Chapter 14
Print ISBN: 978-93-5547-558-9, eBook ISBN: 978-93-5547-559-6

Performance Studies on a Multi-cellular Boost Converter Dedicated for Domestic DC Applications (Cooker)

Rhiat Mohammed [a], Noureddine El Moussaoui [a], Ali Lamkaddem [a], Khalil Kassmi [a,b*], Rachid Malek [a], Olivier Deblecker [c] and Najib Bachiri [b]

DOI: 10.9734/bpi/rdst/v10/7515F

ABSTRACT

In this chapter, we present the structure, the dimensioning and the experimentation of a power system that allows supplying, through solar batteries, the DC equipment with photovoltaic renewable energies (Cookers, distillers, refrigerators, dryers, ...). The proposed system is based on the use of a multi-cell DC/DC converter of Boost type, controlled by a Microcontroller, which generates PWM signals of frequency 20 kHz and variable α duty cycle. The electrical energy, produced by the photovoltaic panels (600 W), is stored in the solar batteries (24V, 520 Ah) and then transferred to the application through the proposed DC/DC converter. During experimentation the system for cooking fries (by Hot plate cooker), shows a DC/DC converter efficiency of 84%, the maximum temperatures of the heating resistance and that of oil are respectively of the order of 640°C and 230°C, oil temperature reaches 100°C after 6 minutes of heating, or 16.67°C / min with a cooking time of the order of 20 minutes. The battery consumption capacity is about 28.72 Ah or 5.52% of the total battery capacity.
The comparison of all the results obtained with those simulated and the economic analysis of the use of renewable energies stored in the batteries, show the good functioning and the validity of the power system, proposed in this work.

Keywords: Photovoltaic panels; solar energy; multi-cellular boost converter; storage, batteries; cooking; solar cooker.

---

[a] Mohamed First University, Faculty of Science, Department of Physics, Laboratory of Electromagnetic, Signal Processing & Renewable Energy LESPRE, Team Electronic Materials & Renewable Energy EMRE, Oujda, Morocco.
[b] Association Humain and Environnement of Berkane (AHEB), Berkane, Morocco.
[c] University of Mons, Faculty of Engineering, Electrical Power Engineering Unit, Mons, Belgium.
**Corresponding author: E-mail: khkassmi@yahoo.fr;*

1. INTRODUCTION

Rapid depletion of energy resources is becoming a crucial global problem due to rising energy consumption [1-6]. Energy-consuming domestic applications represent an important part of total energy consumption, especially for cooking applications [1,2]. The energy used for cooking plays an important role in the energy demand of residential buildings [1]. In the developing world, the majority of residential energy consumption is from cooking. In rural areas of sub-Saharan Africa, it is 90% to 100%, in developed countries, such as the United States, cooking represents 37% to 53% of total energy consumption [3].

Global demand for non-renewable energy sources is projected to exceed annual production, probably over the next two decades [4]. The emergency and global monetary and political clashes can also be triggered by oil or gas shortages. Also, the consumption of non-renewable energy sources releases dangerous emissions by creating environmental issues such as high CO_2 emissions and increased ambient temperature are the main concerns regarding burning fossil fuels [1,4-7].

With the global energy crisis of rapid depletion of fossil fuels [1,7], there is an urgent need to use renewable energy sources, especially in developing countries. Alternative energy sources have become a necessity, and solar energy technologies are very promising in this area [2,5]. Solar energy is a free, sustainable, green, and abundant heat source and one of the simplest, viable, and attractive options widely available in many parts of the world and their direct use for solar cooking does not generate pollution [8-10]. These benefits are expected to make solar cookers attractive to many people around the world, mainly in areas where people have difficulties accessing gas or electricity due to poverty or living in remote areas [5,8].

Solar cooking is considered one of the simplest, most viable, and attractive options for using solar energy instead of burning biomass for cooking in rural communities. The solar cooker a device that uses the energy of direct sunlight [1], i.e. the heat of the sun, to heat and cook food [9] is considered a green, safe, and environmentally friendly, environment and the most convenient way to cook food without consuming fuels, no recurring costs, high nutritional value of food, and high durability [9,11,12]. These devices help alleviate poverty and prevent disease for many human beings who do not have sufficient access to energy sources to cook meals. In countries with easy access to commercial energy sources, a larger-scale use of solar cooking is desirable as it would have a positive impact on reducing environmental problems [13]. There is a critical need for the development of alternative, appropriate and affordable cooking methods [14] for use in developing countries.

Many models of solar cookers have been developed in the world [15-22], with different technologies, and different materials, most of the powerful long-life solar cookers are made with expensive materials [23]. In the case intermittent weather or sudden reduction in solar irradiance during sunshine hours, the concept of energy storage is essential to compensate and stabilize the cooking process during the unexpected absence of solar radiation [9].

In this work, after describing the structure of the power system (Boost type DC/DC converter with three cells), equipped with an electronic block of regulation and controls heated by solar batteries (24 V, 520 Ah), we present the results of simulation, and experimentation of the proposed system. Particular attention is paid to the electrical quantities (voltage, current and power) of the proposed DC/DC converter, according to the duty cycles of the PWM controls of the power switches, the cells of the DC/DC converter, and the transfers of the maximum power supplied by the batteries to the thermal resistance of the hot plate cooker, and the validation of the proposed technique for heating applications.

2. STRUCTURE AND FUNCTIONING OF THE GLOBAL SYSTEM

The proposed system is based on the exploitation of the electrical energy stored in the solar batteries to heat the cookers (Hotplate and Oven Box), via a DC/DC Converter [24] with several cells, provided with a circuit control electronics, and heating resistors. As shown in Fig. 1 and Fig. 2, this system is formed by:

- Photovoltaic panels whose power supplied depends on the application [25]. Their role is to generate electrical energy to charge the solar batteries via a charge/discharge regulator.
- Solar batteries with capacity are dependent on the application. It provides electrical energy to supply thermal resistors, via power block and digital electronics.
- Power block, formed by a DC/DC converter with several cells (3 cells). This structure makes it possible to limit the strong currents which circulate in the 3 inductors following the strong currents debited by the battery. This converter is sized and produced according to the needs of the users. It is formed by 3 inductors (L1, L2, L3) input and output capacitors, 3 power switches (MOSFET), and 3 power diodes. This converter is connected to a common 0V reference.
- A digital electronic block whose role is to control the switches (T1, T2, T3) of the DC/DC converter, in non-linear mode, by 3 identical PWM 1 PWM2, and PWM 3 signals, with a frequency of 20 kHz and a variable duty cycle α. The digital circuit of this command is formed by a microcontroller (Raspberry Pi Pico) which generates the PWM signals, adapted to the input of the power switches by 3 Drivers (IR2111). This block allows:

- The acquisition of all the physical quantities of the system, via current and voltage sensors: electrical quantities (voltages, currents, powers, efficiency), thermal (temperature of the resistance and firing).
- Display all the physical quantities measured on an LCD display by acting on the rotary encoder
- Application: hot plate cooker heated by thermal resistors supporting a temperature of 1400°C, a power of 800W,

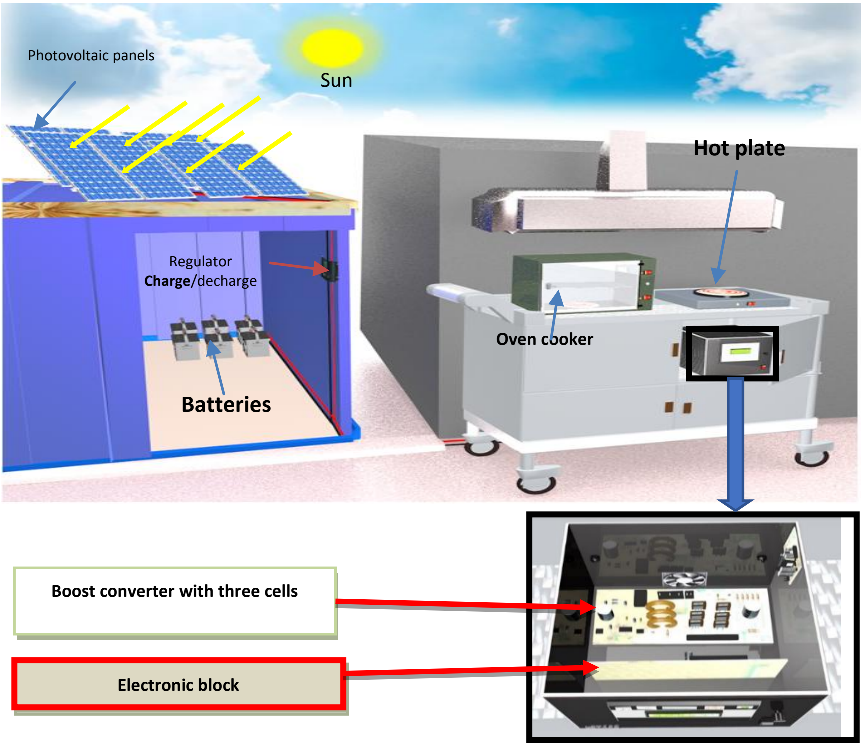


Fig. 1. Synoptic diagram and intern diagrams of the autonomous system of the multistage Boost DC/DC converter. allowing to supply a DC load

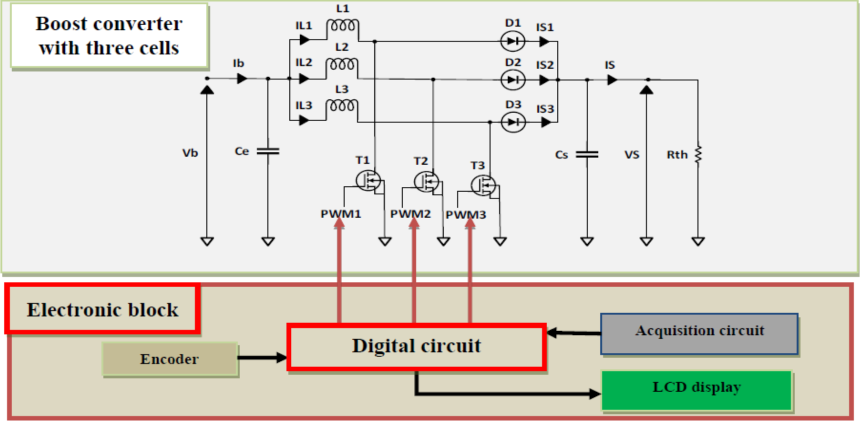


Fig. 2. Structure of the three-cells DC/DC converter and its control

3. DISCUSSION AND RESULTS

3.1 Description of Measurement Equipment and the Experimental Procedure

Fig. 3, represents the power system, allowing the supply of a DC load by a solar battery through a multistage DC/DC converter, and the measurement bench set up to characterize this system. As shown in Fig. 3, we used the following equipment:

- Photovoltaic panels of 600 W, whose role is to provide electrical energy and store it in the solar batteries, via a charge/discharge controller,
- A 24V/520 Ah solar battery, whose role is to supply the multistage Boost DC/DC converter, with a DC voltage of 24 V and variable currents of less than 30 A, depending on the value of the thermal resistance R_{Therm} of the application (hot plate),
- A DC/DC Boost converter, with three identical cells and input and output capacitors (Ce=1000 µF and Cs= 1000 µF). Each cell is formed by an inductor (L= 100 µH), switches (MOSFET IRF540N) and fast diode (Schottky). This structure makes it possible to limit the strong currents which circulate in the inductances following the strong current delivered by the battery. This converter is dimensioned so that this one functions with a power of 300 W, in continuous mode, with a frequency of 20 kHz, input voltage of 24 V, output voltage Vs of 70 V, output current Is=5 A,
- A digital control of the DC/DC converter, which provides three identical PWM signals to control the three switches (T1, T2, and T3) in a nonlinear regime, by a PWM signal of frequency 20 kHz of duty cycle α=0.7. This control is based on the use of the Microcontroller 'Raspberry Pi Pico' and a block of three drivers IR2111, to adapt the PWM signals and the input of the power switches.

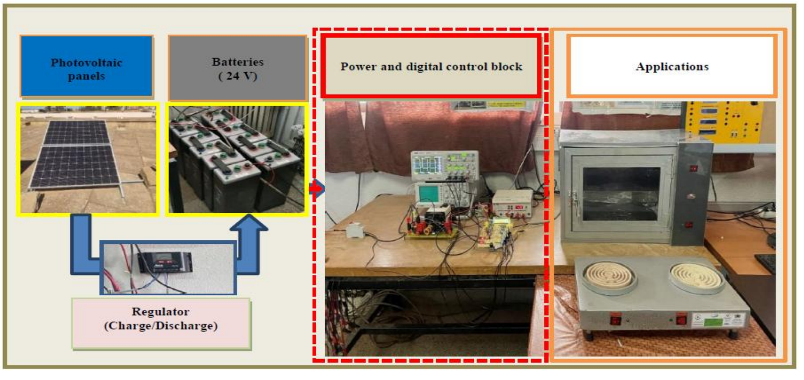


Fig. 3. Synoptic diagram of the autonomous system, allowing to feed a DC load by the solar batteries and a DC/DC converter of multi-cellular Boost type

- Load formed by a hot plate cooker, heated by two thermal resistances, supporting a temperature of 1400°C, a power of 600 W.
- Power switches (ON/OFF) for the supply of the realized system.

3.2 Experimental Validation without Load (Cooking)

The system of the DC/DC converter and these control blocks of the Fig. 3 is implemented in the Pspice simulator in order to follow the operation of the DC/DC converter. In the following, we present the typical simulation results obtained. In Fig. 3 we have represented the battery voltage VBat and output VS for a duty cycle α=0.7. In Table 1 we have represented the comparison of different simulated and experimented electrical quantities at the input (Ib, Pb) and at and at the output (VS, IS, PS) and the efficiency of the DC/DC converter for a duty cycle α =0.7, for a load of 15 Ω where the battery voltage is constant and around 24 V. In the case of a duty cycle of 0.7 and a resistance of 15 Ω the results obtained show:

- The currents in the cells and output of the DC/DC converter are respectively of the order of 5.06 A and 4.8 A.
- The output voltage and current of the DC/DC converter are about 73 V and 4.8 A.
- The input and output powers are of the order of 364.5W and 350.4 W, i.e. efficiency of about 96%.
- An excellent agreement between simulation and experiment

From the analysis of these simulation results, we can conclude that for our power application, which involves heating a cooker (hot plate with 15Ω thermal resistance) at a heating power of 350W, the duty cycle of the PWM signals of the DC/DC converter is on the order of α=0.7. Under these conditions, the input and output currents and voltages, and the efficiency of the DC/DC converter are about 15.19 A, 24 V, 4.8 A, 73 V, and 96%, respectively.

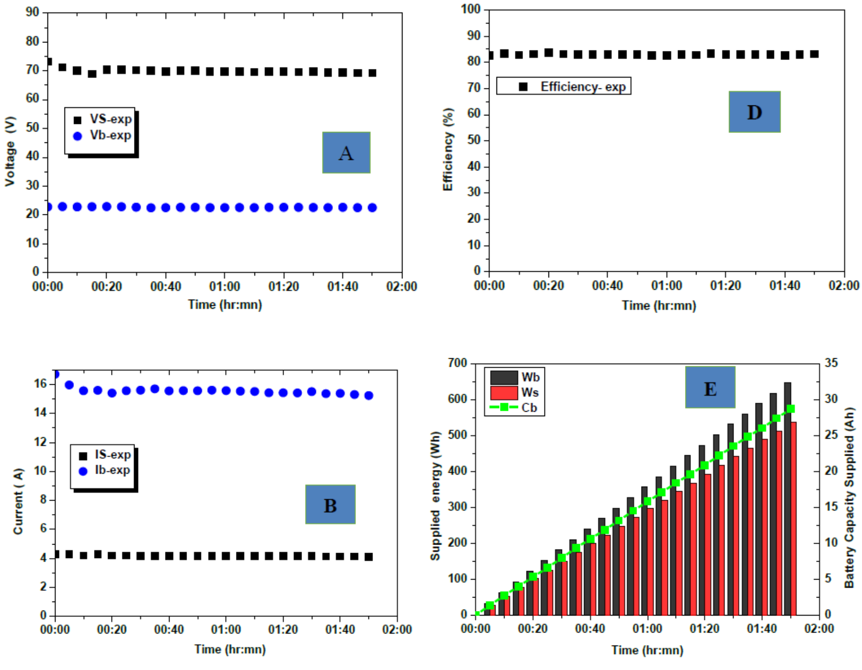
Table 1. Comparison between simulation results and experimental results

Electrical quantities	Simulation	Experience
Ibat (A)	15.19	15
Vbat (V)	24	20.6
$I_{L1}=I_{L2}=I_{L3}$ (A)	5.06	5
I_S (A)	4.8	4,1
V_S (V)	73	65.6
P_S (W)	350.4	266.5
P_{Bat} (W)	364.56	309
Converter efficiency (%)	0,96	0,86

3.3 Application with Load (Cooking Fries)

In Fig. 4, we have represented the typical results obtained, in the case of cooking 1 Kg of fries, by the electrical energy provided by the batteries. All the results obtained show:

- The voltages and currents at the input of the converter are respectively of the order of 22.5 V, 15.6 A, and at the output of the order of 70 V and 4.21 A.
- The input and output power of the converter are respectively of the order of 351W and 295 W, i.e. an efficiency of 84%,
- The oil temperature reaches 100° C after 6 minutes of heating, or 16.67°C / min,
- The maximum temperatures of the heating resistance and that of oil are respectively about 640°C and 230°C.
- When adding 1 kg of fries, the oil temperature decreases and reaches the value of 102°C. Then, during the cooking process, the temperature gradually increases to 230°C after 15 minutes of cooking.
- The cooking time is of the order of 20 minutes (Fig. 4).
- The capacity of the battery consumed is of the order of 28.72 Ah, or 5.52% of the total capacity of the batteries.
- The energy supplied by the batteries and that of heating are respectively of the order of 647.36 Wh and 537.23Wh, i.e. consumption of 1.34% and 1.47% of the total energy supplied by the battery.
- A very good agreement between the experimental results and those obtained by the simulation.



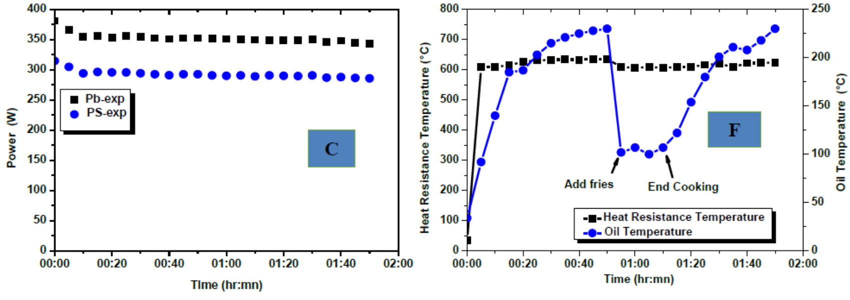


Fig. 4. Experimental electrical quantities, at the input and at the output of the cooker (Fig. 3), in the case of cooking 1 kg of fries.

A- Input and output voltages;
B- Input and output currents;
C- Converter input and output power;
D- Efficiency of the converter;
E- Energy supplied by the batteries, energy consumed by the thermal resistance during heating and Capacity supplied by the batteries;
F- Temperature of thermal resistors and oil.

The comparison of the operation of the cooker powered by solar batteries compared to cookers powered by photovoltaic panels [2-4,20] shows the identical operation in terms of power supply, temperature, and cooking time. We can therefore conclude the feasibility of the operation of the power system (Fig. 3) proposed in this work, for an application using cookers.

4. CONCLUSION

In this chapter, we presented the results of the simulation and experimentation of a new technique for powering solar cookers using batteries (24V DC, 520Ah), by an adaptation stage based on the three-cells BOOST DC/DC converter, controlled by three PWM signals with a frequency of 20 kHz and a duty cycle of 0.7. The obtained results show:

- Simulation of system operation, depending on the duty cycle and the load, heating power of 350W at the output of the DC/DC Boost converter, is obtained for a duty cycle α=0.7 and a load of 15Ω. Under these conditions, the output power is 350.4 W and therefore efficiency of 96%.

- During experimentation the system for cooking fries, shows yields of the DC/DC converter of 84%, the maximum temperatures of the heating resistance and that of oil are respectively of the order of 640°C and 230°C, oil temperature reaches 100°C after 6 minutes of heating, or 16.67°C / min with a cooking time is about of 20 minutes.

- The experimental validation of these simulation results shows a good agreement.

All the results obtained show, on one hand, a good agreement between the simulation and the experiment, remarkable performance for a duty cycle of 0.7, on other hand These performances demonstrate both the proper functioning of the power system and the DC application of heating cooker by solar batteries.

ACKNOWLEDGEMENT

This research is supported within the framework of the projects:

- Morocco-Wallonie Brussels Cooperation Program (2018-2022), Wallonie-Bruxelles-International (Belgium), project 4, n°2,
- Europe-Africa Research and Innovation call on Renewable Energy LEAP-RE, Project No 963530: SoCoNexGen, Solar Indoor Cooking Systems of the Next Generation, 2022-2025
- National Initiative for Human Development INDH, Berkane Province, Morocco, project 2017//29.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Vengadesan, Elumalai, Senthil, Ramalingam. Experimental investigation of the thermal performance of a box type solar cooker using a finned cooking vessel. Renewable Energy. 2021;171:431-446.
2. Al-Nehari, Hamoud A, Mohammed, Mahmoud A, Odhah, Abdulkarem A, et al. Experimental and numerical analysis of tiltable box-type solar cooker with tracking mechanism. Renewable Energy. 2021;180:954-965.
3. Aramesh, Mohamad, Ghalebani, Mehdi, Kasaeian, Alibakhsh, et al. A review of recent advances in solar cooking technology. Renewable Energy. 2019;140:419-435.
4. Omara Adil AM, Abuelnuor, Abuelnuor AA, Mohammed, Hussein A, et al. Improving solar cooker performance using phase change materials: A comprehensive review. Solar Energy. 2020;207:539-563.
5. Thirugnanam C, Karthikeyan S, Kalaimurugan K. Study of phase change materials and its application in solar cooker. Materials Today: Proceedings. 2020;33:2890-2896.
6. Mahajan SB, Sanjeevikumar P, Wheeler P, Blaabjerg F, Rivera M, Kulkarni R. XY converter family: A new breed of buck boost converter for high step-up renewable energy applications. In 2016 IEEE International Conference on Automatica (ICA-ACCA). 2016;1-8. IEEE.

7. Verma Sunirmit, Banerjee Sanjib, Das Ranjan. A fully analytical model of a box solar cooker with sensible thermal storage. Solar Energy. 2022;233: 531-542.
8. Apaolaza-Pagoaga, Xabier, Carrillo-Andrés, Antonio, Ruivo, Celestino Rodrigues. Experimental thermal performance evaluation of different configurations of Copenhagen solar cooker. Renewable Energy. 2022; 184:604-618.
9. Tawfik MA, Sagade Atul A, Palma-Behnke Rodrigo, et al. Performance evaluation of solar cooker with tracking type bottom reflector retrofitted with a novel design of thermal storage incorporated absorber plate. Journal of Energy Storage, 2022;51:104432.
10. Abd-Elhady MS, Abd-Elkerim ANA, Ahmed Seif A, et al. Study the thermal performance of solar cookers by using metallic wires and nanographene. Renewable Energy. 2020;153:108-116.
11. Khallaf AM, Tawfik MA, El-Sebaii AA, et al. Mathematical modeling and experimental validation of the thermal performance of a novel design solar cooker. Solar Energy. 2020;207:40-50.
12. Senthil Ramalingam. Enhancement of productivity of parabolic dish solar cooker using integrated phase change material. Materials Today: Proceedings. 2021;34:386-388.
13. Carrillo-Andrés, Antonio, Apaolaza-Pagoaga, Xabier, Ruivo, Celestino Rodrigues, et al. Optical characterization of a funnel solar cooker with azimuthal sun tracking through ray-tracing simulation. Solar Energy. 2022; 233:84-95.
14. Sagade Atul A, Apaolaza-Pagoaga, Xabier, Ruivo, Celestino Rodrigues, et al. Concentrating solar cookers in urban areas: Establishing usefulness through realistic intermediate temperature rating and grading. Solar Energy. 2022;241:157-166.
15. Sansaniwal, Sunil Kumar, Sharma, Vashimant, Mathur, Jyotirmay. Energy and exergy analyses of various typical solar energy applications: A comprehensive review. Renewable and Sustainable Energy Reviews. 2018;82:1576-1601.
16. Ahmed SM Masum, Al-Amin, Md Rahmatullah, Ahammed, Shakil, et al. Design, construction and testing of parabolic solar cooker for rural households and refugee camp. Solar Energy. 2020;205:230-240.
17. Keith, Angad, Brown, Nick John, Zhou, John L. The feasibility of a collapsible parabolic solar cooker incorporating phase change materials. Renewable Energy Focus. 2019;30:58-70.
18. Kumar Avnish, Saxena, Abhishek, Pandey, SD, et al. Design and performance characteristics of a solar box cooker with phase change material: A feasibility study for Uttarakhand region, India. Applied Thermal Engineering. 2022;118196.
19. Atmane I, El Moussaoui N, Kassmi K, Deblecker O, Bachiri N. Development of an innovative cooker (hot plate) with photovoltaic solar energy. Journal of Energy Storage. 2021;36:102399.
20. El Moussaoui, Noureddine, Talbi, Sofian, Atmane, Ilyas, Kassmi K, Schwarzer K, Chayeb H, Bachiri N. Feasibility of a new design of a

Parabolic Trough Solar Thermal Cooker (PSTC). Solar Energy. 2020;201: 866-871.
21. Schwarzer Klemens, Da Silva, Maria Eugenia Vieira. Solar cooking system with or without heat storage for families and institutions. Solar Energy. 2003;75(1):35-41.
22. Schwarzer, Klemens, Da Silva, Maria Eugenia Vieira. Characterisation and design methods of solar cookers. Solar Energy. 2008;82(2):157-163.
23. Apaolaza-Pagoaga, Xabier, Carrillo-Andrés, Antonio, Ruivo, Celestino Rodrigues. New approach for analysing the effect of minor and major solar cooker design changes: Influence of height trivet on the power of a funnel cooker. Renewable Energy. 2021;179:2071-2085.
24. Padmanaban S, Blaabjerg F, Wheeler P, Ojo JO, Ertas AH. High-voltage dc-dc converter topology for pv energy utilization—Investigation and implementation. Electric Power Components and Systems. 2017;45(3): 221-32.
25. Caselitz P, Kleinkauf W, Pigorsch W, Willer B. Control and power conditioning for photovoltaic power supply systems. InSeventh EC Photovoltaic Solar Energy Conference. Springer, Dordrecht. 1987;156-161.