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Review

Phase Change Materials (PCM) for Solar Energy Usages and Storage: An Overview

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Abstract: Solar energy is a renewable energy source that can be utilized for different applications in today's world. The effective use of solar energy requires a storage medium that can facilitate the storage of excess energy, and then supply this stored energy when it is needed. An effective method of storing thermal energy from solar is through the use of phase change materials (PCMs). PCMs are isothermal in nature, and thus offer higher density energy storage and the ability to operate in a variable range of temperature conditions. This article provides a comprehensive review of the application of PCMs for solar energy use and storage such as for solar power generation, water heating systems, solar cookers, and solar dryers. This paper will benefit the researcher in conducting further research on solar power generation, water heating system, solar cookers, and solar dryers using PCMs for commercial development.

Keywords: PCM; solar energy; renewable energy; energy storage

1. Introduction

In today's world, environmental problems and the energy crisis are two major global issues that need to be urgently addressed [1–3]. The continuous rise in the level of energy consumption, increases in fuel prices and the emission of greenhouse gases are the main forces driving the need for more effective use of renewable energy sources [4–6]. Worldwide, primary energy consumption increased by 1.5% in 2018 compared to consumption levels in 2017 [7]. Many studies on global energy consumption and emissions have been conducted and these topics are discussed at length in [8–10]. One of the solutions to greenhouse gas emissions is the use of renewable energy, and thus, renewable energy initiatives have been implemented in many countries [11–16].

However, the problem associated with some renewable energies like solar and wind, is that they are only available for a certain time period. The supply of renewable energy is difficult to control since it is based on weather-related natural phenomena such as rain, wind and solar energy. Better utilization of renewable energy is possible if it can be stored, as this decreases the demand for fossil fuels, eventually reduces the cost of system maintenance, and in turn, reduces energy waste. In order to balance energy production with consumption, it is necessary to store excess energy for the short/long term. However, at this time, storing excess electrical energy is quite expensive. Instead, the cost related to storing thermal energy is quite low. Excess thermal energy cannot be exported to the energy grid but excess electric energy can be exported through a grid connection. Thermal energy storage may be able to assist during electric utility grid stress. In order to store energy, systems such as batteries or PCMs can be used. However, as the energy storage capacity (kWh) of the batteries is very limited, researchers and users are opting for PCMs as an alternative. It is important to note, that energy storage is economically attractive when it reduces energy consumption and cost and it is a viable substitute for another energy source [17–22]. The different forms of energy storage are presented in Figure 1 [23].

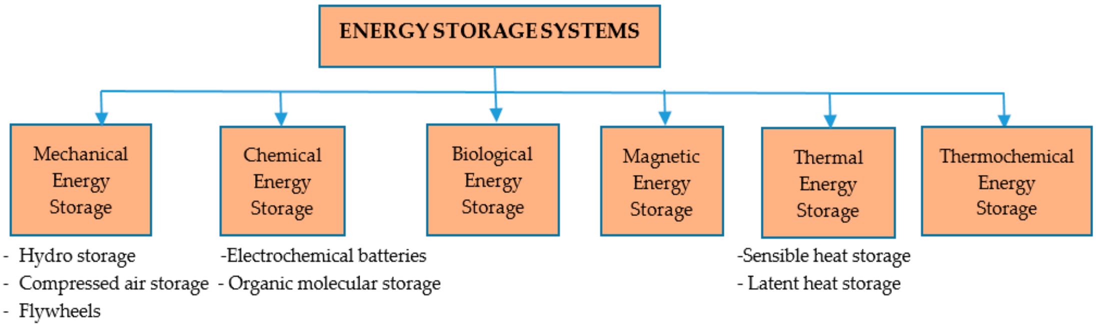

Figure 1. Classification of energy storage systems [23].

Amongst the various energy storage systems, thermal energy storage exhibits the highest efficiency [24]. A thermal storage system can utilize the solar energy and excess thermal energy that is generated throughout the day and can be stored for either short or seasonal periods [25]. Both seasonal storage and diurnal storage can be combined to achieve an efficient system. Diurnal thermal energy storage takes the form of chilled water and ice storage for cooling and hot water tank storage for heating, with greater energy transfer rates [26]. Seasonal thermal storage helps to avoid energy shortage during a period when there is limited sun exposure and lowers high energy costs by storing thermal energy when solar radiation or other energy sources are abundant or inexpensive [27,28]. Therefore, coupling solar energy with sensible storage for diurnal and seasonal periods is important for distributed generation [25,28]. In order for the PCM system to accomplish seasonal heat storage, insulated thermal mass and stable super-cooling are required. Super-cooling is a unique property of PCM storage whereas insulated thermal mass is common to all heat storage media. Stable supercooling PCMs readily supercool, and can remain supercooled at ambient temperatures for seasonal durations. This enables long-term storage without heat loss (i.e., no self-discharge) [29].

PCM is a particularly attractive material because it is able to store a high density of energy and keep a constant temperature or an amount of heat through its heat-storing characteristics [30,31]. The storage of thermal energy can be further classified into three groups: sensible, latent (PCMs) and chemical heat storage [32–34]. Other classifications of the application and characteristics of thermal energy storage can be found in the literature [35–37].

The aim of this paper is to provide a critical review of recent studies of solar energy storage using PCMs. It discusses the classification of energy storage, PCMs integrated with solar power generation, solar water heating systems and solar cookers, and ends with an application of PCM as solar dryer energy. A similar study conducted a review of solar dryers with PCM as an energy storage medium [38,39]. However, that review focused only on using PCM for the solar dryer while the current one examines numerous applications of PCM for solar energy storage.

2. Phase Change Materials (PCMs)

The use of PCMs has recently gained more research interest and importance in the optimal use of energy. The theories, design and analysis of PCMs to store latent heat have been explored thoroughly in the literature [40–49]. Some of the classifications, types and methods will be discussed as follows.

Based on their phase change, PCMs can be classified into four different types: solid-solid, solid-liquid, solid-gas and liquid-gas. Of these four types, solid-liquid PCMs are the most suitable for storing thermal energy, and they can be found as organic PCMs, inorganic PCMs and eutectics, as seen in Figure 2 [50,51].

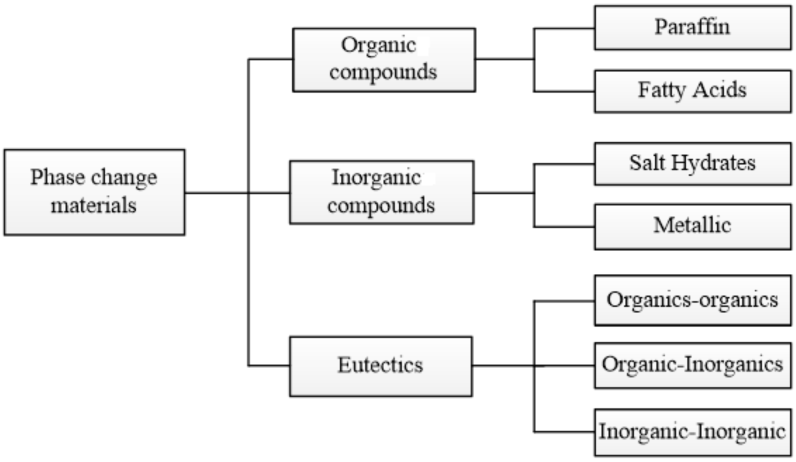

Figure 2. Phase change materials (PCMs) classification [50,51].

Paraffin wax qualifies as a PCM because it can be used over a wide range of temperatures and it has reasonably high heat of fusion. Paraffin wax can also undergo freezing without experiencing super cooling. Hence, technical grade paraffin wax is the most cost effective, feasible and widely used PCM. There are several studies on this topic, including by the authors [52–55]. Fatty acids are organic compounds characterized by $CH_3(CH_2)_{2n}COOH$ with a higher heat of fusion value compared to paraffin wax. Fatty acids have the ability to reproduce melting and freezing with little or no supercooling. One thing that prohibits the application of fatty acids is their cost, which can be 2.0 to 2.5 times higher than the cost of paraffin wax [56,57]. Salt hydrates commonly have a chemical formula of MnH_2O, where M is an inorganic compound and this inorganic compound is important in storing heat due to its high density of volumetric latent heat storage [52,58]. Metals have not been a serious candidate for PCM because of their heaviness. However, when volume is taken into account, metals are likely contenders because of their high thermal conductivities and high latent heat of fusion per unit volume [52,59].

However, PCMs have several disadvantages For example, PCM systems require a long life to recover the installation cost [60]; if any repair of the PCM system is required, it is not possible to carry this out without causing damage to the system; and the supercooling effect reduces the efficiency of PCM material resulting in insufficient heat recovery. Several researchers have tried to add various agents to improve PCMs; however, this has resulted in decreased performance [61,62]. PCM has very low thermal conductivity, which reduces heat transfer during the solid-liquid change of phase [63] and needs to be improved before installation [61]. As PCM may contain multi-components, phase segregation may occur and hamper the long-term stability [64]. Organic PCMs in building envelopes significantly affect fire safety. Researchers have suggested using fire retardants to improve fire safety while using organic PCMs in building envelopes [65,66]. The advantages and disadvantages of both organic as well as the inorganic types of materials are listed in Table 1 [67,68].

Table 1. Pros and cons of PCMs [67,68].

Type of Materials	Pros	Cons
Organics PCMs	1. Available in a large temperature range 2. No supercooling 3. Compatible with other materials 4. No separation 5. Chemically PCMs are stable 6. These are safe to use 7. Non-reactive in nature 8. Can be recycled	1. Low thermal conductivity 2. Relatives large volume changes 3. Flammable 4. Expensive except technical grade paraffin wax
Inorganic PCMs	1. High volumetric latent heat 2. Less expensive 3. Easily available 4. Thermal conductivity is higher 5. The thermal fusion of these PCMs are very high 6. Lower volumetric variation 7. These PCMs are non- flammable	1. Changed volume is remarkably high 2. Supercooling 3. Corrosiveness
Eutectics	1. The melting point of these PCMs are sharp 2. High volumetric storage density	1. Fewer thermophysical properties data is available

It is necessary to have comprehensive and complete information about the thermophysical properties of the materials under consideration. This includes the melting temperature, the heat of fusion, density, thermal conductivity and the stability of thermal properties in successive cycles of heating and cooling. The graphic illustration of PCMs, based on the heat of fusion and melting temperature, is presented in Figure 3 [44]. As shown in this figure, paraffin wax, fatty acids, salt hydrates, and their eutectic mixture have a low melting temperature, while chlorides, carbonates, and fluorides require high melting temperature. The application of these materials can be varied based on their melting temperature and material characterizations.

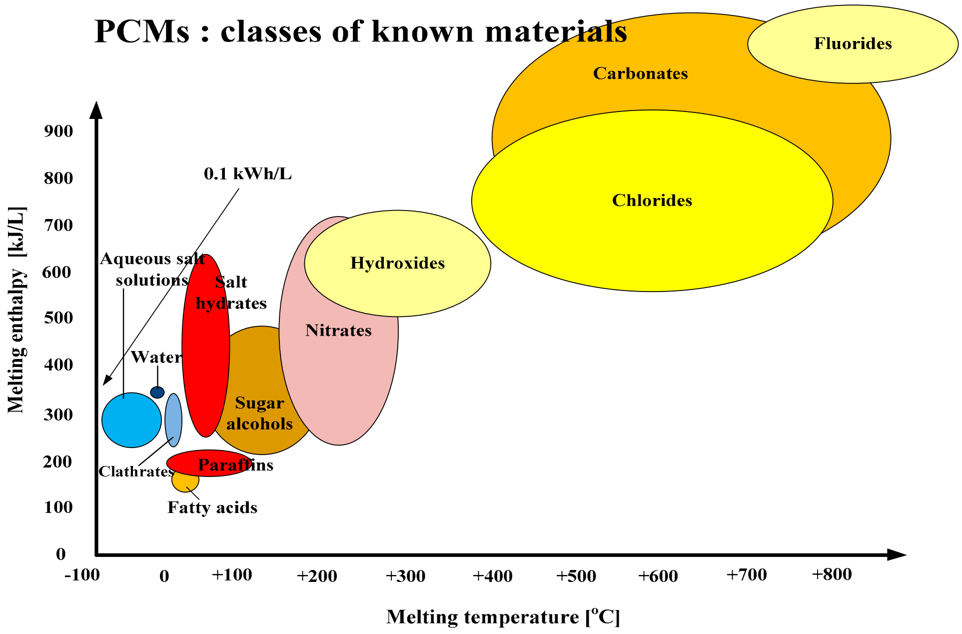

Figure 3. Classes of existing PCMs (graph: ZAE Bayern).

3. PCMs Solar Power Generation

For household use, solar energy is currently the most popular source of renewable power generation in terms of annual investment and offering benefits. There many types of solar energy for power generation, such as photovoltaics, solar thermal [69], solar organic Rankine cycle [70] as well as a solar hybrid [71,72]. In this study, solar thermal electricity generating systems (SEGS) will be discussed due to their ability to be used with PCM to store energy. Therefore, they have great dispatchability potential, which means that they can be used on-demand, making them more efficient and cost-effective. However, high-temperature thermal energy storage (TES) systems have not been widely tested; only a few power plants around the world have been identified as examining this system [73,74]. More recent designs for SEGS have used expensive synthetic oil as storage media and achieved an increase in working temperatures, from the former 300 °C up to 400 °C; however, the technology is still economically infeasible [75]. An example of PCMs used as the heat storage media for SEGS is illustrated in Figure 4.

Although PCM offers a huge opportunity to facilitate the reduction of cost energy produced by SEGS, it has not yet achieved the expected commercial level or large-scale utilization due to low thermal conductivity, which prolongs the charging and discharging period. Hunold et al. [76–78] investigated the heat transfer mechanism for single stage PCMs of different PCM salts by using single-stage PCM storage. The results showed that the PCMs are technically able to produce the desired results and suggested a PCM storage design with vertically-oriented shell and tube heat exchanger.

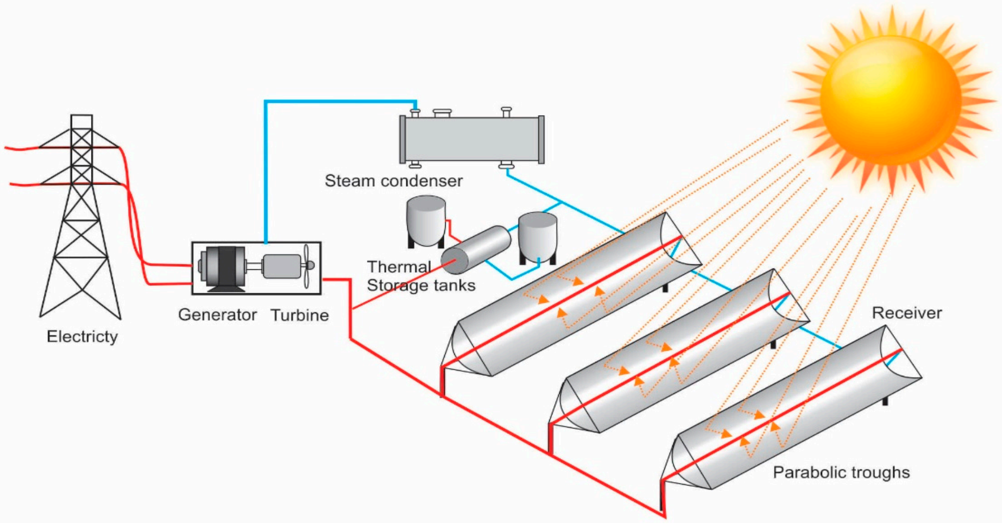

Figure 4. Schematic diagram of a SEGS plant with TES (thermal energy storage).

The fundamental aspect of using latent heat storage in a concentrated solar thermal (DSG) plant is related to the interaction between PCMs and heat transfer fluid during charging and discharging. Figure 5a shows a schematic diagram of a CST plant, which works with latent heat storage and a Rankine cycle. As shown in Figure 5b, latent heat storage and the CST plant can also be connected to a super-critical carbon cycle (s-CO_2), in which it can be connected to a Brayton cycle for power generation [79,80]. This process consists of a heliostat field, central tower (solar receiver), thermal energy storage system, and power block. Solar energy is collected and concentrated on the solar receiver by heliostat fields. Then, the heat transfer fluid (e.g., molten salt) circulates the absorbed heat through the system for introducing to a power block (steam Rankine cycle or s-CO_2 Brayton cycle) in order to convert thermal energy to electrical energy.

LHTES (latent heat thermal energy storage) using high-temperature PCM is not yet popular in commercialized CST plants as research is still ongoing to discover better techniques for high-temperature PCM encapsulation and heat transfer enhancement [81,82]. However, if PCM is adopted as the storage media in commercialized CST plants, the operating temperatures will range from 293 °C to 393 °C, which is similar to the storage temperature that results from current parabolic trough technology. It is also worth noting that a PCM with higher melting temperature is always desirable in CST plants with higher operating temperature (>600 °C) as this ensures higher energy conversion efficiency.

The potential of PCM for steam generation, preheating and superheating through a direct steam generation (DSG) plant was numerically assessed by Pirasaci and Goswami [83]. Usually, the tanks, which are filled with PCMs, are serially connected to increase the temperature of the feedwater entering the TES [84]. The feed water can be heated, evaporated and superheated when it goes through an N number of tubes. The potential of the eutectic mixture (NaCl+$MgCl_2$) with a melting temperature of 550 °C, and latent heat capacity of 317 kJ/kg has been studied through this system. The operating temperature of the water/steam in this system can range between 300 °C and 600 °C, which is suitable for a DSG plant. The results showed that different parameters, such as the flow rate of water/steam, and the design criteria (e.g., tube diameter and length of the tank) of the storage system have a significant effect on the performance of the system [83]. Nevertheless, an experimental assessment of this system has yet to be undertaken. Therefore, further investigation is required to prove the reliability of this system for a DSG plant.

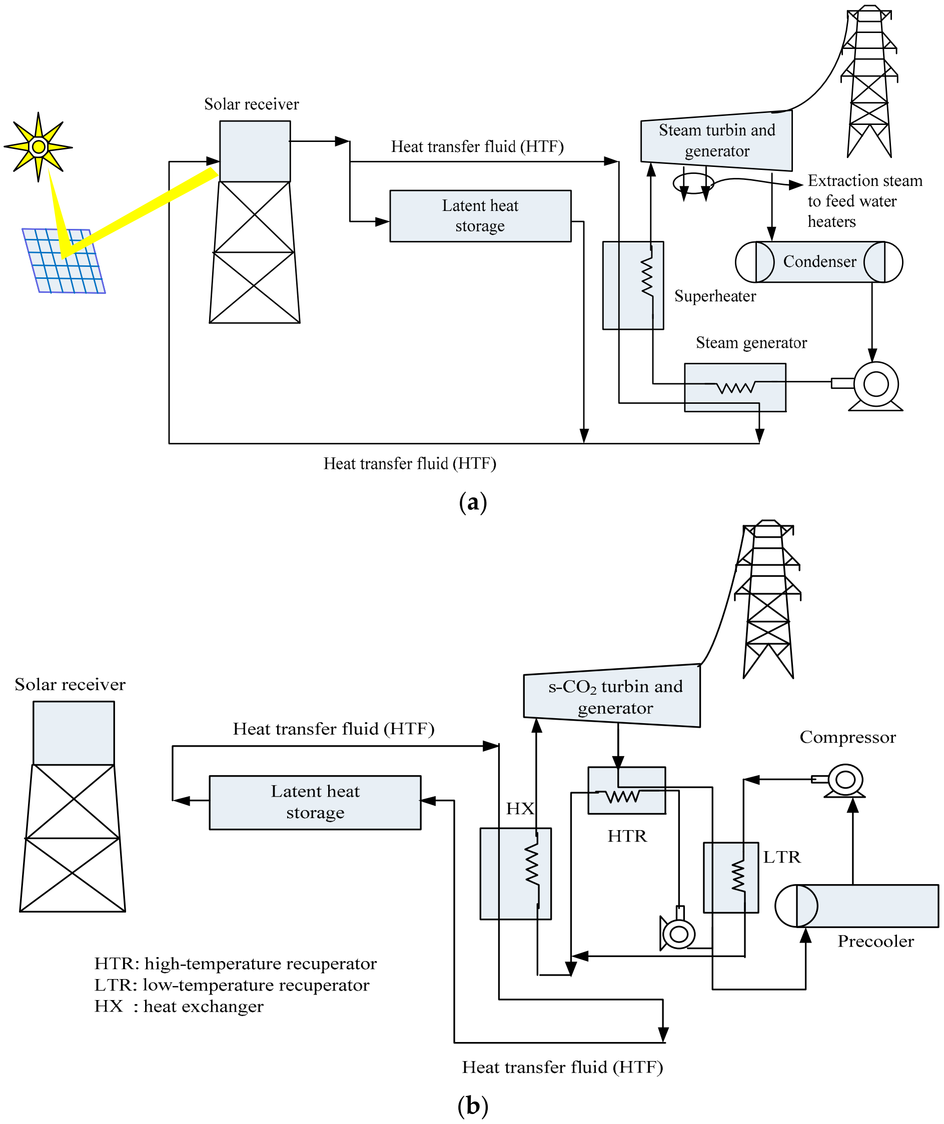

Figure 5. Schematic diagram of CST (concentrated solar thermal) power plant with (**a**) steam Rankine cycle, (**b**) s-CO_2 Brayton cycle.

The same concept has been developed for cascaded latent thermal energy storage (CLHS) by Michels and Pitz-Paal [75]. As shown in Figure 6, CLHS can be used as alternative storage in the parabolic trough where thermal oil is used as a heat transfer fluid. This figure shows that five different PCMs were used in the temperature ranges between 300 °C to 380 °C [85]. The results show that this system can be adapted to the DS123G plant based on the design and material properties. However, the theoretical concepts have not been experimentally verified.

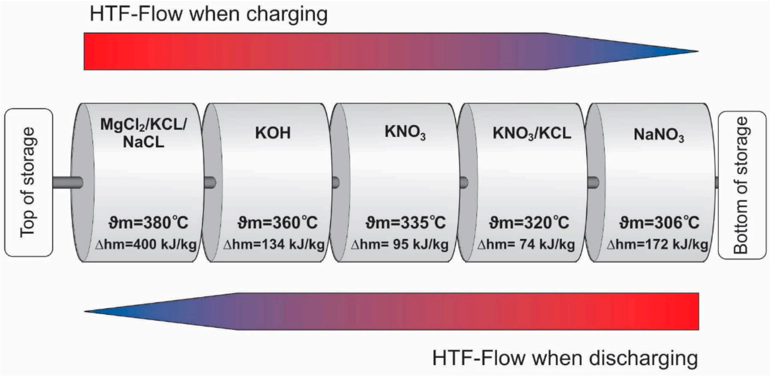

Figure 6. The cascaded latent heat storage system.

Michels and Pitz-Paal [75] used a numerical model to run the simulation for different cascaded latent heat storage (CLHS) configurations and used the Tech-thermos standard library "Dymola/Modelica" to apply the simulation. To simplify the model, a few assumptions were made: the PCM was assumed to be a lumped mass with an evenly distributed temperature. It was also assumed that natural convection occurred for the simulation. The experimental results corresponded with the desired results and this validated their model.

Hybrid PCMs-sensible storage is currently in the early development stage, and has been proposed as a storage system for solar plants; this seems to be a reasonable approach as a next step in the development of PCMs storage [86,87]. The hybrid systems have the ability to make better use of PCM storage capacity and reduce the cost as compared to PCM alone. They are also able to increase the storage ratio compared to sensible heat material systems [73,88]. The potential of combining latent and sensible heat through thermocline thermal energy storage was assessed by Azanganeg el al. [89]. They used sedimentary rock and encapsulated PCMs as sensible and latent storage materials. The results showed that a constant outflow temperature could be achieved with a small amount of PCM, which was approximately 1.33% of the total volume [89,90]. The operating temperature of this system was around 575 °C, which is suitable for a DSG plant. Moreover, the thermal capacity of the proposed system can be increased because it combines sensible and latent heat. Nevertheless, the complicated design of the storage system is considered to be one of the main drawbacks of the proposed system.

4. PCMs Solar Water Heating System

One of the main areas where solar energy has been thoroughly exploitedis in water heating systems. In comparing solar thermal conversion and solar electrical direct conversion, it has been found that solar thermal conversion is more efficient by about 70% compared to 17% for solar electrical direct conversion systems [91,92]. The hot water is needed for residential, commercial and industrial usage. Solar water heaters have gained attention recently because they are relatively inexpensive, maintenance is easy and they are simple to fabricate. In order to ensure hot water is available throughout the day, PCMs can be used as a means of thermal storage. A typical solar water heating system is usually comprised of two units, which both operate simultaneously: a solar water heater and a PCM-contained heater storage unit. During the day, a water heater normally operates by collecting solar energy to heat the water while at the same time, the PCM absorbs thermal energy and stores it within the material. During the night when sunshine is unavailable, thermal energy is retrieved from the PCM to heat the water. A substantial amount of effort by researchers has been aimed at developing solar water heaters. Various PCMs and thermal storage technologies are readily available for use and development in the solar water heater (LHTES) [93–95]. The schematic diagram of an LHTES is presented in Figure 7. The extensive work that has been done on improving the integrated solar water heater storage systems issummarized in Table 2.

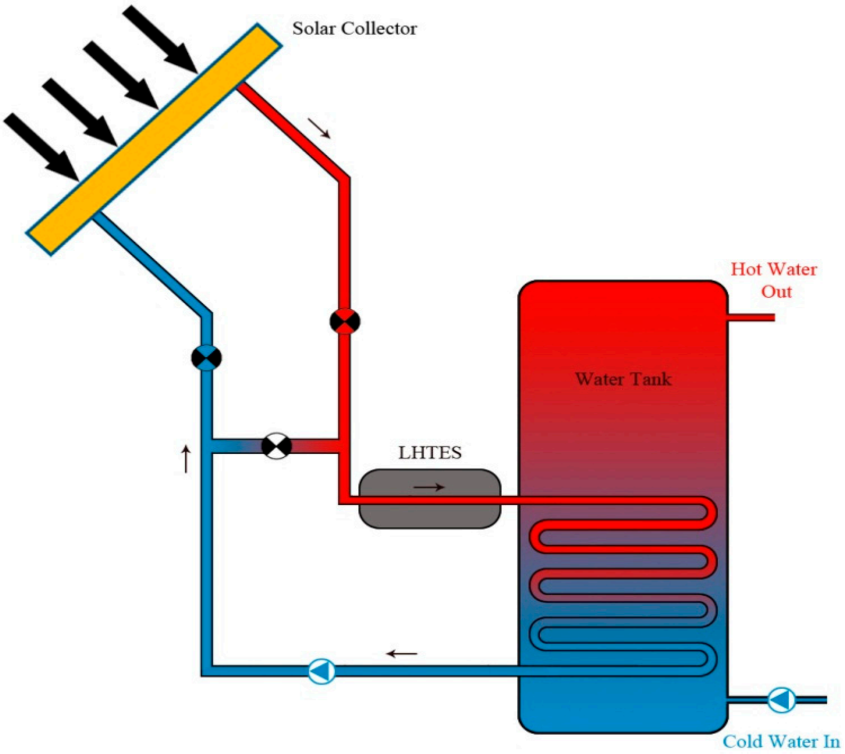

Figure 7. Solar water heater system with LHTES (latent heat thermal energy storage).

Table 2. Summary of various studies of integrated solar water heater storage systems.

Authors	Theoretical/Experimental Description	Results
Prakesh et al. [96]	Studied an integrated storage type water heater, where a layer of PCM is placed at the base of the heater.	The water is heated during the day and the heat is transferred to the PCM below it, which melts as latent heat accumulates. When sunshine is unavailable, the hot water is replaced with cold water, which collects thermal energy from the PCM, in which phases are changed to solid from a liquid. Ineffective transfer of thermal energy between PCM and the water means the system is not as efficient.
Bansal and Budi [97]	Suggested a cylindrical storage unit in the closed-loop with a flat plate collector for its discharging and charging mode. The PCMs used are paraffin wax (p-116) and stearic acid.	Calculations for the fluid temperature and its interface moving boundary were made.
Porteiro, Míguez [98]	A thermal analysis is performed to check the thermal properties of each PCM.	A temperature recovery is seen; the energy due to the water temperature, PCM and the thermal loss to the ambient environment are observed.
Benmoussa, Benzaoui [99]	A numerical study of the thermal behavior of a shell-and-tube latent thermal energy storage (LTES) unit using two-phase change materials (PCMs).	All heat transfer fluid inlet temperature and melting rate of PCM are varied. Also, a variation in the HTF inlet temperature significantly affects the temperature evolution of PCMs.

Table 2. *Cont.*

Authors	Theoretical/Experimental Description	Results
Kamiz Kayguz et al. [100]	Theoretical and experimental study of the performance of phase change energy storage materials for the solar heater unit. The PCM used is $CaCl_2.6H_2O$. A comparison study of heat storage performance for PCM-based, water-based and rock-based system was also conducted.	The solar heating system with $Na_2SO_4.10H_2O$ has more F values compared to $CaCl_2.6H_2O$. The thermal properties of the PCM are not reduced during the operation.
Rabin et al. [101]	Studied a solar thermal collector with thermal energy storage using salt hydrate as PCM and used for heating.	The results of the study show the correlation between transition temperature and thickness of the salt hydrate PCM layer and the effect on the thermal performance during the PCM charging process.
Sharma et al. [102]	Designed, developed and performance evaluated a latent heat storage unit using a box-type solar thermal collector, which can be used during the evening and morning where hot water is needed. The PCM used is paraffin wax.	It was found that the storage unit performed well in keeping the hot water within the desired temperature range.
Mattewa and Assassa [103]	Investigated the thermal performance of a compact PCM solar collector utilizing storage of energy in term of latent heat.	The charging process, the average heat transfer coefficient increases sharply with increasing the molten layer thickness, as the natural convection grows stronger. In the discharge process, the useful heat gain was found to increase as the water mass flow rate increases.
Cabeza et al. [104]	Tested PCM behaviour in real conditions at the University of Lleida by constructing a solar pilot plant. The solar pilot plant is designed to work continuously either with a solar energy system, or an electrical heater.	In order to use numerous cylinders at the top of the water tank, the PCM module geometry is adopted.
Kumar et al. [105]	Designed, developed, and evaluated a latent heat storage system to be used on-demand when warm water is needed, in which the thermal energy is collected by using a box-type solar collector. The system comprised of three finned heat exchangers and the PCM used paraffin wax with a melting point at 54 °C to store heat.	The results show that that storage unit in the heat storage system performed well in keeping the hot water within the desired temperature range. For the experiments, 15 L and 20 L of water were used.
Shukla [106]	Devised two solar water heaters in which the heat storage material is paraffin. One system had tank-type storage and the other system had incorporated storage type with a reflector.	These systems are capable of providing hot water during the day and night on a daily cycle basis. These two systems have an efficiency of 45% and 60%, respectively.
Hasan et al. [107–109]	Analyzed domestic water heater using fatty acids as PCM.	The study found that the best and most promising PCMs are myristic acid, palmitic acid, and stearic acid, all having melting temperatures between 50–70 °C, which are suitable for heating water.
Tiwari et al. [110]	Analyzed the effect of running water flow within a parallel plate on a solid-solid PCM interface to be used as a water heater. To reduce heat dissipated during nighttime, movable insulation is provided to the system.	They found that the hot water can be maintained at a high temperature all the time and increasing the melted region of PCM will reduce water temperature fluctuations.
Ling, Mo [111]	Studied the energy and thermal efficiency of the system, the energy consumption for room heating and the solar fraction.	The heating efficiency of the system would be 31.7% and the solar fraction would be 83.6% while the average temperature indoors was 14.9 °C and outdoors was −1.5 °C.
Boy et al. [38]	Suggested a salt hydrate PCM-based integrated collector storage system to provide instantaneous hot water.	Demonstrated that by incorporating an appropriate PCM the system's efficiency could be raised considerably. However, the system is expected to have a high cost because the salt hydrate PCM is contained in a specially corrugated fin heat exchanger.

Table 2. *Cont.*

Authors	Theoretical/Experimental Description	Results
Tayeb [112]	Developed and investigated a system with $Na_2SO_4.10H_2O$ as PCM used for the domestic water heater.	The results are then used as a comparison with the simulation model, which provides the ideal inlet water flow rate required to keep the water temperature constant at the outlet flow.
Font et al. [113]	Researched a preliminary study using solid-solid PCM in designing domestic water heater device. Simulation with numerical values was utilized using a one-directional model and used to confirm the findings of the experiment.	The agreement of both simulation and experimental results reveals that this model can investigate heat transfer within PCMs and further optimize the water heater device design.
Bhargava [114]	Theoretically investigated a water heater using solar energy with PCM.	The results showed that when the thermal conductivity of solid-solid PCM is increased, outlet water temperature and the efficiency of the system during the evening hours will also increase.
Canbazoglu et al. [115]	Analyzed and compared conventional solar water heater with PCM-powered solar water heating. Polyethylene bottles were filled with approximately 180 kg of PCM and the bottles were left to set in the tank in three rows.	The temperature of the water is found to be constant at 46 °C throughout the night until morning, while the hot water does not change at all.

Solar water heating systems with different types of PCM should be evaluated to find optimum heating [116]. Different heat transfer fluid can be used as an alternative to water to obtain better heat exchange. Furthermore, nanoparticle-enhanced PCM can be used to investigate the system performance.

5. PCMs Solar Cookers

One of the main elements of energy consumption in developing countries is cooking. The sources of energy for current cooking methods are kerosene and liquid petroleum gas (LPG) for urban areas, while in rural areas, non-commercial fuels such as firewood, cow dung and agricultural waste, are used. Solar cookers have the potential to solve global issues related to fuel source limitations and CO_2 emissions. Hence, more research initiatives are needed to successfully commercialize solar cookers as a viable replacement for traditional cooking devices. The use of solar cookers could have a positive impact on the environment by reducing CO_2 emissions and helping to reduce the dependency on fossil fuel. In order to be fully commercialized and widely used, certain social conditions are required in addition to the cost and performance conditions [117–119]. Also, usage of solar cookers has a limitation in that they can only be used in clear, sunny conditions and are unusable during cloudy days or at night. Thus, solar cookers must have the ability to store heat to overcome these limitations and impracticalities during off-sunshine hours. Research and promotional schemes in the PCM field are necessary to ensure that solar cookers are viable and commercialized for future use [120–122]. The schematic diagram of a concentrating type solar cooker using PCM A-164 is presented in Figure 8.

Buddhi and Sahoo [123] designed and tested a solar-powered cooker by storing latent heat as a means of cooking food in the late evening. Thermal energy storage material made of commercial-grade stearic acid (the latent heat of fusion 161 kJ/kg, melting point 55 °C) was placed under the absorbing plate. The heat transfer rate during PCM discharge was slow and it took more time to cook food during the evening [124]. Domanski et al. [125] studied the utilization of PCMs using magnesium nitrate hexahydrate ($Mg(NO_3)_2.6H_2O$) as the heat storage media for a box-type solar cooker to be used during non-sunshine hours. Sharma et al. [126] designed a PCM storage unit in the shape of a cylinder for a hot box solar cooker using commercial grade erythritol (Tm = 118 °C), to be used for cooking food in the evening or at nighttime. The results of their experiment showed that storing solar energy did not affect the solar cooker's performance during the day. They suggested that the PCM range of melting temperature should lie between 105–110 °C for evening cooking [127].

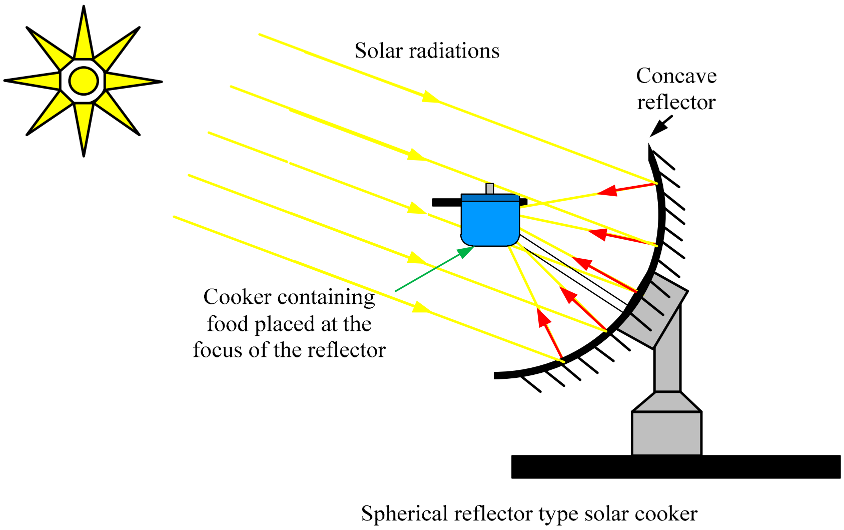

Figure 8. Concentrating type solar cooker using PCM A-164.

Sharma et al. [127] also investigated a solar energy cooker based on an evacuated tube solar collector (ETSC) with storage of PCM. The designed unit has components for cooking and solar energy collection, which were then paired with a PCM storage unit. The solar energy was stored within commercial-grade erythritol as latent heat and released to be utilized later for cooking at night. Cooking experiments during the day were carried out using different loads and loading times, while simultaneously experimenting with PCM storage processes. It was observed that noon and evening cooking are independent of each other, and it was found that evening cooking takes less time when using PCM heat storage compared to cooking at mid-day without PCM.

Hussein et al. [117] designed a new indirect solar-powered cooker that consisted of a solar collector with a flat plate, outdoor elliptical cross-section wickless heat pipes, and an integrated PCM thermal storage which was placed indoors. Two reflectors were used to focus the solar rays on to the collector, while PCM made of magnesium nitrate hexahydrate (the latent heat of fusion 134 kJ/kg, Tm = 89 °C) was used inside the indoor cooking unit. The setup showed an average daily improvement by 24% of incident solar radiation on the surface of the collector when the reflector was placed facing north and south. Other experiments were also conducted without the load as well as different types of load at different loading times. This was done to identify any benefits or effects from solar cookers set up as a means of cooking during the day and for keeping food warm at night and in the early morning.

However, as reported in the literature, based on the thermal stability test, the maximum temperature of PCM as a means of solar cooking is around 120 °C. Indirect heating is found to be the most suitable mode of heating when PCM is incorporated as a heat storage material, for which the temperature drop between the cooking container surface and storage material would be approximately 10–15 °C. Thus, it can be deduced that the maximum possible temperature of the cooking vessel surface is 100 °C, which is below the temperature needed for frying and fast cooking. In order to overcome this problem, a solar cooking system using PCM A-164 as the storage medium is still being studied [128–130]. This system consists of a solar collector with a concentrator, a PCM based thermal storage unit and an indoor cooking unit [131]. The thermic fluid has been chosen to be the heat transfer fluid to allow heat flow between the cooking unit and the collector. PCM A-164 is used as a thermal energy storage medium to store energy during the day and the energy is retrieved in off-sunshine hours. The cooking unit employs a flat surface hot place, similar to electric cooking, and circulation of cooking oil ensures flow below the finned hot plate to ensure that the surface temperature is maintained at around 140–150 °C. This system can be utilized for cooking throughout the day. Although the capital and cost of initiating this system is high, it could be cost-effective for long-term usage if the PCMs could be manufactured at a lower cost [132,133].

6. PCMs Solar Dryers

Drying techniques are processes used to decrease the moisture of products, which can be used for storage of foods and agricultural products [134]. An operating temperature of 40–60 °C is required for drying products such as fruits and vegetables [135,136]. The moisture content and quality of the products (e.g., nutritional properties) can be controlled with the humidity level and operating temperature. These parameters are varied for different products [137].

The solar drying method has received significant attention in the food and agriculture industry because it makes the process of preservation easier [137]. Moreover, it has significant ecological benefits [138]. The potential of paraffin wax as a PCM in the solar dryer has been assessed by Devahastin et al. [139]. They found that PCMs can store surplus energy from the sun and discharge this energy when it is demanded. Different parameters such as heat transfer characteristics, inlet, and outlet temperature, and the effect of air velocity were studied during charging and discharging. The results showed that the extracted energy decreases from 1920 kJ·min/kg to 1386 kJ·min/kg when the inlet velocity increases from 1 to 2 m/s [139]. They also found that sweet potato can be dried up to 40% with this inlet velocity. The schematic diagram outlining the basic concept of this process is shown in Figure 9. As shown in this figure, the PCM is placed in the latent heat storage tank.

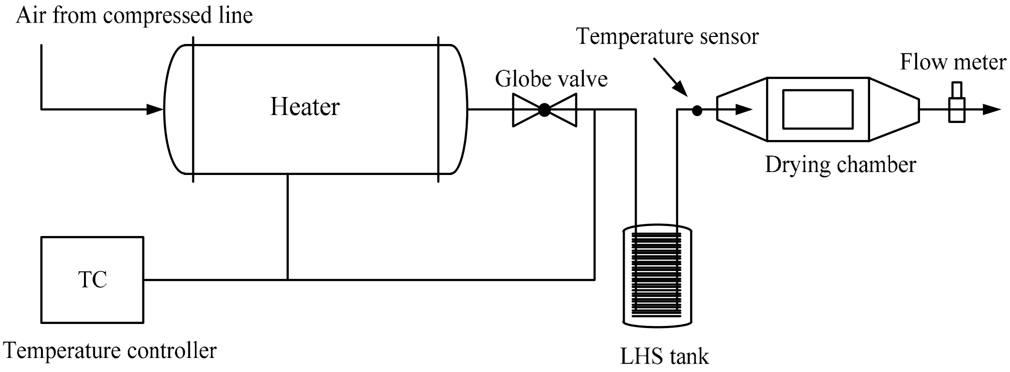

Figure 9. Schematic diagram of the basic concept of the solar drying chamber.

Devahastin et al. [139] proposed latent heat storage from exhausted gas of a modified spouted bed grain dryer via numerical simulation. They claimed that up to 15% of saving could be achieved by combining these methods. Meanwhile, Bal et al. [140] developed and designed a solar dryer with LHS using paraffin wax as the PCM to store any excess solar energy during the day and release it when solar energy was inadequate or not available. Another paper by the same authors gives detailed explanations about a solar dryer with thermal energy storage systems that was used for drying agricultural food products [140–142]. The drying process of pineapple slices and green peas through indirect forced convection and a desiccant bed was assessed by Shanmugam and Natarajan [143]. This system was designed to perform in both sunshine hours and off-sunshine hours.

Another study by Shalaby et al. showed the effect of PCMs on the performance of a solar dryer [138]. The results showed that PCMs could increase the operating temperature of the solar dryer up to 6.5 °C. Syringe et al. [144] studied the thermodynamics of this process for drying garlic cloves. The results depicted that the moisture content of a garlic clove decreased from 55% to 6.5% over 8 hours. The energy and exergy efficiencies of the drying chamber with circulating air were also improved by 14.9% and 88.2%, respectively [144]. Another solar dryer with PCM was fabricated by Jain and Tewari [145]. This solar dryer consisted of a flat plate collector, a storage system (pack bed), natural draft system and drying chamber. The results showed that the temperature of the dryer remains stable at 40–45 °C, which helped the drying process. Moreover, the thermal efficiency of this system reached up to 28.2%. The potential of a natural convection type solar dryer in two different conditions (load and unload) has also been assessed by Sain et al. [146]. In this experiment, ginger was dried under full load conditions, which reduced the moisture content from 74% to 3% over 24 hours.

While the estimated drying efficiency was 12.4%, the overall efficiency of the system reached 22.7%. Moreover, solar collector efficiency increased up to 96% and 55% in no-load and full load condition, respectively [146]. Cocoa beans have also been dried with the help of a solar dryer and desiccant thermal energy storage [147]. The results demonstrated that the temperature of the drying chamber varied between 40 °C and 54 °C during sunshine hours, which is higher than the ambient temperature. They also found that combining a solar dryer with thermal energy storage improves the specific energy consumption and drying time of the product.

The solar hybrid dryer proposed and designed by Reyes et al. [148] consisted of solar panels, a solar accumulator, electrical heater, drying chamber, and centrifugal fan. Paraffin wax was used as a PCM in this system. An outlet air temperature of 60 °C was achieved through this system, while the temperature of the solar panel increased up to 30 °C higher than ambient air. The results showed that the thermal efficiency of the system varied between 22% and 67%. This value fluctuated from 10% to 21% for the accumulator, which leads to a reduction in the electricity consumption of the system. They also found that the use of PCM significantly improved the thermal efficiency of the system.

To improve the thermal performance of solar dryers, PCMs with high latent heat and a large surface area for heat transfer are required. This results in a reduction in the heat loss and the disparity between supply and demand, and improves the energy efficiency of the system [138]. However, the low thermal conductivity of PCM is still a problem and further research and development is required in this regard.

7. Conclusions and Recommendations

Energy storage is very appealing to many parties because of its ability and potential to improve system performance. Storing excess energy for future use makes the development of technology more effective and viable compared to building new power plants. PCMs can play a significant role in storing higher amounts of energy, which is linked with the latent heat of the phase change. Also, PCMs support a target-oriented settling temperature by the fixed temperature of the phase change. The energy storage capacity of PCMs in the heat recovery of solar power plants is affected by several factors. Two forms of heat transfer, heat conduction and convection occur during the phase change process inside the PCMs. Improve heat transfer techniques can increase heat conduction and suppress heat convection. To ensure better and more cost-effective PCM performance in energy storage applications, it is recommended that the available information be consolidated to provide better facilities to end-users. Also, social awareness, along with the technological development of solar stills can significantly motivate people to use PCM-based energy storage systems. However, future research should focus on techniques to improve and optimize the heat transfer of PCMs. Further research on the development of efficient and cost-effective PCMs with less ageing effects for solar thermal energy storage applications is needed to ensure significant and positive social impacts.

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Abbreviations

CLHS	cascade latent thermal energy storage
CST	concentrated solar thermal
DSG	direct steam generation
ETSC	evacuated tube solar collector
LHTES	latent heat thermal energy storage
LPG	liquid petroleum gas
PCM	phase change material
SEGS	solar electricity generating systems
TES	thermal energy storage

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