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**MASTERS**

Field: Mechanical Engineering
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Presented by:

**Dounia BARKAT**

**Theme:**

# Enhanced solar cooking system for continuous operation: A hybrid approach with PV and thermal storage.

**Discussed publicly on 22/06/2025**

**In front of the jury composed of:**

| | | |
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**Academic Year : 2024/ 2025**

# *Dedication*

***Thank God for his grace. prayer and peace for our Prophet and our beloved Muhammad and on his God and his companions and after:***

***Praise be to Allah, by whose grace good deeds are accomplished. Much praise and blessings are due to Him, as befits His majestic countenance and immense sovereignty, and as befits his great blessings upon me. Endless gratitude belongs to Him for illuminating my path with knowledge and granting me the strength to complete this humble thesis and conducting this scientific research.***

***I dedicate this work to my dear mother, whose endless prayers, love, and support have been my greatest source of strength, and to my father, who taught me my first words and instilled in me the values of discipline and perseverance. May Allah bless them both with health, happiness, and lasting peace.***

***To my dearest brothers HANI and BADIS, my sisters FAIREUZ and RADJA and NOUR, my cherished Mama FATMA and Papa BELKACEM, and to my entire family—thank you for your love and encouragement.***

***Dounia.***

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***May Allah bless everyone who helped and supported me in this humble endeavor.***

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# Nomenclature

## Symbols List

| **Symbols** | **Definition** | **Unit** |
|---|---|---|
| $\mathbf{A_{abs}}$ | Effective area exposed to solar radiation | $m^2$ |
| **G** | Solar irradiance | $W/m^2$ |
| $\mathbf{Q_{abs}}$ | Absorbed energy | W |
| $\mathbf{Q_{loss}}$ | Heat losses | W |
| $\mathbf{Q_{st}}$ | Stored energy | J |
| **Qele** | Electric energy | J |
| $\mathbf{m_w}$ | Mass of water | kg |
| $\mathbf{C_p}$ | Specific heat capacity | J/kg.K |
| **H** | Overall heat transfer coefficient | $W/m^2.K$ |
| **T** | Temperature | $^oC$ |
| **T** | Time | s |
| **A** | Surface area | $m^2$ |
| $\mathbf{Q_{PCM}}$ | Stored energy | J |
| **I** | Current | A |
| **V** | Voltage | V |
| $\mathbf{L_{fu}}$ | Latent heat of fusion | J/g |
| $\mathbf{m_{PCM}}$ | Mass of paraffin wax | kg |
| **ΔT** | Temperature difference | $^oC$ |
| **Δt** | time interval | s |

## Greek Symbols List

| **Symbols** | **Definition** | **Unit** |
|---|---|---|
| **A** | Absorptivity | / |
| **T** | Transmittance | / |
| **Σ** | Stefan-Boltzmann constant | $W/m^2.K^4$ |
| **Ɛ** | Surface emissivity | / |
| **H** | Efficiency | % |

## Subscripts List

| **Subscripts** | **Definition** |
|---|---|
| **Int** | Inlet |
| **Amb** | Ambient |
| **Abs** | Absorbed |
| **St** | Stord |
| **W** | Water |
| **U** | Useful |
| **In** | Input |

| | |
|---|---|
| **I** | Initial |
| **Ele** | Electric |
| **F** | Fusion |
| **F** | Final |
| **M** | Melting |
| **We** | Water in Experimental Study |
| **Wn** | Water in Numerical Study |
| **P** | Paraffin wax |

## Abbrevlations List

| **Abbrevlations** | **Definition** |
|---|---|
| **PV** | Photovoltaic |
| **SSC** | Simple Solar Cooker |
| **PCM** | Phase Change Material |
| **TES** | Thermal Energy Storage |
| **HSC** | Hybrid Solar Cooking |
| **LPG** | Liquefied Petroleum Gas |

# General Introduction

# General Introduction

Energy consumption has dramatically increased with the expansion of population in the world, which in turn enhanced the greenhouse gas emissions from burning fossil fuels and raised environmental pollution. The deployment of ecologically friendly renewable energy technologies that can sustainably meet human needs is therefore becoming increasingly important [1].

Of these technologies, solar cooking has emerged an affordable and environment-friendly solution for domestic cooking needs. It reduces dependence on conventional fuels such as firewood and **LPG**, offering substantial ecological and economical benefits by reduces environmental pollution saves energy costs [2].

However, a primary drawback of conventional solar cookers is their need on direct sunshine and this limits its use during cloudy weather and at night. In addition to the intermittency problems, these cookers are frequently linked to excessive energy usage, particularly when using traditional systems that rely on fossil fuels, hence, it increases both household expenses and environmental effects. Furthermore, the sporadic nature of solar energy remains to be the biggest barrier to the reliability and consistency of heat supply. Also, the slow time of cooking may not meet the practical needs of daily meal preparation in most households.

To surmount these drawbacks, comprising the tardy cooking time, the great energy use of regular cookers, and the problem of solar energy intermittency.

A new hybrid solar cooking system that combines photovoltaic (**PV**) and thermal energy storage (**TES**) technologies is proposed, implemented, and tested. Additionally, a numerical model is developed to simulate the system's thermal behavior and evaluate its performance.

This work has been structured into four chapters:

Chapter One presents a general overview of solar cooking, its principles, types, and benefits.

Chapter Two offers a comprehensive review of previous research on hybrid solar cookers, focusing on advancements in photovoltaic integration and thermal energy storage.

Chapter Three details the experimental model, outlining the design process, construction phases, dimensions related to the experimental model, as well as the components of the solar cooker, thermal storage unit, and the equipments used for measurement.

In the fourth chapter, we presented the experimental results obtained, compares them with numerical simulations, and analyzes the temperature variations of water and paraffin wax, along with environmental factors such as ambient temperature, and solar radiation.

# Chapter I

# Generalities on solar cooking systems

## Introduction

Cooking is an essential home activity and represents a large part of energy consumption, with approximately 50% of total primary energy use attributed to cooking needs [3]. Traditionally, cooking stoves fueled by biomass, kerosene, **LPG**, and natural gas-fueled have been widely used, but these systems increase pollution, greenhouse gas emissions, and health hazards from indoor air pollution. It is estimated that around 3 billion people worldwide rely on inefficient cooking devices, exposing them to air pollution levels 100 times higher than the acceptable limit. This causes respiratory diseases like lung cancer, pneumonia, and chronic obstructive pulmonary disease, which caused 3.8 million premature deaths each year. In addition, CO2 and methane emissions from traditional cooking stoves further accelerate global warming, highlighting the pressing need for clean cooking solutions [4].

## 1. Definition of Solar Cooker

A solar kitchen is an eco-friendly cooking setup that harnesses sunlight as its primary energy source, to prepare meals without relying on gas, electricity, or firewood.

## 2. Historical Evolution of Solar Cooking Systems

In fact, the history of solar cooking dates back to very early, beginning with documented efforts of a German physicist called **Tschirnhausen** who conducted experiments on solar cooking from 1651 to 1708 [5]. He successfully boiled water in a mud jar using a large mirror to concentrate sunlight. His experiments were published in 1767 by Swiss scientist Horace de Sousur, who also invented the " hot boxes " he built from wood to produce enough heat to cook fruit as his temperature reached 88 °C [6]. In 1830, the famous English astronomer **Sir John Herschel** cooked food in an isolated box during his expedition to South Africa [7]. French mathematician **Augustin Mouchot** also developed a solar oven combining the principle of heat trap with the idea of a burned mirror in 1860. Although he successfully created a solar-powered steam engine, its size was not practical to use [8]. In 1876, an octagon oven was developed by **W. Adams** consisting of 8 mirrors, and reported that this oven is capable of cooking enough meals for seven soldiers in two hours in India [9]. One year later, **Mouchot** authored the first book on solar energy and its industrial applications. In addition to designing a solar cook for French soldiers in Algeria [8]. In 1894, ducks were roasted using solar cooking principles at Xiao’s Duck Shop in Sichuan, China [10]. In the 1930s, France sent several solar cookers to its colonies in Africa [11]. On the other hand, India began to analyse solar energy as a substitute for dwindling wood and avoiding deforestation. In 1940s, **Dr. Maria Telkes** in the USA researched several composite types of solar cookers including some heat storage materials and also published in 1968 a book entitled "The Solar Cookers" [9]. The first type of solar box cooker was produced by an Indian pioneer named **Sri MK Ghosh** in 1945 and during the 1950s and 1960s, researchers in India, Europe, and the USA designed and built commercial solar cookers and parabolic reflectors [12]. In 1980, **Barbara Kerr** and her neighbor **Sherry Cole**, developed box solar cookers using recycled materials [13].

**Fig I.1: Barbara Kerr** and **Sherry Cole** with their cooker “kit” [14].

In the 21st century, a great deal of research has been conducted to improve the efficiency, affordability, and practicality of solar cooking systems. New hybrid models that combine photovoltaic (**PV**) and thermal storage technologies have emerged, allowing continuous cooking, even during non-sunlight hours. Today, solar cooking remains a promising technology, as it can be a good alternative to reducing fossil fuel dependence and improving energy access in remote areas [15].

## 3. Principle of Solar Cooker

The solar cooker works by harnessing and concentrating solar radiation in a specific area and is then converted into heat energy for food preparation, it includes the three core principles of focus, absorption and retention [16], as represented in **Figure I.2**.

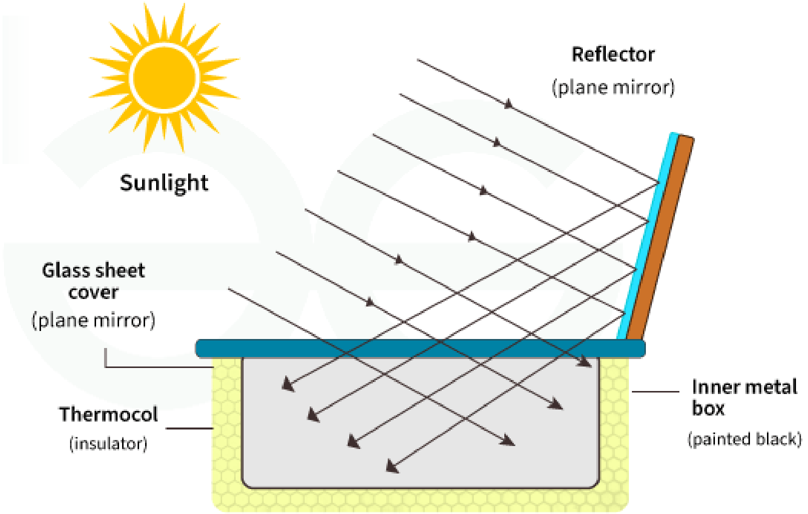

**Fig I.2:** Solar Cooker [17].

### 3.1.Concentration of Sunlight

A solar cooker uses mirrors or parabolic reflectors to focus and direct sunlight onto a small cooking area. This helps to increase the intensity of sunlight, reaching temperatures high ranging from 65 °C to 400 °C, which is sufficient for cooking various foods [17].

### 3.2 Conversion of Light Energy to Heat

Concentrated sunlight is directed at a receiving device that is a cooking pot. The contact between the light energy and the receiver's material aids in transforms the light energy into heat via a process known as conduction. This process, can be optimized using matte black painted cookware to absorb as much light as possible and improves efficiency [18].

### 3.3 Trapping and Retaining Heat

Once thermal energy capture in solar cooker, we must have to keep it inside as much as we can. For this, solar cookers use glass covers or insulated lids, to minimize convection losses and increases the heat storage capacity of the cooker. By isolating the air inside the cooker from the external air [19].

## 4. Types of Solar Cookers

It is known that there are many different types and applications of solar cookers across the world, and researchers are constantly developing and improving them [12]. As a result, it is necessary to classify them. There are three primary types of solar cookers are panel cookers, box cookers, and parabolic (concentrating) cookers.

### 4.1 Solar Panel Cookers

Solar panel cookers can be considered the most commonly available type because their ease of manufacture and low-cost materials [20]. They work similarly to solar box cookers, But the panel cooker utilizes reflective panels instead of insulated box to focus sunlight on the black cooking vessel [21]. It usually is surrounded by a transparent cover, which acts as insulation and creates a greenhouse effect. Panel cooker's performance is highly impacted by reflected radiation, thus it doesn't seem to be effective under cloudy or windy conditions [21]. as represented in **Figure I.3**.

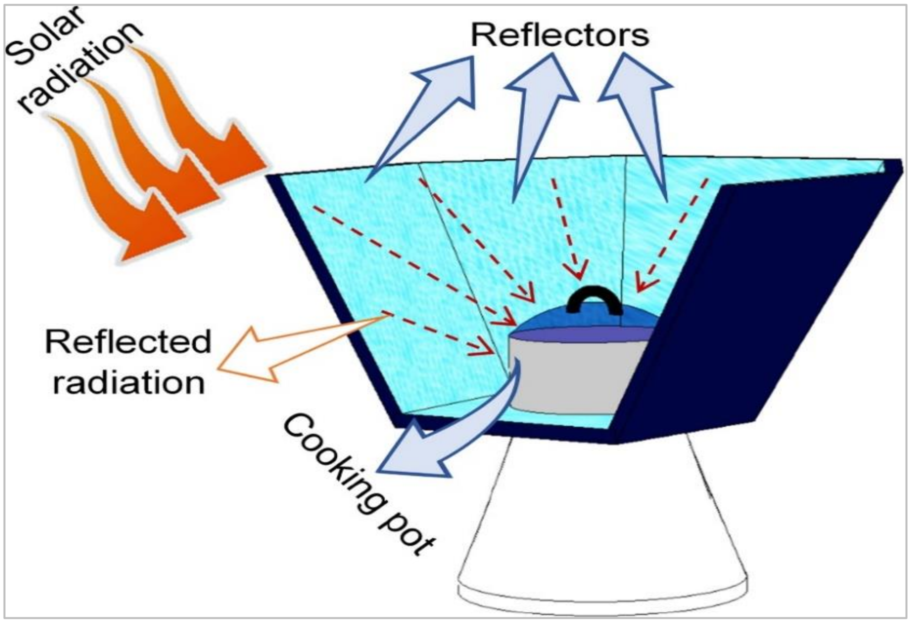

**Fig I.3:** Solar Panel Cooker [22].

## 4.2 Solar box cookers

A box-type solar cooker is an alternate method of cooking food with sunlight as its only energy source [20]. These box cookers have a very simple construction and they are made of an insulated box with single or double transparent window consist of glass or plastic to let heat from the sun in and trap it [21]. Reflector panels are often added to concentrate the suns rays toward the cooking pot [23]. Internal temperatures can reach up to 400°C on clear sunny days [24], making them ideal for cook bread, boiling, and slow cooking but not the best for grilling or frying [25], as presented in **Figure I.4**.

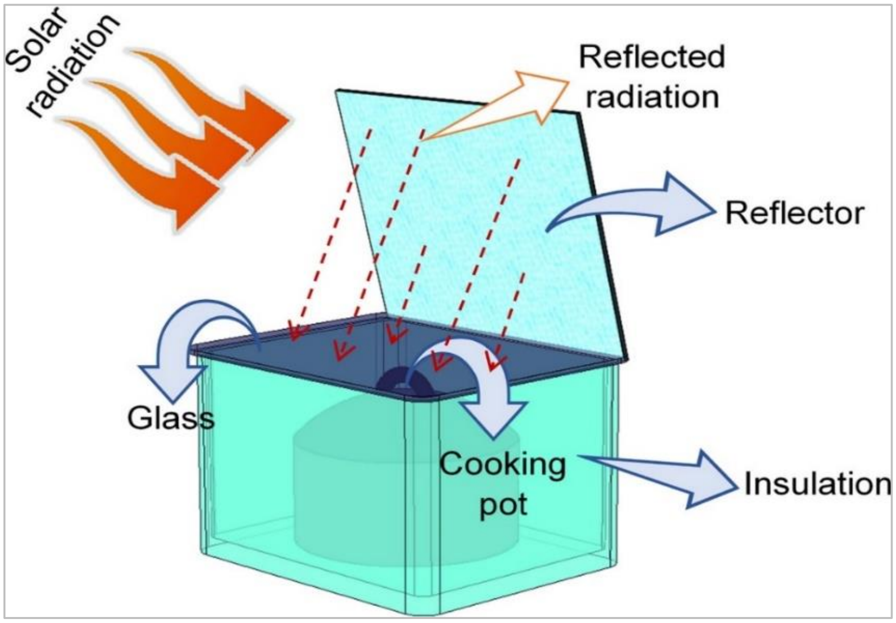

**Fig I.4:** Box-Type Solar Cooker [22].

## 4.3 Solar Parabolic (Concentrating) Cookers

Parabolic cookers may generate high temperatures (up to 500°C) in a very short time [26]. They can be used for cook food very quickly, grilling, or frying [24]. However, a parabolic cooker can be at risk of burning food, if left unattended for an extended amount of time [20]. Parabolic shaped cookers can be simply made from recycled satellite dishes or huge umbrellas to to focus a large amount of sunlight onto a single focal point [26], as represented in **Figure I.5**.

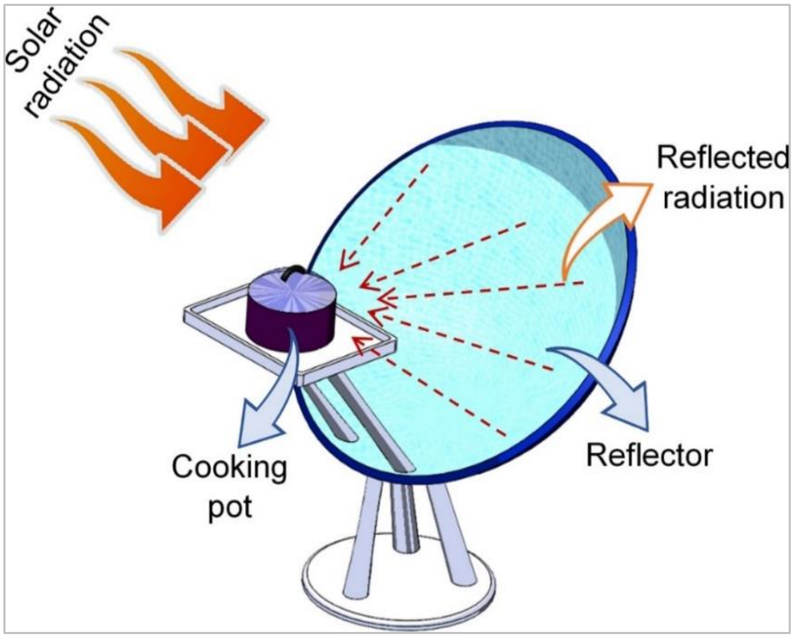

**Fig I.5:** Concentrating Solar Cooker [22].

## 5. Advantages of Solar Cookers

- **Fuel-free and cost-effective:** since solar cookers don't require for gas, or any other fuel, they help save costs and reduce dependence on non-renewable resources [26].
- **Eco-friendly:** Cooking with sunshine generates reduces carbon footprint, and don't emit any harmful environmental pollutants, including air pollution [26].
- **Health Benefits:** Although it takes food longer to cook in a solar cooker, it retains nutrients, and free of carcinogens produced by high-heat cooking methods and helps minimizing respiratory diseases illnesses brought on by conventional cooking fuels like wood and charcoal [27, 28].
- **Safety & Convenience:** Solar cookers are safer for households as they pose no danger of injury, gas leakage, or fire accidents, and make no noise [27].
- **Multipurpose:** Anything can be cooked in the solar cookers such as roasting, make breads, and meat roast [27, 29].
- **Durability & Low Maintenance:** Due to its low maintenance needs and fewer moving parts, solar cookers are ultimately more affordable and long-lasting [29].
- **Portable:** Many solar cookers are small and lightweight, making them suitable for used in anywhere, including backyards, rooftops, and outdoor camping [27].

## 6. Disadvantages of Solar Cookers

- **Weather Dependency:** Solar cookers require direct sunlight (solar energy is not always available) and are affected by strong winds, slowing down the cooking process [26].
- **Longer Cooking Time:** Compared to traditional stoves, solar cookers take longer to cook meals [26].
- **Frequent Adjustments:** Some solar cookers require repositioning to follow the sun's movement for optimal performance.
- **Initial Cost:** Some advanced solar cookers may have a greater initial cost even if they don't require fuel.

## 7. Improvements in solar cooker

- **Photovoltaic-Powered Solar Cookers:** The Combining of photovoltaic panels, power converters and digital controls enhances cooking efficiency, and provides additional energy when solar power is inadequate, making them suitable for both urban and rural environments [30].
- **Thermal Energy Storage (TES): TES** systems using Phase Change Materials (PCMs) help maintain heat, allowing cooking after sunset and improving the performance of the solar cooker [31].
- **Parabolic Reflectors with Tracking Systems:** The addition of internal and tracking reflectors enhances sunlight concentration, leading to maximum efficiency and increased cooking temperatures [32].
- **Advanced Insulation Materials:** Advanced insulation materials reduce heat loss, ensuring better performance in all seasons while minimizing energy consumption and emissions [33].

## Conclusion

In this chapter, we provided an overview of the principles of solar cooking, the types of solar cookers, their advantages and disadvantages, and the latest advancements in solar cooking technology. This analysis highlights the potential of solar cooking systems as a sustainable alternative for food preparation while addressing key technological and practical challenges.

# *Chapter II*

## *Bibliographic research*

## Introduction:

Solar cooking systems offer a sustainable and renewable solution for food preparation, especially in areas with abundant sunlight. However, traditional solar cookers often face limitations in efficiency, particularly during cloudy weather or nighttime, when solar radiation is insufficient. This dependency on sunlight hinders the continuous operation of solar cookers and limits their broader adoption as a primary cooking solution. To address this issue, we have reviewed previous work undertaken by researchers to identify previous results and the types of hybrids approaches previously used. We also focused on the hybrid approach that combines photovoltaic (**PV**) and thermal storage.

## 1. Bibliographical summary

In 2024, Algerian researchers **Hocine Maammeur, et al** [34], conducted an experimental study at the University Kasdi Merbah, Ouargla, Algeria. This study aims to reduce cooking time and determine two new ideal volumetric efficiencies (VE1 and VE2) using two identical solar box cookers constructed of stainless steel with glass coverings, glass wool insulation, and different-sized pots. The results showed that when VE1 was minimized to 6.2% and VE2 maximized to 100%, the absorber temperature peaked at 124.9°C with the shortest boiling time of 2 hours and 50 minutes. This study provided benchmark parameters for developing solar box cooker designs (**Figure II.1**).

**Fig II.1:** Experimental Solar Box Cookers Used for Determining Optimal Volumetric Efficiencies (VE1 and VE2) [34].

The design and assessment of a hybrid solar cooking system that combines solar thermal and photovoltaic (**PV**) technologies was the main focus of a study conducted in India and published in 2024 by **V.V. Modi et al.** [35]. The system combined a black copper sheet, triangular glazing surfaces, a flat plate collector, and a solar trough reflector to absorb and concentrate solar energy efficiently. A **PV** system was included for the purpose of producing electricity, and at certain periods of time, the energy stored in batteries powered a 5W DC lamp, a smartphone charger, and a DC fan. Results showed that maximum cooking pot temperature for the winter experiments was 104.5°C at noon, which was adequate for preparing wholesome meals. A cooking power of 47.68W, an average thermal efficiency of 35.1%, and a cooking duration of 130 minutes as opposed to more than 3 hours for conventional box cookers were all displayed by the system. The hybrid technique demonstrated the system's sustainability and usefulness for areas with plenty of sunshine by making it appropriate for cooking, drying, and basic power requirements (**Figure II.2**).

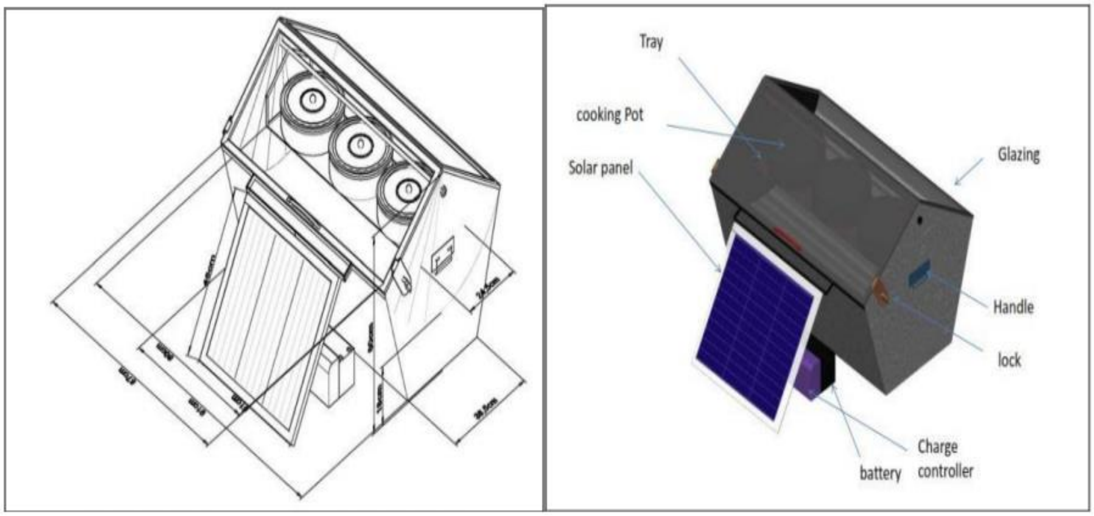

**Fig II.2:** Schematic diagram and actual image of the system [35].

Research done in India and published in 2024, by **Tejash R. Patel, et al.** [36]. examined the performance of two types of box-type solar cookers. The first design was a standalone solar cooker with black-painted surfaces, while the second design incorporated a 600W coil powered by a 12V battery for auxiliary heating. According to experimental studies, the hybrid cooker with the coil attachment obtained a greater efficiency of 45.26%, greatly cutting down on cooking time, while the freestanding solar cooker reached a thermal efficiency of 30.41% under average sun intensity. A a solar collector box made of wood, a black absorber plate, a single-glazed glass cover, and a coil that ran on batteries for additional heat were among the system's components. When 750g of water and 250g of rice were cooked during testing, the coil-powered system reached a maximum absorber plate temperature of 110°C in 32 minutes as opposed to the standalone design's 92°C over two hours. The findings demonstrated the hybrid system's potential for quicker and more effective cooking, providing both urban and rural homes with an eco-friendly and practical alternative (**Figure II.3**).

**Fig II.3:** Experimental setup with arrangements and battery [36].

In 2023, Japanese authors **S.D. Sharma, et al.** [37] made the design and functionality of an advanced solar cooker that combines a phase change material (**PCM**) and an evacuated tube solar collector (ETSC) for continuous cooking, particularly at night and in the evenings. In order to release solar energy during non-sunlight hours, the system employs erythritol as the **PCM**, which melts at 118°C and stores it as latent heat throughout the day. The cook is made up a stainless-steel heat exchanger, a pump for fluid circulation, a cylindrical storage container, and water as the heat transfer fluid (HTF). The **PCM** attained temperatures exceeding 130°C, enabling effective evening and night cooking, according to summertime experiments carried out in Japan. The system made progress more quickly. Results showed that **PCM** could attain temperatures beyond 130°C, facilitating effective night and evening cooking. Due to improved heat transmission from the **PCM**, the system was able to cook more quickly in the evening than at midday. However, the **PCM**'s effectiveness was limited by low solar irradiation during the winter months since it was unable to achieve its melting point. According to the study's findings, this hybrid solar cooking system provides a sustainable substitute for areas with lots of sunshine because it can cook for double sessions (in the afternoon and the evening) on a single **PCM** charging cycle. In particular, it lessens dependency on traditional cooking fuels, which is in line with sustainable development goals and the rising need for clean energy solutions (**Figure II.4**).

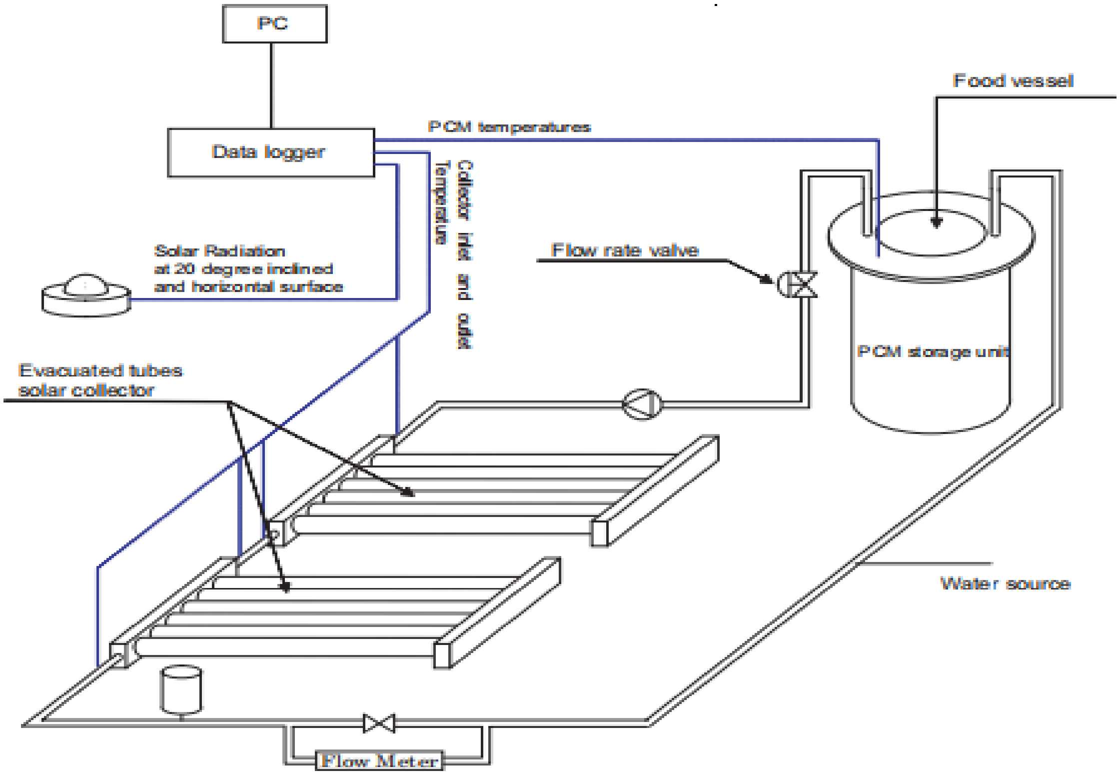

**Fig II.4:** A schematic diagram of advanced solar cooker with PCM storage unit [37].

**Mathew Varghese, et al** [38], they are Indian authors from Kerala, carried out a study in 2021. The goal of this study was to create an eco-friendly, effective solar cooker that could be used at night. In order to reflect sunlight onto a heat storage system composed of layers of clay, coconut husk, and dry sand, the system used a parabolic dish concentrator. To reduce thermal losses, the outer layers of clay and coconut husk were used as insulation for the sensible heat that was held in the sand. The design allowed heat to be effectively stored during the day and used for cooking at night. The results showed that this solar cooker was sustainable and affordable, with a great deal of potential to lessen reliance on biomass and fossil fuels while reducing pollution in the environment (**Figure II.5**).

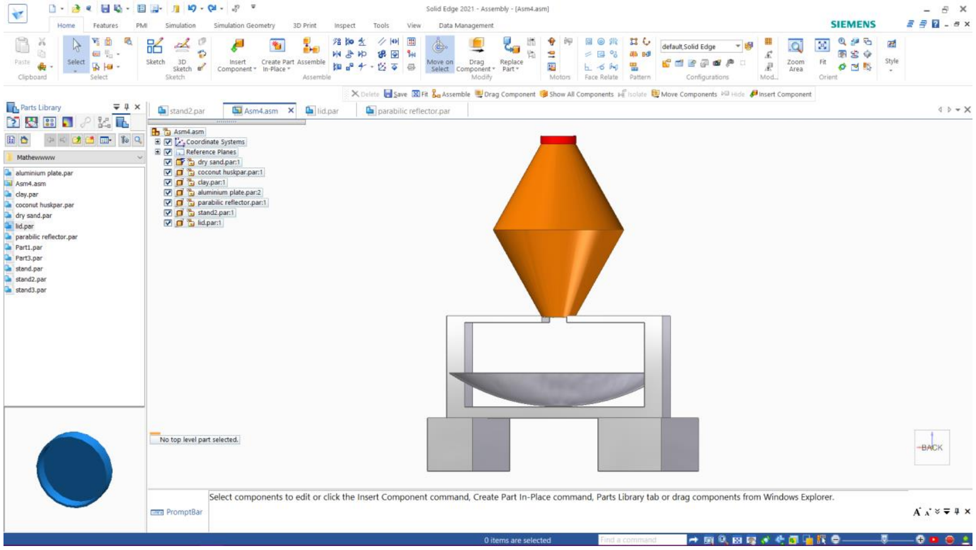

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**Fig II.5:** 3D drawing of solar cooker for night cooking [38].

In Tamil Nadu, India, in 2020, the Indian researchers **Ravisankar T, et al** [3], studied the efficacy of a solar box cooker. In order to lessen dependency on traditional fuels. The solar box cooker utilized mirrors to reflect sunlight, a black-coated aluminum cooking vessel, paraffin wax as a phase change material (**PCM**) combined with stone pebbles, and a thermal energy storage system. Results showed that setup reached a maximum temperature of 94.1°C, according to experimental data, and paraffin wax helped retain heat for cooking in the evening. This economical and environmentally design showed promise for remote locations with limited energy supplies (**Figure II.6**).

**Fig II.6:** Solar box cooker [3].

An article was carried out in 2020 at SRM Institute of Science and Technology in Chennai, India, by Indian researcher **Ramalingam Senthil** [39]. In order to increase the efficiency of a parabolic dish solar cooker (PDSC) and allow cooking to occur during off-sunny hours, the study investigated the integration of paraffin wax as a phase change material (**PCM**). The system included a cylindrical aluminum cooking pot with internal fins for efficient heat transmission and a 90 cm diameter parabolic dish. During the day, solar energy was stored as latent heat by the **PCM**, which has a melting temperature of 80°C. According to experiments, the **PCM** greatly increased cooking efficiency in the late evenings and shortened the time needed to heat water to 90°C from 120 to 90 minutes. The system provided a cost-effective and environmentally friendly substitute for solar cooking, with average energy and exergy efficiencies of 22% and 26%, respectively (**Figure II.7**).

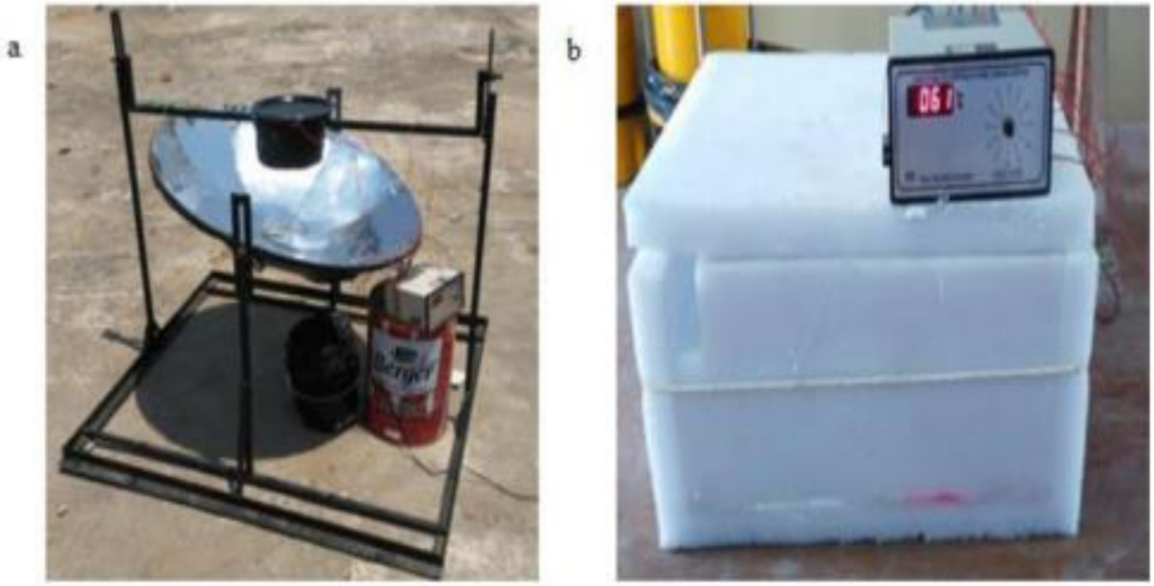

**Fig II.7:** (a) Photographic view of PDSC, (b) photographic view of insulation box for integrated solar cooker [39].

An inventive solar cooking method that aims to lessen reliance on firewood in refugee camps is examined in the 2019, which was prepared by **Angad Keith and others** [40]. in Australia. The study presented a cooking pot with a phase change material (PCM) built into it, together with a folding parabolic solar cooker. This arrangement keeps food warm for evening meals while enabling cooking during the day. Corf lute panels, reflective tape, a container filled with **PCM**, and thermal insulation materials are among the parts. Results showed that **PCM** kept meals at palatable temperatures into the evening. Although the system has cultural, environmental, and health benefits, its uptake depends on increasing its effectiveness and cutting expenses. For a household of four, the payback period is around 52 weeks, demonstrating the solution's feasibility for sustainable cooking in displaced circumstances (**Figure II.8**).

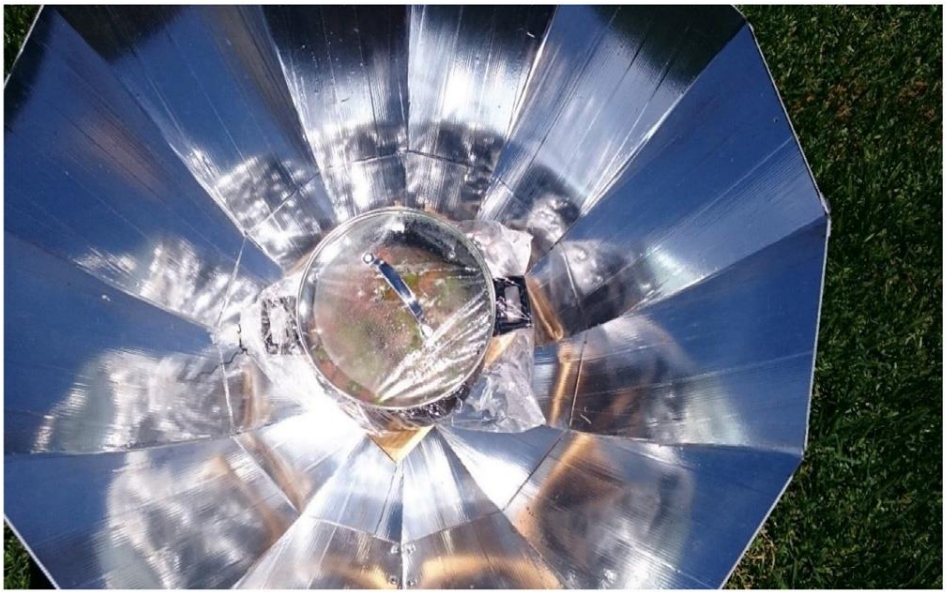

**Fig II.8:** Parabolic solar cooker in operation [40].

Researchers **S.R. Gawali and C.V. Papade** [41], from India designed and tested a hybrid solar cooker that combines solar thermal and photovoltaic (**PV**) technologies to provide continuous cooking capabilities, even under low solar radiation conditions. Their article was published in 2015. The device directs solar energy toward a copper thermal storage tank filled with heat transfer oils (olive oil, soybean oil, and thermic fluid) using a parabolic dish collector composed of anodized aluminum. In order to augment heat during overcast or nighttime conditions, a DC heater that is powered by a photovoltaic panel and battery is included. To prevent heat loss, ceramic wool is used to insulate the cooker. The thermal energy is then stored in the oils for subsequent use as sensible heat. The results showed that by using the auxiliary heater or stored heat, the system could effectively cook 500g of rice both with and without solar radiation. The findings demonstrate how hybrid solar cookers may improve interior air quality, lessen reliance on traditional cooking fuels, and provide a portable, user-friendly design that is appropriate for rural locations and sustainable energy applications (**Figure II.9**).

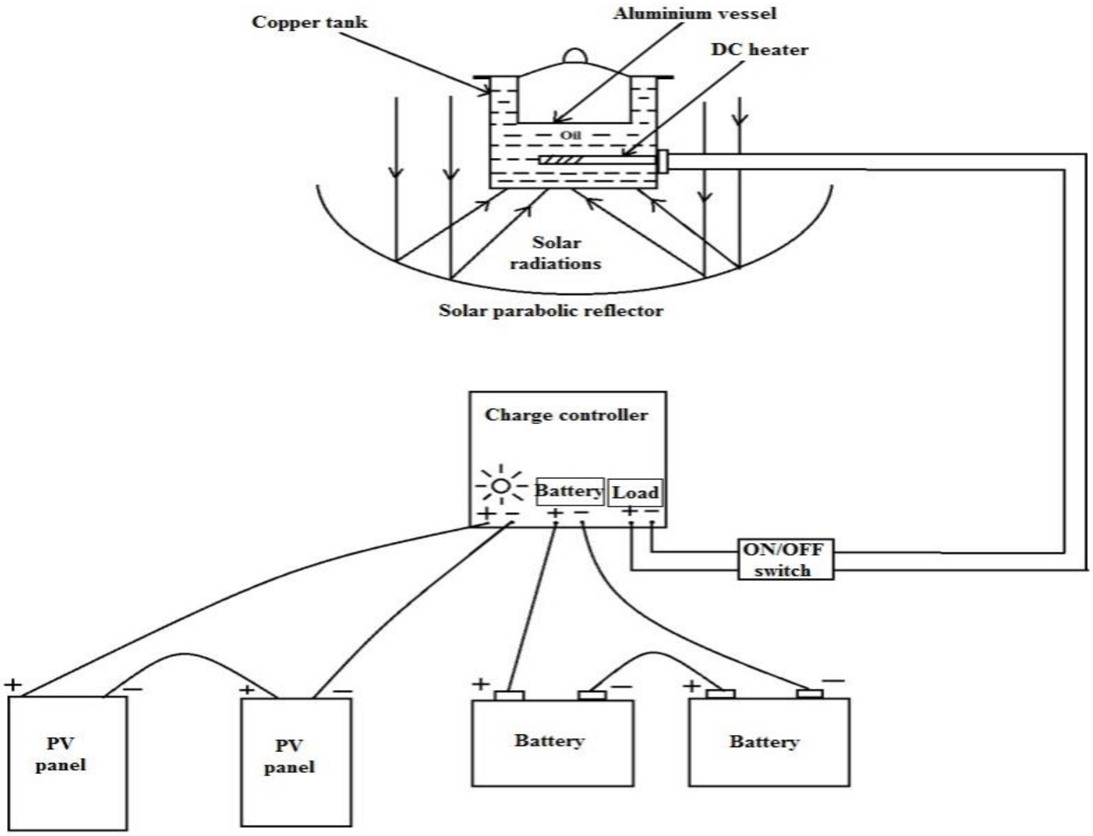

**Fig II.9:** Layout of experimental setup of hybrid solar cooker [41].

The study was carried out in India and published in 2015 by **S.B. Joshi and A.R. Jani** [42], examines a unique hybrid solar cooker that combines thermal and photovoltaic energy. Five 15W photovoltaic panels and a thermal system improve the Small-Scale Box-type Hybrid (SSBH) solar cooker, which gives offers a 38% efficiency and shorter cooking times. It can operate continuously with the aid of a 45 Ah battery, making it usable at night. When thermal and photovoltaic effects are combined, the results showed that it can boil water in around 40 minutes. The cooker is lightweight, user-friendly, and cost-effective, with an estimated price of $120. By utilizing pre-existing solar components, the price can drop to $15. Small households are catered to by this invention, which prioritizes cost and adaptability for clean cooking solutions, particularly in rural and hilly settings (**Figure II.10**).

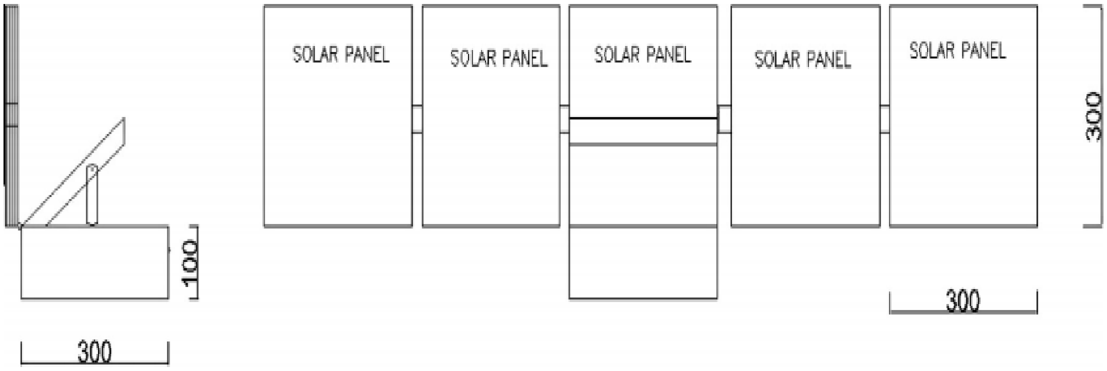

**Fig II.10:** Line diagram of the SSBH solar cooker with open solar panels [42].

2013 research conducted in India by authors **Joshi and Jani** [43], the development of a hybrid solar cooking system that combines thermal and photovoltaic (**PV**) technologies to increase energy efficiency and usability. The cooker incorporates a thermal storage system that uses phase change materials (**PCM**s) to store heat, a parabolic dish collector for thermal energy concentration, and PV panels for power generation. Utilizing solar radiation, the technique stored thermal energy in the **PCM** for prolonged cooking times while also producing electricity through **PV** panels. By addressing issues like uncontrollable characteristics (wind, ambient temperature, sun height, and azimuth angle) that usually impact traditional solar cookers, the findings showed that the hybrid system may work well for indoor and round-the-clock cooking. The cooker was portable and easy to use because it was smaller, lighter, and didn't have any breakable parts like glass or mirrors. By enabling indoor cooking, the technology also lessened user physical strain and made commercialization possible. A suggested change was to use a 75W solar panel to charge a 12V, 40Ah DC battery in place of the power supply. The panel would be set up on balconies or terraces while cooking took place in the kitchen. This hybrid system provides practical, effective, and ecological cooking options for areas with lots of sunshine (**Figure II.11**).

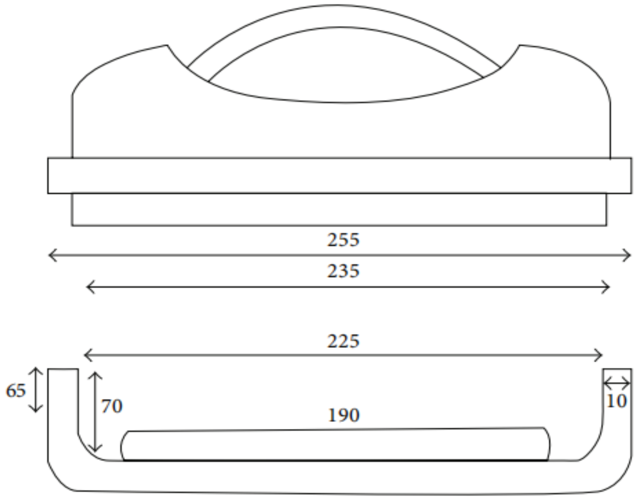

**Fig II.11:** Schematic diagram of Photo-Thermo solar cooker [43].

## Conclusion:

In this chapter, we reviewed several previous studies on types of hybrid solar cookers and explored the operating mechanisms and the results obtained. It was observed that the performance of these systems depends mainly on climatic conditions, particularly solar radiation intensity.

# Chapter III

## Experimental setup and mathematical formulation

## Introduction

In this chapter, we introduced a new hybrid solar cooker integrating photovoltaic and thermal energy storage systems. This system is studied experimentally and numerically. the objective of the study is:

- Realization the hybrid solar cooker system model to calculate the water temperature inside the cooking pot and to evaluate the thermal performance under natural conditions in the region of Ouargla.

## 1. Proposed solar cooker

A schematic design of the proposed solar cooking system is shown in **Figure. III.1**. which is composed of a **PV** panel, an electric stove, a reflector, a double-glazed glass cover, and a thermal storage unit.

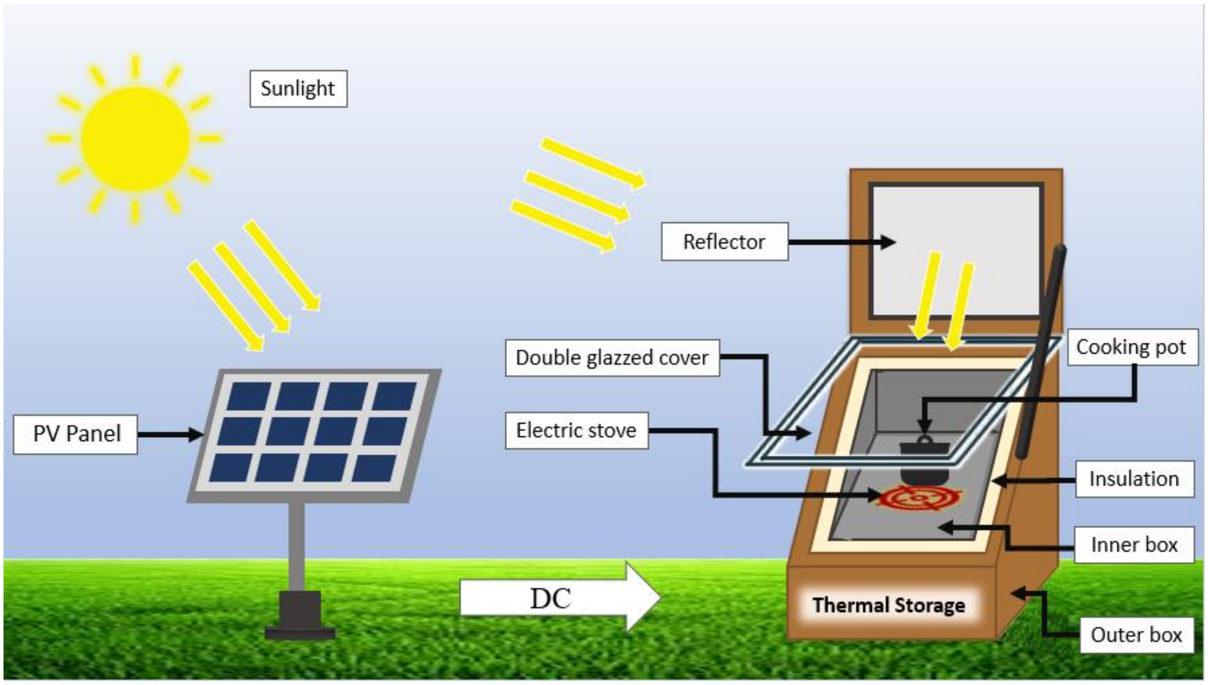

**Fig III.1:** 3D scheme of the proposed solar cooking system.

## 2. Experimental setup

An experimental setup was realized in the renewable energies laboratory number 15 at Kasdi Merbah University in Ouargla to carry on our study and experiments.

This type of cooker is characterized by its simple design and ease of construction using available tools and materials. This experimental setup consists of:

**The inner box:** It was made of iron sheets and slightly larger than the cooking pot used in the experiment. It measured 24 cm in width, 35 cm in length, with a front height of 11 cm and a rear height of 20 cm, and a thickness of 0.2 cm, and an internal volume of approximately 13.02 liters. See the **Figure. III.2**. Iron was selected as the construction material due to its acceptable thermal performance, good heat retention characteristics, structural rigidity, and cost-effectiveness compared to other metals such as aluminum and stainless steel [44].

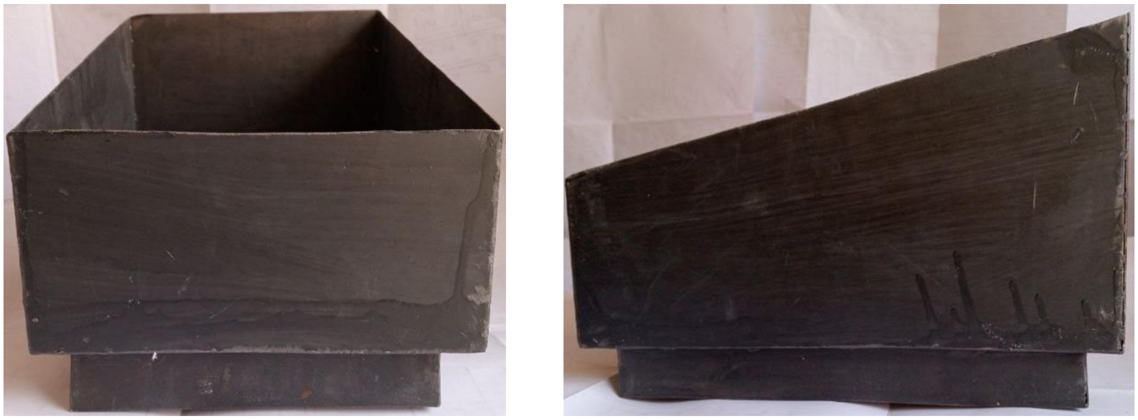

**Fig III.2:** Picture of the inner box.

**Thermal Storage:** A rectangular iron box was installed under the inner cooking chamber to place the paraffin wax inside it as a thermal storage material. The box measures 32 cm in length, 21 cm in width, and 4 cm in height. See the **Figure. III.3** and **Table III. 1.**

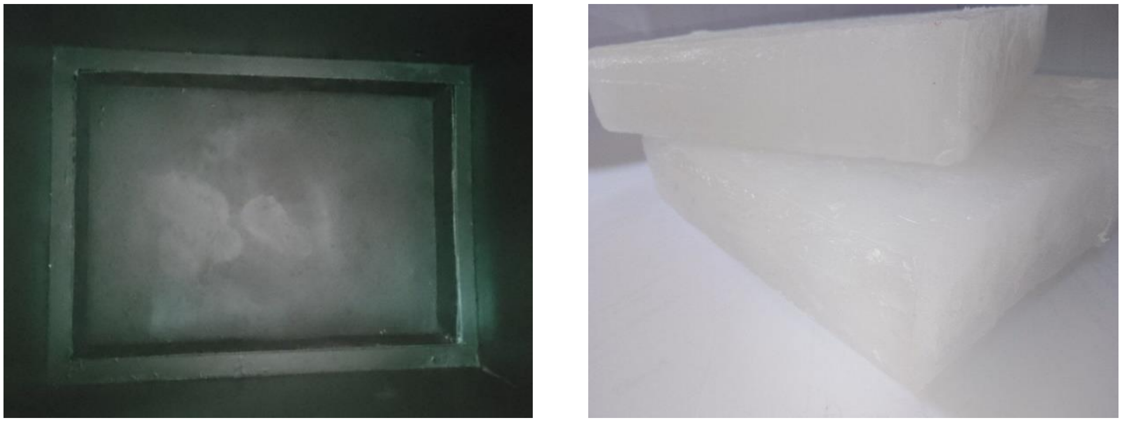

**Fig III.3:** Picture of the thermal Storage box and the paraffin wax material.

**Table III. 1:** Physical and chemical properties of paraffin wax:

| **Property** | **Value or Range** |
|---|---|
| Melting Point | 54–58 °C |
| Color | White or semi-transparent |
| Density (at 20 °C) | 0.88–0.94 g/cm³ |
| Chemical Composition | Mixture of alkanes (approximately C20–C40) |
| Flash Point | Approximately 199 °C |
| Water Solubility | Insoluble |

**The outer box:** It was made of wood and designed to be larger than the inner box, with a uniform gap of 7 cm on all sides between the two boxes. See the **Figure. III.4**.

**Fig III.4:** Picture of the outer box.

**Insulation:** The gap between the two boxes was filled with glass wool as insulation material see the **Figure. III.5**.

**Fig III.5:** Picture of the insulation.

**Electric Stove:** An electric stove with a power rating of 1000 watts was integrated into the solar cooker setup. See the **Figure. III.6**.

**Fig III.6:** Picture of the electric Stove.

**Cooking Pot:** An aluminum cooking pot was used and painted with matte black to enhance solar energy absorption. With a capacity of 2 liters, it is suitable for family cooking and is centrally placed inside the inner box to ensure uniform heat distribution. See the **Figure. III.7**.

**Fig III.7:** Picture of the cooking Pot.

**Double glazzed cover:** The cooker is equipped with a transparent double-glazed glass cover. The outer glass cover is non-heat-treated and has dimensions of 25 × 37 cm with a thickness of 0.5 cm, while the inner glass cover is heat-resistant with the same dimensions (25 × 37 cm) and thickness (0.4 cm). See the **Figure. III.8**.

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**Fig III.8:** Picture of the double-glazzed glass cover.

**Reflector:** A mirror was installed as a reflector to focus and direct sunlight into the cooking chamber. With dimensions of 25 × 37 cm, its curved shape increases the intensity of solar radiation reaching the cooking pot. See the **Figure. III.9**.

**Fig III.9:** Picture of the reflector.

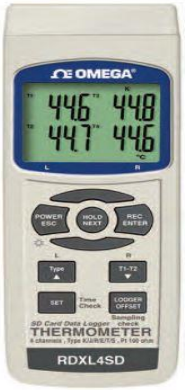
**PV Panel:** A 390 W monocrystalline **PV** module is mounted on the system to convert solar irradiation into electrical energy, which powers the electric heater. The panel's key specifications are:

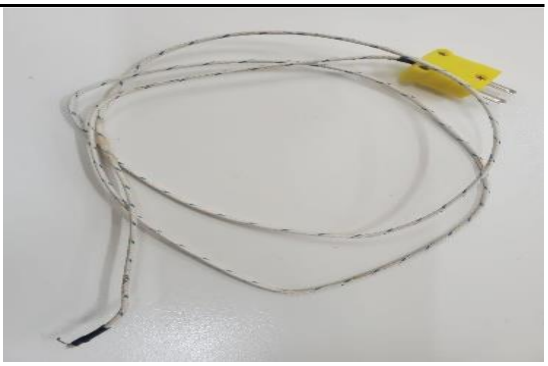
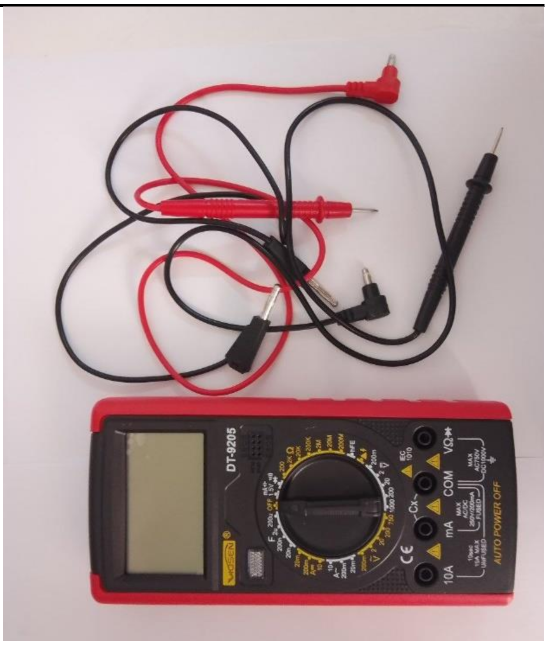
- Voltage at Maximum Power: 41 V
- Current at Maximum Power: 9.53 A
- Open-Circuit Voltage: 47.7 V
- Short-Circuit Current: 10.1 A
- Dimensions: 1967 × 992 × 40 mm

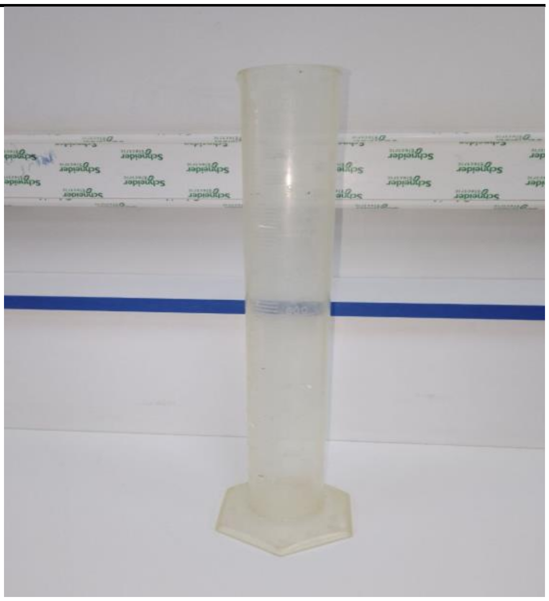
**Fig III.10:** Picture of the PV Panel.

## 3. Measurement equipment

**Table III. 2:** Devices used for measurement:

| Device | Role of the device | Image of the device |
|---|---|---|
| THERMOMETER | Temperature is measured in °C. |  |

| | | |
|---|---|---|
| CABLE TYPE K | |  |
| SOLARIMETER | Solar radiation measurement W/m$^2$. |  |
| MILTIMETER | Electrical tension is measured in V. |  |

| | | |
|---|---|---|
| DIGITAL PRECISION SCALE | Weight is measured in kilograms. |  |
| GRADUATED MEASURING CYLINDER | The volume of liquid is measured in litres. |  |
| THERMO PAINT | Black coating for hot surfaces up to 600°C. |  |

| | | |
|---|---|---|
| UNIVERSAL SEALING COMPOUND 300 SI | Silicone-based sealing compound for sealing joints, flanges, and surfaces. |  |

## 4. Operating mode

The proposed solar cooking system operates by combining photovoltaic (**PV**) and thermal energy storage technologies to ensure continuous cooking capabilities.

As it can be observed in the **Figure III.11** below, sunlight is captured by a PV panel, which converts solar radiation into electricity to power the electric stove embedded in the cooker. At the same time, sunlight is concentrated on the cooking area with the help of a solar reflector and it passes through a double-glazed glass cover those aids in trapping heat as well as retaining heat inside the chamber of cooking (containing the pot), is enclosed by an insulated casing and a secondary outer box to reduce heat losses.

To allow use to go beyond daylight hours or when there is not enough sunlight, thermal energy is stored beneath the stove in a thermal storage unit filled with paraffin wax. This phase change material stores excess thermal energy during the day and releases it when needed, always keeping good cooking temperatures. This hybrid setup ensures reliable, environmentally sustainable cooking, especially in places without grid connection or rural areas.

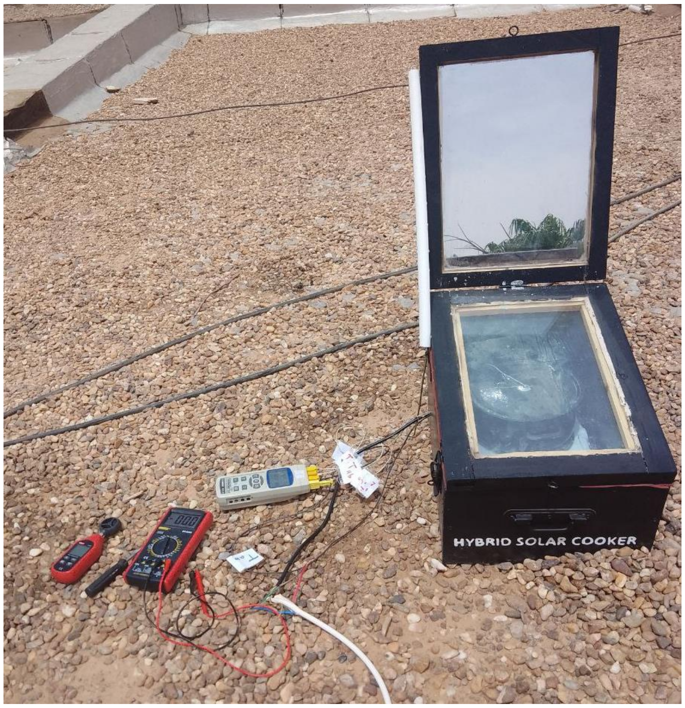


**Fig III.11:** Real picture of the hybrid solar cooking system.

## 5. Mathematical modeling of a hybrid solar cooking system

The objective of the mathematical model is to predict the water temperature inside the cooking pot and to evaluate the thermal performance and efficiency of a hybrid solar cooker system integrating photovoltaic and thermal energy storage.

## 5.1.Theoretical Thermal Modeling of Solar Cooking

The thermal behavior of the cooker can be modeled using the First Law of Thermodynamics (Energy Conservation):

$$Q_{st} = Q_{abs} - Q_{loss} \quad \text{(Eq III. 1)}$$

This equation represents the balance between energy input, losses, and useful energy [45].

### 5.1.1. Absorbed Energy

The absorbed solar energy by the cooker surface can be estimated using the following expression:

$$Q_{abs} = \alpha \cdot \tau \cdot A_{abs} \cdot G \quad \text{(Eq III. 2)}$$

- $\alpha$: Absorptivity (dimensionless).
- $\tau$: transmittance (dimensionless).
- $A_{abs}$: Effective area exposed to solar radiation ($m^2$).
- G: Solar irradiance ($W/m^2$).

### 5.1.2. Stored Energy

The amount of energy stored in the system can be quantified based on the change in water temperature over time, using the following expression:

$$Q_{st} = m_w \cdot C_p \cdot \frac{dT}{dt} \tag{Eq III. 3}$$

- $m_w$: Mass of water (kg).
- $C_p$: Specific heat capacity (J/kg.K).
- $\frac{dT}{dt}$: Rate of temperature change.

### 5.1.3. Heat Losses

Heat losses occur through conduction, convection, and radiation [46]. The overall losses are given by:

$$Q_{loss} = h \cdot A_{abs} \cdot (T_{int} - T_{ext}) + \varepsilon \cdot \sigma \cdot A_{abs} \cdot (T_{int}^4 - T_{ext}^4) \tag{Eq III. 4}$$

- h: Overall heat transfer coefficient ($W/m^2 \cdot K$).
- A: Surface area ($m^2$).
- $\varepsilon$: Surface emissivity.
- $\sigma$: Stefan–Boltzmann constant = $5.67 \times 10^{-8}$ $W/m^2. K^4$
- $T_{int}$, $T_{ext}$: Internal and External temperatures (K).

## 5.2. Global Energy Balance

By combining the above, the global energy balance is written as:

$$m_w \cdot C_p \cdot \frac{dT}{dt} = \alpha \cdot \tau \cdot A \cdot G - h \cdot A \cdot (T_{int} - T_{ext}) - \varepsilon \cdot \sigma \cdot A \cdot (T_{int}^4 - T_{ext}^4) \tag{Eq III. 5}$$

It should be noted that both the solar irradiance G and the temperatures $T_{int}$ and $T_{ext}$ are variables that change over time. Therefore, in Equation (**Eq III.6**), these parameters vary over the simulation period and must be considered as functions of time.

$$m_w \cdot C_p \cdot \frac{dT}{dt} = A_{abs} \cdot \left(\alpha \cdot \tau \cdot G - h \cdot (T_{int} - T_{ext}) - \varepsilon \cdot \sigma \cdot (T_{int}^4 - T_{ext}^4)\right) \qquad \text{(Eq III. 6)}$$

To simplify, we divide everything by $mc_p$:

$$\frac{dT}{dt} = K \cdot \left(\alpha \cdot \tau \cdot G - h \cdot (T_{int} - T_{ext}) - \varepsilon \cdot \sigma \cdot (T_{int}^4 - T_{ext}^4)\right) \qquad \text{(Eq III. 7)}$$

With:

$$K = \frac{A_{abs}}{m_w \cdot C_p} \qquad \text{(Eq III. 8)}$$

To facilitate numerical simulation in MATLAB, the energy balance equation was discretized using the explicit Euler method. This approach allows estimating the temperature at the next time step as follows:

$$T_{n+1} = T_n + \Delta t \cdot K \cdot \left(\alpha \cdot \tau \cdot G - h \cdot (T_{int} - T_{ext}) - \varepsilon \cdot \sigma \cdot (T_{int}^4 - T_{ext}^4)\right) \qquad \text{(Eq III. 9)}$$

## 5.3.Efficiency

Efficiency η is the ratio of useful energy output to total energy input [42]:

$$\eta = \frac{Q_u}{Q_{in}} \qquad \text{(Eq III. 10)}$$

$$\eta = \frac{m_w \cdot C_p \cdot (T_F - T_i) + Q_{PCM}}{\alpha \cdot A \cdot G \cdot \Delta t} \qquad \text{(Eq III. 11)}$$

- A: Effective area exposed to solar radiation ($m^2$).

### 5.3.1. Electrical energy

The electrical energy delivered by the photovoltaic panel can be calculated using the following expression:

$$Q_{ele} = V \cdot I \cdot \Delta t \qquad \text{(Eq III. 12)}$$

- V: Electric potential difference across the photovoltaic panel (V).
- I: Electric current flowing through the photovoltaic panel (A).
- Δt: Time duration over which the current flows (s).

### 5.3.2. Stored energy

The total energy stored in the PCM after the melting process can be expressed as:

$$\mathrm{Q_{PCM}} = \mathrm{m_{PCM}} \cdot f_{liq} \cdot \mathrm{L_f} + \mathrm{m_{PCM}} \cdot \mathrm{C_{p,liquid}} \cdot \Delta T \qquad \text{(Eq III. 13)}$$

- $L_f$: Latent heat of **PCM** (kJ/kg).
- $C_{p,liquid}$: Specific heat capacity of liquid PCM (kJ/kg.K).
- $f_{liq}$: liquid fraction.

## 5.4. Relative Error

The relative error quantifies the deviation of the measured value from the actual value as a percentage:

$$Relative\ Error = \frac{\boldsymbol{X_{actual} - X_{measured}}}{\boldsymbol{X_{actual}}} \times \mathbf{100}\ \% \qquad \text{(Eq III. 14)}$$

This equation indicates how accurately the measurement represents the true value [47].

## Conclusion

In this chapter, we addressed an experimental and numerical study by preparing and setting up the hybrid solar cooking box. We also presented the components of the solar cooker, along with the equipment and measuring instruments used during the testing the solar cooker. The objective of the next chapter is the presentation and discussions of experimental measurements and the numerical results.

# Chapter IV

## Results and discussions

## Introduction

In this chapter, we present the results obtained as part of this thesis work. We begin by outlining the experimental results for different hybrid solar cooking configurations. Subsequently, the developed numerical model is validated by comparing its outputs with experimental measurements from the most efficient configuration. This approach highlights both the reliability of the model and the accuracy of the proposed system's performance analysis.

## 1. Ambient Conditions Overview During the Experiments

The experiments were conducted in a region characterized by dynamic climatic conditions, which played a pivotal role in the observed thermal performance of the system and significantly affected the results obtained. The ambient temperature ranged from 32°C at 10:00 AM and peaked at around 40°C by 14:00 PM for both the solar cooker with paraffin wax and the one with paraffin wax and PV panel. It then slowly dropped to around 35°C by 18:00 PM. This continuous increase in temperature helped reduce heat losses between the cooking medium and the surrounding environment, which improved the thermal efficiency of the system.

On the other hand, data for solar radiation showed a very clear increase from the morning hours, reaching about 1230 W/m² at 10:00 AM. Then it more or less stayed at about 1100 to 1200 W/m² until 14:00 PM. After that, it began to decline clearly, reaching below 700 W/m² by 17:00 PM, and falling to less than 400 W/m² by 18:00 PM, particularly in the solar cooker with paraffin wax and PV panel, due to the presence of some clouds in that period.

It can be concluded from this analysis that solar irradiance was the primary factor determining the performance of the solar cooker since peak irradiance periods coincided with the highest internal temperatures recorded in the system. See **Figure IV.1 and 2**.

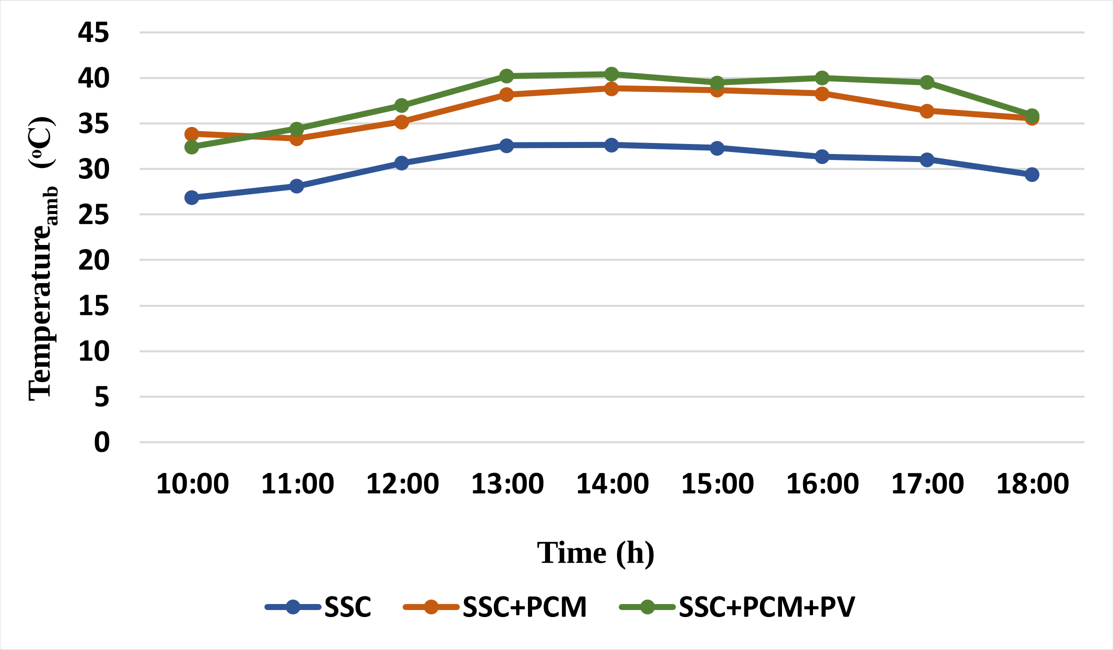


**Fig IV.1:** The ambient temperature measured during the day for **SSC, SSC+PCM** and **SSC+PCM+PV**.

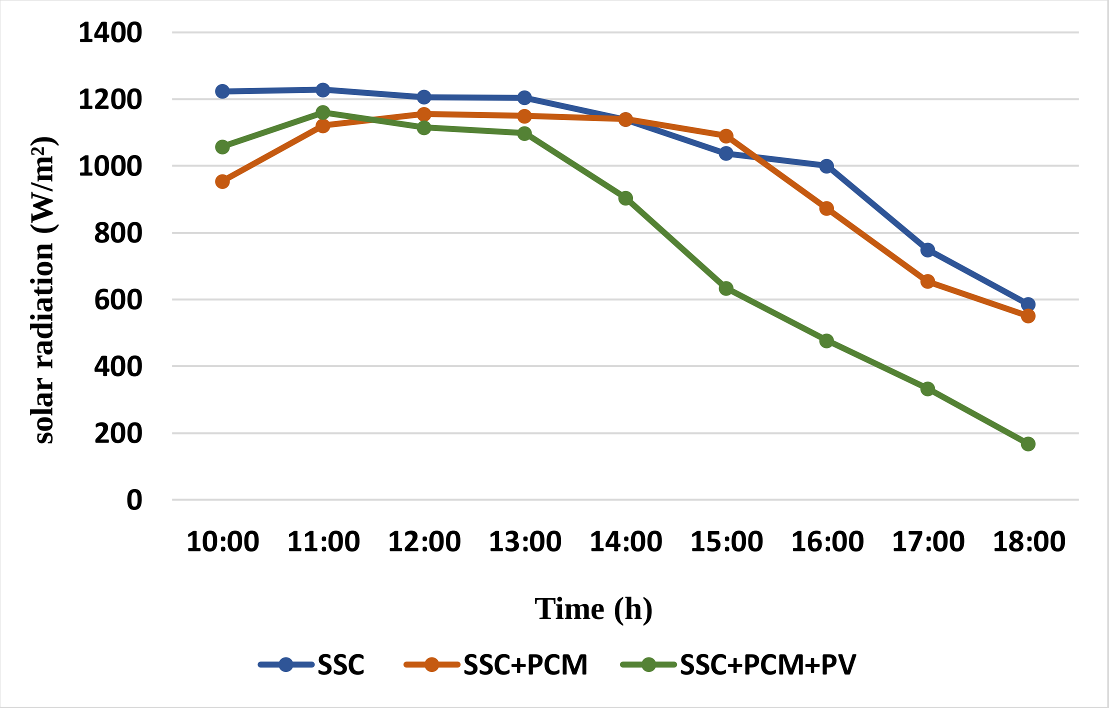


**Fig IV.2:** The solar radiation measured during the day for **SSC, SSC+PCM** and **SSC+PCM+PV**.

## 2. Experimental study of the system

In this study, experimental tests were conducted over three sunny to partially overcast days. On each day, a different solar cooker configuration was tested in real atmospheric conditions. The measurements were taken on the following dates:

- 16/05/2025 – Simple Solar Cooker (**SSC**)
- 06/05/2025 – Simple Solar Cooker integrated with paraffin wax (**SSC + PCM**)
- 08/05/2025 – Simple Solar Cooker enhanced with paraffin wax and a photovoltaic (**PV**) panel (**SSC + PCM + PV**)

Each set of measurements was performed between 10:00 AM and 18:00 PM, under Variable but generally good weather conditions characterized by high solar irradiance (peaking over 1200 W/m²), ambient temperatures between 32°C and 42°C.

### 2.1. Analysis and Discussion of Experimental Results

#### 2.1.1. Simple Solar Cooker (SSC)

**Figure IV.3** shows the evolution in both the water and absorber plate temperatures for the **SSC** configuration. The water temperature increased gradually, peaking at about 74°C at 16:00 PM after hovering about 38°C at 11:00 AM. The temperature of the absorber plate followed closely, rising to between 75 and 78°C in the same time frame.

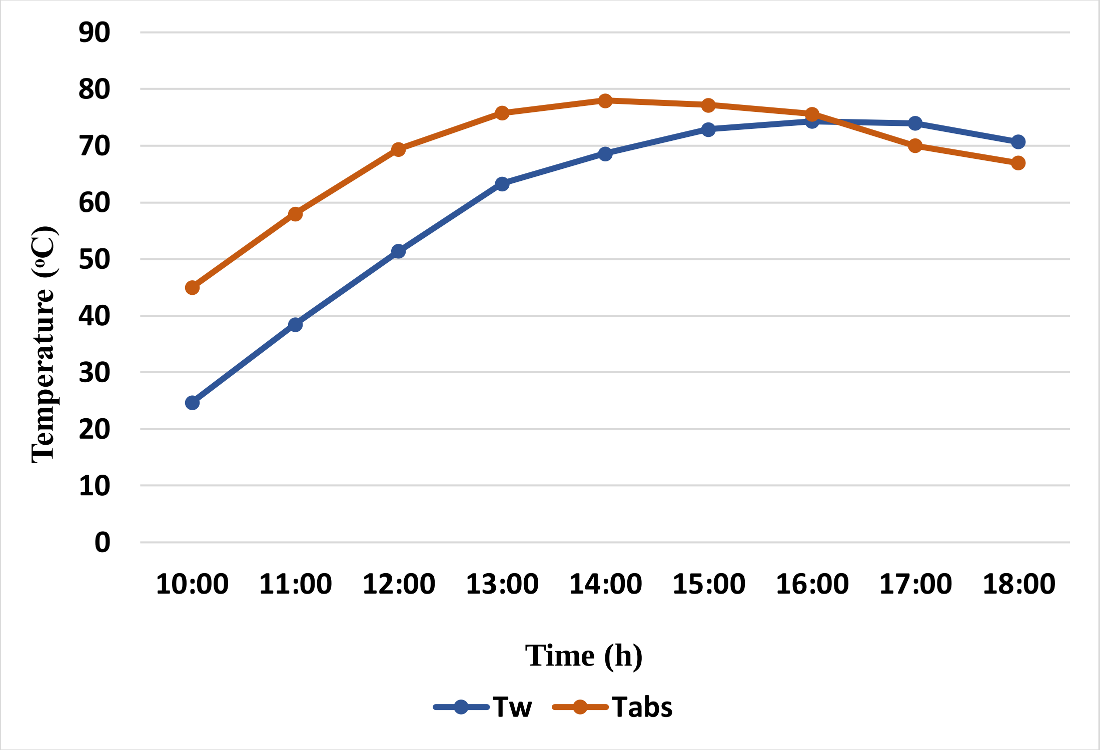


**Fig IV.3:** Water and absorber temperatures during the day in the **SSC**.

**Figure IV.4** illustrates the variation of thermal efficiency over time. According to the results, thermal efficiency peaked in the early hours, exceeding 40% between 11:00 AM and 13:00 PM, before to a steep decline to less than 20% after 15:00 PM. This decline is explained to the decrease in solar radiation and the increase in thermal losses.

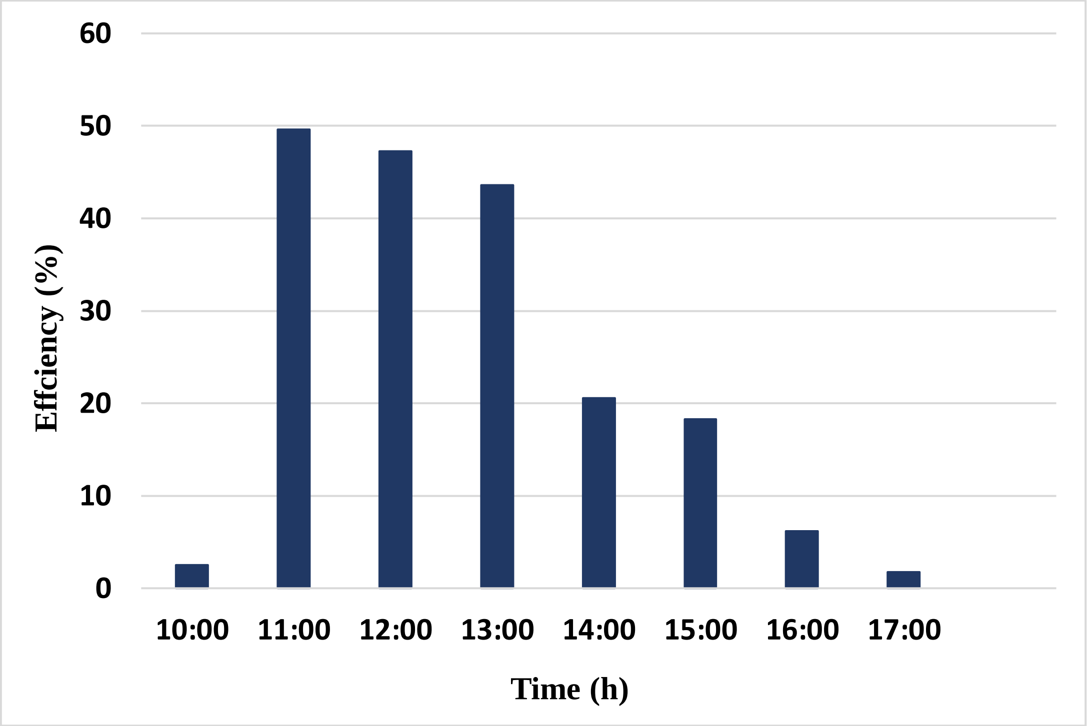


**Fig IV.4:** Efficiency during the day in the **SSC**.

### 2.1.2. Solar Cooker with Paraffin Wax (SSC + PCM)

**Figure IV.5** presents the evolution of water, absorber plate, and paraffin wax temperatures for the **SSC+PCM** configuration. The integrating phase change material (paraffin wax) enhanced stability and thermal performance. The water temperature remained stable at a relatively high level, exceeding 67°C from 14:00, while the absorber plate maintained slightly lower temperatures compared to the SSC case, suggesting that some heat was absorbed by the paraffin.

By the conclusion of the measuring time, the paraffin temperature gradually increased to 59°C. This continuous rise illustrates how well the phase change material absorbs and stores thermal energy during the day.

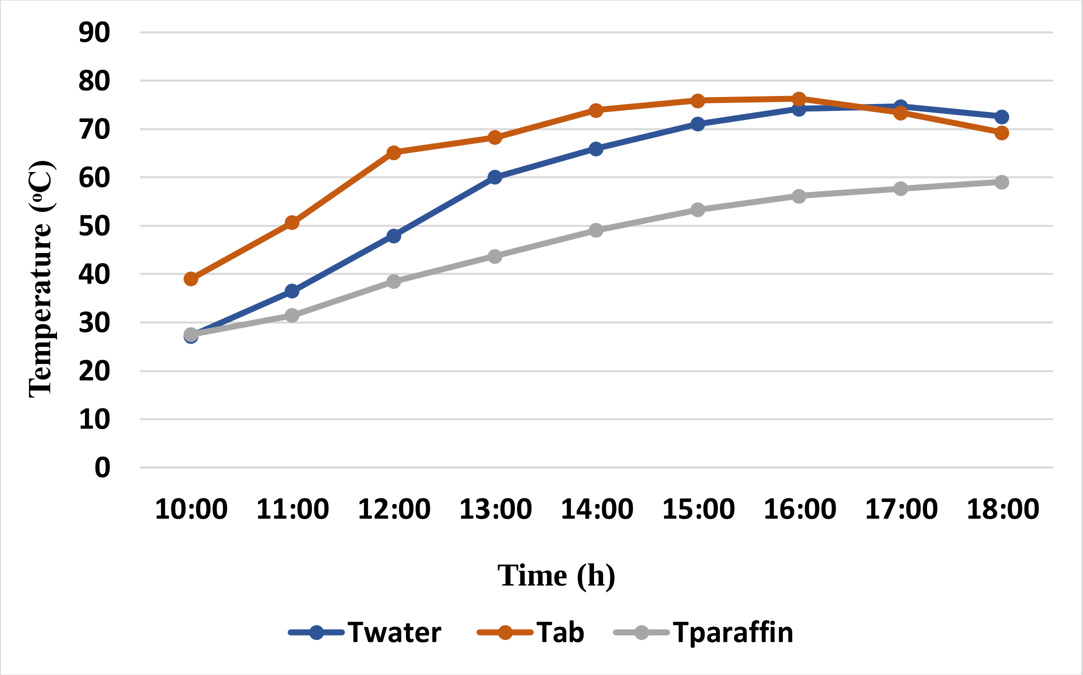


**Fig IV.5:** Water, absorber and paraffin temperatures during the day in the **SSC+PCM**.

**Figure IV.6** illustrates the evolution of thermal efficiency over time. According to the results, the efficiency reached its peaked at 46% between 12:00 and 13:00 PM, then started to decline. This configuration reduced the afternoon performance decline and produced a smoother thermal profile.

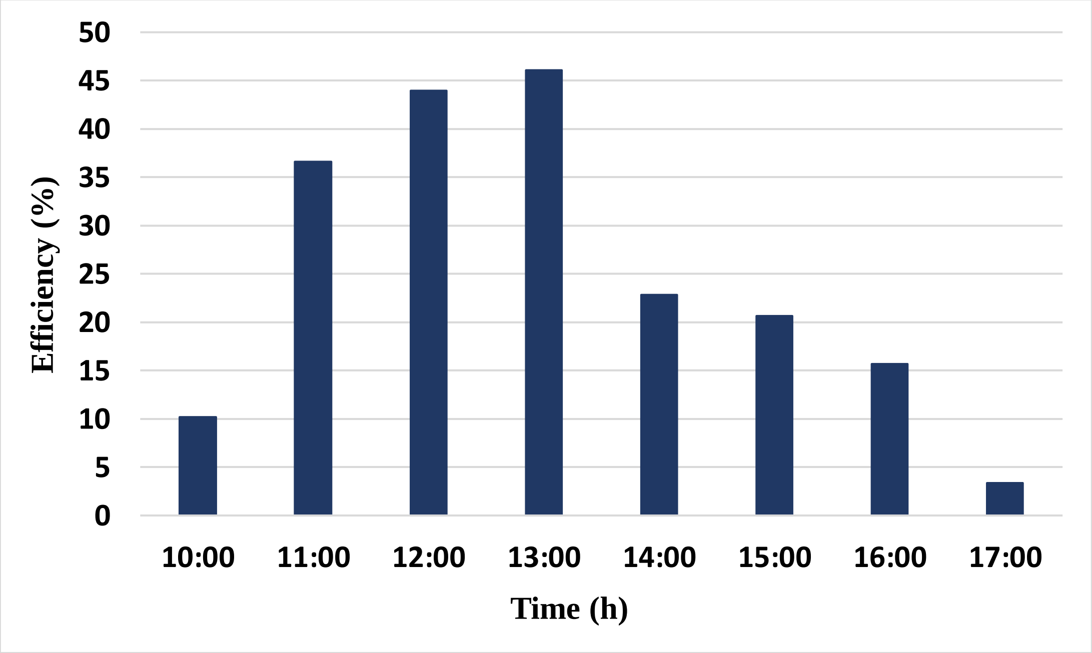


**Fig IV.6:** Efficiency during the day in the **SSC+PCM**.

### 2.1.3. Solar Cooker with Paraffin Wax and Photovoltaic Panel (SSC + PCM + PV)

**Figure IV.7** depicts the change of water, absorber plate, and paraffin wax temperatures for the **SSC+PCM+PV** configuration. When it came to water temperature, the hybrid improved system performed the best. It began reasonably low and rose quickly, reaching the highest temperature of all configurations about 90°C at 14:00 PM. The paraffin wax exhibited the same thermal behavior as in the prior configuration, whereas the absorber plate temperature steadied between 70 and 75°C.

It should be noted that the system utilizes a 390 W photovoltaic panel to operate a 1000 W electric stove. As a result, the water temperature did not reach higher values due to the insufficient power supply, which could be addressed by incorporating multiple PV panels.

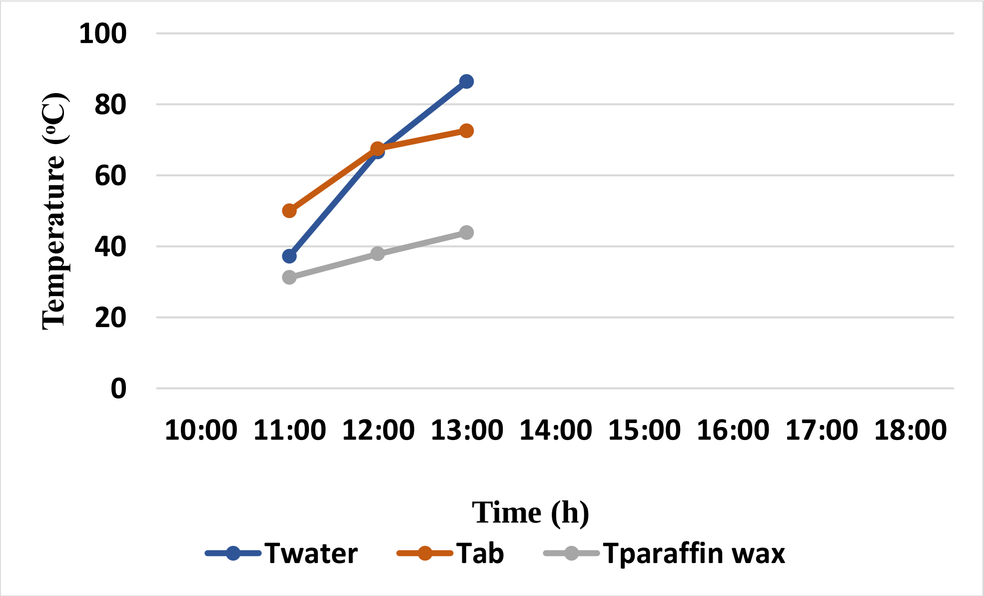


**Fig IV.7:** Water, absorber and paraffin temperatures during the day in the **SSC+PCM+PV**.

**Figure IV.8** shows the thermal efficiency of the hybrid solar system (SSC+PCM+PV) at 12:00 and 13:00. This configuration demonstrated higher efficiency compared to previous setups, mainly due to the additional energy provided by the photovoltaic panel integrated with the system. See **Figure IV.9.**

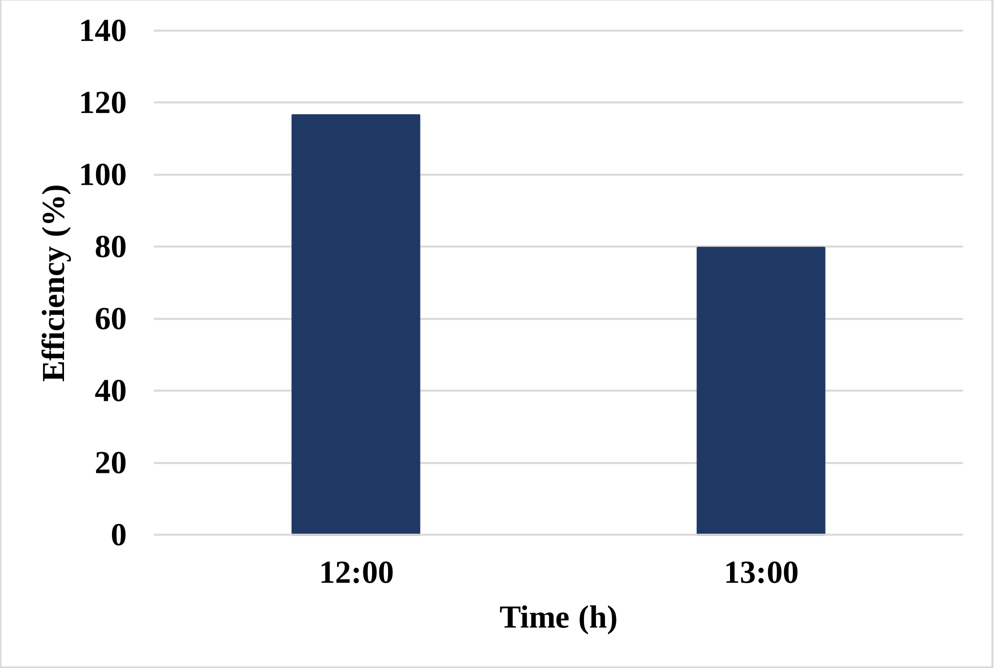


**Fig IV.8:** Efficiency during the day in the **SSC+PCM+PV**.

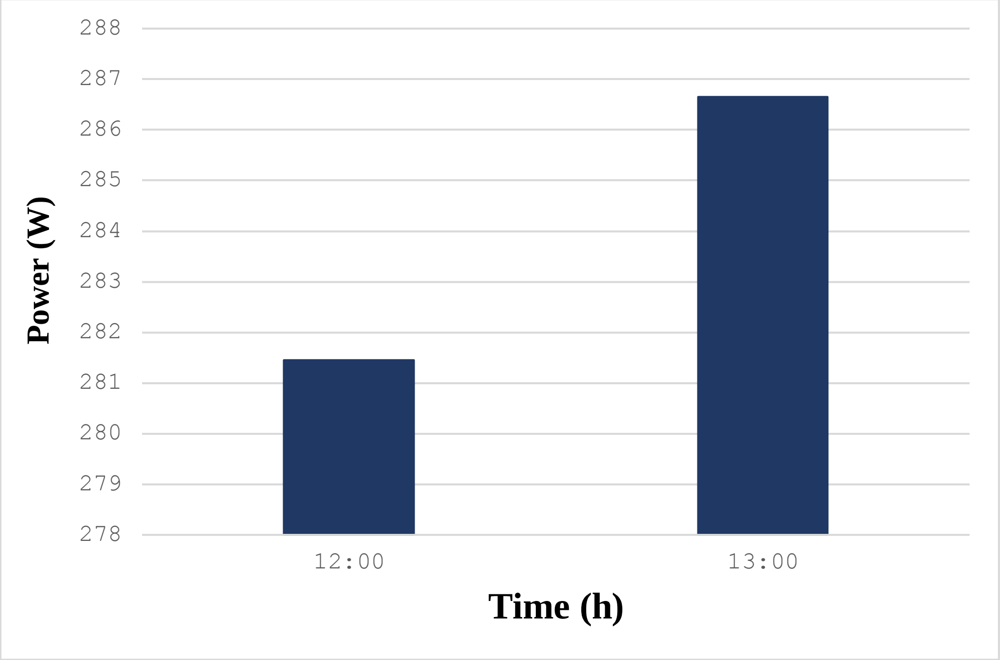


**Fig IV.9:** Power during the day in the **SSC+PCM+PV**.

## 2.2. Summary and Selection of Optimal Design

**Figure IV.10** presents a comparison of efficiency profiles for the **SSC**, **SSC+PCM**, and **SSC+PCM+PV** configurations throughout the day. Among the three setups, the

**SSC+PCM+PV** system achieved the highest efficiencies, making it the most effective configuration, particularly when solar irradiance decreased and the **PV** panel supplied additional energy. The **SSC+PCM** configuration outperformed the basic **SSC** system by providing a smoother thermal profile and reducing afternoon performance drops, thanks to the paraffin wax's heat storage and release capabilities. In contrast, the **SSC** system showed the lowest overall efficiency, with a noticeable decline after midday due to reduced solar input and increased thermal losses.

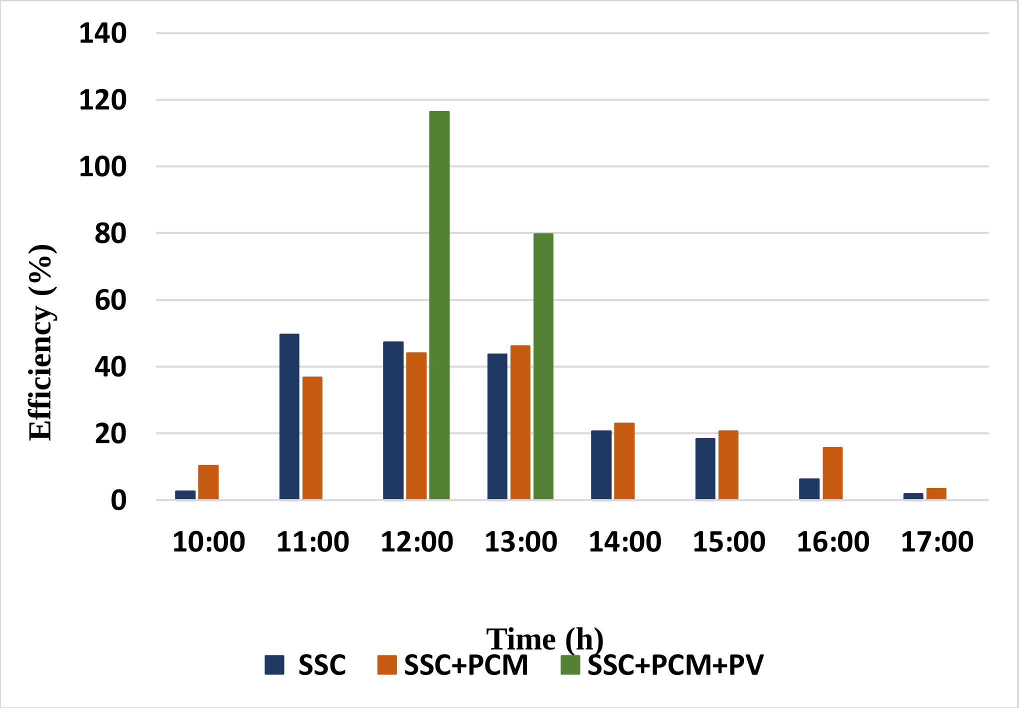


**Fig IV.10:** Comparison of Efficiency Profiles for **SSC, SSC+PCM**, and **SSC+PCM+PV** Configurations Throughout the Day.

## 3. Numerical Model Validation

The numerical model was validated against the experimental measurements obtained during the solar cooker tests. Show in **Fig IV.11** and **Fig IV.12**. **Table IV.1** presents the relative errors between the simulated water temperatures derived from the MATLAB model and the actual experimental data, with a maximum relative error of 10%. This comparison effectively demonstrates the model's accuracy and reliability in predicting the thermal behavior of the hybrid solar cooking system.

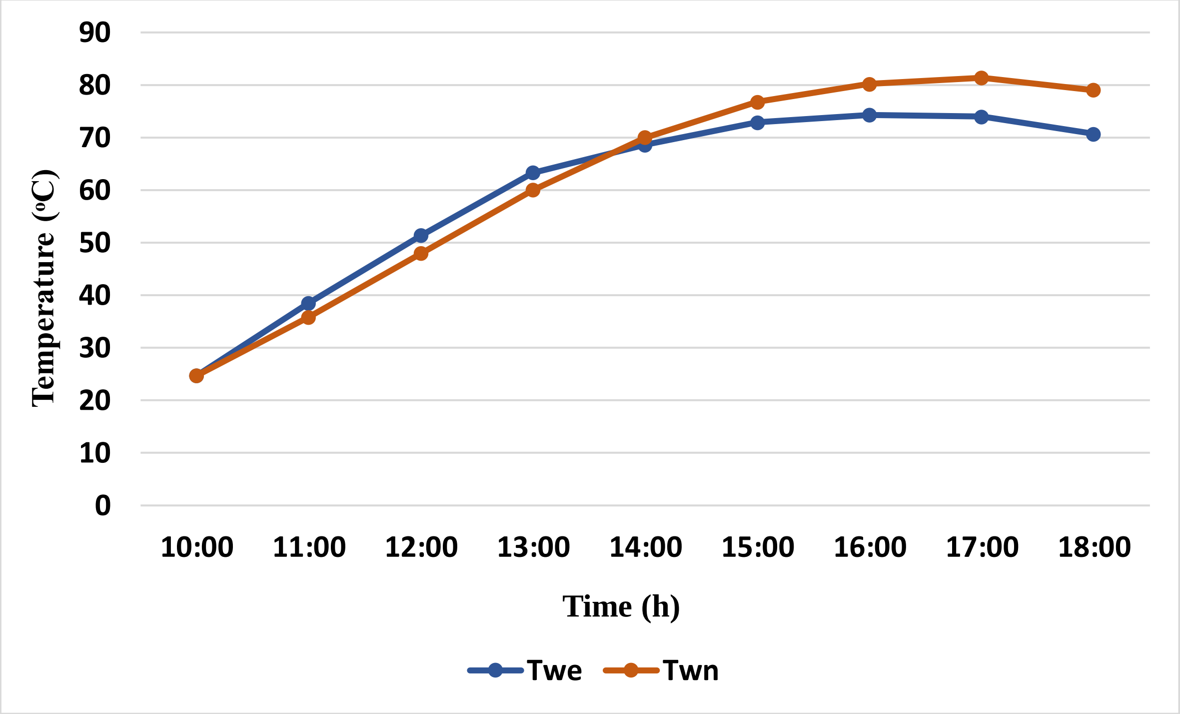


**Fig IV.11:** Simulated and experimental water temperatures in the **SSC**.

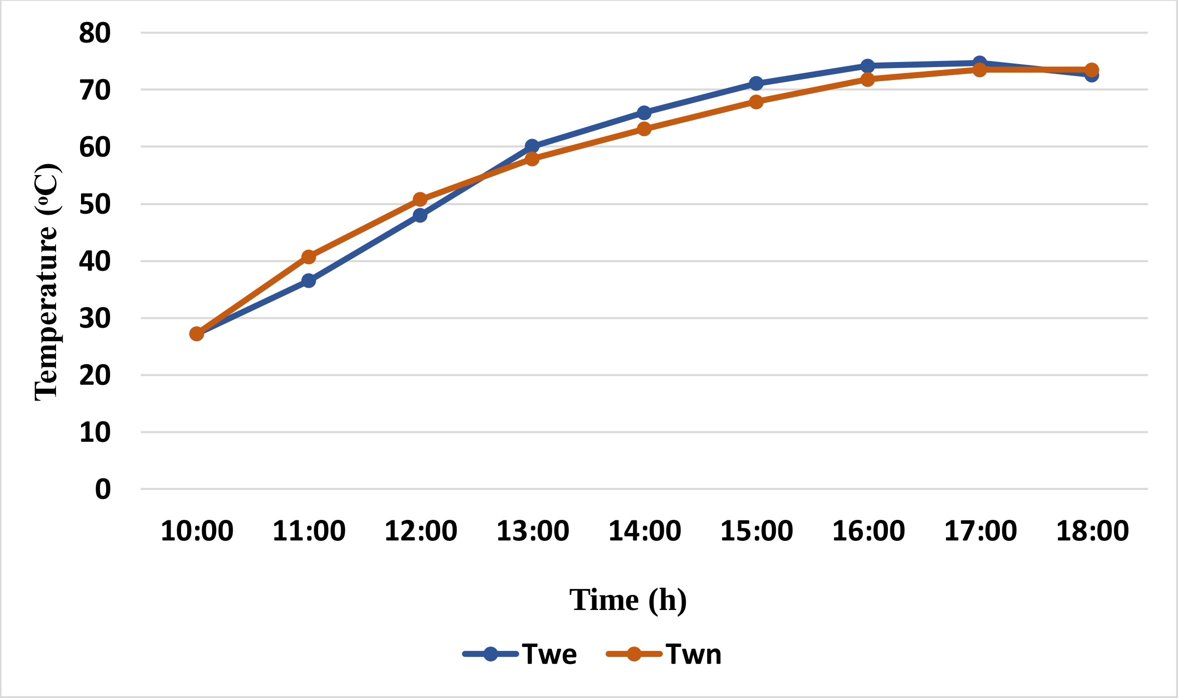


**Fig IV.12:** Simulated and experimental water temperatures in the **SSC+PCM**.

**Table IV.1:** Comparison of Simulated and Experimental Water Temperatures with Relative Errors.

| | SSC | | | SSC+PCM | | |
|---|---|---|---|---|---|---|
| **Time** | **$T_{we}$ (°C)** | **$T_{wn}$ (°C)** | **Relative error (%)** | **$T_{we}$ (°C)** | **$T_{wn}$ (°C)** | **Relative error (%)** |
| 10:00 | 24.7 | 24.7 | 0 | 27.2 | 27.2 | 0 |
| 11:00 | 38.5 | 35.8 | 7 | 36.5 | 40.7 | 10 |
| 12:00 | 51.4 | 47.9 | 7 | 48 | 50.7 | 5 |
| 13:00 | 63.3 | 60 | 5 | 60.1 | 57.8 | 3 |
| 14:00 | 68.6 | 70 | 2 | 66 | 63.1 | 4 |
| 15:00 | 72.9 | 76.7 | 5 | 71.1 | 67.8 | 4 |
| 16:00 | 74.3 | 80.1 | 7 | 74.2 | 71.7 | 3 |
| 17:00 | 74 | 81.3 | 9 | 74.7 | 73.5 | 1 |
| 18:00 | 70.7 | 79 | 10 | 72.6 | 73.4 | 1 |

## 4. Parametric Study

In this part of the chapter, we present the results obtained from simulations conducted using MATLAB. The objective is to identify and analyze the key parameters that influence the water temperature in the studied hybrid solar cooking system. To assess the effect of each parameter individually, all other parameters were held constant during each simulation, as detailed in **Table IV.2.**

**Table IV.2:** Fixed Parameters Used in the Parametric Study.

| **Parameter** | **Value** | **Unit** |
|---|---|---|
| Solar radiation (**G**) | 1000 | $W/m^2$ |
| Mass of water ($\mathbf{m_w}$) | 1 | Kg |
| Air ambient temperature ($\mathbf{T_{amb}}$) | 25 | $^oC$ |
| Mass of paraffin wax ($\mathbf{m_p}$) | 1.6 | Kg |

## 4.1. Effect Solar Radiation on Water Temperature in the (SSS+PCM)

The results presented in **Figure IV.13**, which examine the effect of solar radiation on water temperature in the studied system, clearly indicate a direct correlation: as solar radiation increases, the water temperature also rises. This demonstrates that higher solar irradiance leads to more effective heating of the water within the solar cooking system.

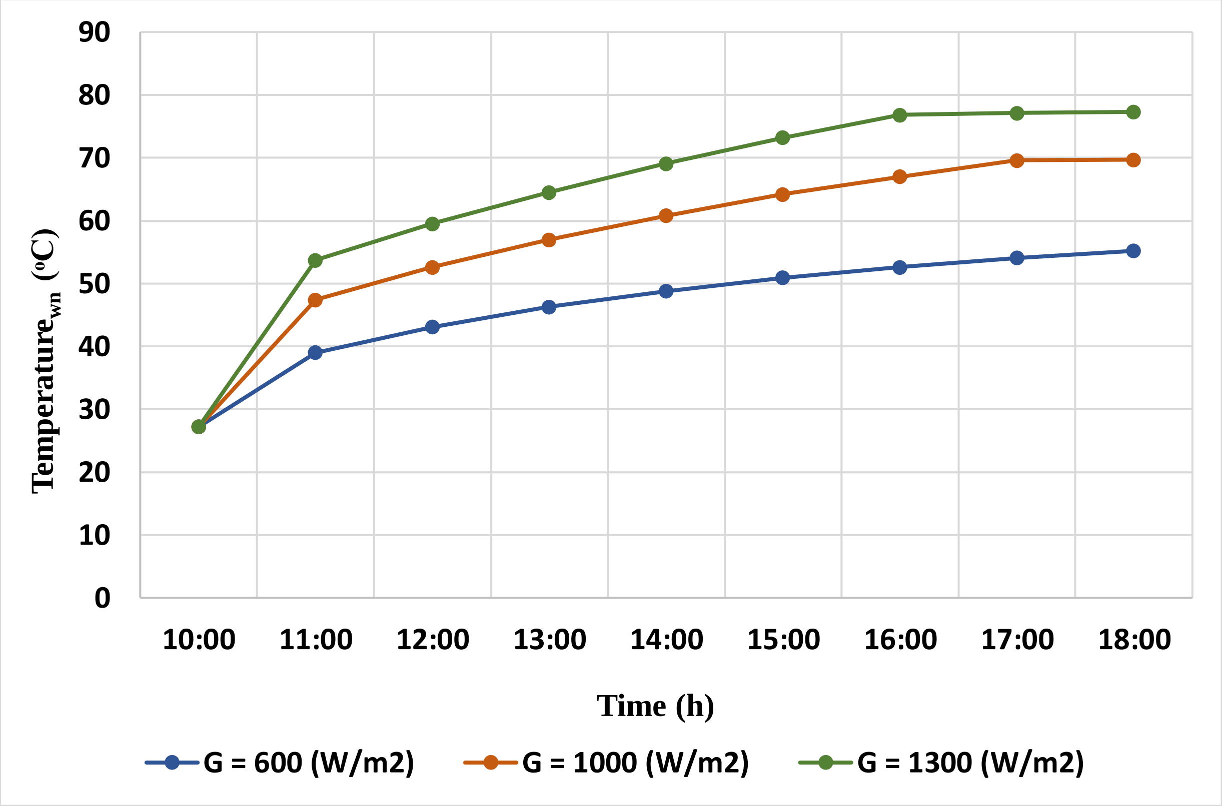


**Fig IV.13:** Effect of solar radiation on water temperature in the hybrid solar cooking system.

## 4.2. Effect of Water Mass on Water Temperature in the (SSS+PCM)

The results in **Figure IV.14** indicate that the mass of water used in the solar cooking system has a significant impact on the temperature rise. Specifically, a lower water mass leads to a faster and higher increase in water temperature due to the reduced thermal inertia, allowing the available thermal energy to more effectively heat the smaller volume.

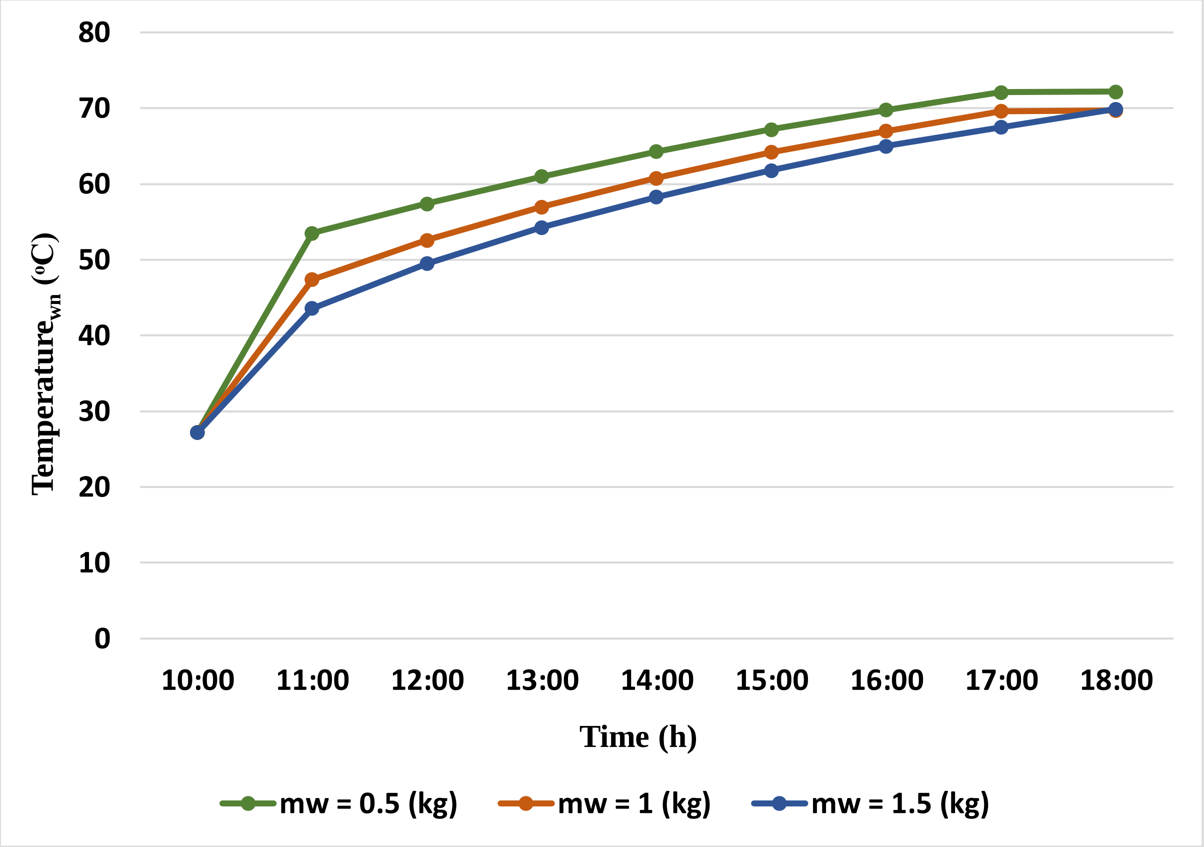


**Fig IV.14:** Effect of water mass on water temperature in the hybrid solar cooking system.

### 4.3. Effect of Air ambient temperature on Water Temperature in the (SSS+PCM)

The findings in **Figure IV.15**, which examine the effect of air ambient temperature affects the water temperature within the studied solar cooking system, show a clear and direct relationship. The water temperature within the cooker rises in tandem with the outside temperature. This implies that higher surrounding air temperatures enhance the thermal insulation and lowers heat loss, enabling the system to hold onto more heat and more effectively raise the water temperature.

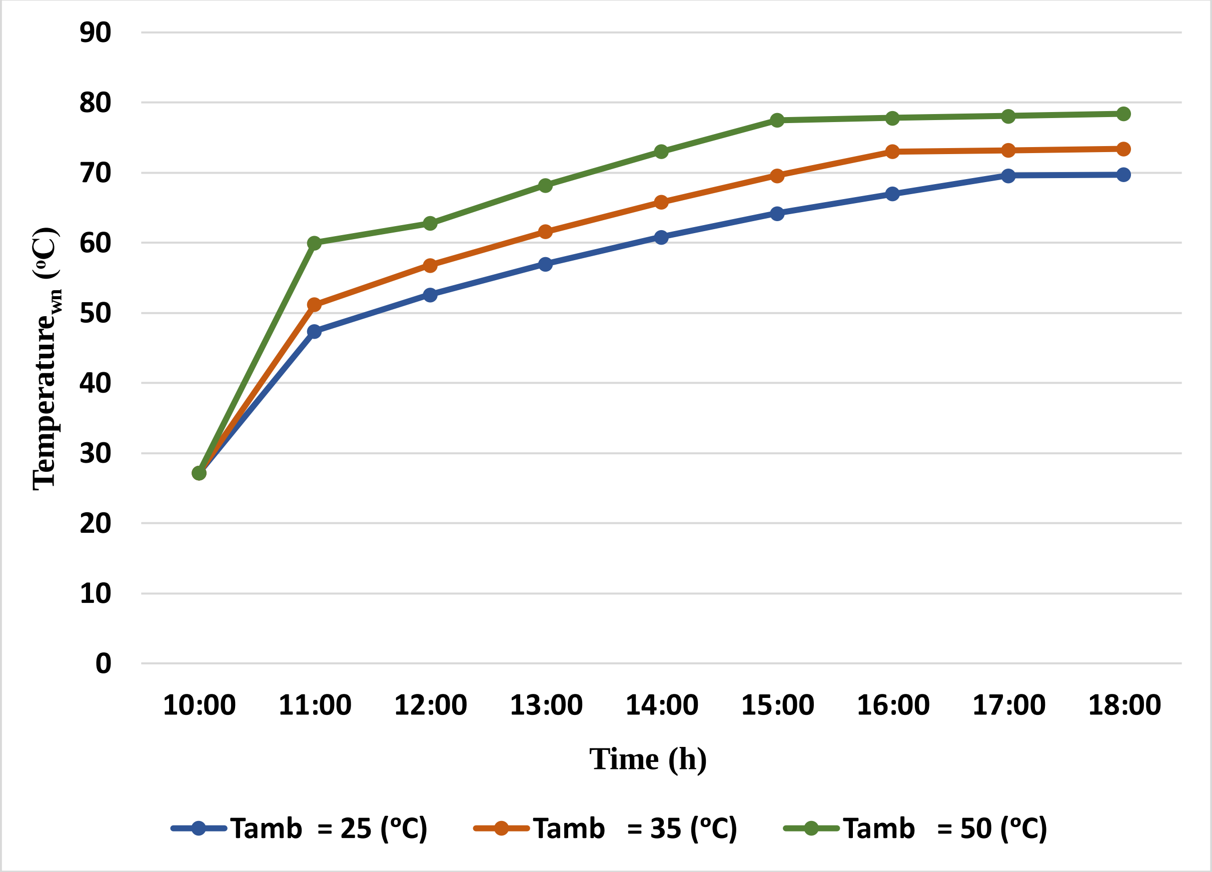


**Fig IV.15:** Effect of air ambient temperature on water temperature in the hybrid solar cooking system.

## 4.4. Effect of Mass of Paraffin Wax on Water Temperature in the (SSS+PCM)

An inverse relationship between the paraffin wax mass and water temperature in the studied solar cooking system is shown by the results in **Figure IV.16**. In particular, the water temperature rises as the mass of the thermal storage material decreases. This is attributed to the reduced heat absorption by the paraffin, which enables the cooking fluid to retain more thermal energy.

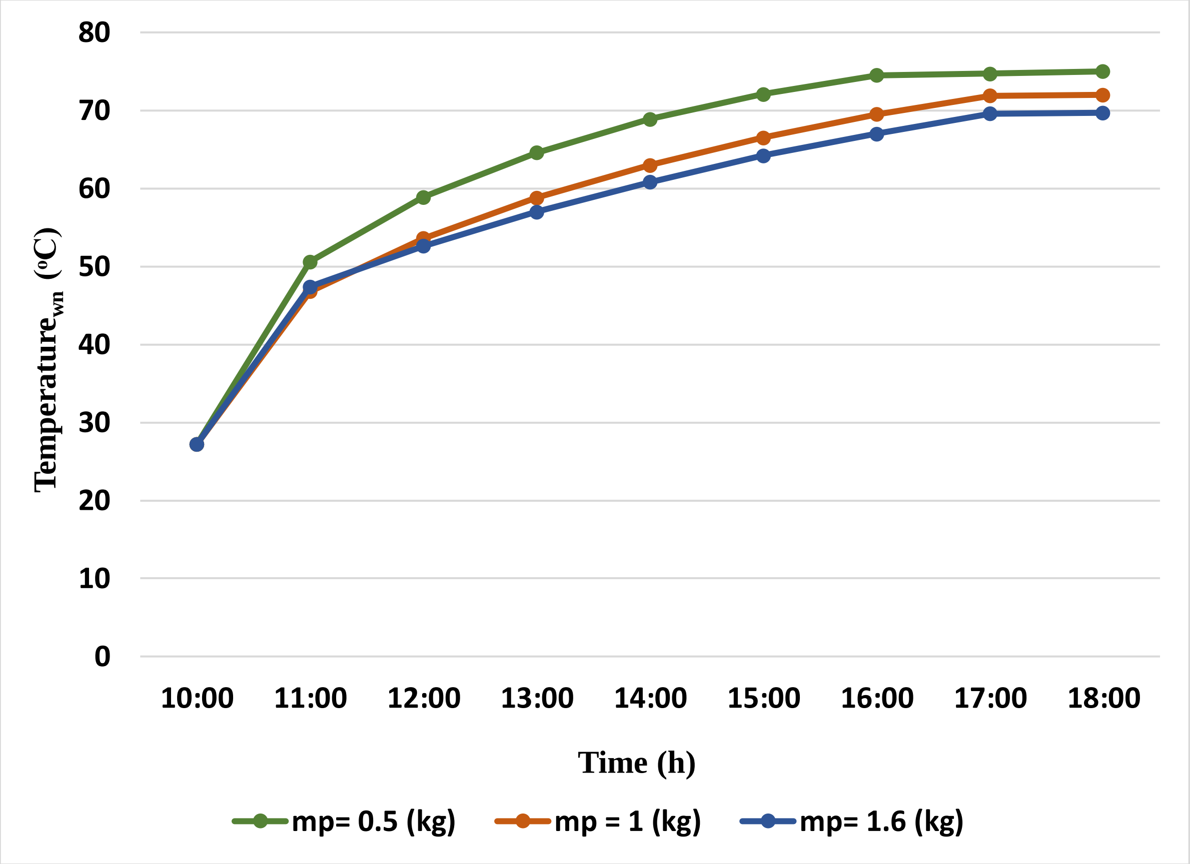


**Fig IV.16:** Effect of paraffin wax mass on water temperature in the hybrid solar cooking system.

## Conclusion

Based on the analyses and results presented in this chapter, and in light of the climatic conditions prevailing in the Ouargla region, the hybrid system (**SSC+PCM+PV**) demonstrated notable performance. Key influencing parameters were identified and their effects on the system were evaluated. Additionally, the thermal performance of the various studied configurations was assessed, highlighting the potential of the proposed design under realistic operating conditions.

# General Conclusion

# General Conclusion

In this research, we investigated a hybrid solar cooking system that combined thermal energy storage using paraffin wax with photovoltaic **(PV)** panels. This system was designed as a clean and sustainable substitute for conventional cooking techniques, especially in solar radiation rich regions like Ouargla, where solar energy is an abundant but intermittent resource.

The main objective of this research was to improve the efficiency and continuity of solar cooking by making up for the limitations of sunshine availability, especially at night or during cloudy conditions. To this end, we proposed a dual-source approach: combining direct solar heating with electric heating powered by photovoltaic panels, and thermal storage to store energy for later use.

This study was conducted in four main stages. We first went over the basic concepts of solar cooking and analyzed existing technologies, highlighting the limitations of traditional solar cookers and the potential improvements. Second, we carried out a comprehensive literature review on hybrid solar cooking systems, highlighting new developments and practical hybridization techniques that improve performance. In the third stage, we designed and built an experimental prototype, which was tested under real climatic conditions in Ouargla. The experimental setup was equipped with detailed instrumentation to record water and paraffin wax temperatures, solar irradiance, ambient temperature, and wind speed. Finally, we developed and validated a mathematical model using MATLAB to simulate the system's thermal behavior. Additionally, we assessed the performance and thermal behavior of three distinct solar cooker configurations: a simple solar cooker (**SSC**), a solar cooker with thermal storage (**SSC+PCM**), and a fully integrated hybrid system (**SSC+PCM+PV**).

From the analysis of the experimental and numerical results, the following conclusions were drawn:

➤ The conventional solar cooker (**SSC**) recorded lower efficiency, with efficiency dropping sharply in the afternoon due to reduced irradiance and increased thermal losses.

➤ The configuration **SSC+PCM** (Solar cooker + Paraffin thermal storage) showed good thermal performance, with a peak efficiency of 46% and a smoother thermal profile throughout the day. Paraffin wax effectively stored thermal energy during peak irradiance and released it in the late afternoon, ensuring extended cooking time even when solar radiation decreased.

- The **SSC+PCM+PV** configuration demonstrated the highest water temperatures, reaching nearly 90 °C, outperforming all other configurations in terms of thermal output. It also proved especially effective under low solar irradiance, where the **PV** input compensated for reduced solar heat.

In conclusion, the **SSC+PCM+PV** system offers a promising and practical solution for continuous, sustainable cooking, particularly in isolated and off-grid areas. It allows for improved reliability, reduced dependency on direct sunlight, and enhanced thermal management, while the **SSC+PCM** system offers optimal energy efficiency during sunny periods. This hybrid approach demonstrates strong potential as a sustainable and scalable solution for clean cooking in solar-rich regions.

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# Annex

**Table. 1:** Additional Test Results of the Simple Solar Cooker (**SSC**)

| Time (min) | Tamb ($^{o}$C) | Tabs ($^{o}$C) | Tw ($^{o}$C) | G (W/m$^2$) | V (m/s) |
|---|---|---|---|---|---|
| 10:00 | 30 | 39.4 | 32.5 | 790 | 2.2 |
| 10:10 | 36.3 | 45.1 | 34.9 | 750 | 1.9 |
| 10:20 | 34 | 49.6 | 36 | 760 | 3.4 |
| 10:30 | 35.8 | 44.5 | 37.1 | 870 | 2.3 |
| 10:40 | 36.5 | 42.9 | 37.9 | 780 | 1.9 |
| 10:50 | 39 | 42.5 | 38.5 | 890 | 3.2 |
| 11:00 | 39.7 | 50.2 | 39.1 | 930 | 2.7 |
| 11:10 | 41.1 | 53.2 | 41.6 | 850 | 2.3 |
| 11:20 | 39.6 | 58.3 | 44.8 | 913 | 2.5 |
| 11:30 | 42 | 58.7 | 46.8 | 918 | 1.5 |
| 11:40 | 40.1 | 60.8 | 48.4 | 951 | 2.7 |
| 11:50 | 44.2 | 62.1 | 51.3 | 975 | 1.6 |
| 12:00 | 42.4 | 64.1 | 54.5 | 970 | 2 |
| 12:10 | 45.7 | 68.1 | 57.2 | 940 | 1.4 |
| 12:20 | 44 | 70.1 | 58.7 | 990 | 1.3 |
| 12:30 | 47.8 | 67.7 | 59.7 | 955 | 0 |
| 12:40 | 39.6 | 71.3 | 62 | 922 | 2.1 |
| 12:50 | 38.7 | 71.5 | 63.3 | 930 | 0.8 |
| 13:00 | 38 | 74 | 64.8 | 905 | 0.8 |
| 13:10 | 40.4 | 75.7 | 66.8 | 910 | 1.3 |
| 13:20 | 39.4 | 77.9 | 67.6 | 940 | 1.1 |
| 13:30 | 43.2 | 79.2 | 68.8 | 918 | 2 |
| 13:40 | 39.3 | 80.4 | 70.3 | 980 | 1.1 |
| 13:50 | 39.4 | 80.5 | 71.7 | 930 | 2.6 |
| 14:00 | 38.8 | 80.6 | 72.9 | 970 | 2 |
| 14:10 | 38.4 | 81.1 | 74.2 | 860 | 1 |
| 14:20 | 39.6 | 79.8 | 74.9 | 530 | 1.1 |
| 14:30 | 39.3 | 77.4 | 75.4 | 460 | 1.4 |
| 14:40 | 38.9 | 75.4 | 75.7 | 420 | 0 |
| 14:50 | 39.2 | 74.2 | 75.5 | 610 | 2.5 |
| 15:00 | 39.1 | 73.8 | 75.1 | 420 | 1.7 |
| 15:10 | 39.1 | 73.9 | 74.9 | 550 | 2.3 |
| 15:20 | 38.2 | 72.4 | 74.6 | 360 | 0 |
| 15:30 | 39.1 | 69.9 | 74.1 | 375 | 2.6 |
| 15:40 | 37.8 | 68.5 | 73.5 | 360 | 0.4 |
| 15:50 | 38.1 | 69.4 | 73 | 315 | 0 |
| 16:00 | 38.9 | 68.8 | 72.6 | 388 | 0 |
| 16:10 | 42.8 | 69.5 | 72 | 445 | 1 |
| 16:20 | 43.8 | 70.5 | 71.5 | 485 | 1.3 |
| 16:30 | 39.1 | 70.7 | 71.4 | 420 | 1.5 |

| | | | | | |
|---|---|---|---|---|---|
| 16:40 | 37.7 | 70.8 | 71.2 | 430 | 0.4 |
| 16:50 | 42.3 | 70.9 | 71.1 | 683 | 0 |
| 17:00 | 43.7 | 70.5 | 71 | 560 | 0 |
| 17:10 | 41.7 | 69.9 | 70.9 | 480 | 0 |
| 17:20 | 39.4 | 69.4 | 70.7 | 506 | 0 |
| 17:30 | 39.4 | 69 | 70.5 | 415 | 0 |
| 17:40 | 37.8 | 67.9 | 70.1 | 300 | 0 |
| 17:50 | 36.6 | 66.7 | 69.6 | 340 | 1.1 |
| 18:00 | 35.9 | 65.2 | 68.8 | 293 | 1.4 |

## Abstract

The objective of this thesis is to study a hybrid solar cooking system combining photovoltaic (**PV**) panels and thermal energy storage. An experimental setup of the **HSC** system was realized at the University of Ouargla to evaluate thermal performance under real climatic conditions. Numerical model is developed using Matlab to simulate thermal performance and to examine the effect of different parameters such as solar radiation, ambient conditions, and mass of paraffin wax used, on the performances of the proposed system. The model was verifted using experimental data that handed good concordance. Results showed that the **SSC+PCM+PV** system achieved the highest water temperatures (90 °C) and proved effective even under low solar irradiance. This study confirms the viability of hybrid cookers in off-grid settings.

**Keywords:** hybrid solar cooker, photovoltaic, paraffin wax, thermal energy storage, efficiency, MATLAB simulation.

## ملخص

تهدف هذه الأطروحة إلى دراسة نظام طهي شمسي هجين يجمع بين الألواح الكهروضوئية (**PV**) وتخزين الطاقة الحرارية. تم تنفيذ إعداد تجريبي لهذا النظام في جامعة ورقلة لتقييم أدائه الحراري تحت ظروف مناخية واقعية. كما تم تطوير نموذج عددي باستخدام برنامج Matlab لمحاكاة الأداء الحراري ودراسة تأثير عدة معلمات مثل الإشعاع الشمسي، الظروف المحيطة، وكتلة شمع البرافين المستخدمة على أداء النظام المقترح. وقد تم التحقق من صحة النموذج باستخدام بيانات تجريبية أظهرت توافقًا جيدًا. أظهرت النتائج أن نظام **SSC+PCM+PV** حقق أعلى درجات حرارة للماء (90 درجة مئوية) وكان فعالًا حتى في حالات الإشعاع الشمسي المنخفض. تؤكد هذه الدراسة على جدوى استخدام أنظمة الطهي الشمسية الهجينة في المناطق غير المرتبطة بالشبكة الكهربائية.

**الكلمات المفتاحية**: طباخ شمسي هجين، ألواح كهروضوئية، شمع البرافين، تخزين الطاقة الحرارية، الكفاءة الطاقوية، محاكاة MATLAB.

## Résumé

L'objectif de ce mémoire est d'étudier un système de cuisson solaire hybride combinant des panneaux photovoltaïques (**PV**) et un stockage d'énergie thermique. Un banc d’essai expérimental du système **HSC** a été réalisé à l’Université de Ouargla pour évaluer ses performances thermiques dans des conditions climatiques réelles. Un modèle numérique a été développé sous Matlab afin de simuler les performances thermiques et d’examiner l’effet de différents paramètres tels que le rayonnement solaire, les conditions ambiantes, et la masse de cire de paraffine utilisée. Le modèle a été validé à l'aide de données expérimentales montrant une bonne concordance. Les résultats ont montré que le système **SSC+PCM+PV** a atteint les températures d'eau les plus élevées (90 °C) et a prouvé son efficacité même sous un faible ensoleillement. Cette étude confirme la viabilité des cuiseurs solaires hybrides dans des contextes hors réseau.

**Mots-clés :** cuiseur solaire hybride, photovoltaïque, cire de paraffine, stockage thermique, efficacité, simulation MATLAB.