Chapter 52
Analysis of Thermal Energy Storage Mediums for Solar Thermal Energy Applications

Shivansh Aggarwal, Rahul Khatri, and Shlok Goswami

Abstract Energy storage mediums are highly popular in solar applications due to their ability to store heat and release it during any time period of the day. This study provides a classification of different thermal energy storage (TES) mediums in various solar energy systems with their feasibility and future applications. The concept of TES and the various studies on the application of TES in solar thermal applications have been presented. Recent advances and the performance of common solar thermal systems with and without TES have also been presented. Working conditions, economical aspects, suitability, and selection criteria of TES materials have also been discussed based on their application. This paper also uncovers the future aspects that possibly will improve the use of TES and lead to the performance optimization of solar thermal systems.

Keywords Charging and discharging · Energy storage materials · Latent heat · Sensible heat · Solar energy

52.1 Introduction

Solar energy has employed in various applications in the current scenario of renewable energy technologies. There is abundance of sunlight available during daytime while during night solar energy is not available. The fluctuations in the supply of energy while using solar energy as primary energy source have been a common concern. Thermal energy storage (TES) systems are employed to overcome this by storing the excess energy and utilizing it during different time periods of the day. TES systems are able to provide a greater evenness in the energy utilization received throughout the day and night which can be used for various industrial or domestic applications. TES systems work on the concept of predominantly storing heat as

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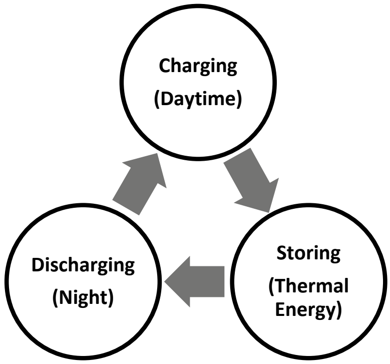


Fig. 52.1 Working cycle of TES system

sensible heat in the substance which can be then followed by the change of phase of the material utilizing latent heat to store energy. Phase change material (PCM) is able to store a larger amount of thermal energy per unit volume than sensible heat storage materials, using the process of melting and freezing, PCMs store and release the thermal energy, these PCMs have a higher energy storage density and have various benefits in particular applications [1, 2].

52.1.1 Working Cycle of TES Systems

Utilizing TES has three major working steps: charging, storing, and discharging, which forms its working cycle as shown in Fig. 52.1. During the daytime, when solar energy is available, the TES system charge themselves and store this energy for future use. This energy is stored until it is actually required during night when sunlight is not available and provides the device with energy continuously which improves efficiency of the system.

52.1.2 Classification of TES Systems

TES systems can be broadly classified under the following criteria as shown in Fig. 52.2 based on the type of technology, storage material, application, and end-user type. This classification of TES systems helps to distinguish between the types, technical, and user-based application of energy storage materials.

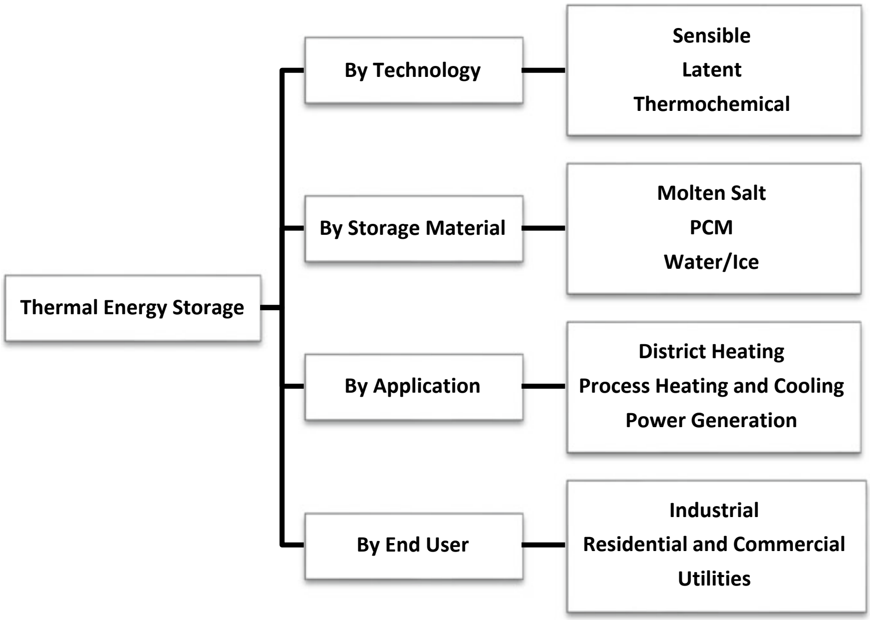
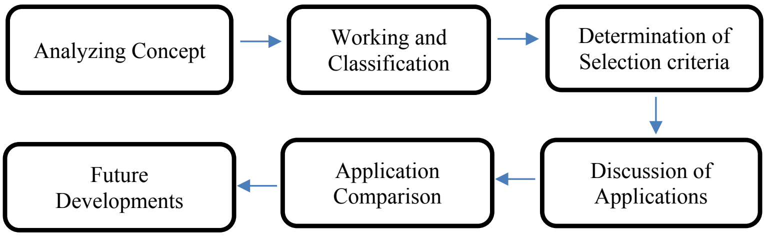


Fig. 52.2 Classification of thermal energy storage systems [3]

52.1.3 Work Methodology



This paper compares the experimental work and methodologies that various authors have utilized to incorporate thermal energy storage. These methods have shown effective means of improving the performance and working time of the energy storing devices. Thus, this paper would provide information about the various TES systems and the extent to which they help in optimizing the performance of these devices.

Thermal energy can be stored in the form of sensible heat, latent heat, and thermochemical energy. Although these mediums have different impacts on the performance of the TES devices, this paper focuses more on the latent heat storage methods.

52.2 General Selection Criteria for a TES System

The appropriate selection of a particular TES system according to a specific application is based on few aspects that govern its use and utility for that application. For optimizing its energy usage, it is very important to choose a TES system according to its application characteristics. JA Duffie and WA Beckman [3] listed these major characteristics as:

- Operating range of temperature
- Storing capacity per unit volume
- Heat removal or addition means and the related difference in temperature
- Storage unit temperature stratification
- Requirements of power for heat removal or addition
- Equipment's and devices related to the system of storage
- Thermal losses control from the system of storage
- Involved cost.

Thus, before selecting any TES system, its feasibility has to be ensured. This can be done by taking into consideration the above-stated factors. Once a TES system is appropriately chosen, it can yield the optimized results. The most commonly used TES systems, which are nowadays gaining the attention of researchers are PCMs that use the phenomenon of phase transition to store thermal energy.

52.2.1 Phase Change

PCMs are highly used due to their difference in the heat storing abilities from sensible heat storage systems. This can be understood by looking at their phase transition change profile as shown in Fig. 52.3.

It can be seen form Fig. 52.3 that there is a huge gap of energy during the change of phase, through which thermal energy can be stored and used whenever required. This enhances the system efficiency. This type of energy storage has been utilized by various authors whose works have been presented in this paper.

52.2.2 Encapsulation of PCMs

Encapsulating means the packing or covering of the PCM inside a shell of material to prevent it from leaking when in liquid phase. This packing has to be chosen very appropriately for efficient use. Encapsulation of PCMs has numerous advantages:

- Separation from the outside surroundings which improves compatibility with the material
- Ensures that the PCM does not mix with the fluid being transferred

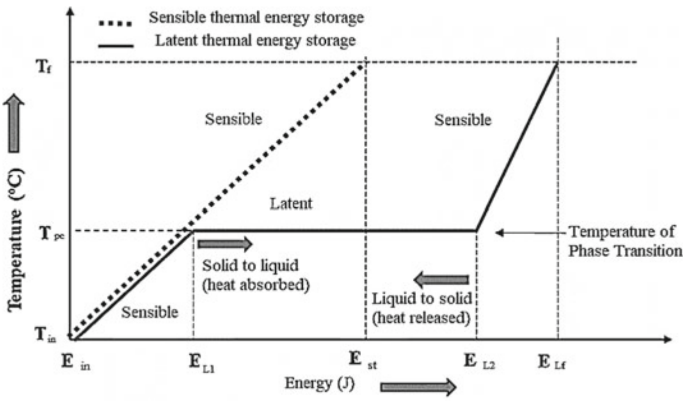


Fig. 52.3 Phase transition profile of phase change materials [4]

- The possible reaction of chemicals is prevented
- Flexibility in the process of phase change
- Reduces changes in the outside volume
- Production improvement in handling of materials
- Surface sufficiency leading to improved rate of heat transfer [5].

The shape of the container for encapsulation can be rectangular, cylindrical, tubular, or spherical. The structure of encapsulated PCMs and the working principle has been shown in Fig. 52.4. Kinga Pielichowska and Kryzysztof Pielichowska [4] worked out on the improvements in the various encapsulation techniques.

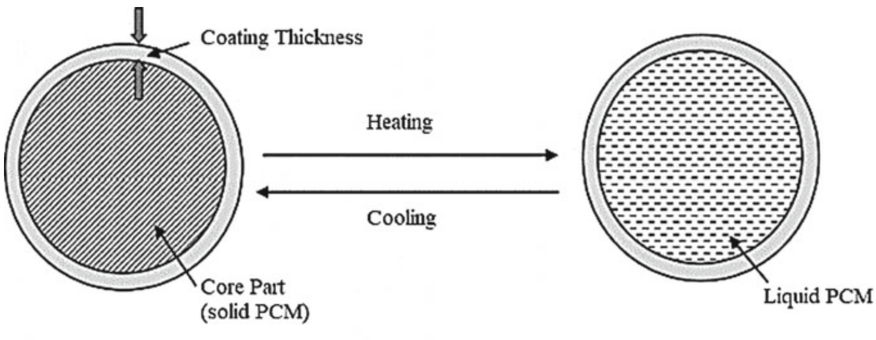


Fig. 52.4 Working principle and structure of encapsulated phase change material [6]

52.3 Applications of TES in Solar Thermal Systems

The use of TES in overcoming the drawback of discontinuous supply of solar energy can be very useful. The thermal energy storage mediums have been used in many applications like solar water heater, solar air heater, solar still, and solar cooking. The thermal performance of these systems can be improved with continuous use even during non-sunshine hours with the use TES mediums. Some of the storage mediums along with their specific use in solar thermal systems has been presented in this section.

52.3.1 Solar Air Heater (SAH)

Solar air heaters have been used for a long time, and research is constantly under process for improving their efficiency. Solar-powered air heaters have shown a decent increase in efficiency with the use of TES systems. Various authors have worked upon integrating TES into SAH which in turn increases the working efficiency of the system. Different types of TES systems have been used by various authors, and their output/efficiencies comparison has been presented in Table 52.1.

Thus, numerous studies have been done for improving the overall output of SAHs, and different methods involving sensible and latent heat storage have shown great results. The outcomes of various studies in which SAH with TES systems were used to confirm that it is very effective and can also lead to some major improvement in the near future.

52.3.2 Solar Water Heater (SWH)

Solar water heaters are very useful and have been used since ages. Regular research is done to improve its performance. Hasan et al. [16–18] worked on some fatty acids which can be used as phase change materials for SWH and concluded that palmitic acid, myristic acid, and stearic acid, having melting point temperatures between 50 and 70 °C are the most suitable PCMs for domestic water heating.

Xue [19] in his experimental study found that as the ratio of tank volume to collector area increases, its energy efficiency consequently increases. It is also discussed that the SWH efficiency depends mainly on the following two factors, i.e., type of PCM and design of the tank.

The author also compared the results in two test conditions: one in exposure and the other one with a constant flow rate, and it was noticed that the setup with a constant flow rate proved to be more thermally efficient. This is because the excess energy which is there can be actually stored in the PCM and is then used to heat the water making it a better performer than the traditional one.

Table 52.1 Performance comparison of TES systems

References	TES system	Inferences
Enibe [7]	PCM-Paraffin	Improvement in thermal efficiency from 7.5 to 18%
Naphon [8]	Porous medium	Increase in the thermal efficiency by upto 25.9%
Alkilani et al. [6]	PCM-Paraffin wax and Aluminum powder	Enhancement in thermal efficiency from 10 to 20%
Tyagi et al. [9]	PCM-paraffin wax and hytherm oil	Efficiency of the system improved from 20 to 53%
Aissa et al. [10]	Granite stone	Outlet temperature of the SAH was 10–25 °C higher than the outside ambient temperature
Yadav et al. [11]	Dessert sand	Enhancement in thermal efficiency from 47 to 69%
Saxena et al. [12]	Carbon Powder (Granular)	Efficiency improvement from 43 to 73%
Karthikeyan et al. [13]	Packed bed of Paraffin wax	With growth of the transfer surface area of heat by using small balls, there was a higher difference in temperature be- tween the phase change temperature of the PCM and the HTF inlet; higher rate of mass flow of HTF had a crucial con- sequence on the SAH's charging time
Bouadila et al. [14]	AC27 Packed bed	Temperature at the outlet was at all times during the night more than the inlet temperature by almost 70 °C
Wadhawan [15]	Lauric acid integrated with the TES device	Mean increment in the temperature of output air was 86.47%

Canbazoğlu et al. [20] used sodium thiosulfate pentahydrate as PCM for their experiment which yielded an average temperature value of 6 °C higher than the conventional SWH with no PCM. It was also found that with the combination of other few salt hydrates with Glauber's salt, the mass of hot water produced along with the storage time of heated water and the cumulative heat in the tank was around 2.59–3.45 times than that of traditional system.

de Gracia et al. [21] in their analysis of a domestic electrical hot water cylinder showed that with the use of phase change materials, hot water discharge capacity had shown an increase from 40 to 55%. Various researchers have worked on different PCMs as TES mediums incorporated in the system's water storage tank.

Mazman et al. [22] used paraffin and stearic acid weighing 3 kg in a tank of 150 L kept the temperature of water near the melting range of the PCM for an average of 6–12 h more compared to without PCM. Al-Hinti et al. [23] used paraffin wax to maintain the water temperature at 30 °C for around 11 h more than without PCM. Kousksou et al. [24] in their simulation incorporated approximately 57 L of NaOAc.3H2O in a tank of 150 L capacity to keep the temperature of water at 50 °C for 6 h more than without PCM.

Murray et al. [25] used lauric acid as TES medium, the result of their simulation showed that the water temperature was maintained at 43 °C for 3 h. Bouadila et al. [26] used 49.4 L of paraffin as TES system in their study which showed a uniform source of heat even during 5 h after the sun was not available.

Fazilati and Alemrajabi [27] worked with paraffin wax PCM of about 5.2 L in a 9.5 L tank as TES medium, which extended the supply time of hot water by up to around 25%. Naghavi et al. [28] in their study used 0.703 kg paraffin wax which maintained the water temperature higher than 55 °C for 2 h when there was low solar radiation and 4 h with regular solar radiations.

Khalifa et al. [29] used 42.4 kg paraffin wax in the a 1.248 m^2 collector to maintain the temperature of the collector plate higher than 40 °C for 4 h after the solar radiations starts decreasing. Al-Kayiem and Lin [30] worked on using 28 kg paraffin wax non-composite 1 w.t.% nano-Cu particles on a 1 m^2 collector and observed that it keeps the temperature of water above 50 °C for extra 1 h than without using the PCM.

Xue [19] in his experimental investigation used 14.2 L of $Ba(OH)_2$.8H2O as PCM in a 1.272 m^2 collector that kept the tank water temperature higher for 2 h in the afternoon. Papadimitatos et al. [31] incorporated dual PCM using 4.2 kg Erythritol and 6 kg Tritriacontane on the collector plate of 0.947 m^2 which resulted in maintaining the temperature of water above 40 °C for 2 h more than without the use of PCM.

Thus, by analyzing the difference in SWHs with and without TES system, it is evident that TES systems play a crucial role in enhancing the working performance of SWHs. The results imply that the usage of TES systems has improved the utilization of solar thermal energy available for use. Research in the field of finding new PCMs and improving the existing ones is being done to optimize the performance of SWH. New composites are also being worked upon to be added to the existing PCMs which could provide better results.

52.3.3 Solar Dryers

Solar dryers are devices that use solar energy for drying substances. A solar dryer is another application of solar thermal energy, which is immensely used in the food and agriculture industry. Present industrialization has created a need for drying products at controlled rates which has led the researchers to find methods that can work according to the requirement.

Butler and Troeger [32] experimentally evaluated a collector-cum-rockbed storage system for drying peanuts. The drying time varied from 22 to 25 h and reduced the content of moisture of the peanuts from around 20% to a range suitable for its safe storage.

Nadukwu et al. [33] in their work used glycerol as TES medium and observed that drying in the solar dryer integrated with a wind air generator and without thermal storage material yielded a relative humidity in range from 7 to 47%. On the other hand, drying integrated with glycerol had a relative humidity of 7–32%. The author also presented results of the potato sample reaching its equilibrium moisture content value of 10.3 ± 1.3% w.b in 20 h without TES and 8–12 h with the TES.

The heat transfer coefficient to dry the potato slice was also compared which was in the range from 13.02 to 18.62 W/m°C and 16.2 to 17.07 W/m°C for without and with the use of TES, respectively. The exergy efficiency compared was ranging from 23.8 to 67.5% and 26.1 to 92.7% for without and with the use of TES, respectively [33].

Alimohammadi et al. [34] worked on a solar dryer with a parabolic trough solar collector by using four fluids. These fluid types were engine oil (10W40), nano-fluid (Al_2O_3, 4%), glycerin, and water. The overall thermal efficiency of the dryer was improved by about 20.2, 9.7, and 12.4 with respect to water. The overall input of thermal energy was 18.46, 17.36, 16.80, and 17.76 MJ for oil, nano-fluid, water, and glycerin, respectively.

Reyes et al. [35] worked with paraffin wax and electrical resistances as phase change material for drying mushrooms using a hybrid solar dryer. Its thermal efficiency was observed to change between 22 and 62%.

Atalay [36] evaluated that the solar dryer without any thermal storage used 28.76 MJ of waste heat energy and 61.36 MJ solar energy for removing 9.027 kg of water from 10 kg of oranges. On the other hand, using a packed bed TES, the system used 23.38 MJ of waste heat energy, 64.2 MJ of stored thermal energy, and 0.815 MJ of thermochemical energy to remove 9.012 kg of water in about the same drying time.

Thus, the emerging need of the world requiring efficient solar dryers for drying products can be met by the utilization of TES mediums which eventually increase the performance of the device and lower the drying time that would have been required otherwise.

52.3.4 Other Emerging Applications

Apart from the above-mentioned solar thermal devices and setups, solar energy is also well utilized in the below-mentioned applications where its use is gaining popularity and is producing efficient results for future needs to be catered through renewable energy. These applications can be termed as follows:

- Distillation
- Heating of buildings
- Pumping
- Agricultural and animal products drying
- Furnaces

- Cooking
- Generation of electric power
- Production of thermal power production
- Green houses.

In solar distillation, PCMs are able to improve the performance and distillate output. Various researches show that by using PCMs, the solar distillation working time of the system can be increased by 3–4 h and the distillate output can also be increased from 50 to 160%. This percentage change is dependent on the type of PCM utilized [37].

In the past decade, it has been seen that building operations account for more than 30% emission of greenhouse gases that involve no use of energy storage. TES systems not only improve the working efficiency for heating buildings but also play a crucial role in reducing these emissions to a great extent [38].

Saxena et al. [39] tested various PCMs for cooking various food items and concluded that stearic acid in the solar cooker achieved appropriate temperature range to cook types of eatables like beans, rice, fish, and pulses.

Thermoelectric generators (TEG) can convert the difference of temperature between two junctions into electrical energy. PCM is embedded near the hot junction of the generator which stores thermal energy from the heat source. This method of installation of PCM as a TES system for generating power, resulted in improving the performance of the TEG to a great extent [40].

Similarly, for other applications, TES systems shown positive result outputs. The recent advances in science have made the use of different TES systems for solar applications possible, which has resulted in the enhanced quality and output of these systems.

52.4 Discussion and Future Development Scope

This paper discusses the working concept of thermal energy storage systems, their classification, advantages, and various mediums that are used to produce improvement in the results. It can be concluded that by using TES mediums, there is high improvement in the working efficiency of the solar energy integrated systems. There are various TES systems used for SAHs like PCMs, granite stone, desert sand, and carbon powder which have shown great effects. The choice of a particular TES system for a specific application is very important as it defines the quality.

SWHs differ in their outputs majorly due to their tank design and the type of PCM if it is used as TES. The amount of TES used, and the area of the collector plate also plays a vital role in governing its thermal efficiency. Solar dryers have also shown significant improvement in performance by employing thermal storage and also reduced the waste heat energy produced. The moisture content was reduced much faster, and the total working cost is also lowered by the use of TES systems.

Their use has shown various benefits but a constructive research with categorization and optimization in this field is highly essential.

The present scenario of using TES systems shows the improvement in performance of solar energy-based devices and extends the scope of their applications. The enhancement in performance is based on the effective use of TES mediums. Various studies have been presented with different TES systems used for the thermal performance improvement of solar energy devices. There is still a large scope for the improvements that can be done to optimize the output of these devices. Future research work in this field can include:

- The development of novel composites for PCMs and other TES systems which can enhance the working performance of solar thermal equipments.
- The use of hybrid solar equipments with TES can show even higher efficiencies
- The improvement in thermal conductivity and heat transfer rate by using extended surfaces or some integrated techniques.
- The improvement in PCM storage tanks and system design optimization can be done to ameliorate the performance of the solar devices.
- Ways to prevent energy losses during its transmission.
- More advanced equipments can be used to properly analyze the appropriateness of TES systems and improve the reliability.
- Light absorption enhancement of PCMs can improve their efficiency.

TES systems pragmatically push us toward the sustainable dwelling in the environment. Thus for the benefit of nature and improved energy utilization, constant research in this field is very important.

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