Feasibility of a Power and Control System for an Autonomous Photovoltaic Hot Plate Type Cooker (600 Wp)

Hajar Chadli, Khalid Salmi, Sara Chadli, Mohammed Hmich, Rachid Malek, Olivier Deblecker, Khalil Kassmi, and Najib Bachiri

Abstract

This chapter provides the experimenting, results, and findings related to the design of a new autonomous solar cooking using photovoltaic energy. The proposed architecture is composed of a PV panel of 600 W/peak, a power bloc containing a DC/DC boost converter, a load in the form of two identical heating plates, and a control bloc to supervise the system, collect, and display the electrical quantities. A 20 kHz PWM signal is used to control the boost with a variable duty cycle. The variation of duty cycle is realized either manually via an analog circuit or automatically via a digital circuit built around the Raspberry Pi Pico microcontroller. The microcontroller is also responsible for the acquisition and display of the electrical quantities (voltage, current, power, efficiency, etc.). The irradiation and ambient temperature are retrieved from a meteorological station in real time. Also, to prevent the malfunction caused by open load problems, we added a switch to cut the line in case of any fault detected problem. The results for both analog and digital control circuits are presented, and experimentation on boiling, respectively, 1 L of water and ½ liter of oil is done. For irradiation between 400 W/m2 and 820 W/m^2, and an ambient temperature of around 24 °C, the proposed system delivers an output power reaching 310 W with an efficiency of up to 95%. The experience with heating water and oil shows that the temperature increases rapidly and attains a boiling temperature of 98 °C in just 25 min in the case of water, and a temperature of 239 °C in 20 min in the case of oil. Comparing our system to other existing architecture shows an improvement in efficiency, maximum temperature, and heating speed, which proves its feasibility in both rural and urban households.

Keywords

Photovoltaic energy • Solar cooker • DC/DC converter • Analog and digital control • PWM signal • Malfunction system • Water and oil heating

H. Chadli · K. Salmi · S. Chadli · M. Hmich · R. Malek · K. Kassmi (✉)
Faculty of Science, Department of Physics, Laboratory of Electromagnetic, Signal Processing and Renewable Energy LESPRE, Team Electronic Materials and Renewable Energy EMRE, Mohamed First University, Oujda, Morocco
e-mail: k.kassmi@ump.ac.ma; khkassmi@yahoo.fr

H. Chadli
e-mail: chad.hajar@gmail.com

K. Salmi · S. Chadli
Faculty of Science, Laboratory of Electronics and Systems, Mohamed First University, Oujda, Morocco

O. Deblecker
University of Mons, Polytech. Mons—Electrical Power Engineering Unit,, Mons, Belgium
e-mail: olivier.deblecker@umons.ac.be

K. Kassmi · N. Bachiri
Association Human and Environment of Berkane (AHEB), Berkane, Morocco

1 Introduction

In the last decades, population growth and economic development are considered the main reasons for increasing energy consumption. Burning fossil fuels such as coal, gas, and oil, deforestation, and forest degradation caused by the use of wood as fuel for cooking in the rural area that has no (lack) access to convenient and affordable sources of energy and the emission of greenhouse gas are severely damaging our environment and our health.

The use of clean energy equipment, such as solar cookers, helps to limit deforestation, solve problems related to cooking in rural and forest areas, improve the quality of life for villagers who are sometimes cut off and isolated due to a lack of energy resources and reduces the consumption of charcoal, wood, gas, and electricity, thus reducing the emission of greenhouse gases. As a result, it protects and

M. Bendaoud et al. (eds.), *Advances in Control Power Systems and Emerging Technologies*, Advances in Science, Technology & Innovation, https://doi.org/10.1007/978-3-031-51796-9_3

preserves the environment (Thakur et al. 2018; Ramalingam 2021; AL-NEHARI et al. 2021).

A good number of researchers worked on solutions to supply cookers via solar energy. In a theoretical analysis of the performance of an induction cooking system under different loads, Dhar et al. presented a design of a small voltage PV-based induction cooker (Dhar et al. 2020). The proposed structure was developed based on an induction cooker capable of boiling water and cooking multiple dishes per day. In another work, the characteristic of a photovoltaic cooking system was modeled and simulated (Swarupa et al. 2021). The voltage, current, and output power values of different PV systems were calculated for various cooking temperatures and irradiation levels. In another work, Prabu et al. proposed a solar cooker with PV panels that could be used without interruption for a full 24 h per day (Prabu et al. 2021). The proposed structure is based on evacuated tubes with compound parabolic collector (CPC) reflectors, batteries, and a charge controller using the microcontroller PIC 16F877A. Altouni et al. developed a PV-based solar induction cooker dedicated to people from remote and rural areas who do not have access to grid electricity (Altouni et al. 2022). In addition, studies of energy transfer to cooker pots have shown that steel pots (diameter of 13 mm, thickness of 1 mm) provide the transfer of the large amount of energy. Under these conditions, under a voltage of 45V, the heating temperature reaches the value of 63°C.

In accordance with this research topic and within the H2020 (LEAP-RE, 2022–2025) project, we proposed the design, feasibility, and experimentation of an autonomous solar cooker powered by electricity produced by solar PV panels and solar batteries. The system is capable of supplying 1,2 kW of energy which is more than sufficient for cooking (3–5 kg) of food in a family of five to eight people. The proposed system is composed of 600 W/Peak PV panels, solar batteries of 200 Ah to store the electrical energy, a DC/DC converter, a heating plate made of two thermal resistances, and a control bloc. The control bloc was designed in two different ways. The first architecture was made using a completely analog circuit, and the duty cycle of the PWM signal was controlled via a rotating potentiometer. The second one was designed based on a Raspberry Pi Pico, and the duty cycle this time was generated numerically by the microcontroller by using the MPPT method. The proposed system is also equipped with sensors on both input and output which allow us to measure the voltage and current and deduce the corresponding power and efficiency for different irradiations, ambient temperatures, and duty cycles. An additional bloc was added containing electronic switches based on MOSFET transistors. The switches could be activated by the user via a rotating encoder or automatically when an eventual malfunction is detected (overvoltage or overcurrent).

In this paper, we propose the feasibility, realization, and experimentation of the proposed cooker for a power of 600 Wp without storage in solar batteries. This prototype was implemented and experimented both in the laboratory and in three household families in the eastern region of Morocco.

2 Synoptic Diagram of the Overall System

The overall structure of the proposed solar cooker is presented in Fig. 1. The system is divided into four main blocs: a photovoltaic generator, formed by the PV panels with overall power of 600 W/peak; a power bloc containing the DC/DC boost converter, switches, and sensors; a control bloc delivering a 20 kHz PWM signal and retrieving the input and output voltage and current; and a load bloc constituted by two thermal resistances of 15 Ω each.

The meteorological condition (illumination and external temperatures) was acquired via a new acquisition system designed to determine, through a pyrometer and digital temperature sensor, the intensity of the illumination and the ambient temperature. The proposed meteorological acquisition system was built around a Raspberry Pi Pico microcontroller, a CMP6 pyranometer, and DS18B20 digital thermometer.

2.1 Power Bloc

To maximize the efficiency of the PV panels and to ensure the adaptation between the solar PV panels and the heating load, we used a boost converter to increase and regulate the input voltage to the level needed by the load (Fig. 2). The power bloc receives the input signal from the 600 W PV panels and injects it into the DC/DC boost converter. The components' choices were made to endure the high power. We choose to work with a MOSFET power transistor which supports a maximum voltage of 500 V and a maximum current of 20 A, and we also used a power diode with a maximum voltage of 400 V and forward current of 30 A, a large capacitor of 1000 µF to resist the high current in order to achieve higher output voltage, and a large inductor of 1 mH to maintain the high current flow of the boost converter.

The safety of the system should be considered while designing the solar cooker, to solve the problem of the open-circuit load in a boost converter so that it does not operate at no-load condition and thus avoid its damage. If not, there will be no discharging of energy through the load; therefore, a voltage buildup will occur for each cycle, eventually causing the capacitor to burst. We have designed a circuit that detects the open-circuit load problem. This circuit allows disconnecting the PV panel from the load (heating plate) as soon as the load current drops to 0.5 A,

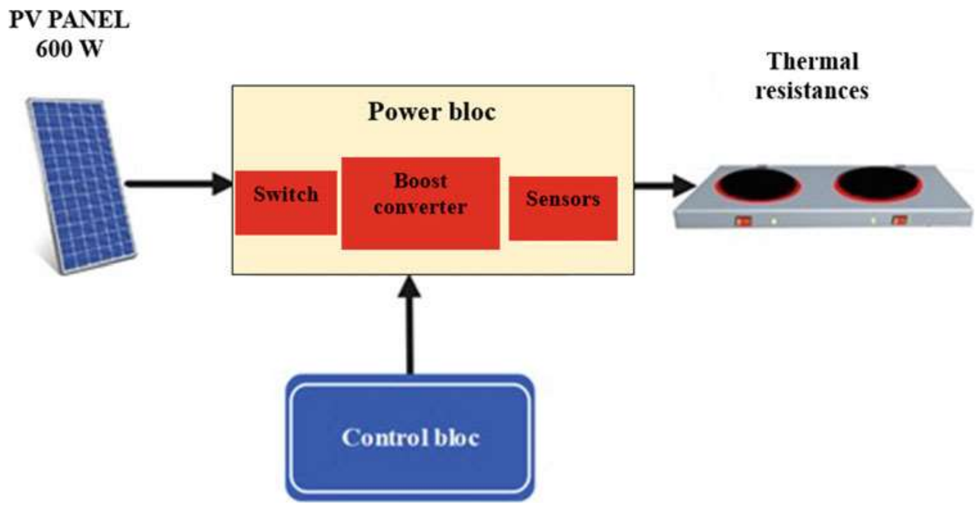


Fig. 1 Proposed solar cooker synoptic diagram

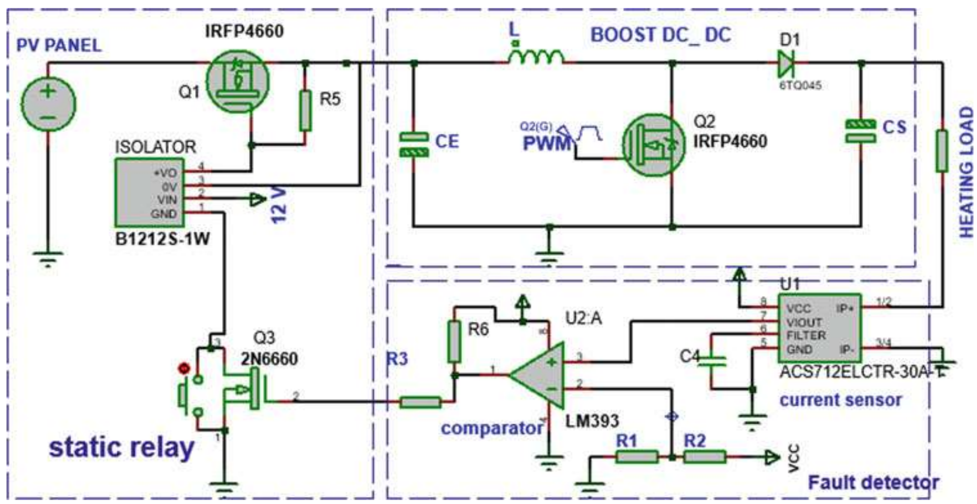


Fig. 2 The fault detection circuit in case of open load problem

corresponding to the cooker's malfunction. The proposed circuit (Fig. 2) is constituted of a comparator LM193 used to compare the output current acquired by the ACS712 sensor to the 0.5A threshold current represented by a threshold voltage generated by a voltage divider. If the load current falls below 0.5A, the comparator generates an undercurrent alert signal that will trigger the static relay connecting the PV panel to the boost converter, thus disconnecting the boost from the power source. The static relay is built around a MOSFET transistor operating in high side. Once the problem is solved, we can reconnect the power source using a push button. This circuit is essentially composed of two blocks.

A static relay designed around a power MOSFET transistor. This transistor operating in high side requires a bootstrap driver or a floating control to ensure that V_{GS} is greater than the voltage from which the transistor can saturate. We used an isolator circuit with a floating outputs voltage of 12 V.

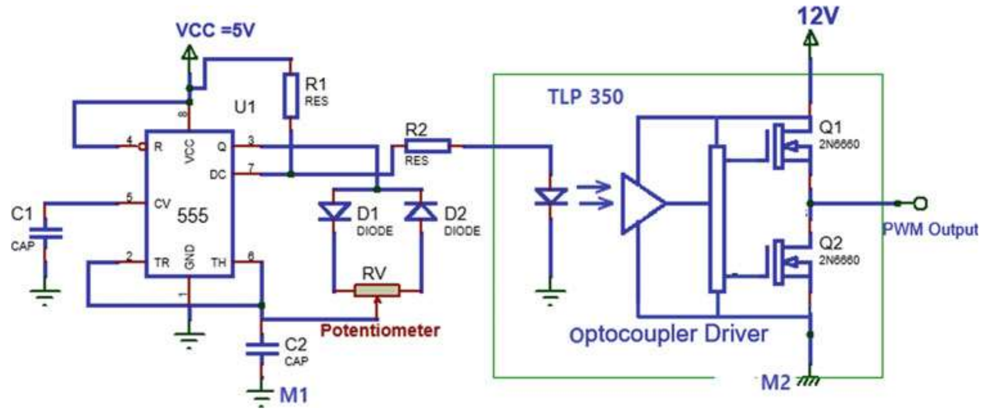
A comparator based on LM 393 which compares the output voltage from the current sensor to a threshold value corresponding to 0.5 A. When the current supplied by the sensor is less than 0.5 A, which corresponds to an open output, the comparator output switches to the low state which blocks the transistor, thus disconnecting the PV panel from the DC/DC converter. The push button is used to reactivate the relay to connect the source after correcting the problem.

2.2 Control Bloc

To control the whole cooker system, we opted for two methods: an analog control circuit and a digital control circuit:

In the case of the analog control circuit (Fig. 3), the boost converter is controlled via PWM signal produced by an NE555 timer (Atmane 2019). The NE555 timer is used in astable mode to generate the PWM control signal with

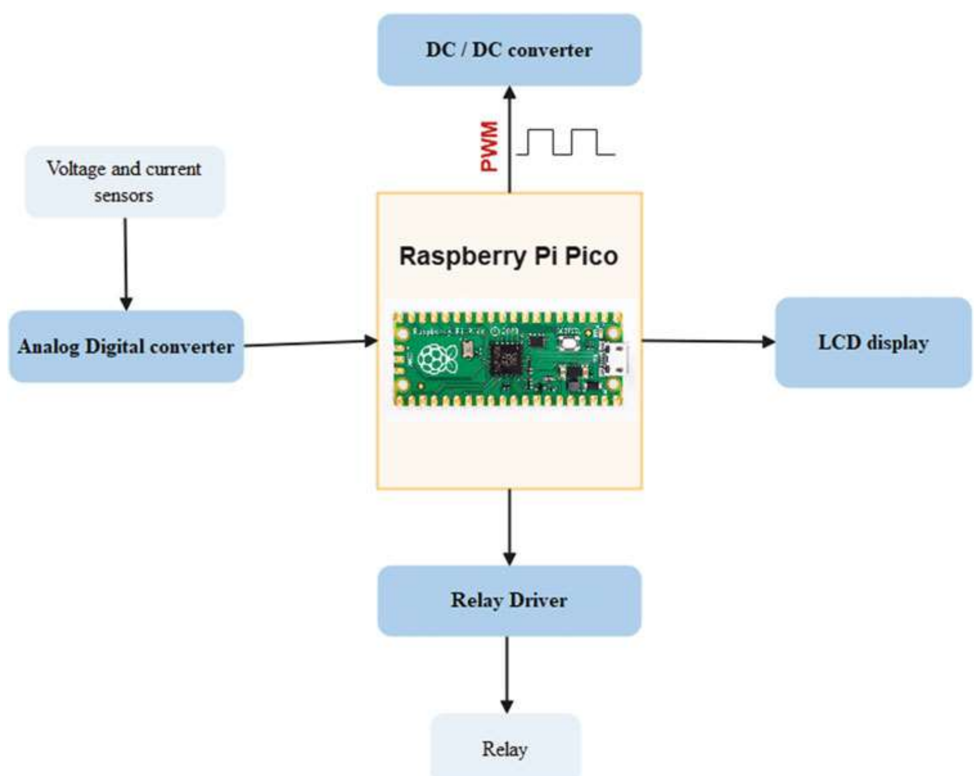
Fig. 3 The proposed analog control circuit



variable duty cycle and fixed frequency (20kHz) by varying the time duration of charging and discharging of the capacitor. The duty cycle of the PWM signal is varied manually using a potentiometer, which allows us to control the amount of power delivered to the heating plate. To ensure the isolation between the low-power part (control bloc) and the high-power part (DC–DC boost converter), we opted for TLP 350 driver optocoupler with push–pull output. The voltage and current supplied by this optocoupler make it ideally suited to drive the gate of the transistor to make sure that it is fully turned on.

In the case of the digital control circuit (Fig. 4), another solution to drive the power bloc was proposed based on a completely digital board. The proposed structure was built around a Raspberry Pi Pico microcontroller. The microcontroller is responsible for the generation of the PWM signal at the required frequency of 20 kHz to operate the photovoltaic panels at their maximum power for a given illumination. The variation of the duty cycle is automatically adjusted by the microcontroller using maximum power point tracking method (MPPT) (Al Hamri 2019; Melhaoui et al. 2014). The digital control method (MPPT) is implemented using the microcontroller to extract the maximum electrical power from the PV solar panel under various atmospheric conditions so that the boost converter operates in maximum efficiency and stability conditions. The general process is done following the perturb and observe (PO) algorithm presented in the flowchart below (Fig. 5).

Fig. 4 The proposed digital control circuit



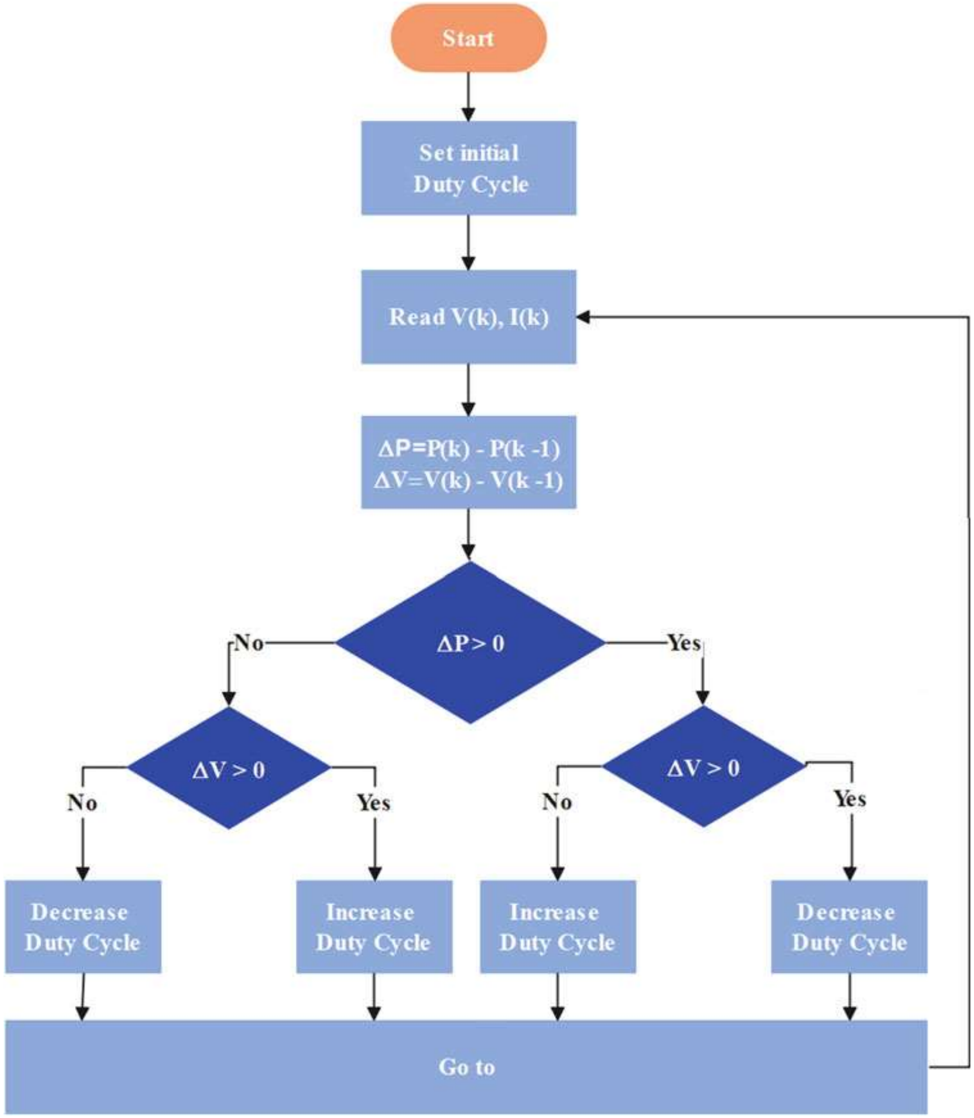


Fig. 5 The perturb and observe method flowchart for MPPT

Furthermore, the acquisition of the electrical data (voltage, current, power, efficiency) is carried out by two types of sensors: the ACS712 current sensors and a voltage sensor in the form of a voltage divider. The sensors are located in both the input and output of our system and are connected to the Raspberry Pi Pico. All the acquired data are instantly shown on an LCD display.

The Raspberry Pi Pico is also responsible for the detection of the case of an open-circuit load which could conduct to the system's malfunction. The microcontroller will periodically supervise the measured output current. If the current falls below a threshold value, which means the load is unplugged, the microcontroller automatically disconnects the power sources from the system.

3 Results and Discussions

3.1 Experimental Procedure

To validate the operation of our designed solar cooker, we implemented and tested the system shown in Fig. 6. The realized system is composed of the following:

- A meteorological station to determine the intensity of the illumination and the ambient temperature (illumination and external temperatures) through a pyrometer and digital temperature sensor.
- A photovoltaic generator, formed by PV panels with overall power of 600 W/peak.

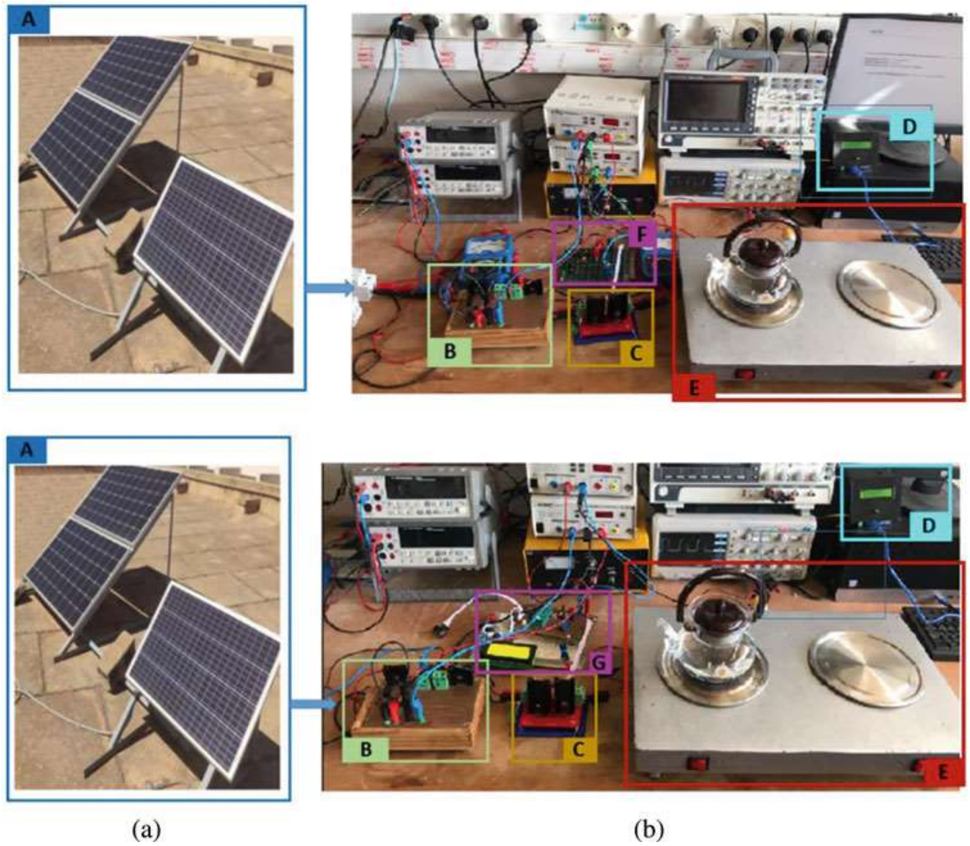


Fig. 6 The proposed cooker system implementation. **a** Digital circuit; **b** analog circuit

- A DC–DC boost converter which operates at a frequency of 20 kHz in continuous mode, supporting a maximum current of 20A. The boost MOSFET is controlled by the PWM control signal generated either manually by the analog circuit presented in Sect. 2.2 or automatically by the digital circuit based on Raspberry Pi Pico.
- A microcontroller based on Raspberry PI Pico which is responsible of the following tasks:
  - Executing the MPPT controller algorithm to operate the PV panel at its maximum power point.
  - Generating automatically the 20 kHz frequency PWM control signal with a variable duty cycle.
  - Acquisition of electrical value (input current, input voltage, output current output voltage) via current and voltage sensors and calculating the corresponding power and efficiency.
  - Displaying the acquired data on an LCD display.
  - Ensuring the protection of the solar cooker by detecting the no-load operation of the boost converter and generating an alert signal to disconnect the boost from the power sources.
- A heating plate, composed of two thermal resistances of 15 Ohms. Each resistance can be turned on separately or combined with the other one.

The components used in this proposed system are as follows: A: PV panels, B: fault detection circuit, C: DC/DC converter, D: meteorological station, E: heating plates, F: analog control circuit, G: digital control circuit.

3.2 Experimenting with the DC/DC Converter

The first experimental tests were conducted over the boost converter to study its correct operation. Figure 7 shows the output waveform of the PWM signal provided, respectively, by the analog and digital control bloc. The PWM signal is generated at 20 kHz frequency, and the duty cycle is manually variable with the analog circuit or automatically calculated with the digital circuit. To obtain the PWM signal, we used the waveform created by charging and discharging a capacitor shown in Fig. 8. The obtained signal is then compared to a variable threshold corresponding to the duty cycle value to obtain the desired waveform. In Fig. 9, we have represented the variation of the electrical quantities both at the input and output of our system (voltage (Ve, Vs), current (Ie, Is), power (Pe, Ps)) and the efficiency η of the DC/DC converter in terms of the duty cycle. The results show that the maximum output power corresponding to maximum efficiency is obtained for

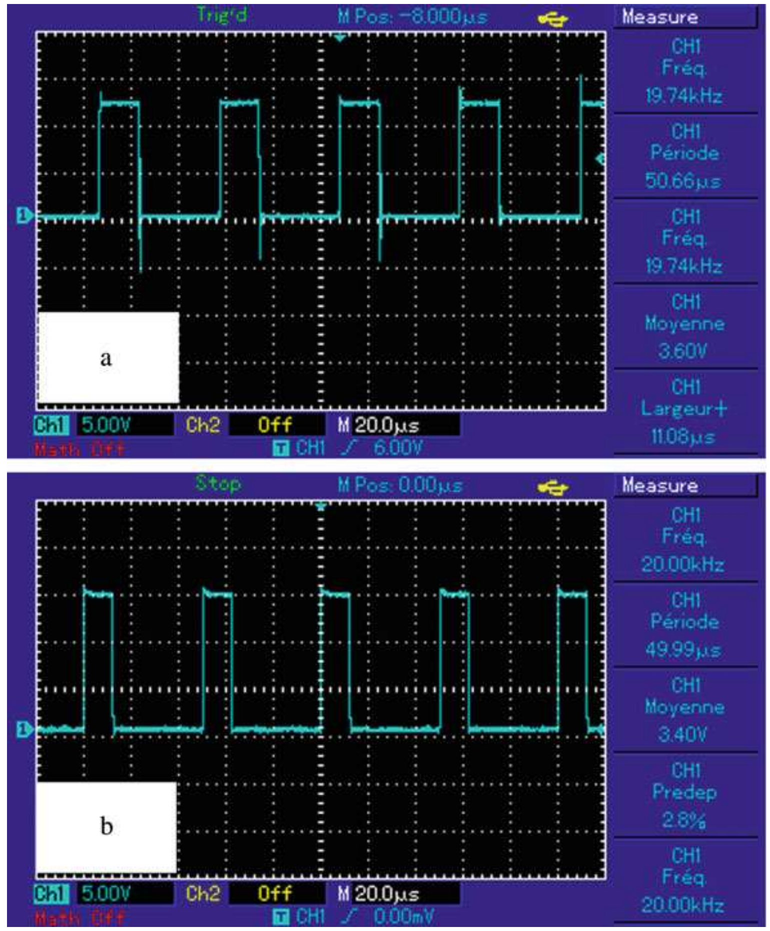


Fig. 7 PWM output signal waveform. **a** Analog control bloc; **b** digital bloc

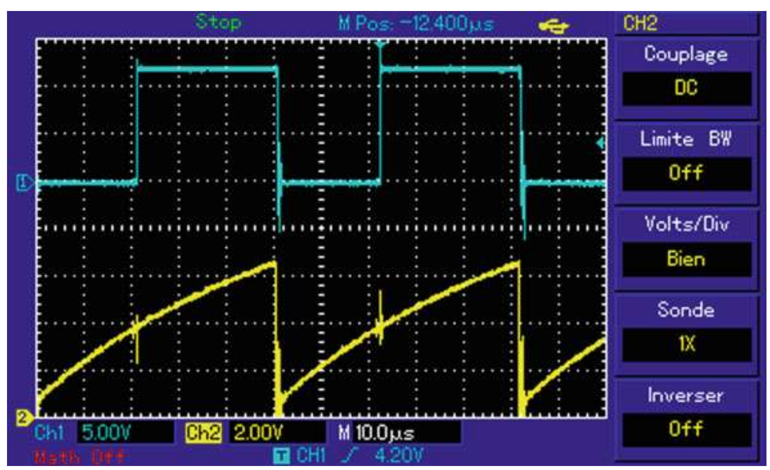


Fig. 8 Charging and discharging capacitor waveform

a duty cycle of 40%. This result is obviously corresponding to the value of the thermal resistance (15 Ohms). The duty cycle will change with a different resistance values. For instance, when the two parallel resistances are both turned on (with an equivalent value of 7.5 Ohms), the duty cycle decreases to 20% as shown in Fig. 10. This figure presents the input and output voltage, current, and power in the case where both resistances are working at the same time.

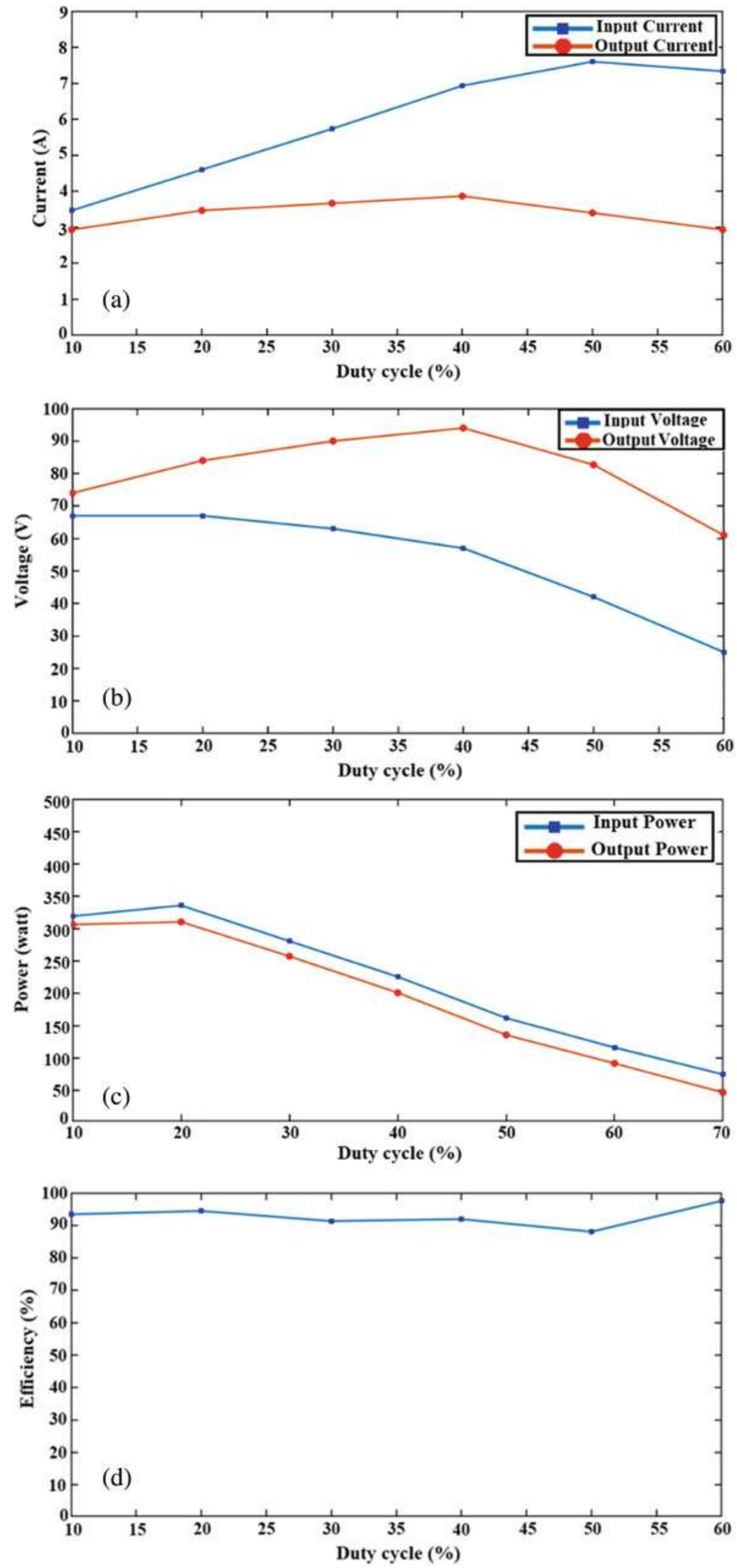


Fig. 9 Variation of the electrical quantities in terms of the duty cycle for one thermal plate in the case of analog control. **a** Current, **b** Voltage, **c** Power; **d** Efficiency

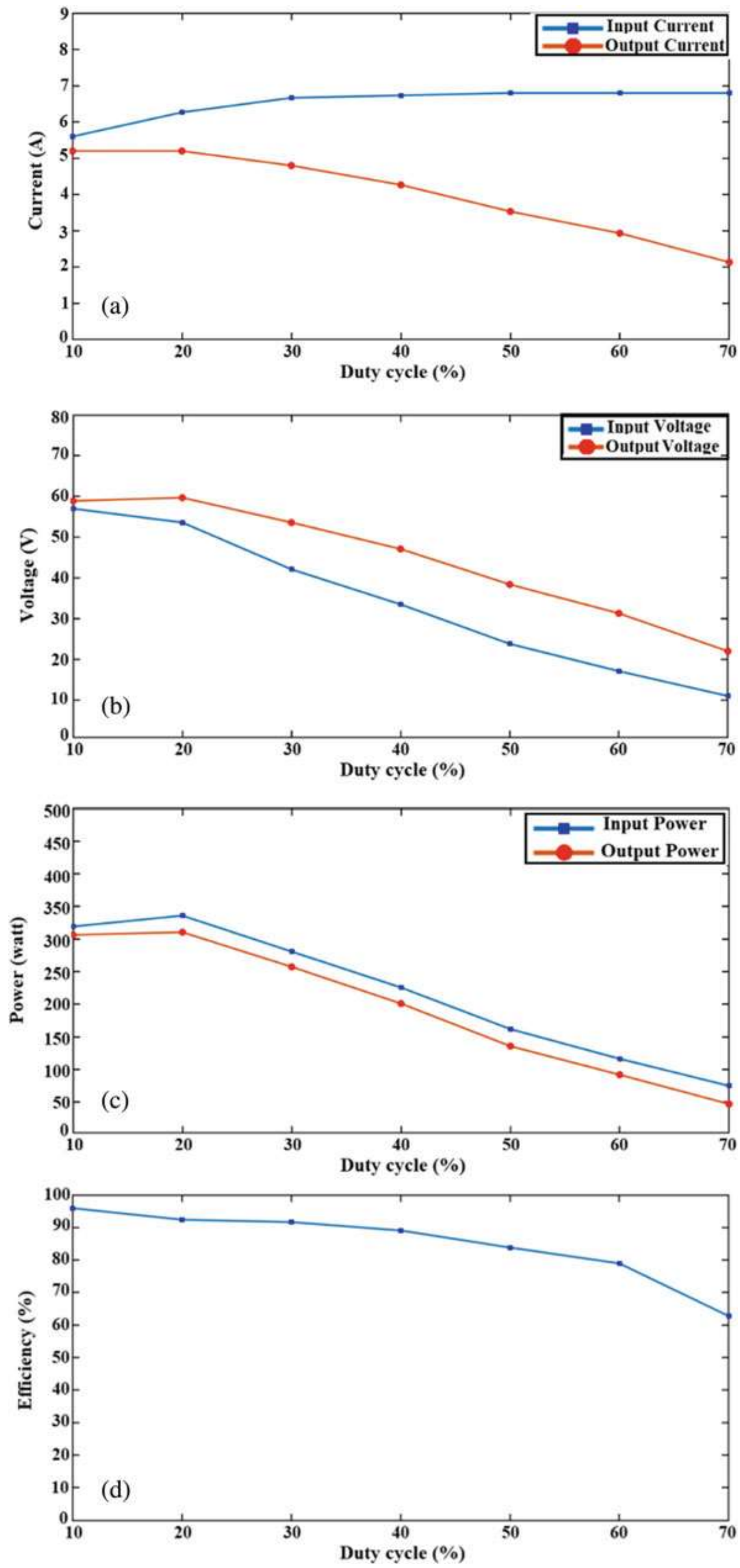


Fig. 10 Variation of the electrical quantities in terms of the duty cycle for two parallel thermal plates in the case of analog control. **a** Current, **b** Voltage, **c** Power; **d** Efficiency

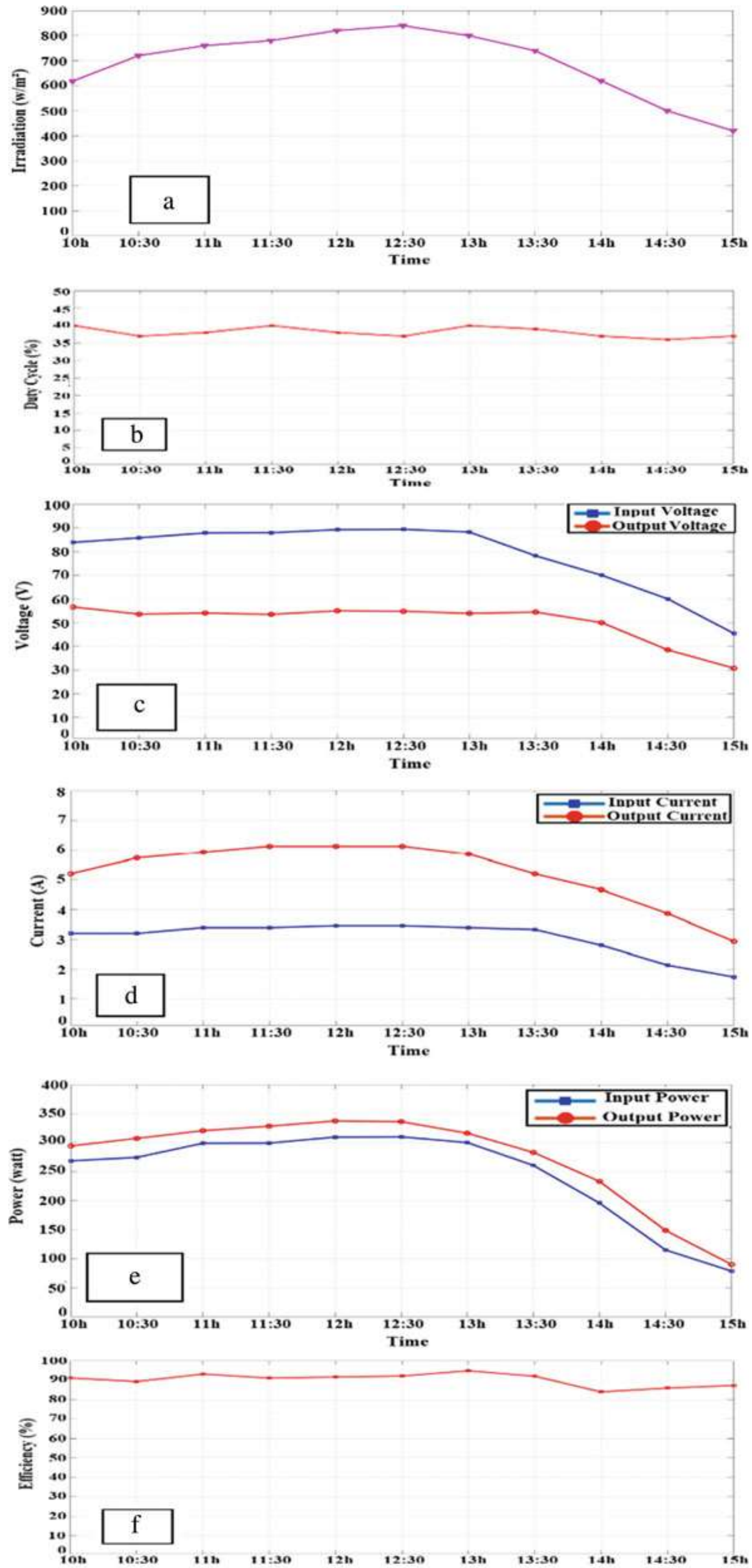


Fig. 11 Experimentation of the cooker in the case of digital control: **a** Illumination intensity; **b** duty cycle; **c** input and output voltage; **d** input and output current, **e** input and output power, **f** efficiency

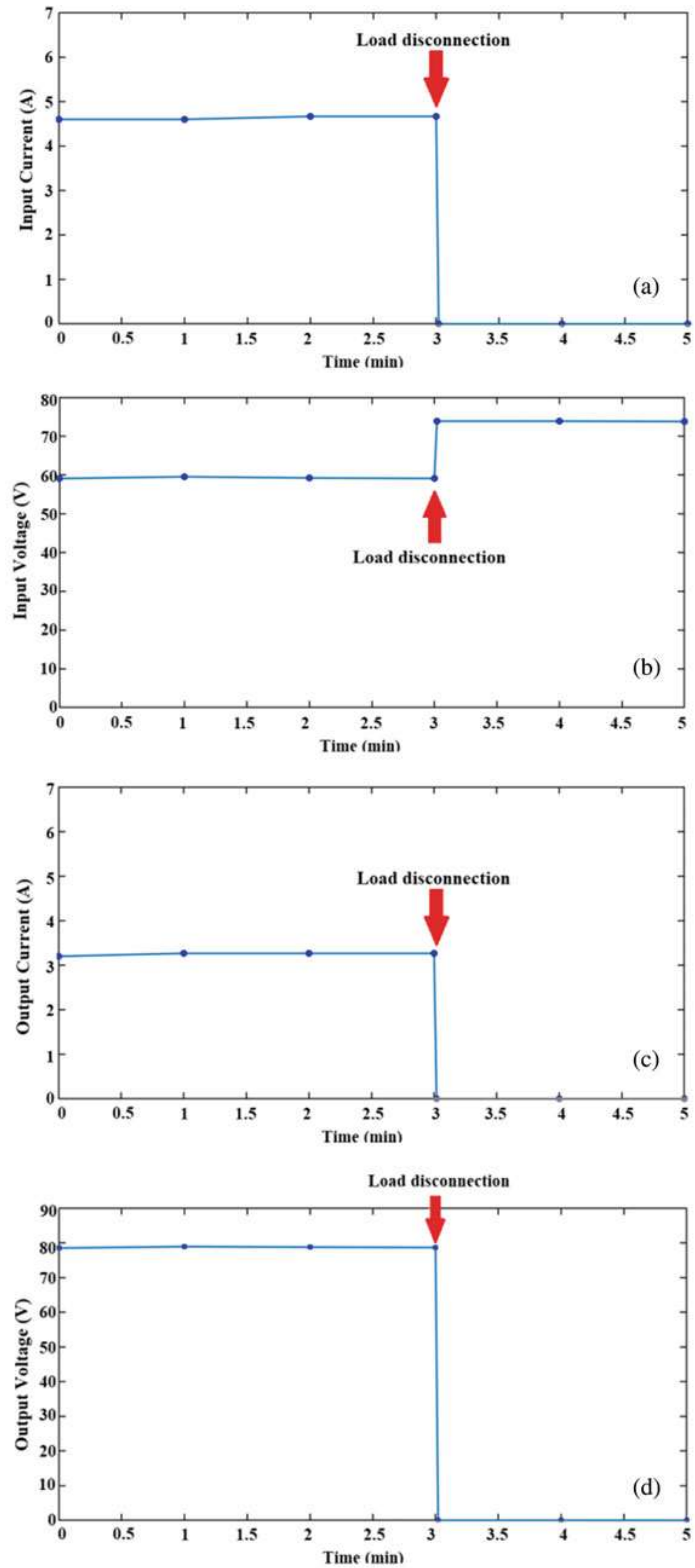


Fig. 12 Experimentation and validation of the fault detection circuit before and after a load disconnection. **a** input current; **b** output current; **c** input voltage; **d** output voltage

On the other hand, we also tested and validated the digital control system working with the Raspberry Pi Pico microcontroller. The results were collected for a whole day, and the corresponding irradiation and ambient temperature were also recorded using the meteorological station. The microcontroller automatically generates the optimal duty cycle value corresponding to the maximum power. The typical experimental results for a 15 Ohms thermal resistance are shown in Fig. 11. The outcome of these experiments shows that:

- The duty cycle is around 40%.
- The maximum output power is around 310 W and is obtained for an irradiation of 820 W/m2 and an ambient temperature of 24 °C.
- The efficiency of the proposed system is above 84% and reaches 95%.
- The system regulates the input voltage and current at a range of 30–56 V and 3.0–6.2 A, while the output values vary around 45.5–89.5 V and 1.8–3.5 A.

Furthermore, we also tested and validated the fault detection circuit presented in Fig. 2. This circuit ensures the disconnection of the photovoltaic panel when the load is disconnected or presents an anomaly. To validate the correct operation of our proposed circuit, we experimented the fault detection with the solar cooker and tried to disconnect the load at a certain point in time and observe and measure the input and output voltage and current. The results are represented in Fig. 12 and show that once the load is disconnected, the relay cut the PV panel from the DC/DC converter immediately. Indeed, the output voltage drops to a few mV while the input voltage shifts to around 73.9 V which correspond to its value in open circuit. As for the input and output current, they both drop to 0 A. The proposed circuit shows an instantly response and prevents the solar cooker from working with no load. This operation is ideal to protect the system and avoid its damage which could be caused by the buildup energy.

3.3 Solar Cooker Application: Water Heating and Oil Heating

To give valuable feedback about the reliability of the designed solar cooker, field deployment of the prototype was conducted in the laboratory. For that, we tested the system by heating one liter of water and ½ liter of oil. The typical results (irradiation, ambient temperature, thermal resistance, water temperatures, input and output powers, and efficiency) obtained during a sunny day are represented as follows:

- In the case of water heating:
  - The measurements were done for an illuminance intensity and an ambient temperature reaching a maximum value of 850 W/m^2 and 24.6 °C, respectively.
  - The voltage and current at the converter input are, respectively, around 53 V and 6.2 A, while the voltage and current at the converter output are, respectively, around 90 V and 3.5 A.
  - The input and output powers of the converter are about 328W and 315W. Thus, an efficiency of 96% is achieved.
  - The thermal resistor temperature reaches a value of 340 °C after 20 min and 500 °C after 60 min.
  - During 5 min of heating, the water temperature varies from 24 °C to 42 °C, which mean a variation of 3.6 °C per minute.
  - After 31 min of heating, the water reaches its maximum boiling temperature, which is 100 °C.
- In the case of oil heating:
  - The illuminance intensity and the ambient temperature reach the maximum values of 850 W/m2 and 27 °C, respectively.
  - The voltage and current at the converter input are, respectively, 52 V and 6.2 A while the voltage and current at the converter output are, respectively, around 89 V and 3.5 A.
  - The input and output powers of the converter are about 322 W and 311 W. Thus, an efficiency of 96% is achieved.
  - During 20 min of heating, the oil temperature varies from 25 °C to 239 °C, which mean a variation of 10.7 °C per minute.

A comparison to the literature shows that our proposed solar cooker displays better performance and higher efficiency. Moreover, the heating plates in our case reach a much higher temperature than traditional solar architecture. For example, Verma et al. proposed a box-type solar cooker supplemented with heat storage for nocturnal cooking (Baghaz et al. 2013), but only attained an efficiency between 51 and 71%, while our designed system presents a maximum efficiency of 97%. In another research, Saha et al. presented cooking plates based on the MPPT method (Verma et al. 2022). Testing with 500 ml of water, they reached a boiling temperature of 98 °C in 20 min, while in our case, we obtained the same results but for the double quantity of water (1000 ml). The same tests were conducted by Edmonds (Saha et al. 2019), using a solar concentrator cooker with pan style, for 2 L of water, he obtained a temperature of 65 °C in 20 min and a boiling point in 55 min.

4 Conclusion

We presented in this paper a new autonomous cooking device working on solar energy and controlled either analogically or digitally by Raspberry Pi Pico. The system is composed of PV panels (600 Wp), DC/DC boost converter, two heating plates, a switch to detect malfunction and open load problem, and a control bloc. The last bloc generates a PWM signal either manually with a completely analog circuit, or automatically with Raspberry using MPPT. The Raspberry Pi Pico allows also the acquisition of the different electrical quantities while the meteorological data are collected separately with our meteorological station. The obtained results show the reliability and good functioning of our proposed cooking system. The heating process shows a rapid response, and the resistance temperature reaches a maximum of 500 °C, which is more than enough to cover the thermal needs for cooking food.

The proposed PV solar cooker was also validated and experimentally tested both in the laboratory and in the field. The prototypes of the solar cooker were offered to three different families in rural areas. The outcome was a complete satisfaction with the results.

In conclusion, the proposed solar cooker is a perfect clean alternative to traditional cooker using conventional energies such as gas and petroleum which are widely known for their pollution effects. The presented system could also be used in rural areas that are disconnected from the electricity grid. The use of the proposed system by local inhabitants could also prevent deforestation and protect the environment from pollution.

As perspectives, we intend to increase the power by using a 1.2-KW PV panel and store the extra power in batteries (48 V, 200 Ah) to use at night when there is no light. To manipulate the operation of the system between the day and night, we will also use switches to supply the system either with the solar energy directly provided by the panel during the day, or with the batteries during the night.

Acknowledgements This research is supported within the framework of the projects:Europe-Africa Research and Innovation call on Renewable Energy LEAP-RE, Project No 963530: SoCoNexGen, Solar Indoor Cooking Systems of the Next Generation, 2022–2025Morocco-Wallonie Brussels Cooperation Program (2023–2027), Wallonie-Bruxelles-International WBI (Belgium), project 3.3,National Initiative for Human Development INDH, Berkane Province, Morocco, project 2017/29.

References

Al-Nehari HA, Mohammed MA, Odhah AA et al. (2021) Experimental and numerical analysis of tiltable box-type solar cooker with tracking mechanism. Renew Energy 180:954–965

Altouni A, Gorjian S, Banakar A (2022) Development and performance evaluation of a photovoltaic powered induction cooker (PV-IC): an approach for promoting clean production in rural areas. Cleaner Engg Tech 6:100373

Atmane I (2019) System of control and supervision of the solar distiller to install in DouarAl Hamri of the rural district of Boughriba (Province of Berkane). Mater Today: Proc 13:587–596

Baghaz E et al (2013) Design, realization and optimization of the photovoltaic systems equipped with analog and digital MPPT commands. Energy Proc 42:270–279

Dhar S, Sadhu PK, Roy D, Das S (2020) Feasibility study of the solar powered and induction cooking based mobile food court station in rural area of West Bengal. J Inst Eng. India: Series B 101:181–195

Edmonds I (2018) Low cost realisation of a high temperature solar cooker. Renew Energy 121:94–101

Melhaoui M et al (2014) Contribution to the Improvement of the MPPT control functioning of photovoltaic systems. Int Rev Electri Eng (IREE) 9(2):393–400

Prabu AS, Chithambaram V, Bennet MA et al (2021) Microcontroller PIC 16F877A standard based on solar cooker using PV—evacuated tubes with an extension of heat integrated energy system. Environ Sci Pollut Res. https://doi.org/10.1007/s11356-021-16863-2

Saha A, Sultana F, Haque MA, Nasif SSM (2019) Design of MPPT mounted solar based double coil DC electric cooker with smart temperature control device. In: 2019 5th International conference on advances in electrical engineering (ICAEE), Dhaka, Bangladesh, 2019, pp 212–217. https://doi.org/10.1109/ICAEE48663.2019.8975451

Senthil R (2021) Enhancement of productivity of parabolic dish solar cooker using integrated phase change material. Mater Today: Proc 34:386–388

Swarupa ML, Kumar EV, Sreelatha K (2021) Modeling and simulation of solar PV modules-based inverter in MATLAB-SIMULINK for domestic cooking. Mat Today: Proc 38:3414–3423

Thakur M, Nuyts PA, Boudewijns EA, Kim JF, Faber T, Babu GR, Van Schayck OC, Been JV (2018) Impact of improved cookstoves on women's and child health in low and middle income countries: a systematic review and meta-analysis. Thorax

Verma S, Banerjee S, Das R (2022) A fully analytical model of a box solar cooker with sensible thermal storage. Sol Energy 233:531–542