the innovative cooker, proposed in these two projects, is controlled by two electronic cards, designed and developed in this work (Figures 3 and 4). The structures and functions of these two cards are:

- The card of Figure 3, mainly constituted by a PIC18f4550 microcontroller [25], in order to carry out the tasks of Acquisition of electrical quantities, execution of the MPPT algorithm (in Automatic mode), and creation and sending the frame to the computer, via serial communication for processing. These tasks are carried out by a program, in C language, developed and injected into the microcontroller, according to the steps of the algorithm of Figure 4. The different stages of execution of this program are:
- Read the command, sent by the user, to turn on the first power stage, the second power stage or both stages at the same time. If no command is sent by the user, the program proceeds to the acquisition of meteorological quantities (ambient temperature and lighting) after a delay of ΔT.
- Once the stage or stages are activated, the program checks for the existence of anomalies, to avoid any problem or damage to the converters, then carries out the acquisition of electrical quantities.
- Once the acquisitions of all the quantities are made, the PIC generates the PWM signals in Automatic mode, with variable duty cycle $\alpha 1$ and $\alpha 2$, at each power stage separately. In this mode (Automatic), the regulation of the operation of the DC / DC converters is based on the processing of the powers of each stage and of the Hill Climbing method to converge towards the maximum power point (PPM) (MPPT command) [15,17], Then, the PIC acquired the other electrical quantities (output voltage and current of the two stages),

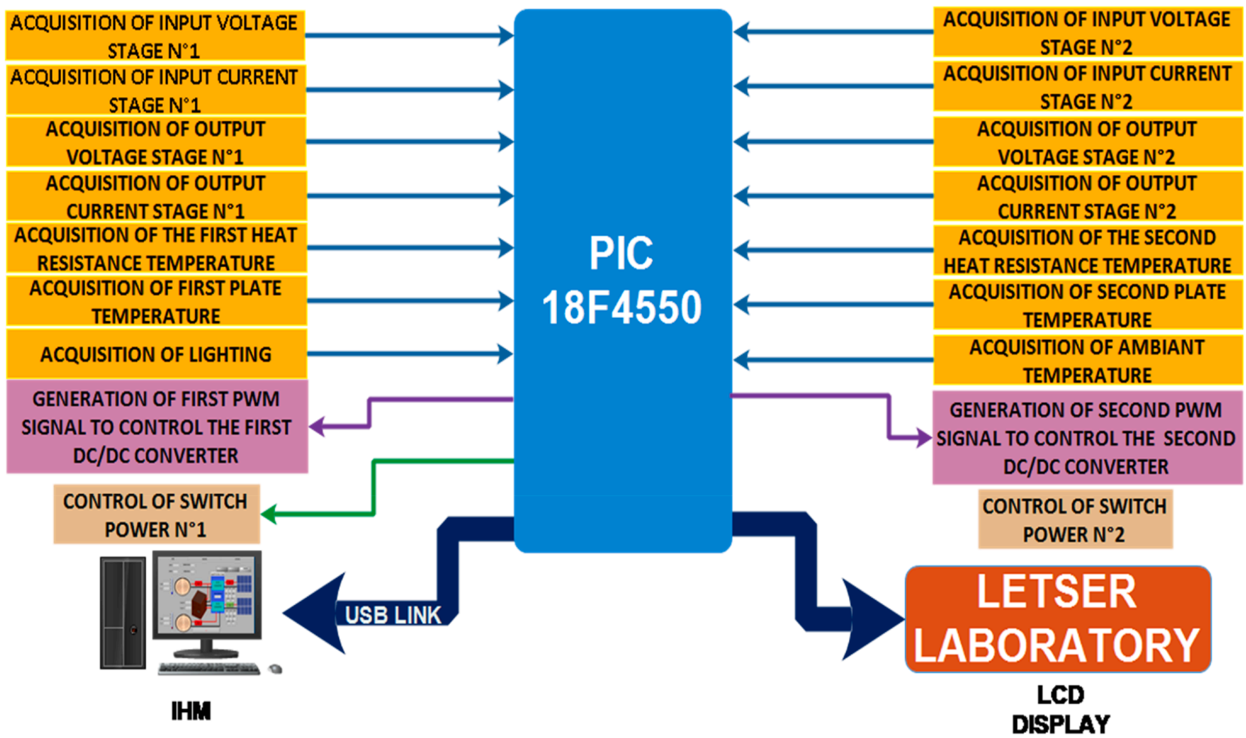

Figure 3. Electrical diagrams of the solar cooker acquisition and control card

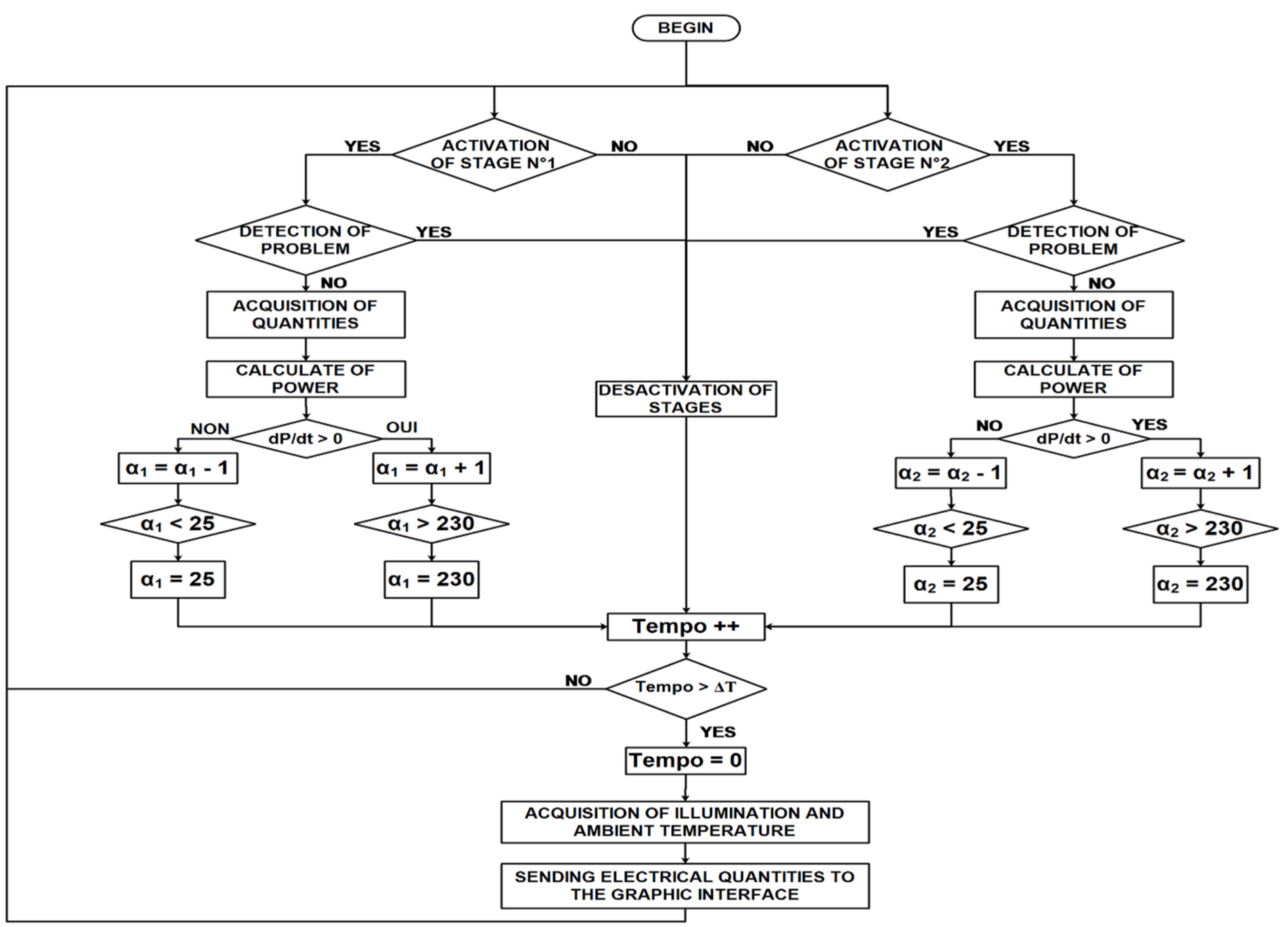

Figure 4. algorithm of Control, acquisition and supervision program of Figure 2.

thermal (temperatures of the two heating and cooking resistors) and meteorological (lighting and ambient temperature). Finally, the program builds and sends a frame after a time ΔT, containing all the measurements made, to a supervision computer via a USB link. These functions are executed in infinite loop in order to measure the electrical and thermal quantities in real time.

- The card in Figure 4 for manually regulating the power supplied by the PV generator to thermal resistances. This is based on the manual variation of the duty cycle α1 and α2 of the PWM signals that control the power switches of the two DC / DC converters. As shown in Figure 5, the circuit is made up of two electronic components:
- An integrated circuit used to generate a saw tooth signal with 12 V amplitude and 10 kHz frequency.
- A comparator, which compares the saw tooth signal generated by the integrated circuit to a continuous signal, whose value varies between 0V and +12 V, using a potentiometer.

The integrated circuit, the comparator and the potentiometer therefore make it possible to generate a PWM signal, with variable duty cycle (α), and therefore, control of the power supplied to the heating resistor. Regarding the acquisition of all electrical and thermal quantities in this mode of use (manual), the microcontroller follows the same steps, mentioned above, as in Automatic mode.

2.3.2. Control interface

As described in the previous paragraph, the electronic card acquires all the electrical and thermal quantities and sends all the data to a control and supervision interface. This data, in the form of frames, is sent every second to ensure the visualization and the processing in real time on the computer. The application (Figure 6), installed on the computer, is developed via LabVIEW and MySql [25] for database management. The essential features of this application are:

- It manages and supervises the PV system in real time and has a strong interaction between the various windows, the microcontroller and the PV system.
- It presents on its main window (Figure 6-A), the detailed synoptic diagram of the PV system of figure 2. By launching the acquisition of the data, these arrive towards the computer in the form of continuous flows, then their visualizations in real time. In addition to the digital display of the different acquired, we have added a functionality allowing to visualize all the quantities in real time in the form of a graph (Figure 6-B).
- Storage and consultation of previous PV system operating data. These functionalities (Figure 6-C) are very important for monitoring the performance of the cooker with a view to improving it. Data access is by day, month and year. In addition, this stored data can be exported to a text or Excel file as needed by the user.

The use of the computer is just for monitoring and acquiring electrical and thermal quantities in the laboratory or remotely. The proposed cooker is autonomous, without batteries and computer.

2.3.3. Plate and thermal resistance

Concerning the cooking equipment and supports, we designed and produced a hot plate, in steel, of a shape comparable to that of the usual cooking plates (Figure 7). This plate is formed by:

- Two heating resistors of 12 Ω-14 Ω each, housed in two temperature-resistant ceramics, with a diameter of 16 cm and 20 cm,
- Two contactors, provided with indicator light, to connect or disconnect the two resistors independently,
- Two inputs from the two outputs of the two DC / DC converters (Figures 1 and 2) to supply the two resistors.

3. Experimental results and discussions

3.1. Experimental procedure

The solar cooker (Hot Plate) with PV energy, which is the subject of our study, and the fully automated measurement bench are presented in Figure 8. This complete system is composed of :

- PV generators (A) formed by two types of PV panels. Type 1 is formed by two 100 W/peak power panels, and Type 2 by a single 230 W/peak panel. In paragraph III.2, we characterize the functioning of these two types of panels, their optimal electrical quantities and the assembly of the panels, of type 1, suitable for our application.
- Power unit (B) formed by:
- Two DC/DC Boost type converters. Each converter is designed to operate at a chopping frequency of 10 kHz, a power of 500 W and a maximum current of 10 A. The different active and passive components are discussed and dimensioned in section II.1.
- Two acquisition and control cards using a microcontroller (PIC 18F) which performs the following tasks:
- The acquisition of the electrical variables of the PV panels, meteorological (lighting and ambient temperature) and thermal (temperature of the thermal and cooking resistances).
- Display of acquired data on the LCD display,
- Transfer of acquired data to the graphical interface,
- Automatic generation of two PWM signals, with a frequency of 10 kHz and duty cycles α1 and α2, by running of the MPPT algorithm to extract the maximum electrical power from the two types of PV panels, and therefore supply the thermal resistors under optimal conditions.
- Manual generation of PWM signals whose duty cycles ($\alpha1 = \alpha2 = \alpha$) are varied manually by an adequate circuit (Figure 5). This makes it possible to control the power at the outputs of the two converters and

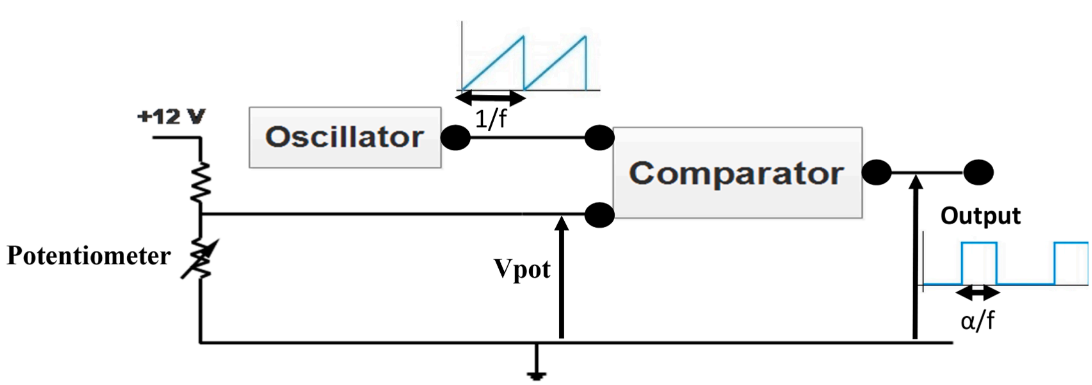

Figure 5. Circuit and signals allowing manual control of the power supplied by the PV generator.

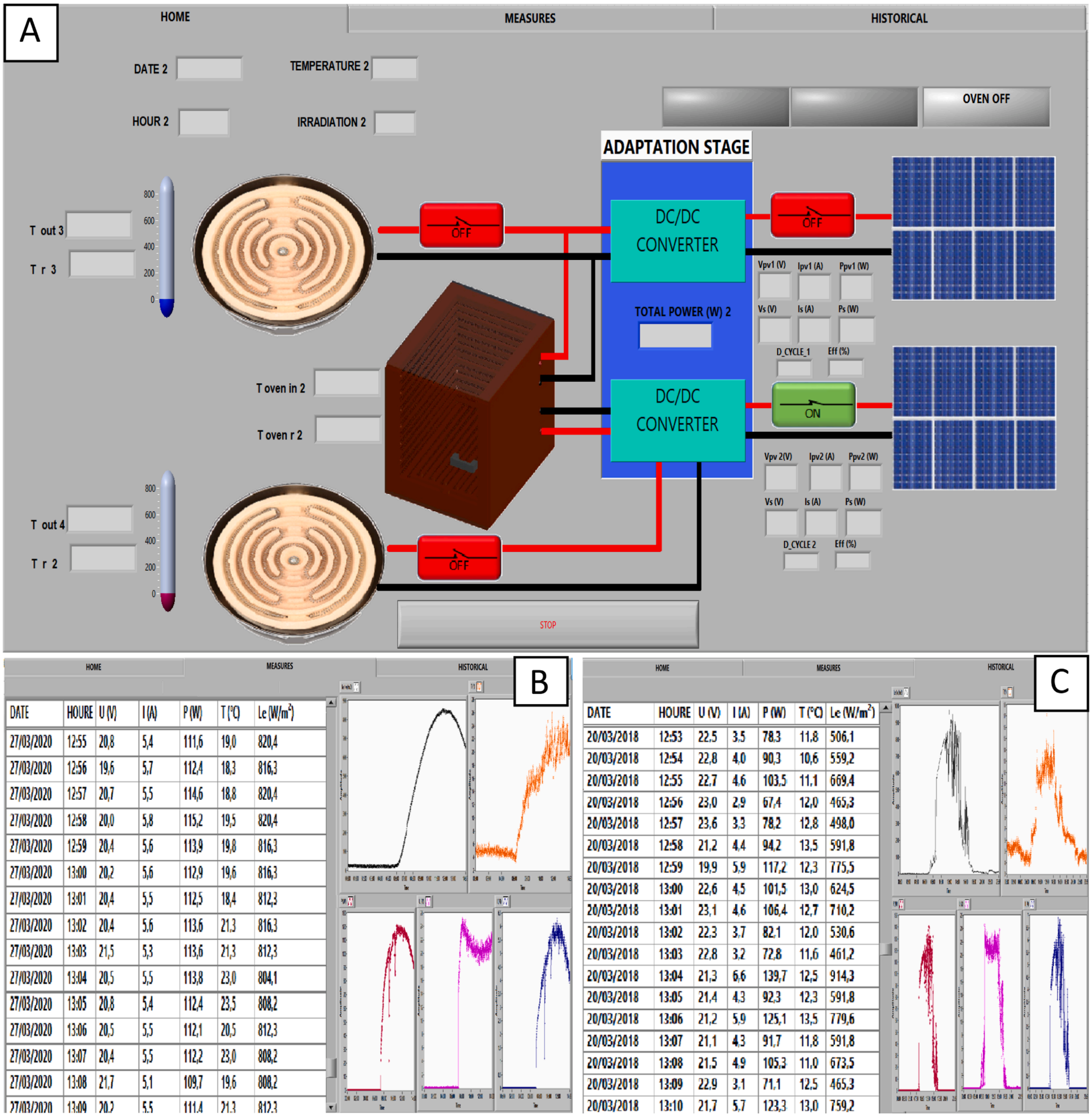

Figure 6. Command and supervision interface. A: Main window, B: Display of electrical quantities in table and graph form, C: Measurement history consultation window.

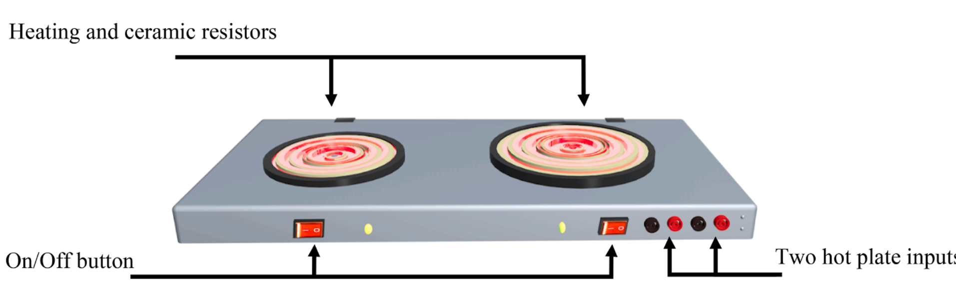

Figure 7. 3D diagram of hot plate designed and produced during this work.

therefore to set the cooking temperature according to the needs of the user.

- Two heating resistors (C) of value 10 Ω – 12 Ω each. They are chosen to withstand currents of 10 A and temperature of 1000°C.
- A weather station (A) which measures the intensity of the light and the ambient temperature. A 10 W panel (3), a CTN type probe and adequate electronic circuit form it. The station is connected to the card and the acquisition interface (B).

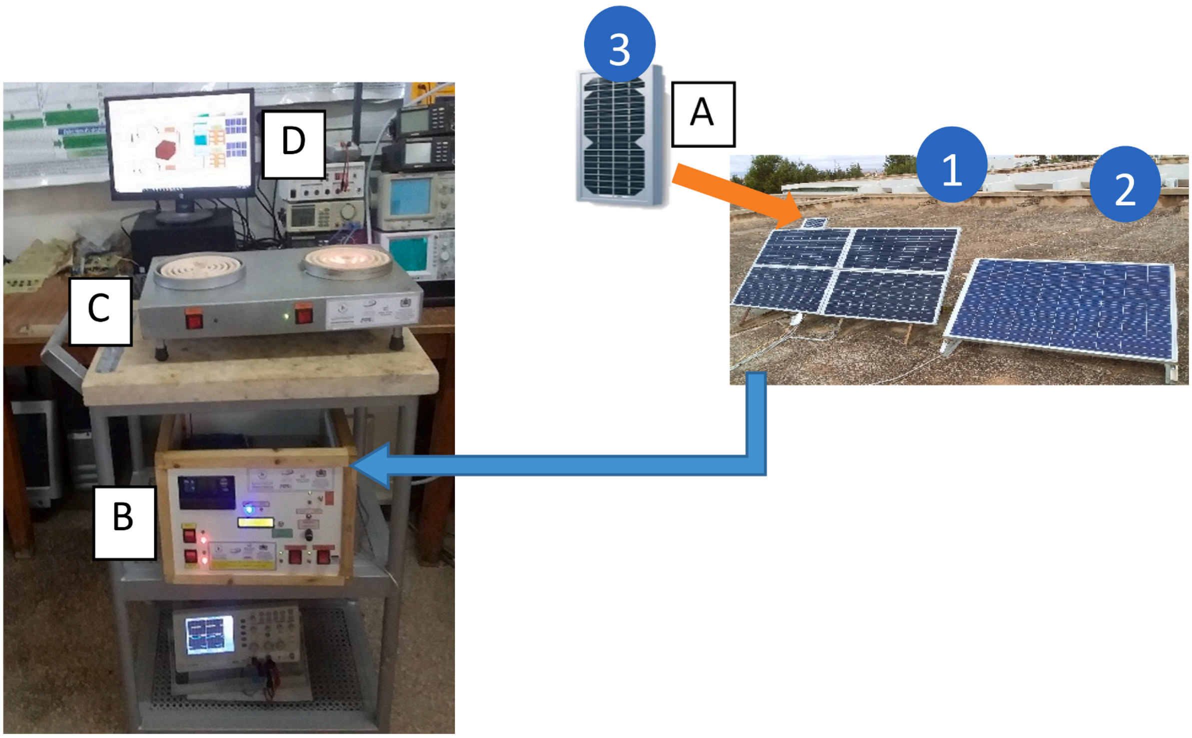

Figure 8. Photovoltaic solar energy cooker developed during this work.

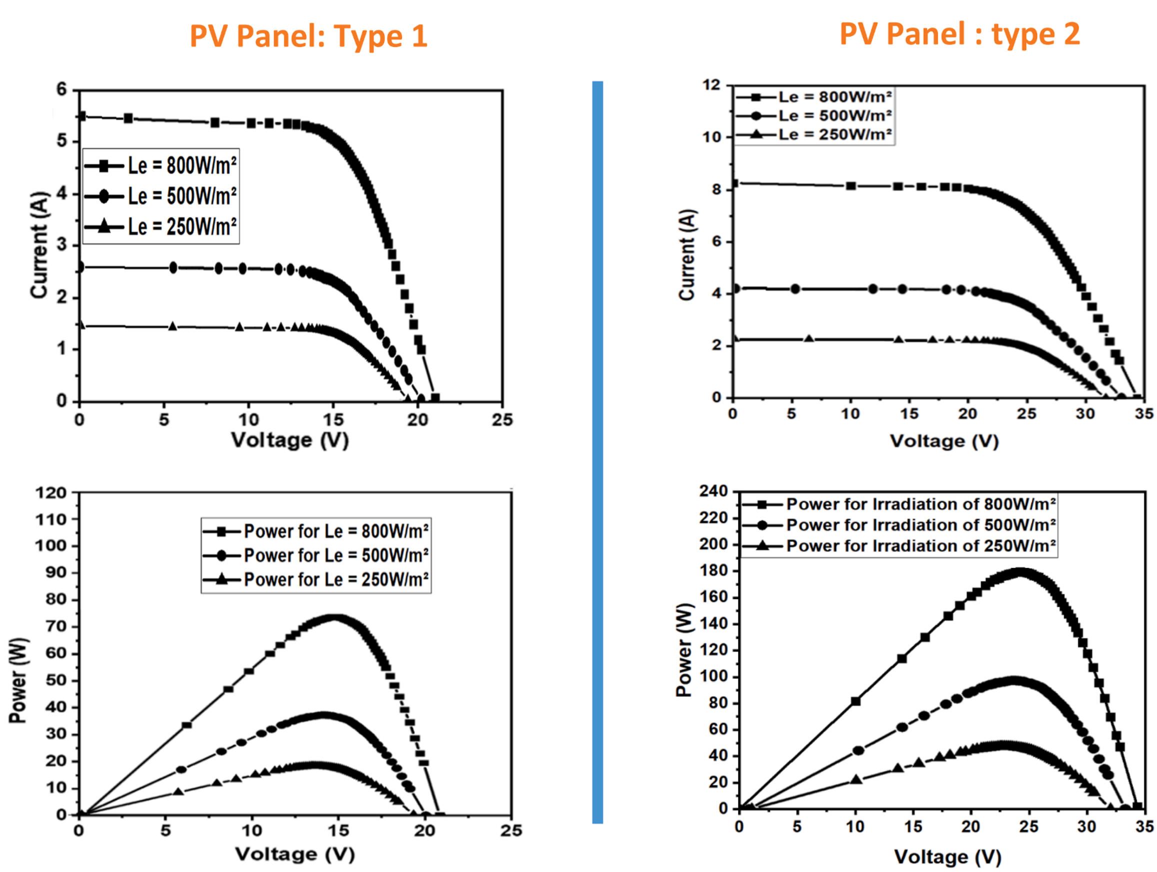

Figure 9. Current-voltage and power-voltage characteristics of the two types of photovoltaic panels used, for three illuminations (250 W/m^2, 500W/m^2, 800 W/m2). Ambient temperature = 25°C.

- A computer (D) connected to the control and data acquisition card, via a USB link. It runs an application in LabVIEW language for the acquisition and storage of data in an SQL database. In addition, it allows connecting / disconnecting PV panels and thermal resistors according to the needs of the user, locally and remotely [25] (figure 7).

The cooker in figure 8, tested and analyzed during this work, is the one that will be delivered as part of the projects undertaken by the team.

3.2. Photovoltaic generator

The optimal use of the cooker (Hot plate), requires the dimensioning of the thermal resistances and the DC / DC converters, and the knowledge of the electrical characteristics of the PV panels which form the PV generator to be used. To do this, we noted the current-voltage and power-voltage characteristics of the two types of PV panels (1 and 2) used (Figure 8), during a sunny day. The typical electrical characteristics obtained on a panel, of types 1 and 2, for illuminations varying from 250 W/m^2 and 800 W/m^2, are represented in Figure 9 From these characteristics, we have determined and represented on the table 1 the optimal electrical quantities. So we can deduce:

- The optimal characteristics of the two types of panels are in accordance with those supplied by the supplier (Specifications in paragraph II.1))[18,35]
- Type 1 panels: when the illumination varies from 250 W/m^2 and 800 W/m^2, the power and optimal resistance of a single panel vary from 19 W to 70 W and from 11.38 Ω to 3.4 Ω respectively. Within the framework of our specifications, and taking into account the value of thermal resistance, and the Boost nature of the converters, the two panels are connected in series. In this situation, the optimal power and resistance of our PV generator vary from 38 W to 140 W and from 22.76 Ω to 6.8 Ω respectively.
- Type 2 panels: the optimal power and resistance of the panel vary from 48 W to 180 W and from 12 Ω to 3.4 Ω respectively.

As part of our application, the baking only took place from 10 a.m., when the intensity of the lighting is greater than 600 W/m^2. Consequently, the values of the optimal resistances of the PV panels (Ropt < 5 Ω) and those of the resistances perfectly verify the operating conditions of the two DC/DC converters in continuous mode [20].

3.3. Typical operation of dc/dc converters

For an illumination of 700 W/m^2 and an ambient temperature of 22°C, we analyzed the operation of the two converters of the cooker in Figure 8. To do this, we noted, for each converter, the PWM signal that controls the switch, the voltages at the output of the switch (v_Q) and the diode (v_D), the input voltages (vpv) and output (vs), the inductance current (i_L). The typical results obtained in figure 10 show, in the case of the two converters:

Table 1
Optimal electrical quantities of a PV panel, types l and 2, of figure 8, according to the illumination. Temperature = 25°C.

	Le (W/m^2)	Vopt (V)	Iopt (A)	Ropt (Ω)	Popt (W)
PV panel : type 1	250	14.8	1.3	11.38	19.24
	500	14.9	2.5	6	37.25
	800	15	4.5	3.4	70
PV panel : type 2	250	24	2	12	48
	500	24.5	3.9	6.3	95.5
	800	24.5	7.3	3.4	180

- The duty cycles of the first and second converters are respectively of the order of α1 = 0.42 and α2 = 0.51,
- When the switches are closed (PWM amplitude = +12 V), the switches are closed (vQ = 0V), the diodes are blocked (vD = - 48V) and the inductors charge,
- When the switches are open (Amplitude of PWM = 0 V), the switches are open (vQ = 48 V), the diodes are conducting (vD = 0 V) and the inductors discharge.
- The undulations of the inductance current are in the order of 1.5 A. From the value of these currents, we can deduce the currents at the input of the converters (supplied by the PV panels) which are of the order of 4.5 A for the first converter and around 7.3 A for the second.
- The average input voltage of the first converter is 30 V and 24.5 V for the second. Their undulations are less than 100 mV.
- The average values and the undulations of the output voltage of the two converters is vs = 50 V and 20 mV.
- From the values of the output voltage vs and the resistance RTherm = 10 Ω, output currents (iS1 + iS2) are in the order of 5 A,
- From the power calculations, the efficiencies are respectively η1 = 85 % and η2 = 88 %. The overall efficiency of the two converters is 86.5 %.

The different waveforms and values of electrical quantities are consistent with the relationships that govern the operation of DC / DC converters in continuous operation [23,26]. These results and the good efficiencies obtained testify to the good functioning of the two converters, and consequently of the PV system dedicated to our application (PV energy cooker).

3.4. Operation of the photovoltaic energy cooker

In order to show the feasibility and reliability of the photovoltaic energy cooker, developed during this work, we tested the prototype of Figure 8 in automatic mode (optimization of the powers supplied by the PV panels by the MPPT command), for whole days in the laboratory, by heating one liter of water and cooking food requiring high temperatures (2 Kg of fries). For each series of experiments, we noted the intensity of the lighting and the ambient temperature, the input and output powers of the converters, the duty cycles controlling the DC/DC converters, the efficiencies of the converters, the temperature of thermal resistances and those of water and food (oil). From the temperature of the water heating, we estimated the thermal efficiency of the cooker according to the model of the literature [19,20]:

$$\eta_{Therm} = \frac{m.Cp.\Delta T}{P_s t} \tag{1}$$

Where,m: mass of heated water (Kg),
Cp : Specific heat of water (Cp = 4190 J/Kg-K),
Ps : Electrical power delivered to the heat resistance.

3.5. Water heating

We heated a liter of water until it boiled and noted the meteorological, electrical and thermal quantities. Typical results obtained in Figure 11 show:

- The illumination and the ambient temperature are respectively of the order of 750 W/m^2 and 22°C,
- The PWM duty cycles of the first DC/DC converter (α1) varies from 0.28 to 0.4, and for the second one (α2), from 0.48 to 0.57. The frequency of these PWM signals is f = 10 kHz.
- The powers at the input of the PV panels are respectively PPV1 = 144 W and PPV2 = 149.5V, and that at their output PS = 254.5W. These values show that the yields of these two converters are respectively η1 = 85% and η2 = 88%, that of η = 86.5 %.

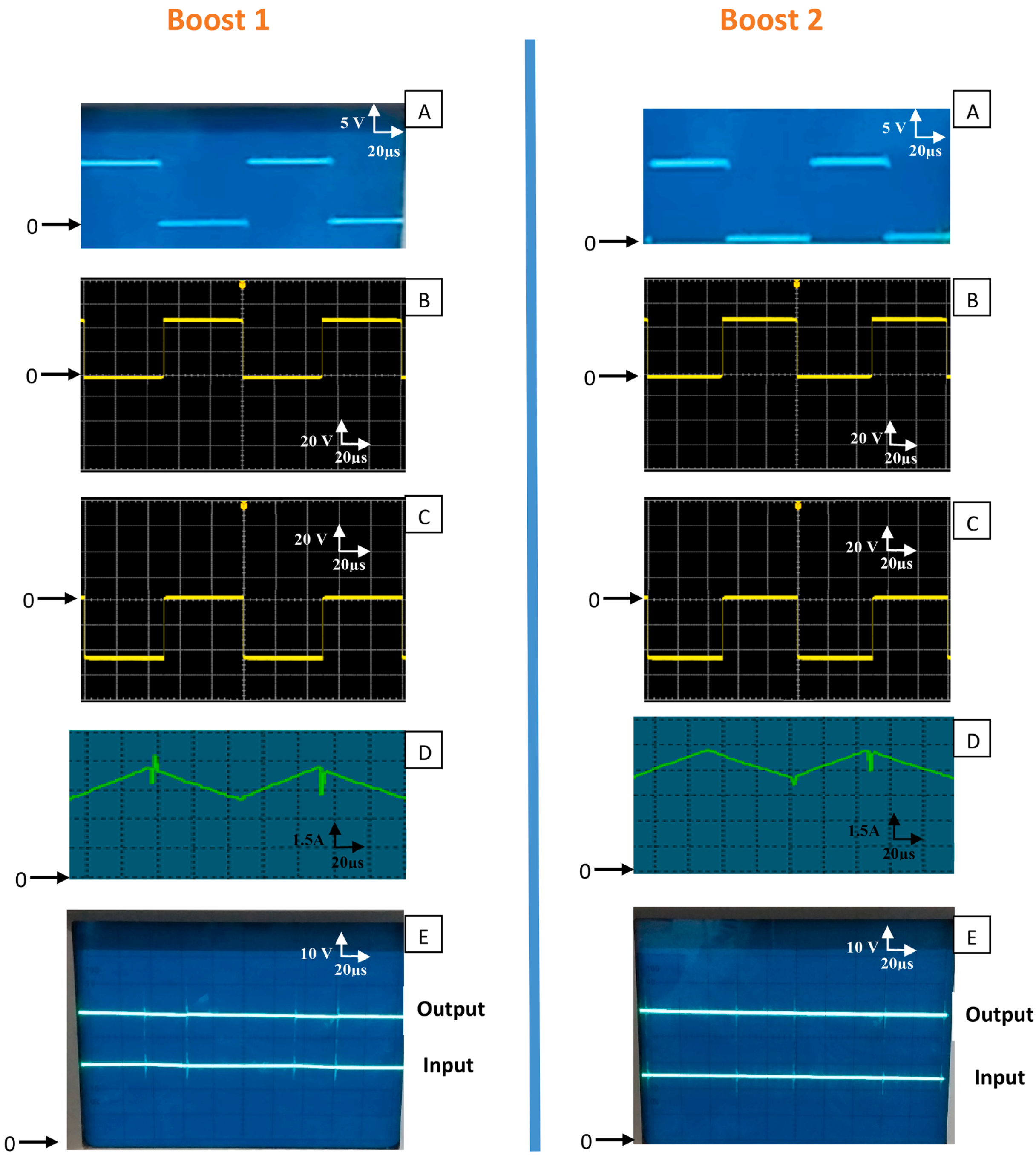

Figure 10. Waveforms experiment of DC / DC converters for an illumination of 800 W/m^2. A: PWM signals controlling the converter MOSFETs, B: Voltage at the output of the power switches, C: Voltage at the output of the diodes, D: Current in the inductances, E: Input and output voltages.

- Theses PWM signals regulate, under optimal conditions, the voltages and currents at the input of converter 1 (30 V, 4.8 A) and converter 2 (23 V, 6.5 A), and at their common outputs (40 V - 54 V, 4 A - 5.4 A).
- The temperature of the thermal resistance reaches the value of 200°C after 10 seconds (i.e. 20°C/s) and the maximum value 600°C after 30 seconds.
- During 10 minutes of heating, the water temperature varies from 20°C to 51.3°C, or 3.13°C/min. From relation 2, the thermal efficiency of the cooker is estimated at 86 %.
- After 25 min of heating, the water reaches the maximum boiling temperature, which is 98°C.

The results obtained in this paragraph show on the one hand the good functioning of the power and control blocks, and on the other hand, the rapid variation of the temperature of the heating of the thermal resistance and that of the heating of water. The comparison with the literature [3,20], in the case of conventional thermal ovens, allows us to deduce, concerning the temperature of heating, and the heating time of the water, a very significant improvement of 531 % (i.e. a factor of 6.31) and 86.1 %. Furthermore, we deduce a clear improvement in the thermal efficiency of 59.2 %.

All the results obtained on water heating, show the proper functioning of the PV energy cooker, developed during this work, in terms of water heating for a power of 293.5 W. The increasing this power, by adding PV panels, improves the power and the heating time in the same proportions: if we double the power of the PV panels, the heating time

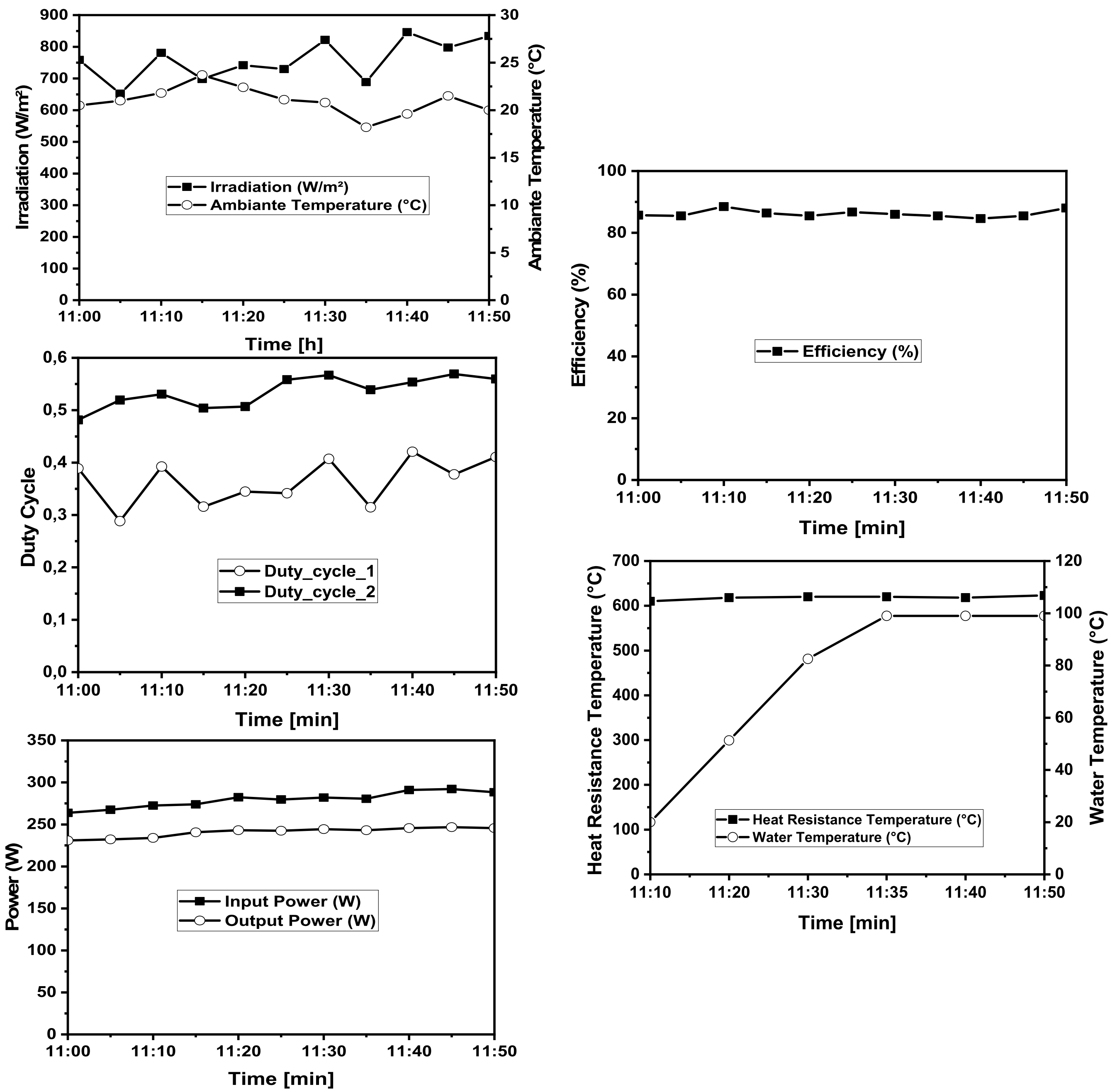

Figure 11. Illumination intensity and ambient temperature, Duty cycle controlling the two converters (α_1, α_2), Input and output powers of the converters, Converters efficiencies, Temperature of thermal resistances and of water. 03 March 2020

decreases by half, the rate and the maximum value temperature increase by a factor of 2.

3.5.1. *Cooking food*

Under the same conditions as above (Paragraph II.4.1), we tested the cooker in Figure 8, following the cooking of food throughout the day for the 4 seasons of the year. Typical results, in the case of cooking fries (2 Kg), shown in Figure 12 show:

- During the cooking period the intensity of the lighting varies from 630 W/m^2 to 730 W/m^2 and the ambient temperature from 14°C to 24°C,
- The oil temperature reaches 100°C after 20 min of heating, i.e. 5°C/min,
- The PWM duty cycles of the first DC/DC converter (α1) varies from 0.2 to 0.5, and for the second one (α2), from 0.4 to 0.7. The frequency of these PWM signals is f = 10 kHz.
- The powers at the input of the converters are respectively PPV1 = 143 W and PPV2 = 148.2V, and that at their outputs PS = 254.1W. These values show that the yields of these two converters are respectively η1 = 86 % and η2 = 87 %, and that overall η = 86.5 %.
- These PWM signals regulate, under optimal conditions, the voltages and currents at the input of converter 1 (31.1 V, 4.6 A) and converter 2 (23.5 V, 6.3 A), and at their common outputs (40 V- 78 V, 4 A – 8 A).
- Around noon, and under an illumination of 730 W/m^2, the temperature of the heating resistance and that of the oil respectively reach their maximum values of 580°C and 265°C.

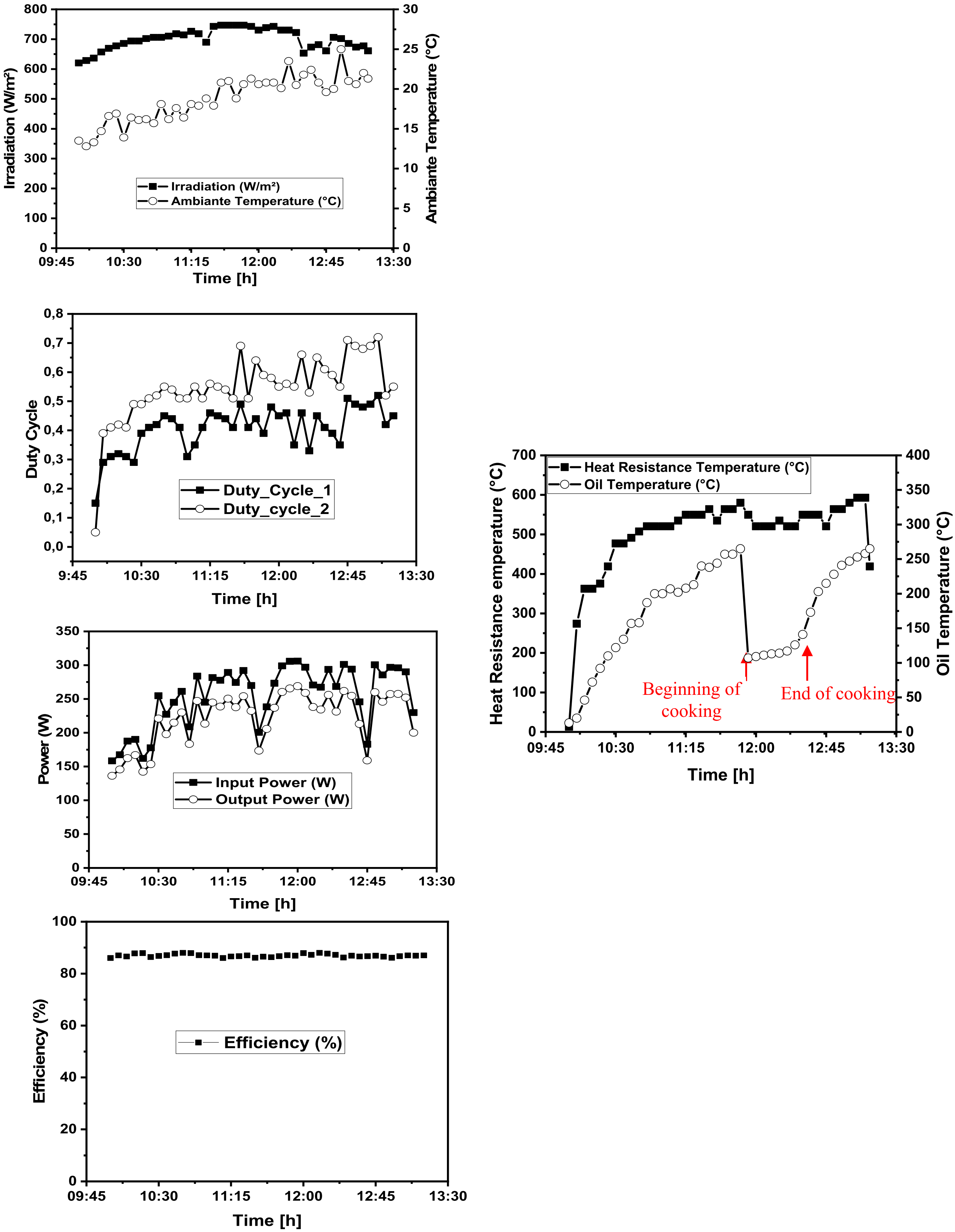

Figure 12. Illumination intensity and ambient temperature, Duty cycles (α_1, α_2), Input and output powers of converters, Efficiency of converters, temperature of thermal and cooking resistances (oil). 04 March 2020.

- When adding 2 kg of fries, the oil temperature decreases to the value of 108°C, then increases gradually, during cooking to reach the value of 261°C after 30 min of cooking.
- Cooking took place at an average temperature of 108°C after a duration of 25 min.

By comparing these results to those obtained on conventional thermal cookers (box, ...) [6,13], we can deduce better cooking performance on the heating plate with photovoltaic energy, developed during this work: improvements in the cooking temperature and the cooking time respectively of 178 % (i.e. a factor of 2.79) and 83.3 %. These performances and the autonomous cooking mode, inside and outside homes, allow us to conclude the effectiveness of the prototype developed and produced within the framework of the projects, engaged during this work.

In the applications shown in the figures, the cooker operates under an illumination of 730 W/m^2 and an ambient temperature of 24°C. This typical operation makes it possible to generate electrical powers of 300 W and cooking temperature above 200°C. These electrical and thermal quantities are largely sufficient for the targeted users in the rural and urban world. When the users' need increases, in terms of cooking temperature, for the same weather conditions, we only increase the number of photovoltaic panels. In general, the operation of these cookers depends only on the intensity of the illumination that could be achieved over the entire globe. Furthermore, in cold areas, with the same intensity of illumination, the performance of photovoltaic panels increases. A 10°C decrease in temperature generates a 4 % increase in the power of the photovoltaic panels [33], and therefore in the cooking temperature in the same direction.

This technology is considered as an interesting alternative to solve the problem of the effects caused by the use of conventional sources (gas, petroleum, etc.) [29–31]. This new autonomous cooking method powered only by photovoltaic energy does not require any other energy source, such as electricity from the electricity grid, gas and storage battery. The proposed cooker has no gas emissions, contributes to the protection of forests, and consequently the conservation of the environment [27–29,32].

4. Conclusion

In this paper, we have shown the feasibility of a new type of solar cooker (hot plate) operating with photovoltaic (PV) energy. This cooker is formed by PV panels, power blocks (DC/DC converters) and controls, and thermal resistances supporting temperatures of 1000°C. We have dimensioned the DC/DC converters, according to the nature of the PV panels, to provide a power of 400 W of cooking in automatic mode (Extraction of the maximum power of the PV panels by the MPPT command). Then, we experimented the proposed cooker in the case of heating of one liter of water and cooking food requiring high temperatures (2 kg of fries). The results obtained show:

- The good functioning of the proposed blocks and the optimization of the powers supplied by the PV panels. During the period of operation, the efficiency of the converters is 86.5%.
- The heating resistance temperature reaches 500°C after 15 seconds of heating (i.e. 33.33°C/s),
- The rapid rise in water heating temperature of 3.13°C/min, for a panel power equal to 293 W,
- The boiling time of water is 25 min for a power of 293 W. From these measurements, we have estimated the thermal efficiency of the cooker at 86 %,
- Cooking fries took place after a duration of 25 min.

The comparison of these results with those of the literature, obtained on the classic solar cookers 'Thermal', shows better performances on the solar cookers with photovoltaic energy developed during this work:

- Increases in water heating rate and maximum cooking temperature by a factor of 10.43 and 6.3 respectively.
- Reductions in boiling times of water and cooking of food (fries) by 91.6 % and 86.1 % respectively.

All of these results obtained and better performances, in terms of cooking, show the feasibility of the cooker (hot plate) with photovoltaic energy, developed during work. In perspective, this prototype will be delivered as part of the projects undertaken, during this work, for twenty families from the rural world, from forest areas, who exploit the forests of the Oriental Region (Oujda). The expected objective of this initiative, in the short and long term, is to adopt this new ecological cooking method in homes, to protect forests, consequently the environment, by exploiting photovoltaic renewable energy applications.

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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