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Design Evolution and Performance Review of Solar Water Heating Systems with Phase Change Materials

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Abstract: *A comprehensive investigation into the progress in solar water heating technologies since inception is presented in this paper. The efficient utilization of solar energy for heating water is crucial for sustainable energy practices, and thermal energy storage in the form of latent heat emerges as a promising solution. The research summarizes various studies examining thermal storage systems with and without phase change materials (PCMs), classifying them into the kind of collector and the category of storage in action (either sensible or latent). An exhaustive literature study underscores the importance of PCM selection criteria, emphasizing the requirement for materials that possess high latent heat capacity and extensive surface areas to ensure heat transfer optimally. This article highlights the significance of PCM-based thermal storage in enhancing the performance (thermal) of solar water heaters, paving the way for more efficient and sustainable heating solutions.*

Keywords: **Thermal energy storage, solar water heating, phase change materials**

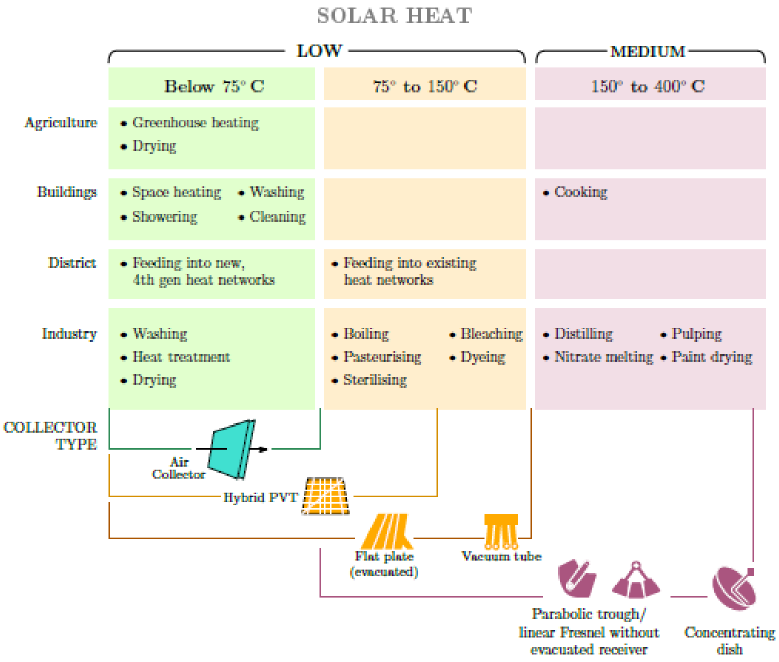
1. Introduction

The backbone of human activities is energy. There exists a critical relationship between energy and economic development, as energy plays a vital role in driving economic activities. Throughout history, solid fossil fuels like wood and coal have served as the primary energy sources. Later, with the exponential increase in energy demands globally, propelled by growth in population and the revolution in industries of the 20th century, fossil fuels have usheredin a transition. It is broadly acknowledged that for sustainability, conventional energy sources such as nuclear power and fossil fuels must swiftly give way to renewable energy sources. These sources offer the ability to meet current and future global energy needs sustainably, without leading to adverse environmental effects. Various options of renewable energy are solar, hydropower, wind, and biogas, which emerge as promising solutions for meeting global energy needs in a sustainable manner.

The fruitful implementation of solar energy relies heavily on the efficiency of thermal storage systems. Among various methods, the use of latent heat storage plays a pivotal role. Latent heat, the substantial energy required for the transition of phase of a material between solid and liquid, is crucial in achieving the desired efficiency of thermal storage. A stark demonstration of this lies in the comparison between the sensible heat capacity of materials like concrete (1.0 kJ/kg K) and phase change materials (PCMs) like paraffin wax (154 kJ/kg). The significant difference underscores the advantage of PCM-based energy storage systems, which occupy considerably less volume than those utilizing only sensible heat. Additionally, latent heat storage offers another advantage: heat absorption and release occur within a fairly narrow range of temperature, typically around the temperature of change of phase.

In numerous applications, the requirement for effective and dependable thermal storage systems is paramount. Among these applications, solar energy finds extensive use in water heating. Solar water heaters have gained popularity [1-3] due to their relative affordability and ease of fabrication and maintenance. Serving as a practical supplement or alternate option to heat water by electricity or gas, they contribute to mitigating harmful emissions of greenhouse gas related to electricity generation. Warm water, essential for various purposes including washing, drinking, and bathing, is a necessity in commercial, residential, and industrial sectors. Over a span of 20 years, emissions of more than 50 tons of carbon dioxide can be mitigated by one solar water heater alone. A well-designed, correctly installed, and properly maintained solar water heating system can supply anywhere between about 50% and nearly all of a household's hot water needs, depending on the local climate and usage patterns. Operational in any climate, its performance depends on available solar energy at the site and the temperature of incoming water.

In 2007, the global installed capacity of solar hot water systems reached around 154 GW, with an ambitious target of reaching 210 GW by 2020. Since 2020, the global solar hot water market has experienced steady growth as nations strive to meet their renewable energy targets. As of date, solar thermal systems are extensively employed to meet low-temperature heating needs in buildings by supplying hot water for domestic purposes and space heating (Figure 1). These systems can be installed on-site for individual residences or integrated into district heating networks to serve multiple buildings. In industrial settings, solar thermal technologies are effectively utilized for processes requiring temperatures up to 150°C, such as in food processing, chemical production, and textile manufacturing. Notably, over 150 large-scale Solar Heat for Industrial Processes (SHIP) systems have been documented worldwide, with capacities ranging from 0.35 MWth to 27.5 MWth (equivalent to 39,300 m² of collector area).


SOLAR HEAT

	LOW		MEDIUM
	Below 75° C	75° to 150° C	150° to 400° C
Agriculture	• Greenhouse heating • Drying		
Buildings	• Space heating • Washing • Showering • Cleaning		• Cooking
District	• Feeding into new, 4th gen heat networks	• Feeding into existing heat networks	
Industry	• Washing • Heat treatment • Drying	• Boiling • Bleaching • Pasteurising • Dyeing • Sterilising	• Distilling • Pulping • Nitrate melting • Paint drying

Figure 1. Solar Water Heater: A Wide Range of Applications

2. Thermal Performance of Different Collectors of Solar Energy

Flat plate, concentrating collector, and evacuated tube are the different types of solar energy collectors on the basis of energy collection methods. They can also be classified as active and passive on the basis of mode of operation. Being an active system, it uses an electric pump for transferring heatduring the circulation of fluids. A passive system works on the principle of natural convection of the working fluid. These systems are also termed as direct and indirect; in case of direct system, the household water directly circulates through the collector, making them unsuitable for freezing climates, while indirect systems operate using a heat transfer fluid.Energy transport can occur through active or passive modes, applicable to evacuated tube, flat plate, and concentrating collectors. The efficiency of a solar collector is given by

$$\eta = \frac{\dot{Q}_{out}}{\dot{Q}_{in}} = \frac{\dot{m}c_p\left(T_{out} - T_{in}\right)}{AI} \tag{1}$$

Here, where, η = collector efficiency, $\dot{Q}_{out}$ = useful thermal energy transferred to the heat transfer medium [J/s], $\dot{Q}_{in}$ = incident solar energy on the collector [J/s], $\dot{m}$ = mass flow rate of the heat transfer fluid [kg/s], c_p = specific heat capacity of the fluid [J/kg K], T_{out} = outlet temperature of the fluid [K], T_{in} = inlet temperature of the fluid [K], A = collector surface area [m²], I = incident solar radiation per unit area [W/m²].

The above formula provides the efficiency as the percentage of energy received from the sun that is effectively used for heating purposes. The collector efficiency graph provides an important parameter in evaluating the performance of a water heater system. This graph measures the efficiency of the collector using the ratio of heat collected to the radiation energy received. A comparative analysis among different solar collectors (Figure 2) highlights that radiation losses predominantly influence efficiency. Concentrating collectors, in particular, experience higher losses due to their open collector area. It's worth noting that the efficiency of a collector isn't a fixed value; rather, it varies depending on factors such as location, temperature, and wind speed [4, 5].

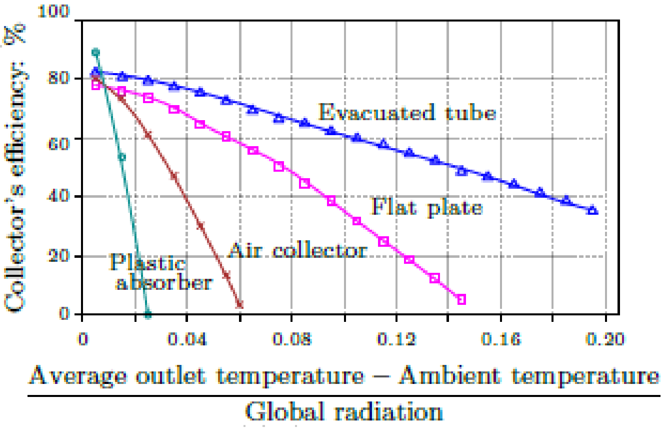


Figure 2. Efficiency curves of diverse solar collectors

Huang and Du [6] proposed a comprehensive approach to assess the overall efficiency of thermo-syphon solar water heaters by integrating their thermal performance (energy collection phase) with the cooling loss of the cooling phase. Historically, the overall performance assessment has emphasized solely on these two aspects. However, Chang et al. [7] advocated for considering the heat removal efficiency during the system application phase as well. Contrary to this popular belief, a group of researchers [8-10] accounts only the energy-collecting phase for evaluating the thermal performance of a system. It does not consider the actual usable energy available to the user, which is in fact affected by the mixing of hot water of the storage tank with the cold water during system operation. Knudsen [11] delved into the efficacy of the volume of storage tank on the thermal performance of solar direct hot water systems, highlighting the prominence of system operation from the consumer's standpoint, and a relation between energy consumption and tank volume is established. However, Knudsen's study did not consider the heat loss during the system application (hot water draw-off) phase.

Sodha et al. [12] conducted a comparative evaluation of the hourly thermal performance of three 100-litre solar water heaters with built-in storage, each featuring a distinct design. Design I presented three tanks connected in cascade, Design II introduced a rectangular parallelepiped tank segmented into five zones with baffles, while Design III utilized a simple parallelepiped tank. The first two designs aimed to induce thermal stratification within the tank. Their findings revealed that Design II exhibited superior performance among the three systems studied. Additionally, Sodha et al. [13] investigated the thermal efficacy of a multi-tank water heating system in six distinct climatic situations, characterized by the fraction of required energy supplied by the sun (solar fraction). Their analysis demonstrated that the proposed design yielded a higher solar fraction compared to conventional solar water heaters, thus proving to be more cost-effective and efficient.

Substantial research was dedicated to incorporating phase change materials (PCMs) into solar water heating systems to improve thermal energy storage capabilities. Researchers investigated a range of PCMs, such as paraffin waxes and hydrated salts, with the goal of enhancing heat storage and release during phase transitions. To overcome obstacles like low thermal conductivity and phase segregation, modifications to materials and system designs were explored. Solutions such as the addition of fins and the use of encapsulation methods were developed to boost heat transfer efficiency and system performance. These advancements paved the way for more effective solar thermal technologies.

Contemporarily, research has accelerated in refining PCM properties and integrating them into more advanced solar water heating systems. Recent investigations have concentrated on Nano-enhanced PCMs, where nanoparticles are incorporated to boost thermal conductivity and enhance material stability. Furthermore, hybrid systems that combine photovoltaic and thermal components with PCM storage have been introduced to optimize energy use. Future research is aimed at developing cost-efficient, long-lasting PCMs with customized melting points suited for different climates. Innovations in encapsulation methods and composite materials are anticipated to improve the efficiency further and dependability of solar water heating systems, facilitating their broader implementation.

Aftab et al. [14] developed a phosphorene-based photonic nanoheater integrated with solid-solid phase change materials (PCMs) to enhance thermal energy storage efficiency. By leveraging the broad solar absorbance of exfoliated phosphorene nanoflakes (PNFs) and the latent heat storage capacity of the PCM matrix, the composite system achieved superior photo-thermal conversion efficiency. Notably, applying this solar heat storage material onto fabric substrates demonstrated promising potential for practical applications. Ding et al. [15] conducted a parametric study to assess the potential of power savings achievable through various phase change material (PCM) design parameters across different regions, identifying optimal phase change temperatures and determining appropriate PCM quantities to enhance the efficiency of solar water heating systems.

A recent study [16] introduced an innovative asymmetrical evacuated tube compound parabolic collector (CPC) integrated with phase change material (PCM) for in-line water heating applications. This solar collector underwent numerical analysis to evaluate its thermal and optical performance, focusing on the charging and discharging processes of the PCM. Various internal fin configurations were compared against a baseline design without fins to identify the most effective arrangement. The optimal fin design demonstrated a 96% increase in daily useful heat production compared to the no-fin scenario, highlighting the significant impact of internal fin structures on enhancing the collector's efficiency.

3. Solar Heat Storage Methods

3.1. Sensible Heat Storage

Sensible heat storage systems work by using the difference in temperatures in a material, with the amount of heat storage being based on the product of its heat capacity and the change in temperature. During both processes of charging and discharging, these systems make use of the materials' capacity for storage and delivery of heat based on the differences in their temperatures. Heat storage levels are affected by numerous factors, including the heat capacity of the material and changes in temperature, among others.

$$Q = mc_p(\Delta T) = mc_p(T_f - T_i) \tag{2}$$

Here, Q = useful thermal energy stored [J], m = mass of the material [kg], c_p = specific heat capacity of the material [J/kg K], ΔT = rise in temperature of the material [K], T_f = final temperature of the material [K], T_i = initial temperature of the material [K].

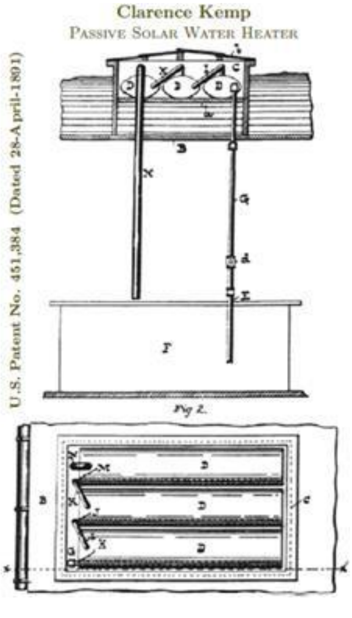


Figure 3. Revolutionary solar innovation: The first commercial solar water heater

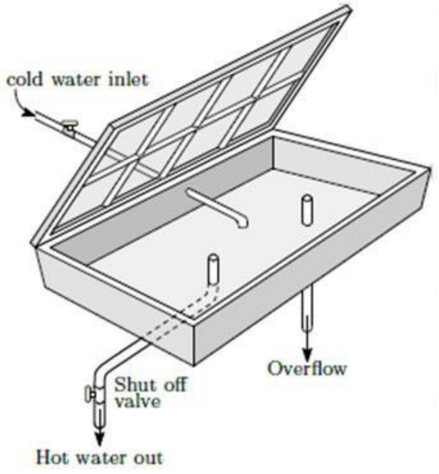


Figure 4. Japan's solar pioneer: Yamamoto's first solar water heater

The first commercial solar water heater, The Climax (Figure 3), was patented by Clarence M. Kemp in 1891 and represented a major advancement in solar technology [17]. Kemp's design featured a metal tank housed inside a glass-covered wooden box, capable of heating water to temperatures exceeding 38.8°C on sunny days. Notably, his concept remains relevant today, particularly in integral collector storage solar water heaters. Later, William Bailey further improved solar water heating technology [17] by developing a two-component system consisting of a solar heat collector and a separate water storage tank. His innovation introduced an insulated storage tank and utilized the thermo siphon principle to facilitate water circulation between the collector and the storage tank. Yamamoto pioneered Japan's first commercial solar water heater (Figure 4), drawing inspiration from a rural area where he noticed a large bathtub left in the sun all day, covered by a sheet of glass [17]. This observation sparked his design. Later, the ‘closed-pipe’ system, which serves as the foundation for many modern Japanese units, was introduced.

Rosen et al. [18] investigated the effectiveness of sensible heat storage systems using exergy analysis instead of conventional energy analysis. They formulated relationships for two distinct thermal storage systems, both undergoing an identical charging process. In the first system, heat was recovered after a single day using a 5000 kg water stream, which entered at 25°C and exited at 35°C. In contrast, the second system extracted heat after 100 days with a 100 kg water stream, entering at 25°C and leaving at 75°C. A comparative assessment of both systems demonstrated that, despite having identical energy efficiencies, their exergy efficiencies varied significantly, 26.70% for the first system and 72.80% for the second.

Husain et al. [19] conducted a theoretical analysis of a solar collector and storage water heater model, where water flows at a constant rate between a glass cover and an absorber plate. They investigated the effects of varying water depths, flow rates, and absorber plate lengths on system performance. Their findings suggest that understanding these parameters simplifies the design process for such systems. Additionally, flat plate collectors have been widely studied, and their performance equations are well established, known as the Hottel-Whillier-Bliss equation [20].

3.2. Latent Heat Storage

In sensible heat storage, there is always a change in the temperature of the medium during both charge and discharge operations. On the other hand, in latent heat storage, the temperature remains fairly constant because of the phase change that occurs. Latent heat storage offers a higher storage density than sensible heat storage, and heat losses are also reduced in latent heat storage. Several researchers [21-27] have shown the importance of latent heat storage systems.

Materials that are utilized in order to store latent heat in the form of thermal energy by virtue of changing their state from solid to liquid form or vice versa, are known as phase change materials (PCMs). Phase change materials store five to fourteen times more heat than sensible heat storage materials like water, masonry, and rock per unit volume. The capacity of storage in a latent heat thermal energy storage (LHTES) system using PCMs mainly depends on the heat transferred in a phase change process.

$$Q = mc_{p,s}\left(T_{mp} - T_{i}\right) + mL + mc_{p,l}\left(T_{f} - T_{mp}\right) \tag{3}$$

Here, Q = useful thermal energy stored in PCM [J], m = mass of PCM [kg], $c_{p,s}$ = specific heat capacity of PCM in solid phase [J/kg K], $c_{p,l}$ = specific heat capacity of PCM in liquid phase [J/kg K], mp = melting point of PCM [K], L = Specific latent heat of melting of PCM at melting point [J/kg], T_i = Initial temperature of PCM [K], T_{mp} = Melting point temperature of PCM [K], T_f = Final temperature of PCM [K].

Two solar water heaters employing paraffin as thermal energy storage material were designed by Shukla [28]. The first system had the tank-in-tank configuration (Figure 5), whereas the other system had the integrated tank with reflector configuration. The two systems were able to provide hot water for a period of 24 hours, both night and day. The efficiency of the two systems was reported as 45% and 60%, respectively. Galenen and Vanden [29] similarly utilized paraffin for domestic hot water and space heating.

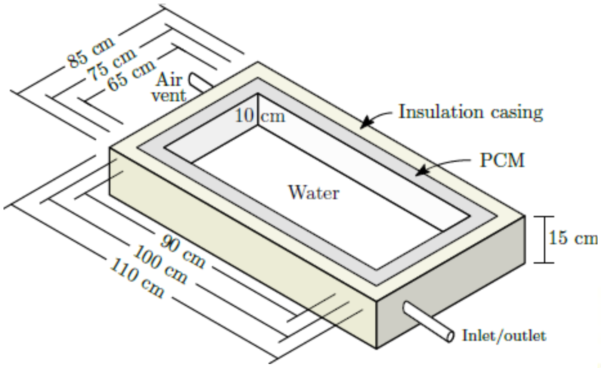


Figure 5. Shukla's cutting-edge solar water heater design

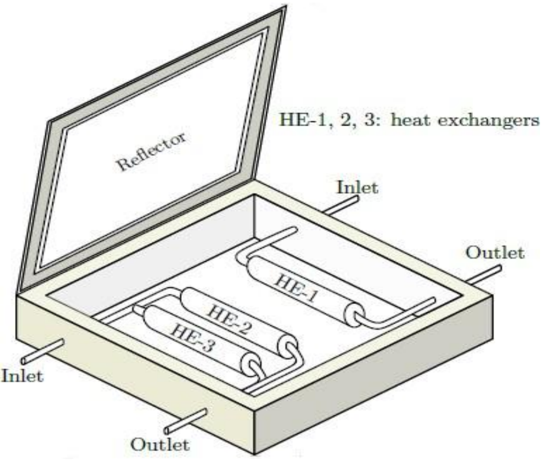


Figure 6. Kumar's solar-powered water heater

A study was conducted by Kumar [30] where he designed, developed, and evaluated a latent heat storage unit intended to meet the requirements for hot water during evening and morning periods. His design included the use of three fin-type heat exchangers (Figure 6). The paraffin wax material was selected due to its high melting point of 54°C. Kumar noted that the system used latent heat storage, which proved highly efficient in producing hot water at a desired temperature. Experimental trials were conducted with water volumes of both 15 litres and 20 litres.

Analysis of PCM storage for a water heater was done by Tiwari et al. [31]. The research focused on analyzing the effects of water movement along a parallel plate at the solid-liquid interface. In order to reduce the loss of heat at night, the scientists recommended moving the insulation. According to their results, hot water kept at 15°C to 20°C above the environmental air temperature could be retained for both day and night. Furthermore, the increase in the molten region of the PCM led to lower variations in water temperatures.

Prakash et al. [32] analyzed a built-in storage-type water heater incorporating a PCM layer at the bottom, as shown in Figure 7. During daylight hours, water is heated and transfers thermal energy to the PCM below, causing it to store energy as latent heat and undergo melting. At night or in the absence of sunlight, when hot water is drawn and replaced by cold water, the PCM releases stored energy as it solidifies, helping to maintain water temperature. However, the system may encounter efficiency challenges due to poor heat transfer. Meanwhile, for both charging and discharging phases, Bansal and Buddhi [33] conducted a theoretical study on a cylindrical storage unit integrated into a closed-loop system, a flat plate collector. As phase change materials, paraffin wax (P-116) and stearic acid are used, and the calculations accounted for the moving boundary interface and fluid temperature.

For domestic water heating, palmitic acid, myristic acid, and stearic acid are identified as the most promising options as phase change materials (PCMs) by Hasan et al. [34-36] while exploring certain fatty acids whose melting temperatures range from 50°C to 70°C. Lane [37] conducted a study on ammonium alum ($NH_4Al\ (SO4)_2.12H_2O$, 95°C) for the same.

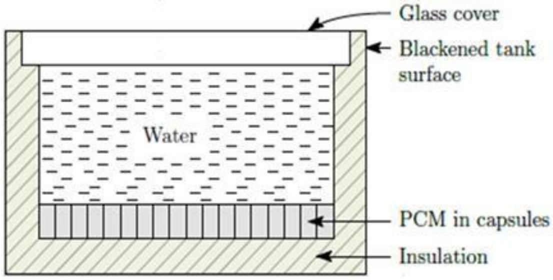


Figure 7. Prakash et al.'s innovative solar water heater

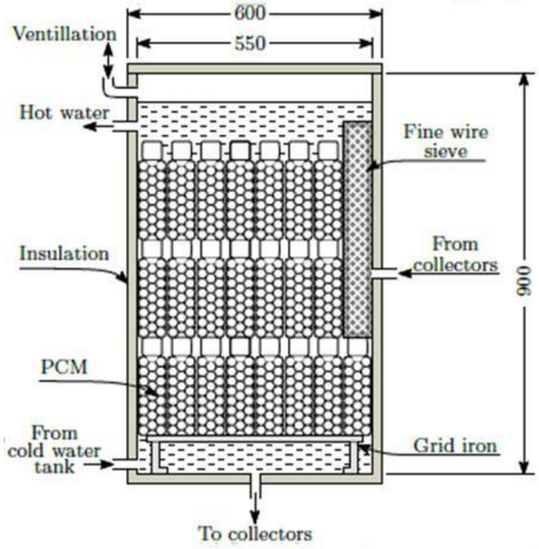


Figure 8. Storage Unit Designed by Canbazoglu et al.

Chaurasia [38] conducted a comparative study of solar energy storage systems to preserve solar-heated hot water for night time use. The choice of paraffin wax as a PCM for solar water heater involved the use of two equal storage units, which consisted of paraffin wax weighing 17.5 kg (melting point 54°C) being placed inside the aluminum tube heat exchanger on one side and water stored in a galvanized tank on the other side. The independent charging of both the units was done using flat plate solar collectors having equal absorber surface area on each. It was observed that higher quantity of hot water is obtained from latent heat storage system compared to the sensible heat system.

A comparison between solar water heating systems utilizing phase change materials (PCMs) in Figure 8 and conventional solar water heating systems was conducted by Canbazoglu et al. [39]. In their setup, polyethylene bottles were filled with 180 kg of PCM and were arranged in three rows within the heat storage tank. The findings showed that when hot water was not used, the water temperature remained steady at 46°C throughout the night. Additionally, the temperature difference between the midpoint of the heat storage tank and the collector outlet averaged 6°C higher in the PCM-based system compared to the system without PCM, demonstrating enhanced heat storage efficiency. This significant temperature difference underscores the effectiveness of PCM in heat storage. The PCM system demonstrated approximately 2.59-3.45 times greater storage time, hot water mass production, and total heat accumulation compared to conventional solar energy systems without PCM. Theoretical examination of hydrated salt PCMs like $Na_2S_2O_3.5H_2O$, $Zn(NO_3)_2.6H_2O$, $Na_2HPO_4.12H_2O$, $CaCl_2.6H_2O$, and $Na_2SO_4.10H_2O$ was conducted. The study also highlighted the influence of vessel size and shape on solar radiation collection; vessels with a higher exposed surface area-to-volume ratio heat water more quickly. Haskell [40] acknowledged the significance of this aspect and patented an "enhanced" integrated collector storage solar water heater design. This design featured a shallow rectangular tank, which offered a higher surface area-to-volume ratio compared to traditional cylindrical storage vessels.

Through time, the primary focus of research conducted by the Japanese was on open collectors that had rectangular tanks and cylindrical containers that were eventually improved into long, narrow pipes. This type of collector had a relatively smaller ratio of surface area to volume than that which emerged from the USA. The system was effective as it heated up faster in the morning and was able to provide hot water even on a partially sunny day. Chinnappa & Gnanalingan [41] used galvanized pipes in coil form as storage units. Thermal analysis of any system will need to include an analysis of its effectiveness in removing heat in its usage stage.

Rabin et al. [42] developed an integrated solar collector storage system (Figure 9) utilizing salt hydrate. They utilized a salt hydrate eutectic mixture composed of 0.4% NaCl, 4.5% KCl, 48% $CaCl_2$, and 47.1% H_2O, incorporating $BaCl_2.2H_2O$ as a nucleating agent at 1% by weight. This mixture had a phase transition temperature of 27°C-29°C and a latent heat of fusion of 164 kJ kg^{-1}. Their study established that the PCM layer played a crucial role in determining the propagation distance of the solid-liquid interface within the phase change material. But, its impact on the liquid interface was found to be minimal.

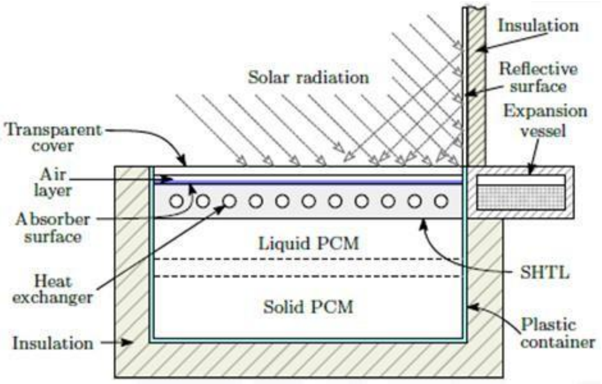


Figure 9. Cross-sectional view of integrated solar collector storage system developed by Rabin et al.

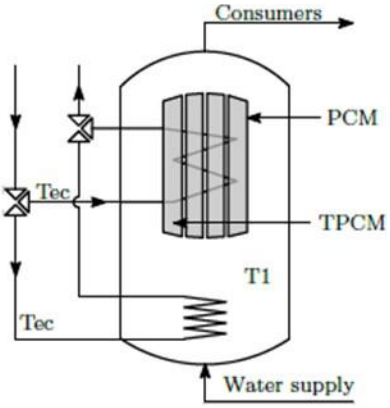


Figure 10. Outline of a storage tank
Tec: temperature of energy carrier
T1: temperature of water
TPCM: temperature of phase change material

Bajnoczy [43] examined a dual-stage heat storage system (Figure 10) operating at temperature ranges of 60°C-30°C and 30°C-20°C, utilizing calcium chloride tetrahydrate and calcium chloride hexahydrate. The study focused on variations in storage capacity over multiple cycles and explored the feasibility of using solar energy for domestic water heating applications. Similarly, Ghoneim [44] conducted a comparative analysis of latent heat storage vessels of different sizes against sensible heat storage in a water tank, considering varying levels of thermal stratification. The storage vessel comprised several closed cylindrical pipes filled with a phase change medium, surrounded by heat transfer fluid. Kaygusuz [45] conducted both experimental and theoretical studies to evaluate the effectiveness of phase change materials in solar water heating systems. Calcium chloride hexahydrate ($CaCl_2.6H_2O$) was used as the phase change material (PCM) in the analysis. The study compared the performance of PCM-based storage with conventional storage systems utilizing water and rock as heat storage media. Solar energy, when available, was collected and transferred to an energy storage tank filled with 1500 kg of encapsulated PCM. This tank was constructed with cylindrical tubes packed horizontally, containing the energy storage material ($CaCl_2.6H_2O$) inside PVC plastic tubes, with water flowing parallel to them.

Font et al. [46] conducted an initial study to design a domestic water heating device utilizing a solid-solid phase change material (PCM). They employed numerical simulations based on a unidirectional heat transfer model and validated the results through experimental testing (Figure 11). The strong correlation between the experimental and simulated data confirmed the model's reliability in analyzing heat transfer behavior within the PCM, aiding in the optimization of the device’s design. Similarly, Tayeb [47] developed a domestic hot water system using $Na_2SO_4.10H_2O$ as a PCM and compared its performance with a simulation model designed to determine the optimal inlet water flow rate required to maintain a stable outlet temperature. Additionally, Bhargava [48] conducted a theoretical investigation of a solar water heater incorporating PCM, concluding that increasing the thermal conductivity of the solid-liquid phases enhances both system efficiency and the outlet water temperature, particularly during evening hours.

An assimilated collector storage system was proposed by Boy et al. [49]. It is based on salt hydrate phase change materials to provide hot water instantaneously. They showed that incorporating an appropriate PCM device could significantly improve the thermal efficiency of such systems. In their design (Figure 12), the salt hydrate PCM was enclosed within a specially designed corrugated fin heat exchanger, which enhanced heat transfer efficiency but also resulted in higher overall system costs.

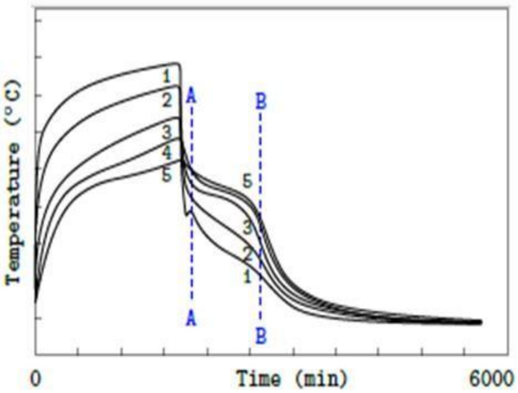


Figure 11. The temperature variations were recorded by different probes for the charge at 65°C and the subsequent restitution phase. Points A and B mark the beginning and end, respectively, of the latent heat discharge during the restitution period

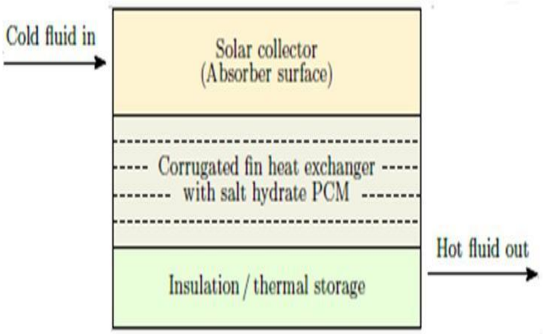


Figure 12. Scheme of assimilated collector storage system

In the recent era, solar water heating (SWH) systems that integrate phase change materials (PCMs) have attracted considerable interest because of their ability to significantly improve thermal storage efficiency while minimizing reliance on external energy sources. Consequently, much of the research has been dedicated to enhancing the properties of PCMs, optimizing their integration with solar collectors, and overcoming challenges related to thermal conductivity and material stability. These advancements aim to make SWH systems more effective and sustainable by better utilizing solar energy and improving long-term performance.

A novel solar water heating system (SWHS) has been developed by Wu et al. [50] to mitigate the effects of fluctuating solar radiation by integrating phase change materials (PCMs) for thermal energy storage and oscillating heat pipes to enhance performance (Figure 13). This system offers adaptable operating modes suitable for various seasonal and climatic conditions. Comprehensive testing was conducted over multiple years in Nanjing, China, evaluated key performance metrics, including collecting efficiency (CE), average collecting efficiency, coefficient of performance (COP), and exit water temperature (EWT). Results indicate that the PCM-enhanced system significantly outperforms its non-PCM counterpart; daytime CE fluctuations are reduced by over 30%, summer night time EWT remains above 50°C, and winter night time COP exceeds 3.0, facilitating quicker attainment of 50°C water temperatures. These findings demonstrate the system's effectiveness and practicality in harnessing solar energy for water heating applications.

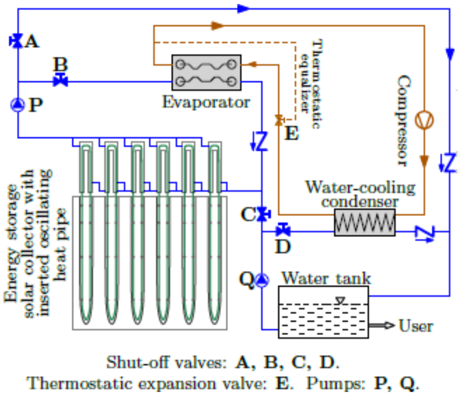


Figure 13. SWHS with inserted oscillating heat pipe

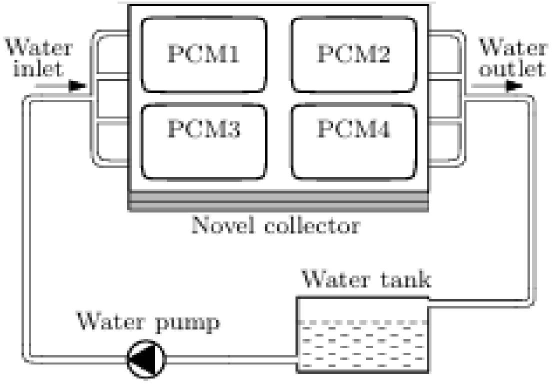


Figure 14. Schematic diagram of novel SWSH

Xiao et al. [51] have focused on enhancing the thermal performance and stability of sodium acetate trihydrate (SAT) as a phase change material (PCM) for solar water heating systems (Figure 14). They prepared composite PCMs by incorporating expanded graphite (EG) and graphene oxide (GO) into SAT using physical hybrid methods. These composites, such as SAT/EG and SAT/GO/EG, exhibit melting temperatures around 57.9 °C with latent heats up to 218.1 J/g. The addition of GO, even in trace amounts (less than 0.1 weight%), has been shown to improve the shape stability of the compressed PCMs, allowing them to maintain good form at higher densities of 0.8 g/cm³ for SAT/EG and of 1.0 g/cm³ for SAT/GO/EG. When applied in solar water heating systems, these composites demonstrate efficient solar-thermal conversion, achieving temperatures above 70 °C and conversion efficiencies around 54.5% under real solar radiation conditions. These findings suggest that SAT-based composite PCMs with EG and GO enhancements hold significant promise for improving the efficiency and reliability of solar thermal energy storage applications.

In arid and coastal regions, the demand for efficient water desalination methods has led to the development of innovative solar still designs. One such advancement [52] is the oval tubular solar still (OTSS), which integrates cover cooling and phase change materials (PCM) to enhance performance (Figure 15). The OTSS features a transparent oval tube that allows sunlight penetration from multiple directions, maximizing solar irradiance. Its black basin improves absorption and facilitates water evaporation. Incorporating PCM as a thermal management solution has been shown to improve both the efficiency and productivity of the OTSS, leading to higher daily thermal exergy efficiency compared to traditional designs.

Solid-liquid phase change materials (PCMs) are widely utilized for thermal energy storage due to their high latent heat capacities. However, challenges such as poor light absorption, leakage, and low thermal conductivity hinder their effectiveness in solar thermal applications. To address these issues, researchers [53] have developed biomass-derived porous carbons using methods like high-temperature carbonization of bamboo with calcium hydroxide as a precursor. These porous carbons enhance the performance of PCMs by improving light absorption and thermal conductivity while mitigating leakage problems. This approach offers a promising avenue for utilizing biomass in solar thermal energy storage applications.

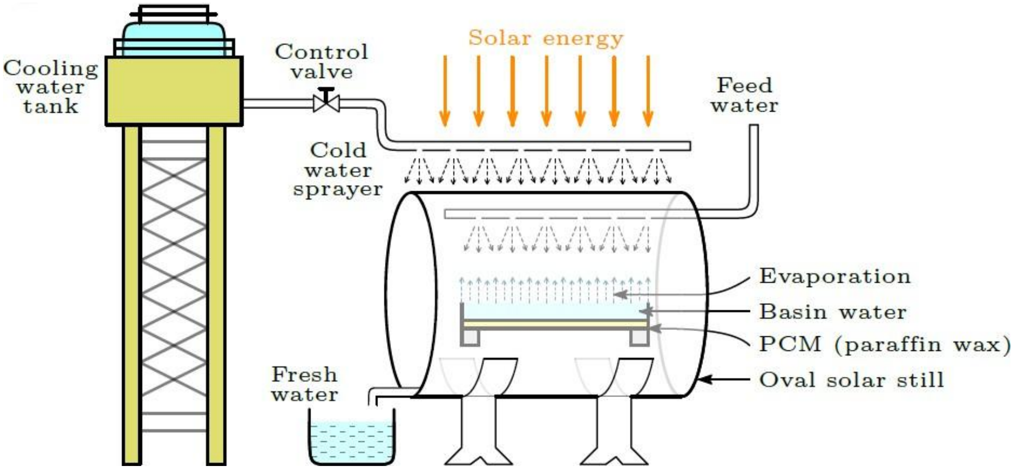


Figure 14. Experimental configuration for the OTSS

The increasing need for efficient energy storage solutions has led to a rising focus on thermal energy storage, particularly for domestic hot water systems. A promising method involves integrating encapsulated phase change materials (PCM) within hybrid accumulators (Fig.16) to improve energy retention. Bianqui et al. [54] conducted a detailed study on the phase transition and heat transfer mechanisms in encapsulated paraffin, utilizing a cylindrical stainless-steel container. Their findings contribute to a deeper understanding of PCM behavior, enhancing the design and optimization of thermal storage systems.

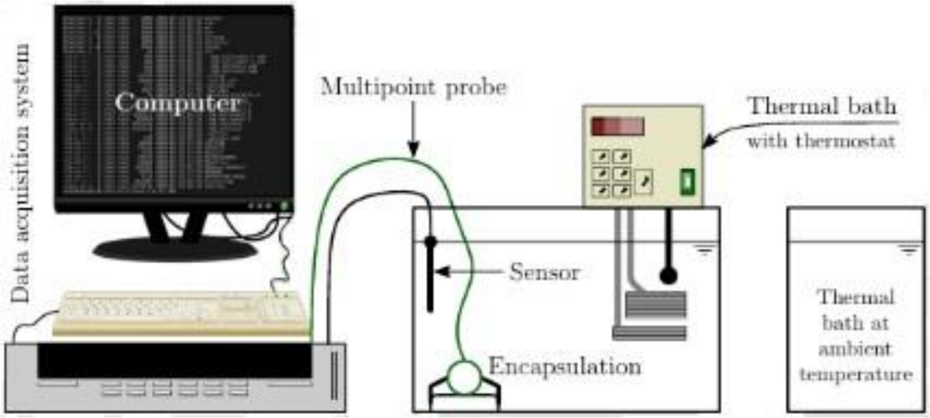


Figure 15. Schematic diagram of the experimental setup for phase change analysis

Solar-thermal-electric generators (STEGs) play a crucial role in harnessing solar energy, offering significant potential for sustainable energy applications. However, achieving rapid photothermal conversion and efficient heat transfer in wood-based composite phase change materials (PCMs) remains a major challenge. To address this, a novel energy storage material was developed by applying an adhesive photothermal coating containing graphene oxide (GO) onto wood-based composite PCMs [55]. This innovative design enhances heat storage efficiency, minimizes thermal losses, and improves solar-thermal-electric conversion, making it a promising solution for advanced solar energy utilization.

4. **Results and Discussions**

In sensible heat storage systems, the storage of heat occurs through the increase in temperature of the storage material, which is normally water. The efficiency of the system is highly dependent on the design of the collectors, environmental conditions, and stratification of the storage tanks.

The efficiencies of flat plate collectors can be determined from the efficiency curves (Figure 1), where they have been shown to be within the range of 40-70%, based on water inlet temperatures and insolation levels. However, their efficiencies decrease drastically as the temperature differences increase between the collector and the ambient environment due to heat loss.

From experimental data, it has been observed that in sensible heat storage systems, water temperatures usually rise to 50-70°C during hours of intense sunlight; however, they drop sharply at night due to lack of thermal buffer capacity.

Stratification is critical for enhancing performance. According to previous findings, the use of multi-tanks or baffles enhances stratification and allows for an increase in thermal efficiency of about 5% to 15% compared to single-tank systems. However, despite this advantage, the main problem is the quick loss of stored energy, which leads to inadequate hot water supply when the sun is not shining.

In general, sensible heat systems have the following features:

Average efficiency (45%–65%).
Large temperature changes ($\Delta T \approx 20\%$–30% between day and night).
Less complex system and lower costs.

Latent heat storage systems employ phase change materials (PCMs) that absorb and release thermal energy at relatively constant temperatures, enhancing thermal stability and thermal energy storage.

From the experiments and theory, collector efficiency for PCM-based systems is reported to be between 50% and 75%, slightly greater than that of traditional systems owing to decreased thermal loss. Even more impressively, the incorporation of PCM results in stabilized water outlet temperature.

The temperature profiles of the system equipped with PCMs reveal that the water temperature does not change much during night time (at about 45-60°C), without any sun rays. In contrast to sensible systems, the reduction in temperature is negligible (ΔT = 5-10°C during night). This shows that latent heat systems exhibit better thermal energy storage characteristics.

The following is observed in experiments employing paraffin wax and hydrated salts:

Heat storage capacity is 2.5-3.5 times that of sensible systems.
Longer hot water supply, by 8-12 hours during night and early morning.
Quasi-stable temperatures are maintained throughout the phase change process.

In a nutshell but not limited to, the comparative analysis between the two classes of solar water heaters is tabulated below:

Table 1. Comparison of solar water heaters

Attributes	Sensible Heat Storage Systems	Latent Heat Storage (PCM-Based) Systems
Storage Mechanism	Energy storage through heating (sensible heat)	Energy storage by phase transition (latent heat)
Storage Material	H_2O, rocks, concrete	Paraffin wax, fatty acids, salts (e.g., $CaCl_2.6H_2O$, $Na_2SO_4.10H_2O$)
Energy Storage Capacity	Low	High (5-14 times more than sensible storage)
Temperature Changes	Big temperature fall at discharge	Constant temperature throughout phase change
Heat StorageDuring Night	Weak	Extensive heat storage at night (hot water availability)
Size/Volume	Need bigger space for same amount of energy storage	Small size because of high energy density
Thermal Efficiency	Decent	Greater efficiency due to low heat losses
Heat Retention Time	3 - 5 hours	10 - 15 hours
Design Complexity	Relatively easy design	More complex design (PCMs' encapsulation needed)
Cost	Low	Costly (due to expensive PCM and its encapsulation process)
Commercial Availability	Plentiful	Experimental stages, less commercialized
Collector Type	Flat plate collectors	Flat plate collectors, integrated collector storage with PCM
Stability of Performance	Sensitive to the intensity of solar radiation	Relatively stable output temperature
Primary Weakness	Poor performance during nighttime	Low thermal conductivity, high cost
Research Emphasis	Stratification optimization	Selection of PCMs, their encapsulation

5. Conclusions

Researchers have made significant efforts in the development of solar water heaters, utilizing a wide range of phase change materials (PCMs) and technologies. This review highlights the evolution of earlier stage sensible heat solar heaters to modern latent heat storages with various potential PCMs and their associated heat exchange mechanisms.

Usefulness of Latent Heat Storage: Solar water heaters combining with latent heat storage leave behind sensible heat systems in terms of prolonged heat preservation, hot water availability during night time, and thermal stability.

PCM Selection Criteria: PCMs like paraffin waxes, fatty acids etc., with melting points in the range of 50°C–70°C, are most suitable for domestic hot water applications due to their availability and thermal capacity.

Encapsulation and Heat Transfer Limitations: Although thermal conductivity remains a major challenge, which affects charging and discharging rates, encapsulated PCM systems are capable to improve storage concentration.

Effect of Storage Geometry: Optimized designs of the geometry of the storage unit are sought; a higher ratio of surface area to volume improves heat absorption but also enhances heat losses.

Performance Improvement: PCM-based systems have longer storage durations, greater accumulation of energy, and better hot water output compared to traditional solar water heaters without PCMs.

Lack of Commercially Developed Designs: Research is going on an integrated thermal storage system, which can provide a simpler and more cost-effective alternative to current solar water heater designs. Research indicates that integrated thermal storage systems offer a viable substitute for conventional solar water heaters. Despite extensive research, most PCM-based solar water heater designs remain at the laboratory level or pilot phase. This necessitates design modification cum simplification to evolve standardized, market-ready systems in future.

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