

*Original Research*

# Advanced Heat Storage Integration Strategies for High-Efficiency Solar Water Heating Applications

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**Abstract:** This study experimentally investigates the integration of paraffin-based Phase Change Material (PCM) into a solar water heating system to improve post-sunset thermal retention under Saharan climatic conditions (Ouargla, Algeria). Two PCM masses (0.5 kg and 1 kg) were tested and compared with a conventional storage tank. Results show that, while the conventional system reached a peak water temperature of 65 °C, the PCM-assisted system stabilised around 60 °C and maintained temperatures above 52 °C for nearly four additional hours after sunset due to the phase change plateau. Increasing the paraffin mass from 0.5 kg to 1 kg extended the phase change duration by approximately one hour, significantly enhancing heat retention. The analysis demonstrates that PCM integration effectively reduces thermal losses, stabilises water temperature, and improves the overall thermal performance of the solar water heater using a simple and low-cost configuration suitable for arid regions.

**Keywords:** Phase Change Material (PCM); Solar Thermal Systems; Paraffin; Renewable Heating Technologies; Thermal Energy Storage

## 1. Introduction

The accelerating global transition towards sustainable energy systems is driven by escalating concerns over climate change, energy security, and the depletion of fossil fuel reserves. Conventional fossil-based energy systems are responsible for a significant share of greenhouse gas (GHG) emissions, which contribute to global warming and severe environmental degradation [1]. In response, the decarbonisation of energy production and consumption has become a central pillar of energy policies worldwide, with renewable energy technologies playing a pivotal role in this transformation. Among these, solar energy is one of the most abundant, clean, and promising resources, capable of supplying a substantial fraction of global energy demand if harnessed efficiently [2]. Its utilisation for domestic water heating is particularly attractive due to the relatively low-temperature requirements and the direct conversion of solar radiation into usable thermal energy [3].

Despite its vast potential, the effective use of solar energy faces two fundamental challenges: intermittency and variability. Solar radiation is inherently dependent on diurnal cycles and meteorological conditions, resulting in fluctuations in thermal energy supply. These fluctuations often fail to coincide with periods of peak demand, creating a temporal mismatch that reduces system efficiency and reliability [4]. Consequently, the development of efficient and cost-effective thermal energy storage (TES) systems is essential for improving the performance and utilisation of solar thermal systems. TES allows excess heat collected during sunny periods to be stored and released

during periods of low solar availability, thus stabilising supply and enhancing overall system performance [5].

Traditionally, sensible heat storage materials such as water, rocks, or oils have been widely used in solar water heating systems. These materials store energy through temperature changes; however, they require large storage volumes and significant temperature gradients to achieve meaningful storage capacity [6]. To overcome these limitations, latent heat storage using phase change materials (PCMs) has gained considerable attention. PCMs store and release large amounts of energy during their phase transition (typically solid–liquid), enabling high storage density at nearly constant temperatures [7]. This property makes them particularly suitable for low-temperature solar thermal applications such as domestic water heating, space heating, and industrial waste heat recovery [8].

PCMs offer several advantages over conventional sensible heat storage systems. Their high energy density allows for smaller storage volumes, reducing system size and installation space. The nearly isothermal storage process simplifies thermal management and improves system efficiency. Additionally, PCMs can stabilise outlet water temperatures, enhancing user comfort and reducing the need for auxiliary heating [9]. However, challenges remain, including low thermal conductivity, supercooling, phase segregation, and material degradation after repeated cycling [10]. Addressing these challenges is a focus of current research, with approaches including the use of composite PCMs, encapsulation techniques, and the incorporation of high-conductivity additives [11].

A wide range of PCMs has been investigated for thermal storage applications, including organic materials (such as paraffins and fatty acids), inorganic salts (such as nitrates and hydrates), and eutectic mixtures [12]. Among these, paraffin wax is one of the most extensively studied due to its desirable properties, including chemical stability, negligible supercooling, low vapour pressure, non-corrosiveness, and a melting temperature range suitable for domestic water heating (typically 45–70 °C) [13]. Nevertheless, its low thermal conductivity (~0.2 W/m·K) can limit the heat transfer rate, prompting researchers to explore enhancement techniques such as metal foams, fins, graphite additives, and nano-enhanced composites [14].

Numerous experimental and numerical studies have examined the integration of PCMs into solar water heating systems. Eze et al. [15] reviewed PCM-based TES technologies and demonstrated that PCM integration can increase daily solar fraction by 20–40% compared to conventional systems. Nanda et al. [16] showed that paraffin-based PCMs significantly reduce temperature fluctuations in solar water heaters, leading to improved load matching and reduced auxiliary energy demand. Abdalaali et al. [17] reported that incorporating PCMs in domestic solar water heaters can reduce storage tank volume by up to 40% while maintaining the same thermal capacity. In another study, Ren et al. [18] reported that the integration of optimized fin structures into PCM thermal energy storage modules can enhance charging rates by about 40–60% compared to systems without fins. Similarly, Huang et al. [19] demonstrated that the inclusion of expanded graphite in paraffin enhances thermal conductivity and accelerates melting and solidification processes, leading to higher overall system efficiency.

Advanced system designs have also been proposed, combining PCMs with heat pipes, cascaded storage tanks, and hybrid systems. Jurczyk et al. [20] investigated a hybrid solar water heater with cascaded PCMs of different melting points, achieving improved exergy efficiency and prolonged thermal output. Kchaou. [21] proposed a novel shell-and-tube PCM storage unit integrated into a solar collector loop, showing significant improvement in charging/discharging times compared to traditional designs. Moreover, the application of encapsulated PCM micro- and macro-spheres has been shown to improve thermal stability and cycle life, as reported by Menale et al. [22].

Beyond domestic applications, PCM-based TES has broader implications for sustainable energy systems. Industrial processes, district heating, and building heating/cooling networks can benefit from high-density thermal storage, improving energy utilisation and reducing peak load demands. Moreover, integrating PCMs with renewable sources such as solar thermal systems contributes to decarbonisation goals and aligns with global climate targets. Studies have demonstrated that PCM-

enhanced solar water heating systems can reduce CO<sub>2</sub> emissions by 15–30% compared to conventional systems [23], making them a crucial component of future low-carbon energy strategies.

The novelty and significance of this work lie in the experimental quantification of the influence of PCM mass on post-sunset thermal retention in a simple and reproducible solar water heating system operating under real Saharan climatic conditions. Unlike many previous studies that rely on complex enhancement techniques or numerical modelling, this work focuses on a direct experimental comparison between a conventional storage tank and a PCM-integrated tank using two different paraffin masses (0.5 kg and 1 kg). The study particularly analyses the phase change temperature plateau and its direct effect on maintaining stable water temperatures for several hours after sunset, providing a practical and low-cost solution for improving domestic solar water heating performance in arid regions.

## **2. Materials and methods**

### *2.1. Solar Sensor Bench Presentation*

In this work of experimental study, we will examine the impact of paraffin (MCP) on the water temperature inside the tank, both in the presence and absence of this material. We will use measuring tools such as thermocouples during the experiments conducted on the solar collector. The results will be illustrated in graphs and accompanied by commentary detailing the analysis of the curves and their comparison.

Solar thermal collectors as shown in Figure 1, convert solar radiation into heat using a heat transfer fluid (such as water or a water-glycol mixture). This heated fluid transfers thermal energy to a storage system or a heat exchanger for applications like domestic water heating or space heating.

Thanks to an absorbing surface often coated with a selective layer, these collectors maximise the capture and conversion of solar energy, providing an efficient and sustainable solution for heating needs.



**Figure 1.** Solar panel.

### *2.1. Solar Sensor Bench Presentation*

A Solar thermal collector mainly consists of a transparent glass cover, spiral aluminium tubes, and a black solar absorber. The glass cover allows solar radiation to enter while reducing heat losses and protecting the collector from external conditions. The spiral aluminium tubes carry the heat transfer fluid, enhancing heat exchange due to their high thermal conductivity and corrosion resistance. The black absorber captures solar radiation and converts it into heat; its selective coating maximises energy absorption while minimising thermal losses. Experimental Measurement Instruments were used to monitor and evaluate the system's performance as shown in Figure 2.



Figure 2. Experimental Measurement Instruments (Thermocouple devices).

To ensure clarity and reproducibility of the experimental work, the main technical characteristics of the solar collector, storage tank, PCM integration, and measurement conditions are summarised in Table 1. This table presents all relevant system parameters, including collector specifications, insulation properties, PCM placement, flow rate, and instrumentation used during the experiments. Providing these details allows a clear understanding of the operating conditions under which the tests were conducted and facilitates comparison with similar studies in the literature.

Table 1. Experimental setup and operating conditions.

Parameter	Value	Unit
Collector type	Flat plate solar collector	—
Collector area	1	m <sup>2</sup>
Tilt angle	30	°
Absorber material	Black coated aluminium	—
Glass cover thickness	3	mm
Collector insulation thickness	20	mm
Storage tank volume	50	L
Tank insulation type	Polyurethane foam	—
PCM placement	Inside tank, in a metal container in direct contact with water	—
PCM masses tested	0.5 and 1	kg
Water flow rate	1.08	L/min
Pump power	—	W
Thermocouple type	K-type	—
Measurement interval	10	min
Experiment location	Ouargla, Algeria	—
Test period	May 2025	—

### 2.3. Thermo-physical properties of the PCM

#### 2.3.1. Characteristics of Paraffin

The paraffin used has a purity of about 99%, ensuring stable and reliable thermal properties. It has a melting temperature between 52 and 54°C, allowing it to absorb heat during melting and release it during solidification. In the liquid state, it is transparent, while in the solid state, it becomes opaque. Its latent heat of fusion, measured at 188 kJ/kg, represents the amount of energy required to melt or

solidify one kilogram of paraffin without a temperature change. Table 2 presents the physical properties of the material used in the experiment, while Figure 3 illustrates this material.

**Table 2.** Physical values of the material used.

Property	Value	Unit
Fusion temperature of PCM (°C)	52	°C
Latent heat of fusion of PCM	188	kJ/kg
Specific heat of liquid PCM	2.95	kJ/kg. K
Specific heat of solid PCM	2.195	kJ/kg. K
Thermal conductivity of liquid PCM	0.15	W/m .K
Thermal conductivity of solid PCM	0.232	W/m .K
	31.09	1.6773
	33.88	0.273
	35.70	0.4205



**Figure 3.** Paraffin.

Figure 4 shows the insulated water storage tank containing the internal heat exchanger and the paraffin-based phase change material (PCM). The heat exchanger is positioned inside the tank to ensure effective heat transfer between the circulating hot water and the stored water volume, while the PCM is placed in thermal contact with the tank to absorb excess heat during the charging phase and release it gradually during the discharging phase, thereby enhancing thermal retention after sunset.



**Figure 4.** Water tank.

### 2.4. Operating principle

A solar water heating system warms the water in the storage tank using a thermal collector. A water pump powered by an external electricity source is installed to circulate water from the tank through the solar collectors, where it absorbs solar heat before returning as hot water to the insulated tank. The temperature and water level in the tank are monitored using a thermometer to ensure efficient operation.

A water inlet valve is placed at the top of the tank for refilling, and a drain valve is installed at the bottom for emptying. The system is designed to maintain the same flow rate during filling and draining to prevent air from entering the water circuit between the tank and the thermal collector, ensuring optimal heating and energy efficiency.

Furthermore, the incorporation of paraffin as a Phase Change Material (PCM) enhances the system’s thermal performance by storing excess heat during periods of high solar radiation and releasing it gradually after sunset. This mechanism helps maintain a more stable water temperature inside the storage tank and reduces thermal losses, thereby improving the overall efficiency of the solar water heating system. The experimental study was conducted in May 2025 in Ouargla, Algeria.

As illustrated in Figure 5, the experimental procedure consisted of operating a solar water heating system integrated with paraffin-based PCM and comparing its performance with that of a conventional system under identical conditions. Water temperatures were recorded during solar exposure for two PCM masses (0.5 kg and 1 kg) to evaluate their latent heat storage capacity. The analysis focused on post-sunset temperature stability, heat retention duration, and thermal loss reduction to assess the effect of PCM integration on overall system performance.

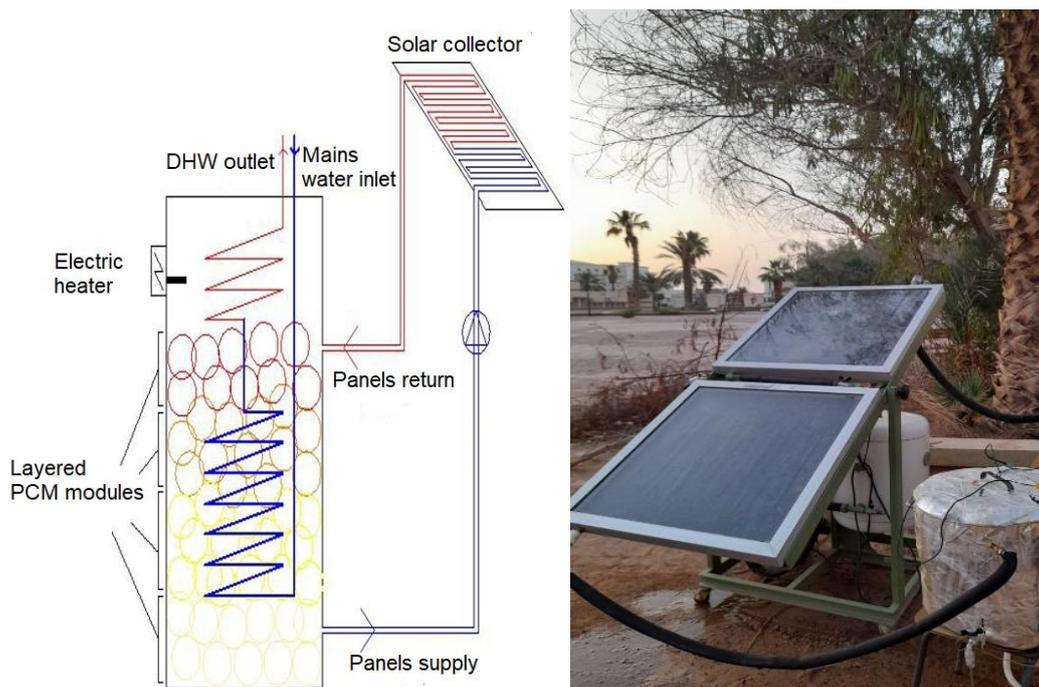


Figure 5. Diagram of the operating principle of a water heating system.

### 2.5. Measurement accuracy and uncertainty analysis

Temperature measurements were performed using K-type thermocouples with an accuracy of  $\pm 0.5$  °C. The data acquisition interval was set to 10 minutes throughout the experimental period. The uncertainty in temperature difference measurements was estimated using standard uncertainty propagation:

$$U = \sqrt{U_1^2 + U_2^2} \quad (1)$$

where  $U_1$  and  $U_2$  represent the uncertainties of the thermocouples used at different measurement points.

To ensure repeatability, the experiment was conducted over three consecutive days under similar climatic conditions. The temperature profiles obtained showed very close agreement, with a standard deviation lower than 1.2 °C, confirming the reliability and repeatability of the measurements.

### 3. Results and discussion

#### 3.1. Energy balance of the system

The thermal energy stored in the water inside the tank is calculated using:

$$Q_w = m_w c_w (T_{max} - T_{min}) \tag{2}$$

where  $m_w$  is the mass of water,  $c_w$  is the specific heat capacity of water, and  $T_{max}$  and  $T_{min}$  are the maximum and minimum recorded water temperatures.

The latent heat stored by the phase change material during melting is given by:

$$Q_{PCM} = m_{PCM} L_f \tag{3}$$

where  $m_{PCM}$  is the mass of paraffin and  $L_f$  is its latent heat of fusion.

The improvement in thermal retention due to PCM integration is evaluated by comparing the retained thermal energy in the tank after sunset for both the conventional system and the PCM-assisted system.

#### 3.2. Effect of PCM Integration on Water Temperature Retention

Figure 6 presents the variation of water temperature inside the storage tank with and without PCM over a full daily cycle. During the charging phase, both systems show a similar increase, reaching peak temperatures of approximately 65 °C for the conventional system and 60 °C for the PCM-assisted system. After sunset, the conventional tank temperature drops rapidly, falling below 45 °C within about 2 hours. In contrast, the PCM-integrated system maintains a nearly constant temperature around the paraffin melting point ( $\approx 52$  °C) for nearly four additional hours. This temperature plateau corresponds to the latent heat release during the solidification process of paraffin, which significantly slows the cooling rate and improves post-sunset thermal retention.

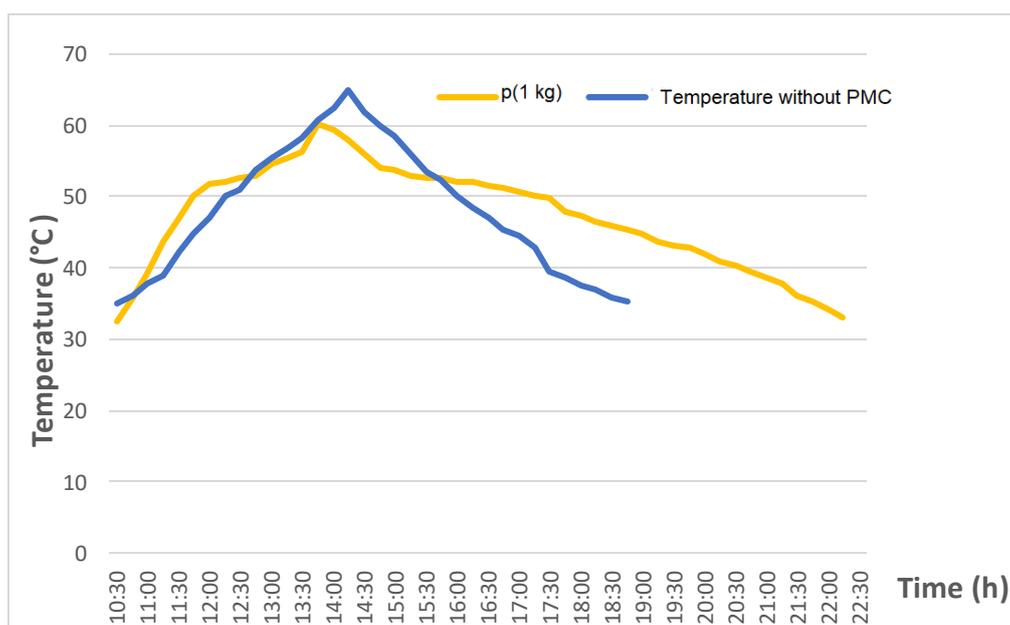


Figure 6. Effect of integrating the Phase Change Material into the reservoir.

### 3.3. Charging and Discharging Behaviour of Paraffin During Phase Change

Figure 7 illustrates the temperature evolution of paraffin during charging and discharging for two PCM masses (0.5 kg and 1 kg). During charging, the paraffin temperature rises from 32 °C to the melting point at 52 °C, where a clear plateau is observed due to latent heat absorption. After complete melting, the temperature reaches approximately 60.02 °C at 13:45. During discharging, the same plateau appears around 52 °C as the paraffin solidifies and releases stored energy. The plateau duration for 1 kg of PCM is approximately one hour longer than for 0.5 kg, confirming that increasing PCM mass enhances latent heat storage and prolongs heat release.

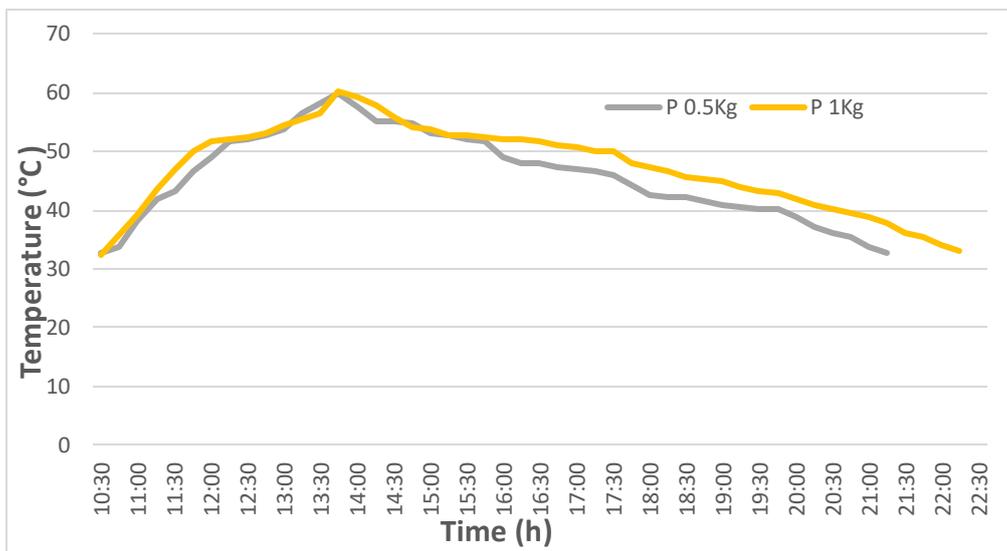


Figure 7. Temperature variation of the Phase Change Material in the reservoir.

### 3.4. Effect of Paraffin Quantity on Phase Change Duration

It is essential to highlight the influence of the amount of paraffin used in the reservoir. The experiment was conducted with two different quantities, 0.5 kg and 1 kg of paraffin, to evaluate their impact on the phase change duration and thermal performance. For 0.5 kg of paraffin, the temperature reached the phase change plateau at 52 °C and remained stable for a relatively short period. In contrast, with 1 kg of paraffin, the temperature reached the same plateau but maintained stability for approximately one hour longer. This indicates that a larger amount of paraffin provides a greater latent heat storage capacity, resulting in an extended plateau duration at 52 °C. Consequently, the 1 kg sample not only absorbs and releases more thermal energy but also sustains a stable water temperature for a longer period compared to the 0.5 kg sample, demonstrating its superior effectiveness in thermal energy storage and release.

Figure 8 compares the water temperature behaviour in the tank for different paraffin quantities. Without PCM, the water reaches about 65 °C but drops quickly after sunset, losing nearly 20 °C within the first 3 hours. With PCM integration, the maximum temperature is limited to about 60 °C, as part of the heat is absorbed by the paraffin. More importantly, the cooling rate is significantly reduced, and the temperature remains above 50 °C for several hours, especially with 1 kg of paraffin, demonstrating improved thermal regulation and extended hot water availability.

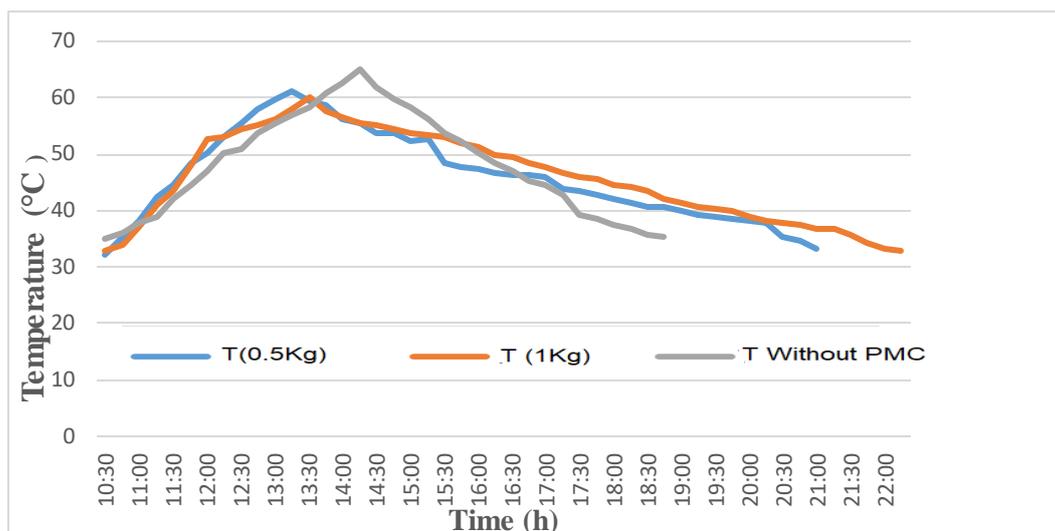


Figure 8. Effect of paraffin on the water temperature in the tank.

3.5. Temperature variation between the tank mixture and the outlet (pressure losses)

Figure 9 shows the temperature profiles measured inside the tank and at the outlet. The temperature difference between the two points does not exceed 1–2 °C throughout the experiment, indicating very low thermal losses during water circulation. This confirms the effectiveness of the tank insulation and the quality of heat transfer within the system.

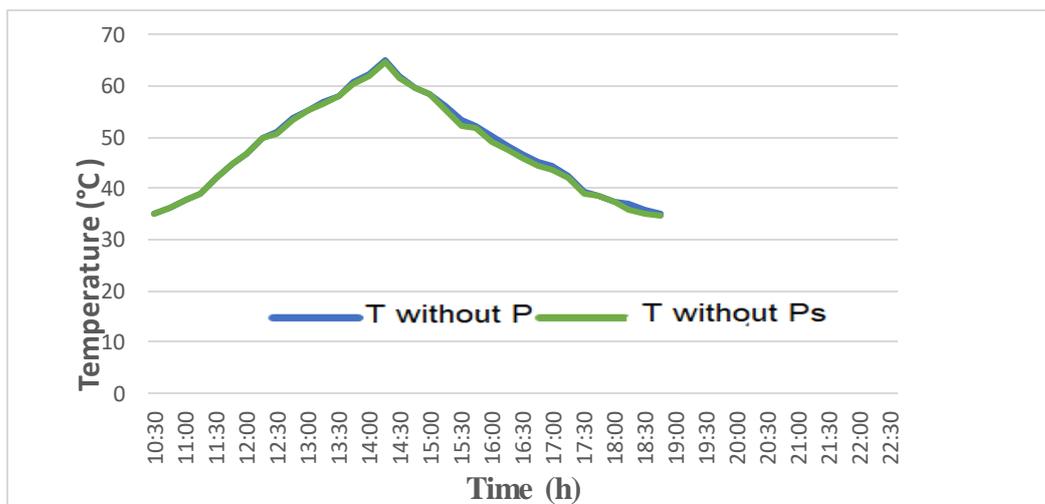


Figure 9. The temperature variation between the tank mixture and the outlet (pressure losses).

3.6. Temperature variation of the solar sensor over 3 days in terms of time

Figure 10 presents the solar collector temperature profiles over three consecutive days. The curves are nearly identical, with peak temperatures around 70 °C and deviations lower than 1.2 °C between days. This consistency confirms the repeatability of the experiments and the stability of the climatic and operating conditions during the test period.

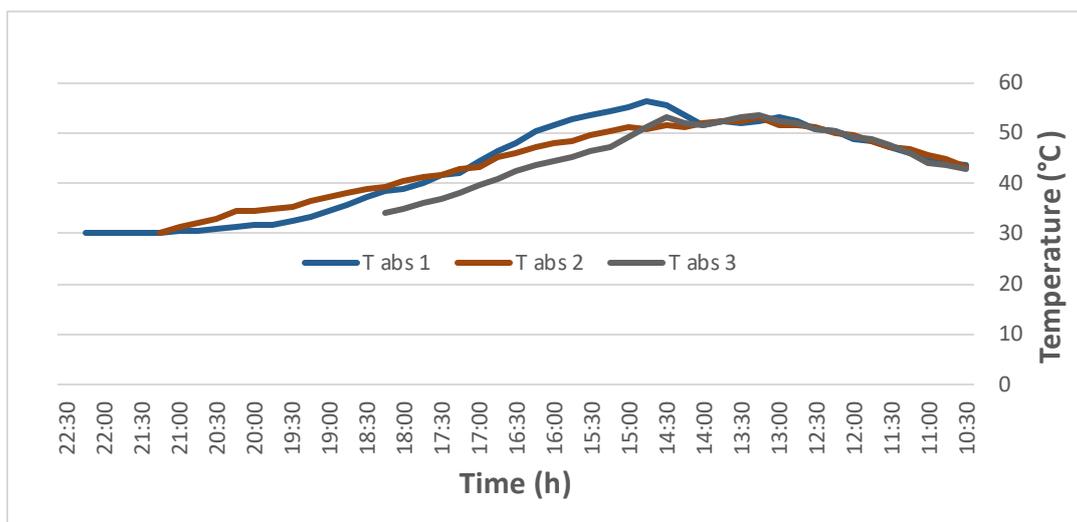


Figure 10. The temperature variation of the solar sensor over 3 days in terms of time .

#### 4. Conclusion

This study experimentally evaluated the integration of paraffin as a Phase Change Material (PCM) in a solar water heating storage tank under Saharan climatic conditions (Ouargla, Algeria). Two PCM masses (0.5 kg and 1 kg) were tested and compared with a conventional system to assess their effect on thermal retention after sunset.

Results showed that while the conventional system reached a peak temperature of about 65 °C, the PCM-assisted system stabilised around 60 °C during charging due to heat absorption by the paraffin. After sunset, the PCM system maintained water temperatures close to the melting point ( $\approx 52$  °C) for nearly four additional hours. Increasing the PCM mass from 0.5 kg to 1 kg extended the phase change plateau by about one hour, confirming the positive effect of PCM quantity on heat storage capacity. Repeatability tests over three days showed deviations below 1.2 °C.

These findings demonstrate that a simple and low-cost PCM integration significantly improves thermal stability, reduces heat losses, and enhances hot water availability without complex system modifications, making it suitable for domestic applications in arid regions.

Future work will focus on improving PCM thermal conductivity and optimising its placement inside the tank to further enhance heat storage and release performance.

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**Conflicts of Interest:** The author declares no conflict of interest.

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