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Exploring the Potential of a Battery-Assisted Solar Cooking System

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Abstract

This chapter presents research on the operation and evaluation of an innovative photovoltaic (PV) solar cooker that incorporates battery storage for enhanced efficiency, reliability, and autonomy. The system is designed to optimize energy utilization by integrating a heating plate (thermal resistor) powered by a 48 V/250 Ah battery bank, which is charged *via* 600-Wp PV panels. The charging process is managed by a BOOST-based DC/DC converter and a digital control circuit. Experiments conducted both during the day and at night, based on user needs, confirm that the stored electrical energy ensures continuous cooking, independent of sunlight fluctuations. The power conversion system operates with an efficiency exceeding 95%, while the heating element reaches 400°C within 30 minutes, with a temperature increase rate ranging from 12 to 33°C per minute. Boiling one liter of water (100°C) requires approximately 45 minutes, corresponding to a heating rate of 3.2°C per minute. The analysis of experimental data highlights that the battery system successfully delivers the necessary electrical energy for heating and daily cooking, providing an operational autonomy of up to 14 days. The overall results validate the feasibility of using a PV-powered battery system for cooking applications, catering to the energy needs of rural and urban households alike.

Keywords: Photovoltaic energy, battery storage, electrical power, solar-powered cooker, energy management, power conversion, DC/DC power regulator, electronic control unit

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9.1 Introduction

For a long time, cooking has predominantly depended on energy sources like coal, firewood, and natural gas, whether for household use or in the food service industry [1, 2]. According to the International Energy Agency, global coal consumption hit a record high in 2022, rising by 3.3% and bringing total demand to 8.3 billion tonnes [3]. A study carried out in Kisangani reveals that coal accounts for 81.4% of energy consumption, while firewood represents 31% [4]. As a response to the challenges brought about by climate change and the rise in greenhouse gas emissions [5, 6], the transition to renewable and environmentally friendly energy sources [7], such as solar power, has become crucial. Photovoltaic-powered solar cookers present a viable alternative [8, 9], enabling cooking without relying on fossil fuels, firewood, or coal, thereby contributing to forest conservation and improved air quality. However, despite their benefits in terms of efficiency and continuous operation, modern solar cookers still face notable limitations: Their efficiency and reliability do not always align with user expectations, and their operation remains inconsistent due to insufficient monitoring. Furthermore, the solar cooking systems found in the literature—including parabolic cookers, Fresnel reflector cookers [10, 12], box cookers [13, 16], and photovoltaic-powered models [17–19]—often lack reliability and have yet to see widespread household adoption. To address these limitations, integrating battery-based energy storage and enhancing the digital control of solar cookers are essential steps toward improving their performance, efficiency, and autonomy, particularly in the absence of sunlight.

Battery energy storage systems (BESS) are available in a range of technologies, each with its own specific characteristics, adapted to different needs:

- Lithium-ion batteries are widely used in solar energy systems due to their numerous advantages. They are known for their high energy density, which allows a significant amount of energy to be stored in a compact form, and their impressive energy efficiency (85–95%), reducing energy loss during charging and discharging. Additionally, lithium-ion batteries have a long lifespan (typically 10 to 15 years or more, with around 4,000 to 6,000 cycles), making them ideal for both residential and commercial solar applications [20, 21]. These batteries are also favored for their quick response time and their ability to function across a broad range of temperatures. Their characteristics make them an excellent choice for storing energy generated by photovoltaic panels during daylight hours and delivering it when sunlight is limited or absent [22, 25].

- Sodium–sulfur (NaS) batteries, on the other hand, operate at high temperatures and are suitable for large-scale, long-term storage. They have a longer service life of around 4,500 cycles, but a slower response [20, 26].
- While lead-acid batteries are more affordable, they provide less energy storage capacity and have a reduced lifespan, typically ranging from 1,000 to 1,500 cycles, making them more suitable for backup purposes or small off-grid solar setups. In contrast, redox flow battery systems utilize liquid electrolytes stored in separate tanks, which allows for scalable energy storage. These systems are well suited for long-term applications, offering a service life of over 20 years and virtually unlimited cycles, though their efficiency is lower (65–75%) [27, 30].
- Finally, lithium-iron-phosphate ($LiFePO_4$) batteries, a variant of lithium-ion batteries, are distinguished by their high thermal and chemical stability, offering enhanced safety and longer service life (2,000 to 4,000 cycles). They are commonly used for applications requiring enhanced safety [31, 33].

This overview of batteries on the market shows that each type of BESS offers specific advantages in terms of energy storage requirements, charge capacity and service life. This diversity and performance of batteries enables us to meet the challenges of integrating renewable energies. In the context of our application, the performance and characteristics of lead-acid batteries are best suited to storing the electricity needed for cooking in the absence of sunlight. The batteries are charged on sunny days and supply the electrical energy needed for cooking all year round (day and night).

In addition, solar cookers suffer from regulation and optimization problems, with poorly controlled performance and insufficient monitoring. On current solar cookers, these regulation and control systems are practically non-existent [17, 19]. The integration of digital technologies would enable real-time monitoring of electrical quantities such as voltages, currents, power, and duty cycles of DC/DC converters, identifying recurring malfunctions and proposing appropriate solutions. This approach aims to optimize the design of cookers and facilitate their use in both rural and urban households.

To incorporate electrical energy storage in batteries into innovative solar cookers that are adaptable and meet the needs of domestic users, we are conducting research within the framework of the European WBI 3.3 and LEAP-RE 'SoCoNexGen' projects. The goal is to provide rural and urban users with hot-plate-style solar cookers, which combine energy generated by photovoltaic panels during sunlight hours utilizing energy stored in solar-powered batteries. The aim is to offer a reliable, accessible technology for households in regions with high solar potential year-round (e.g., Africa).

This chapter presents the initial results from the innovative solar cooker, where the electrical energy needed for cooking is supplied by lead-acid solar batteries, charged through photovoltaic panels (600 Wp) *via* a micro-
Q3 controller-based MPPT Solar Charge Controller. Special focus is given to the electronic control system, which controls the energy supplied by the batteries to power the heating plate, made up of a thermal resistor. By comparing our results with those found in existing literature, we demonstrate the viability of operating the solar cooker by storing photovoltaic energy in batteries.

9.2 Innovative Cooker Structure

9.2.1 Specifications

The proposed prototype cooker, a griddle-type model (Figure 9.1), allows cooking using solar batteries on days with limited sunlight and at night. The cooker operates through the integration of a power board (Block 1) and a digital electrical board (Block 2). The digital board features a microcontroller (Raspberry Pi), which manages all the cooker's functions *via* the photovoltaic panels and batteries. These functions include the acquisition and display of electrical data, fault detection, and the manual or automatic operation of the cooker. Based on our fieldwork, we present the prototype cooker (Figure 9.1), which is designed to meet users' daily cooking energy needs of approximately 2 kWh/d. The proposed cooker must therefore meet the following specifications:

- Produce daily electrical energy for cooking (day and night) using batteries (48 V/250 Ah),

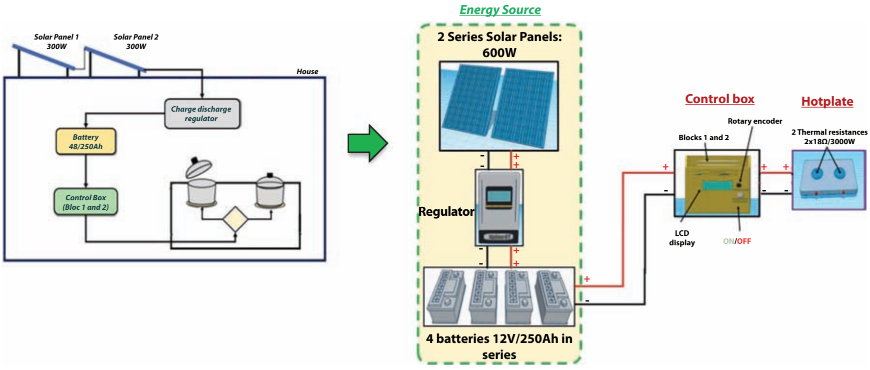

Figure 9.1 Schematic diagram of the prototype cooker to be designed and produced in the WBI and LEAP-RE projects.

- Two photovoltaic panels (600 Wp) charge the batteries, producing between 3.5 and 4.2 kWh per day,
- Cooking on nights and days with little sunshine, depending on user requirements, at 200–450 W for 5 hours (equivalent to 1–2.25 kWh/d of energy).
- The batteries' full charge (12 kWh/d) ensures 5 to 12 days' cooking autonomy, without sunshine.

9.2.2 System Schematic

Figure 9.2 shows the schematic diagram of Cooker 2 and the structure of the photovoltaic heating system (Blocks 1 and 2) developed as part of this study. The key components of this cooker include:

- Power source: This system provides energy to the cooker and is made up of 48 V/250 Ah solar batteries (four 12 V/250 Ah batteries connected in series). These batteries are charged by two 600 Wp photovoltaic panels on sunny days. They store between 4 and 5 kWh per day, ensuring autonomy for 5 to 7 days. They also guarantee the continuous operation of critical components (e.g., Raspberry Pi board, power switches).
- Heating element (length: 50 cm; width: 32 cm; height: 10 cm): It includes two 18 Ω thermal resistors. One of these resistors is powered by the solar batteries, allowing cooking even during cloudy weather or at night.

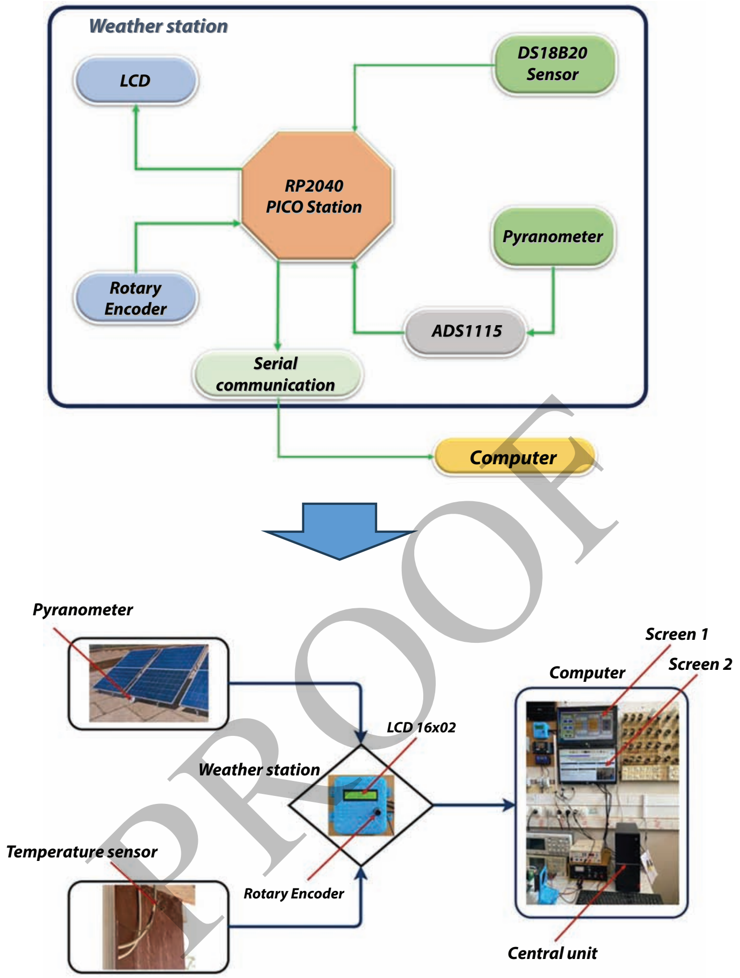

Figure 9.2 Block diagram of photovoltaic cooker and system structure (Blocks: 1 and 2).

- Power supply unit (Block 1): This unit consists of a boost DC/DC converter functioning at 20 kHz, delivering a power output of 1 kW. It is powered by the solar batteries during periods of low sunlight or at night.
- Control system (Block 2): This system includes both traditional and modern electronic circuits, supplied by the batteries *via* a voltage regulation circuit. The microcontroller manages the entire operation of the cooker, overseeing and coordinating all its functions.

- A computer (optional) for which an interface (application) is set up to store, process, and display the various electrical quantities acquired. This application can also be used to monitor operation locally and remotely (via the Internet). It can also be used to remotely control certain functions (system ON/OFF). This is achieved by activating/deactivating the various power relays, enabling the cooker to be switched on/off.

Drawing on field studies conducted with several rural and urban households, we developed the cooker shown in Figure 9.1 to accomplish the following functions:

- Function 1: Ensure cooker operation using solar batteries during periods of low sunlight or nighttime. This is achieved through an external control button (Button 2) equipped with a potentiometer (Potentiometer 2), which regulates the heating of the thermal resistor. The microcontroller controls this process by activating the switch and generating a PWM signal operating at 20 kHz, with an adjustable duty cycle between 0.1 and 0.45.
- Function 2: Acquire and display electrical parameters of the converters (voltages, current, and efficiency) on an LCD screen, with both local and remote monitoring capabilities. A digital multiplexer is used to collect these values. Q4
- Function 3: Detect potential malfunctions such as overvoltage, overcurrent, or disconnection of the thermal resistors from the DC/DC converter outputs. In case of an anomaly, the microcontroller deactivates the switch to isolate the power sources of the two converters.

9.3 Cooker Design and Operation

9.3.1 Solar Cooker Test with Battery Storage

To ensure effective monitoring and validation of the proposed cooker, it is essential to assess weather conditions (illumination levels and surrounding temperature), the characteristics (voltages, currents, and power) of the batteries and heating plate, as well as the thermal characteristics of the cooker (temperature of the heating element). To achieve this, we developed a weather station and a comprehensive computer-controlled measurement system, programmed in Python, to track meteorological conditions and the electrical and thermal performance of the cooker. The next sections give a concise summary of the structure and operation of each component of this station and measurement system.

9.3.1.1 Weather Station

As part of our work, the station is designed to collect data on ambient temperature and illuminance from the weather station installed in the laboratory, ensuring validation of the cooker's performance across different seasons of the year. Figure 9.3 shows the synoptic diagrams and equipment

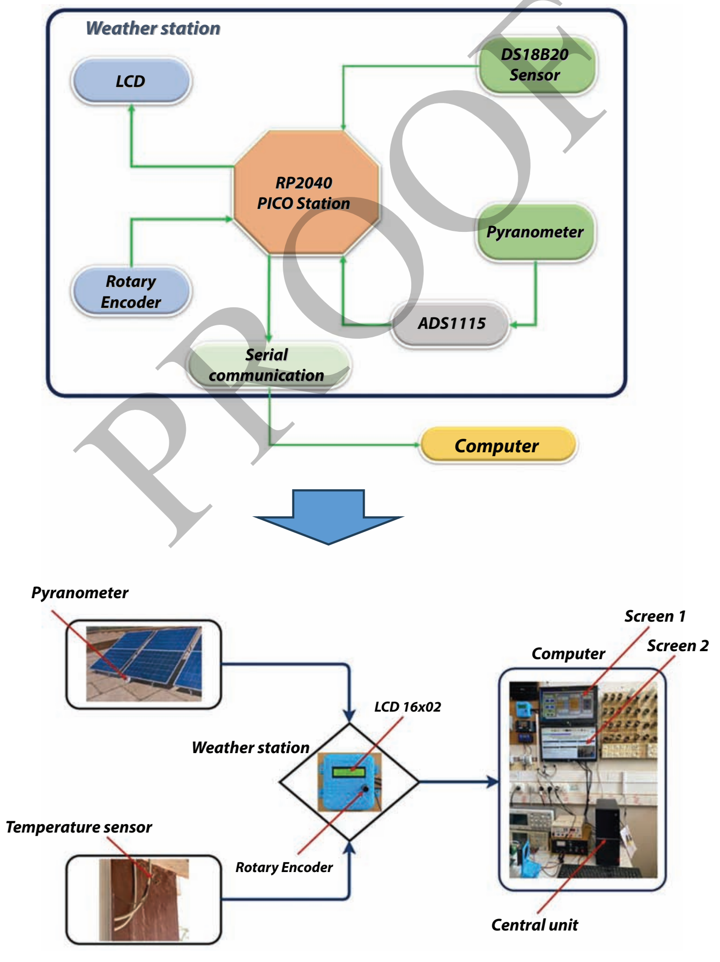

Figure 9.3 Synoptic diagram and meteorological station equipment.

of the meteorological station and the system for acquiring, controlling, and displaying meteorological quantities from the meteorological station. The station consists of:

- A pyranometer to measure light intensity.
- A digital sensor (DS18B20) to measure ambient temperature.
- An electronic module incorporating a 'Raspberry Pi' microcontroller to perform the following tasks:
  - Acquisition of ambient temperature *via* digital sensor.
  - Acquisition of illumination intensity, using the ADS1115 pyranometer and analog-to-digital converter.
  - Transmission of measured values from the microcontroller to the local computer *via* FT232 level converter.
  - LCD display of acquired values.
  - Use a rotary encoder to scroll and select, on the LCD, the type of quantities to be displayed: illuminance intensity, ambient temperature, or both simultaneously.
- A computer that receives data from the weather station box for storage, display, and subsequent analysis.

9.3.1.2 Measurement Bench

Figure 9.4 illustrates the experimental setup used to monitor both the operation of the cooker and the weather station. This comprehensive test bench has been installed as part of the research projects led by the MEER team. The setup includes:

- Two 600-Wp photovoltaic panels (2) connected in series, supplying energy to the batteries (5) through a charging and discharging regulator (4).
- A charge/discharge controller (4) responsible for managing the charging process of the solar batteries (5) via the photovoltaic panels.
- Four solar batteries (5), each rated at 12 V/250 Ah, charged by the 600-Wp photovoltaic panels (2) through the charge/discharge controller (4).
- An energy management and control unit (11), powered by the batteries (5). It controls the heating of the hotplate (10) through a converter and an electronic circuit that oversees the entire cooker system.

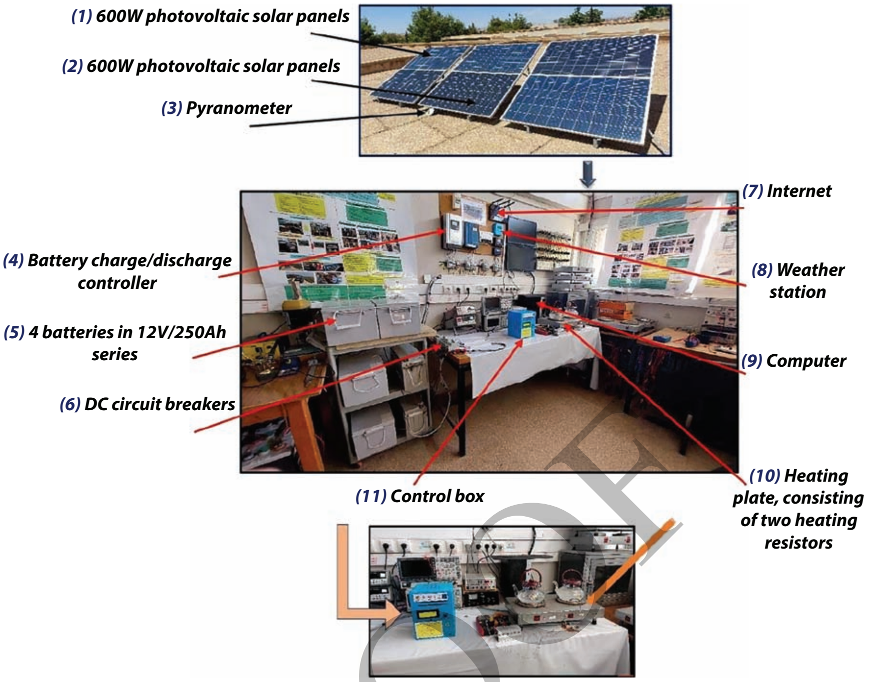

Figure 9.4 Photo of the complete measurement bench set up at the LETSER laboratory.

- A heating plate (10) equipped with a heating resistor, rated at 2 kW, capable of reaching a temperature of 1000°C.
- A meteorological station (8), including a pyranometer (3) and a thermal sensor, to measure ambient temperature and solar irradiance (Figure 9.3).
- A computer setup with dual screens (9), used for programming the control board (Raspberry Pi microcontroller), as well as for monitoring, regulating, and controlling the cooker's operation both locally and remotely via the Internet (7).

9.3.2 Measurement Results and Discussion

As part of this study, we have carried out a series of experiments designed to test and validate the operation of our innovative battery-powered cooker (Figure 9.1). To do this, we propose:

- Analyzing the charging behavior of batteries powered by photovoltaic panels, as a function of the metrological

conditions deduced from the meteorological station set up during the course of this work.
- Experimenting with the operation of the cooker to analyze the temperature evolution and the maximum heating capacity of the thermal resistor powered by the batteries..
- Experimenting with the operation of the cooker by boiling 1 liter of water to analyze the temperature evolution of the water heated by the batteries.

9.3.2.1 Battery Charging by Photovoltaic Panels

We monitored the charging process of the 48 V/250 Ah batteries by the 600-Wp photovoltaic panels using an MPPT solar charge controller (Figure 9.4). From this controller, we extracted the electrical parameters of both the panels and batteries, including voltages, currents, power, and efficiencies. From the meteorological station's data acquisition system (Figure 9.4), we extracted the weather conditions (illumination intensity and ambient temperature). The results obtained (Figure 9.5) show the following:

- The day's measurements were characterized by cloud passages, resulting in sudden variations in illuminance intensity, without affecting the ambient temperature value. Illuminance peaked at around 1000 W/m^2 at midday. However, ambient temperature varies between 25°C and 35°C.
- The voltages of the photovoltaic panels and batteries vary very little throughout the day. They are around 60 and 48 V, respectively. Fluctuations in PV panel voltage are due to passing clouds. Throughout the day, battery voltage is lower than that of the photovoltaic panels.
- Photovoltaic panel currents and battery charge currents vary according to variations in irradiance. If irradiance increases (decreases), currents increase (decrease). Photovoltaic panel and battery currents reach 9 and 10 A, respectively. Throughout the day, the battery current is higher than that of the photovoltaic panels.
- The energy provided by the photovoltaic panels and the battery charging rate increase with rising illuminance intensity and decrease as it declines. They reach a peak of approximately 500 W around midday.
- The regulator's efficiency is highly satisfactory, at over 95%.

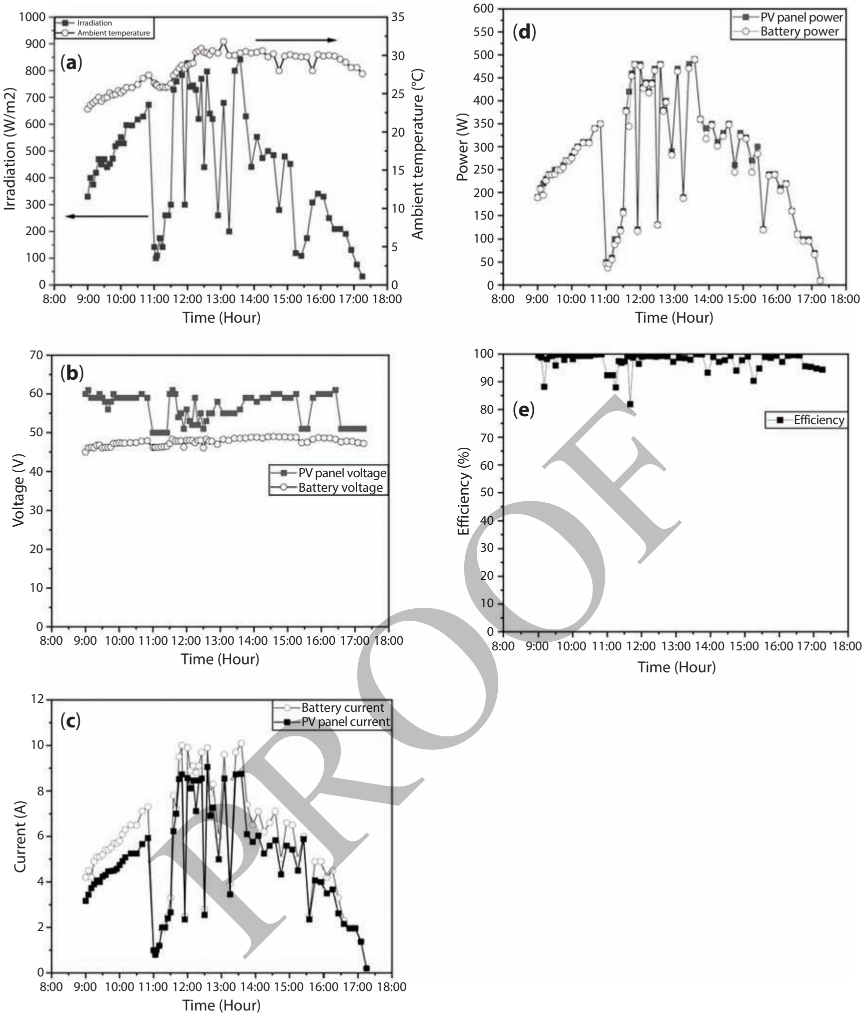

Figure 9.5 Meteorological parameters of the station and electrical parameters of the battery charge controller (Figure 9.4): (a) illuminance and ambient temperature, (b) voltages of photovoltaic panels and batteries, (c) photovoltaic panel and battery currents, (d) power of photovoltaic panels and batteries, (e) controller efficiency.

All the results obtained demonstrate that the controller's power block (DC/DC converter) effectively operates as a buck converter. The voltage (current) from the photovoltaic panels is higher (lower) than that of the batteries, with an efficiency exceeding 95%. During the day, the batteries charge at a rate of approximately 64 Ah, which represents 26% of the total battery capacity (250 Ah). From this, we can conclude that, under similar meteorological conditions, a full battery charge would require 31 hours (or 4 days) of charging.

9.3.2.2 Solar Vacuum Cooker

To evaluate the temperature evolution of the thermal resistor, we tested the vacuum cooker for 2 hours, operating at a power of approximately 400 W. The electrical values of the batteries and the thermal resistance (voltages, currents, power) are shown in Figure 9.6. From these measurements, we deduced and plotted on the same Figure 9.6 the efficiency of the Block 1 converter (Figure 9.2). From these measurements we conclude the following:

- Battery and resistor voltages stabilize at around 48 and 78 V, respectively,
- Battery and resistor currents stabilize at around 8 and 4 A, respectively,
- Battery and resistor power ratings are stable at around 400 and 320 W, respectively,
- The converter achieves an efficiency exceeding 88%,
- The temperature of the thermal resistor reaches 100°C, 150°C, 200°C, and a maximum of 350°C after 3, 4.5, 6, and 30 minutes, respectively. This shows that the heating rate of the resistor is 0.2–0.56°C (or 12–33°C/min).
- The battery capacity needed to boil the water is 6 Ah, which represents 2.4% of the total battery charge. If these batteries were charged three times a day, the cooker could operate for up to 14 days.

The analysis of these results reveals that the power block (DC/DC converter) performs as expected for a boost DC/DC converter: input voltages (currents) are lower, while output voltages (currents) are higher. The converter's efficiency, exceeding 88%, confirms its suitability for our application. When comparing the heating temperatures of the heating plate, powered by solar batteries, to those of box-type or concentration solar cookers found in the literature [11, 14, 15, 34, 35], we observe a significant improvement in the maximum temperature and heating rate. Therefore, we conclude that both blocks 1 and 2, along with the heating plate, are functioning effectively for battery-powered cooking (Figure 9.2). It is worth noting that, as stated in Section 9.2.3, the maximum temperature and heating rate of the heating element could be further enhanced by adding rings around the element to trap heat and reduce heat loss.

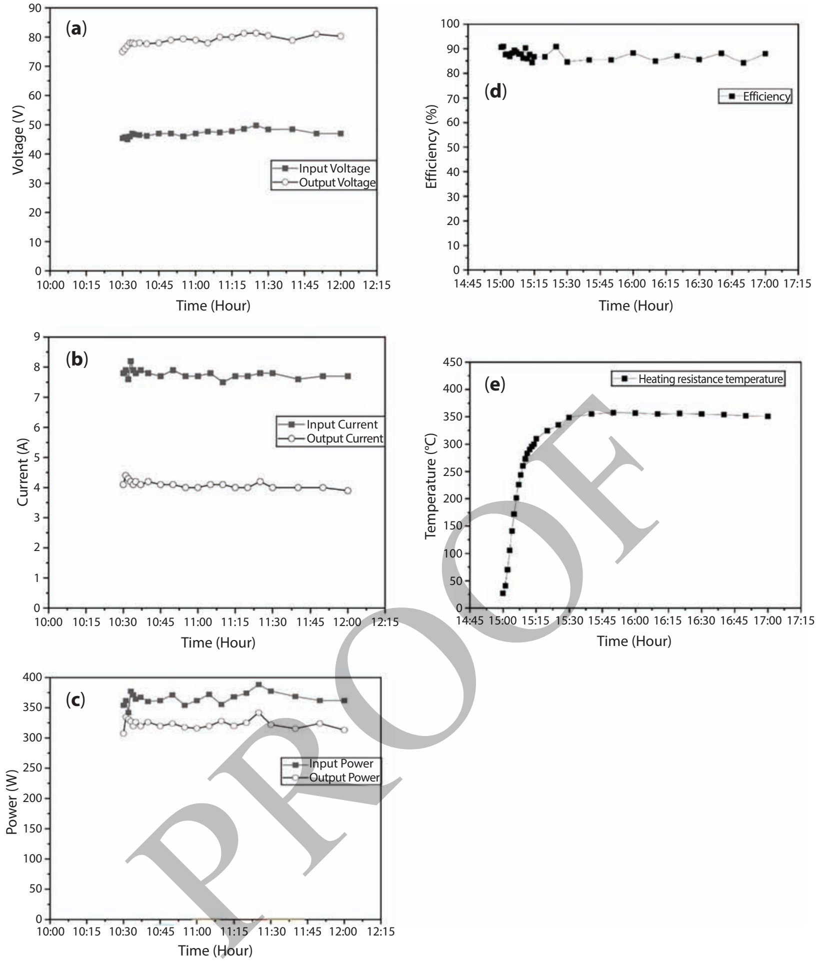

Figure 9.6 Typical cooker operation with vacuum batteries. (a) the voltages at the input and output of the converter, (b) the currents at the input and output of the converter, (c) the powers at the input and output of the converter, (d) power conversion efficiency, (e) temperature of the heating element.

9.3.2.3 Water Heating

To assess the evolution of the thermal resistance heating and cooking temperatures, we assessed the cooker shown in Figure 9.4 by boiling one liter of water with a power consumption of approximately 400 W. The electrical parameters of the batteries and thermal resistance (voltages, currents, power), along with the temperatures of the heating element and the boiling water, are presented in Figure 9.7. From these measurements, we deduced

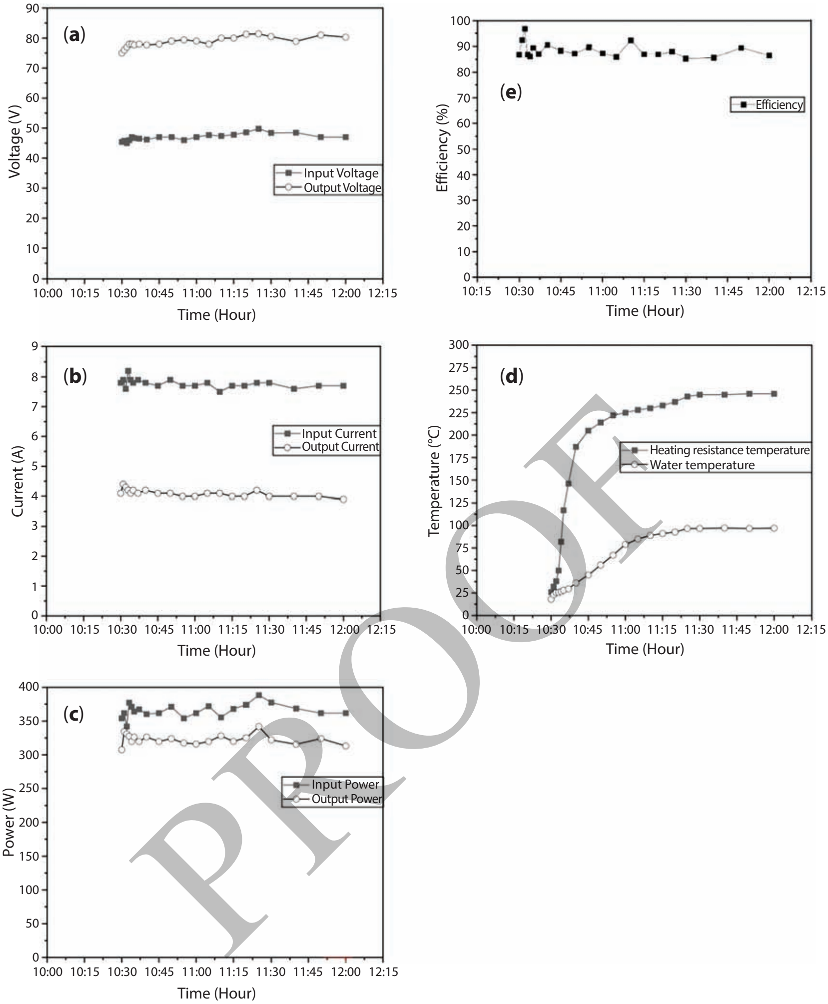

Figure 9.7 Heating 1 liter of water with the cooker shown in **Figure 9.4**. A: the voltages at the input and output of the converter, B: the currents at the input and output of the converter, C: the powers at the input and output of the converter, D: power conversion efficiency, E: temperature of the heating element.

and plotted on the same Figure 9.7 the efficiency of the Block 1 converter (Figure 9.2). From these measurements we conclude the following:

- Battery and resistor voltages stabilize at around 48 and 77 V, respectively,
- Battery and resistor currents stabilize at around 8 and 4 A, respectively,

- Battery and resistor power ratings are stable at around 350 and 320 W, respectively,
- The DC/DC converter achieves an efficiency greater than 89%,
- After 45 minutes of heating, the thermal resistor's temperature peaks at 255°C,
- The water temperature reaches 60°C after 15 minutes and 95°C (boiling point) after 45 minutes. This indicates a water heating rate of 4–4.6°C/min, or approximately 3.2°C/min.
- A full charge of the batteries could heat three times a day with a 14-day autonomy.

All these results confirm that the power block (DC/DC converter) functions as a boost DC/DC converter, with lower input voltages (currents) and higher output voltages (currents). Furthermore, the efficiency of the DC/DC converter, exceeding 89%, affirms the proper functioning of power block 1 (Figure 9.2). Moreover, in the literature, we observe that in concentration cookers, water heating reaches about 90°C after 67 minutes [36], and. [13]. Comparing these results with those obtained on our cooker, we deduce that our cooker reduces water boiling time by a factor of 3.

In conclusion, the performance of our cooker, in terms of both temperature and heating time, is highly promising, largely due to the energy stored in the batteries. Currently, we are focused on enhancing the temperature and heating efficiency of the heating element and the cooker itself, particularly by reducing heat loss through the addition of heat-retaining rings, as illustrated in Figure 9.8. Ongoing work on this cooker will be published at a later date.

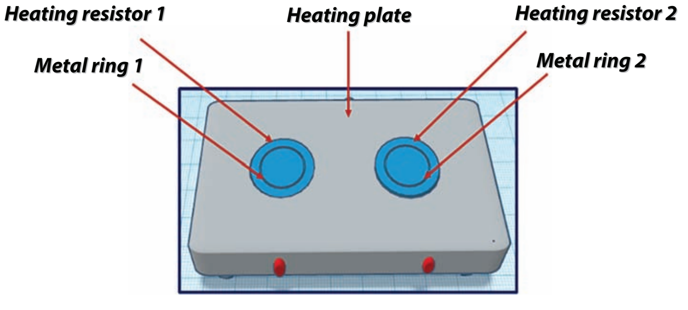

Figure 9.8 Hotplate shape with heat-retaining rings.

9.4 Conclusion

This chapter outlines the design, construction, and operation of a novel cooking device, consisting of a hotplate with two thermal resistors, fueled by solar energy stored in batteries. The cooker is tailored to address the needs of users in both rural and urban settings. Experimentation with this 400-W cooker has shown us the following:

- Charging behavior of batteries powered by 600-Wp photovoltaic panels, as a function of weather conditions. We observed an average charging current of 8 A, allowing around 64 Ah of charge to be accumulated in the batteries over 1 day, representing 25.6% of their total capacity. This allowed us to conclude that 3–4 days of similar sunshine would be needed to fully charge the batteries.
- During heating, battery voltage and current are around 48 V and 4 A, respectively.
- The proposed DC/DC converter achieves an efficiency greater than 89%.
- When boiling 1 liter of water, the temperature increases by 4–5°C/min, reaching 95°C after 45 minutes. Meanwhile, the hotplate temperature reaches a maximum of 350°C following 30 minutes of operation, with a temperature increase of 12–33°C per minute.

A comparison of these results with conventional solar cookers, whether concentrated or canned, shows an improvement in heating temperature and a threefold reduction in the time required to boil water (a factor of 3). These performances show that the solar battery cooker proposed in this work is an effective solar cooking solution, tailored to address the challenges brought about by climate change and energy crises. Additionally, the integration of the digital techniques we have proposed (control, supervision, optimization of operation) strengthens the impact and scope of this initiative, contributing to the wider use of renewable energies in the daily lives of users, in particular for cooking using photovoltaic electrical energy stored in solar batteries.

In the future, this work will be continued to improve water temperature and heating time, and hence cooking time, by reducing power losses through the use of rings placed around the hotplate's heating resistors.

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