Advanced Solar Photovoltaic Hybrid Cooker with Storage and Thermal Insulation

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Abstract : In the field of sustainable energy solutions, solar cooking is a promising alternative to meet the energy needs of households. However, for this alternative to be truly viable and adopted on a large scale, it must adapt to modern cooking habits and ensure continuous use, even in the absence of direct sunlight. This work is positioned within this perspective, with the aim of proposing a solar cooker powered by electricity generated directly by photovoltaic panels and/or stored in solar batteries, to cover the daily energy needs of families. To achieve this goal, a prototype was developed, integrating photovoltaic panels and batteries, as well as an advanced electronic control and regulation system. The cooker is composed of power blocks and digital modules dedicated to powering a two-zone heating plate equipped with thermal resistors, complemented by thermal insulation materials such as bakelite and fiberglass. Experiments showed that the addition of insulating materials significantly improves thermal performance: at a heating power of 350 W, the thermal resistor temperature reaches320°C in 25 minutes with insulation, which represents a 33% improvement on temperature rise compared to the non-insulated case. Similarly, the time required to bring water to a boil is reduced by 55%, from 55 minutes to 25 minutes. These results demonstrate a significant gain in terms of heating speed and energy efficiency. Additionally, the temperature of the outer plate remained stable at 58°C, ensuring optimal safety while maintaining heat concentrated at the resistor level. These advancements highlight the relevance of the proposed hybrid solar cooker as an ecological, high-performance solution tailored to the energy needs of households, particularly in contexts where access to conventional energy is limited.

Keywords : hybrid solar cooker, photovoltaic energy, energy storage, DC-DC converter, thermal resistor, thermal insulation, ecological cooking, sustainable energy systems, energy efficiency.

1. Introduction

Solar cooking, although promising, remains marginal and struggles to be adopted on a large scale due to its limitations in performance and continuity of use [1]. In light of the urgency to reduce dependence on fossil fuels and address the global energy crisis, the development of autonomous, efficient, and sustainable cooking solutions is crucial. While thermal solar cookers, despite their simplicity, remain largely dependent on weather conditions, photovoltaic (PV) cookers offer greater autonomy through energy storage but require optimized energy management and thermal regulation [2-4]. Furthermore, the rising cost of conventional fuels and the depletion of natural resources intensify the need for sustainable alternatives for domestic cooking [5]. In regions with high sunlight, particularly in Africa and certain rural areas of the world, harnessing solar energy appears to be an ideal solution to address energy deficits and ensure equitable access to clean cooking methods. However, challenges related to the intermittency of sunlight and thermal losses limit the widespread adoption of solar cookers. Therefore, it is essential to design more efficient systems that can ensure continuous cooking with optimized energy performance. Among solar cooking technologies, PV solar cookers stand out as a promising alternative to traditional cooking methods, offering advantages in terms of energy storage and flexibility of use [5-6]. However, these systems still face several major challenges, including electrical management, energy efficiency, and equipment cost. Previous works [6-10] on heating cookers powered by PV panels and batteries showed that heating temperatures did not exceed 100-120°C, which is insufficient to meet users' needs (above 150°C). Furthermore, the analysis of thermal losses and heat dissipation at the heating plates level has not been sufficiently explored in the literature.

In this context, we propose an innovative hybrid solar cooker combining PV panels with an energy storage system to improve energy efficiency and ensure reliable cooking under all sunlight conditions. This work is part of international projects such as WBI 3.3 and LEAP-RE, which aim to design sustainable energy solutions tailored to the specific needs of households, especially in Africa. To address technical constraints and daily usage requirements, our solution relies on a hybrid photovoltaic architecture, combining optimized storage with intelligent control. This configuration represents a high-performance alternative to traditional cooking methods while minimizing thermal losses and ensuring continuity of service. Unlike classical approaches reported in literature [7-10], our system stands out by integrating a centralized control box, coupled with a multiparametric optimization algorithm ensuring dynamic management of electrical (voltage, current) and thermal (temperature) parameters. This control enables fine, adaptive, and eco-efficient regulation, based on sunlight conditions and cooking requirements.

The developed prototype integrates: PV panels with a total power of 1.2 kWc, a 48V/250 Ah battery pack, a DC/DC converter coupled with an advanced electronic management unit. The produced and stored energy powers a heating plate with thermal resistors, designed with enhanced thermal insulation and optimized geometry to maximize thermal efficiency and reduce energy losses. The entire system is sized to meet daily cooking needs, estimated between 2 and 3 kWh/day. To quantify the impact of thermal insulation on overall performance, two configurations were experimented: one with insulation and the other without. Insulation is provided using high-temperature-resistant materials such as bakelite and fiberglass, combined with a thermal cover to limit losses at the resistor level. Our goal is to highlight significant gains in energy efficiency and heating speed, emphasizing the relevance of an integrated design combining intelligent energy management and thermal optimization.

In this paper, we present the conceived prototype of solar photovoltaic cooker and the entire experimental setup developed in the laboratory. We then analyze its performance in terms of temperature and heating time and evaluate its efficiency compared to existing solutions, highlighting the advances brought by our innovative approach. By exploring a new configuration integrating optimized management and improved thermal insulation, this work contributes to the evolution of solar cooking technologies and opens up perspectives for wider adoption of these sustainable energy solutions.

In the following sections, we detail the various stages of the work carried out so far, from prototype design (including modeling, sizing and development of control algorithms) to performance analysis through experimental testing. The objective is to demonstrate the feasibility and reproducibility of an innovative and robust solar cooking solution adapted to low-energy resource contexts.

2. Hybrid solar cooker design

2.1. Technical specifications

The proposed hybrid PV solar cooker prototype (of the cooking plate type) is shown in Figure 1. It allows cooking with PV panels during sunny days, and solar batteries during poorly sunny and nighttime conditions. The operation of the cooker is based on the use of a power block 1 and a digital electrical block 2 (Figure 2). The block 2 uses a microcontroller that manages all the functions of the cooker through the PV panels and/or the battery pack, notably the acquisition and display of electrical quantities, malfunction detection, manual or automatic operation of the cooker. In this contribution, we propose a cooker prototype that is designed considering the daily cooking energy needs of users, around 2-3 kWh/day. Based on fieldwork, it is established that the prototype should comply with the following technical specifications for producing daily cooking electrical energy (day and night):

- By PV panels (600 Wp), a maximum cooking power of 450W for 5 hours (providing a maximum energy of 2.250 kWh/day).
- By batteries (48V/250Ah/12kWh), charged by two other PV panels (600 Wp, during nights and poorly sunny days), a maximum cooking power, according to users' needs, of 400W for 5 hours (providing an energy of 2 kWh/day). The total battery charge (12 kWh/day) therefore ensures cooking autonomy of 5 to 12 days without sunlight.
- A total cooking energy provided by the PV panels and batteries of 4.25 kWh/day, which is more than sufficient to meet the needs of the inhabitants (2 to 3 kWh/day).

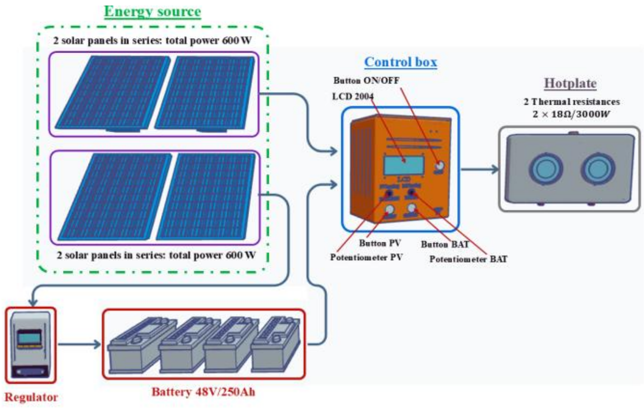

Fig.1 : General representation of the proposed hybrid PV cooker prototype

2.2. Schematic diagram of the control box.

The Figure 2 presents the schematic diagram of the control box of the proposed PV cooker. This box consists of two main blocks. The block 1 (power) includes two 1-kW DC/DC Boost converters, operating at the switching frequency of 20 kHz. The first DC/DC converter (converter 1) is powered by the PV panels during sunny periods, while the second DC/DC converter (converter 2) is powered by the solar batteries during periods of low sunlight or nighttime. The block 2 (low-power electronics) includes analog and digital circuits, powered by the batteries via a polarization circuit (+5V and +15V). The overall operation of the cooker is managed by a Raspberry microcontroller handling the regulation and system optimization tasks. These tasks are described below:

- Task 1: Cooker operation with solar power, heating a thermal resistor. In this case, two operating modes are possible: optimal operation of the PV panels (automatic mode), by acting on a specific external button 1 equipped with a potentiometer 1, via an MPPT control (Perturb and Observe). This is achieved by activating relay 1 and controlling the power MOSFET of the DC/DC converter with a PWM signal at 20 kHz and a variable duty cycle α. Manual operation of the cooker (manual mode) is ensured by acting on a specific external button 1 equipped with potentiometer 1, activating relay 2, and varying the operating point of the photovoltaic panels. This is achieved by varying the duty cycle α of the PWM signal generated by the microcontroller to control the power switch of the DC/DC converter.
- Task 2: Cooker operation by solar batteries during low sunlight or nighttime periods, by acting on a specific external button 2 equipped with a potentiometer 2, heating the second thermal resistor. For this, the microcontroller activates relay 2 and generates a PWM signal at 20 kHz and a duty cycle variable between 0.1 and 0.45.
- Task 3: Acquisition and display on LCD, local and remote control of the different electrical quantities of the DC/DC converters (voltage, current, power, and

efficiency). Acquisition of the quantities is performed via a digital multiplexer.

- Task 4: Detection of possible malfunction (overvoltage, overcurrent, short circuit, disconnection of thermal resistors from the outputs of the DC/DC converters). If this occurs, the microcontroller will deactivate the relays 1 and 2 to disconnect the energy sources from the two DC/DC converters.
- An Optional Computer, for which an interface (Application) is set up to record, process, and display the different electrical quantities acquired. This application also allows local and remote monitoring (via the Internet). It also enables remote control of certain functions (ON/OFF of the system). This is achieved by activating/deactivating the various power relays, enabling the start/stop of the cooker.

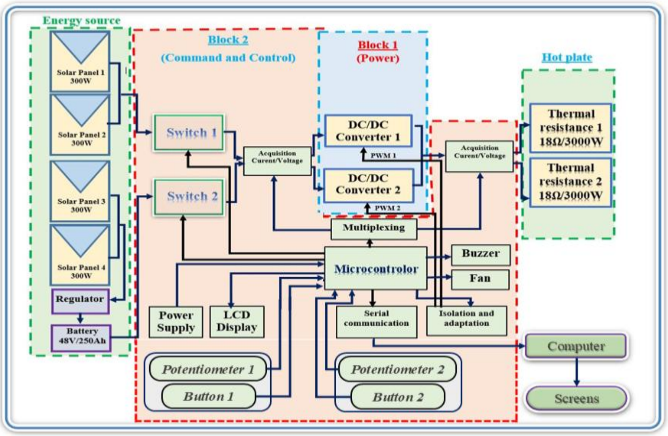

Fig. 2. Synoptic diagram of the control box (block 1 and block 2) of the hybrid cooker shown in Figure 1.

3. Experimental work and results

3.1. Implementation of power and control blocks and the Heating Plate

Figure 3 shows the printed circuit boards integrating the electronic components mentioned in the cooker's specifications for blocks 1 and 2. These boards were developed in accordance with the technical specifications and requirements to regulate the operation of the cooker illustrated in Figure 1. The power sources, namely the PV panels and the batteries, are connected to the two DC/DC converters via the switches of the switching board. The control board is then connected to these boards (switches and converters), as well as to a computer for the acquisition and display of data on two screens, thus allowing monitoring of the heating of the plate with two zones.

Figure 4 shows the steps for the realization of the two-zone heating plate, heated by thermal resistors (2kW/1000°C). It is designed to isolate the heating resistors from the metal plate using insulation materials, such as Bakelite, fiberglass, and a metal cover, in order to optimize thermal performance.

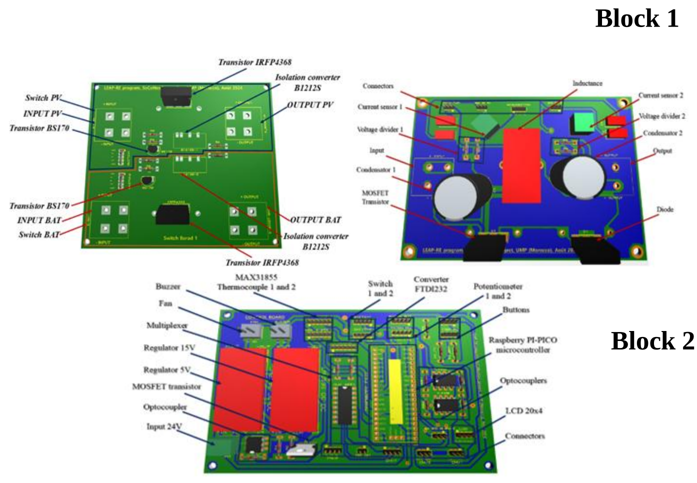

Fig. 3. Printed Circuit Boards of the Power block (Block 1) and Control block (Block 2). Only the DC/DC converter 2 is shown, with the DC/DC converter 1 being identical

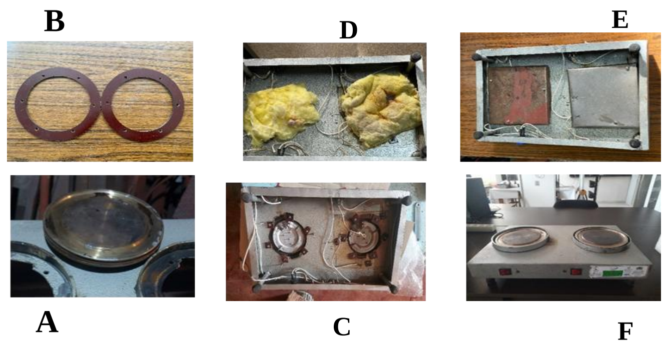

Fig. 4. Two-zone heating plate: A) Thermal resistor, B) Front face insulation with Bakelite, C) Back face insulation with Bakelite, D) Glass wool on the back face, E) Metal rear cover, F) Final heating plate..

3.2. Final solar cooker prototype

The Figure 5 shows the solar cooker prototype in its complete configuration, consisting of four PV panels with a total power of 1.2 kWc, four 12 V/250 Ah batteries assembled to form a 48 V/250 Ah battery pack, as well as the control box consisting of the blocks 1 and 2 illustrated in Figure 3 and the heating plate shown in Figure 4. This configuration has been developed and optimized to meet the performance criteria defined in the framework of the projects and to ensure efficient management of the produced energy, allowing controlled heating. The complete system has been tested in the laboratory to achieve the objectives of the ongoing projects, using equipment and applications intended to monitor weather conditions (light intensity, ambient temperature), as well as the electrical quantities of the cooker (voltages, current, power, and efficiency of both converters) and thermal quantities (temperature of the heating plate resistors and the corresponding metal sheet). The conducted experiments have validated the system performance while meeting the technical requirements and project objectives, identifying areas for improvement.

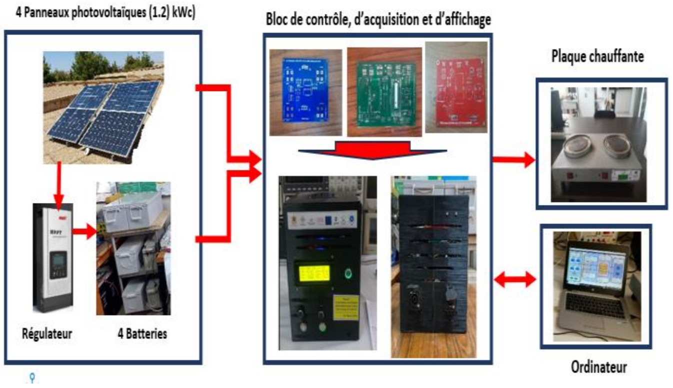

Fig. 5. Complete solar cooker: PV panels, batteries and regulator, control box, and fully insulated heating plate.

3.3. Typical operation of the cooker.

The solar cooker prototype above-described was experimentally tested in the different operating modes, by powering it with PV panels, solar batteries, or a combination of both. Moreover, two design configurations of the heating plate were tested to heat one liter of water: one without insulation for the heating elements, and the other with insulation. Using the developed interface, we recorded the voltages, the currents, and the electrical powers at both ports of the DC-DC converter, as well as its efficiency.

In this contribution, the typical measurements obtained with the system powered by the solar batteries are considered. These are are obtained by considering a duty cycle of 0.45 in the PWM control of the power switch of converter 2. At the power level of 350 W, input and output voltage/current values of 46V/7.8A and 80V/4.1A are measured (see Figure 6), respectively, whether the system is insulated or not. As for the efficiency of the DC-DC converter (also shown in Figure 6), it is estimated at around 91% which is in the upper range of reported performances in literature for this type of application (typically between 85% and 92% [11]). The relevant temperature evolutions are also represented in Figure 7. Observations reveal that:

- Without insulation, the temperature of the thermal resistor reaches 240°C in 35 minutes and the water reaches its boiling point (95°C) in 55 minutes.
- Adding insulation allows the thermal resistor to reach a higher temperature of 320°C in only 25 minutes, while the water reaches its boiling point (95°C) in 25 minutes.

In both cases, the plate metal temperature stabilizes at nearly the same value of 58°C.

Analysis of these experimental results highlights a significant improvement in the thermal performance of the solar cooker with the addition of insulation around the heating elements. Indeed, the time required to reach the boiling point of water is reduced by 30 minutes, which corresponds to a heating speed about twice as fast. This thermal optimization also results in a faster rise in the resistor temperature reached (80°C higher with insulation). Indeed, the rate of temperature rise goes from 6,8 °C/min (without insulation) to 12,8 °C/min (with insulation). It must be noted that this gain does not come at the expense of safety, as the external plate temperature stabilizes at the same temperature (58°C) whatever the case, indicating good concentration of heat at the resistor level and effective control of thermal dissipation. Compared to similar studies on solar cookers, both electrical and thermal [6-10], the results obtained are not only encouraging but clearly superior, especially in terms of temperatures exceeding 250°C, reduction in heating time, and the thermal stability achieved with insulation. These findings confirm that integrating a thermal insulation system is a key lever to improving the overall energy efficiency of these devices.

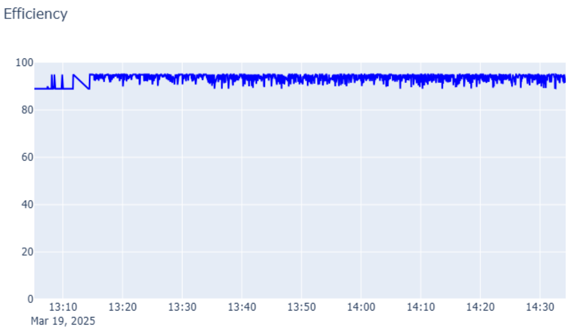

Fig. 6. Electrical quantities experimentally measured on the the solar cooker prototype heating one liter of water. From top to bottom: voltage, current, power, and efficiency.

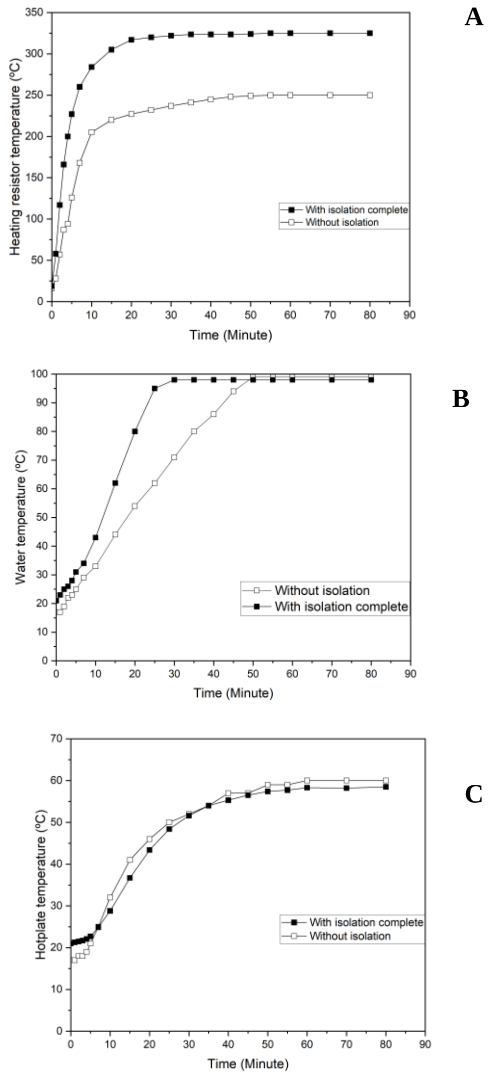

Fig. 7. Boiling of 1 liter of water by the heating plate with or without insulation. A) Thermal resistor temperature, B) Water temperature, C) Plate temperature.

4. Conclusion

In this paper, we have proposed an innovative hybrid solar cooker prototype powered by PV panels and solar batteries, in combination with an advanced energy management system. This prototype comprises a two-zone heating plate equipped with thermal resistors insulated with bakelite, fiberglass, and a cover. Typical measurements were presented when the cooker is powered by the batteries supplying an electrical power of 350 W. For instance:

- Typical voltage and current of 46 V/7.8 A and 80 V/4.1 A at the input/output ports of the DC/DC converter (converter 2), respectively, which corresponds to a 91% efficiency.
- The temperature of the thermal resistors rises more quickly, reaching 320°C in 25 minutes with insulation, compared to 240°C without insulation. Hence, the time required to reach boiling point of one liter of water is reduced by more than two compared to the configuration without insulation.

Compared to other studies on electric and thermal solar cookers, our results are particularly promising, especially regarding the temperature of the heating resistors (up to 320°C), heating speed, and thermal efficiency achieved thanks to insulation. These results confirm the importance of thermal insulation as a key lever for improving the energy efficiency of solar cookers.

In conclusion, the tested prototype demonstrates a successful synergy between efficient electrical conversion and thermal optimization, making it suitable for domestic, semi-nomadic, and variable solar radiation contexts. Future improvements include optimizing energy management, integrating a multiport DC/DC converter, automatic temperature regulation, and better energy storage management. In the long term, we aim to develop a fully autonomous hybrid solar cooker, offering greater usage flexibility and easier integration into households or humanitarian situations.

Looking ahead, improvements are ongoing, particularly in intelligent energy management, automatic temperature regulation, energy storage optimization, and the integration of more advanced and multiport DC/DC converters capable of managing all energy sources. Ultimately, the goal is to offer a fully autonomous hybrid solar cooker, with increased usage flexibility and easy integration into homes or humanitarian contexts.

5. Acknowledgment

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- Federation of Arab Scientific Research Councils, The Initiative of Arab Alliances for Scientific Research and Innovation ARICA, Project 'ARICA23_703', (2024-2026)

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