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Thermal Energy Storage Technology in solar Energy Utilization: A Review

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Abstract: Thermal energy storage (TES) is a promising technique that conserves accumulated thermal energy from heat and cold mediums, making it available for future use. This method allows energy to be stored under various conditions, presenting an attractive solution for harnessing solar radiation efficiently and in large quantities. TES is becoming increasingly important as renewable electricity integration grows and the demand for low-carbon energy rises. Concentrating solar power plants benefit from TES, enabling them to store excess solar energy during peak times and utilize it during periods of lower solar radiation, ensuring a continuous power supply. Additionally, standalone TES systems for grid applications are gaining popularity, especially with the declining costs of renewable energy. These systems facilitate energy integration and help meet the increasing energy demands sustainably. Energy conservation is greatly aided by phase change materials (PCMs) used in thermal energy storage systems. They are perfect for storing and releasing large quantities of thermal energy because to their high thermal storage density and low temperature volatility. As a result, PCMs have gained popularity in this field. Research papers pertaining to storage materials and procedures are the primary focus of this investigation into thermal energy storage systems. It explores sensible heat storage, which involves altering material temperatures to store energy, latent heat storage that capitalizes on phase change properties like those of PCMs, chemical storage utilizing chemical reactions for energy storage and cascaded thermal storage systems that combine different methods for optimized energy storage. By exploring these areas, this research aims to advance the understanding of thermal energy storage and contribute to the ongoing efforts in achieving sustainable and low-carbon energy solutions for the future.

Keywords: Thermal energy storage, Solar Radiation, Low carbon energy, Phase change material, Clean energy.

1. Introduction

Government worldwide have shifted their focus to energy, the environment, and sustainable development as long-term reliance on fossil fuels has led to pollution, greenhouse effects, global temperature rise, and resource depletion, posing risks to human existence and progress [1].

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Renewable energy sources, including solar, wind, hydro, and geothermal power, are gaining popularity due to their sustainability and cleanliness. Among these sources, solar power stands out as one promising option due to its widespread availability and accessibility [2]. But as solar radiation is intermittent, the output of solar power systems is also highly variable, calling for energy storage technologies to bridge the gap between energy demand and supply. Numerous proposals have been made for developing efficient and cost-effective energy storage systems; they include compressed gas energy storage, pumped storage hydro-power, flywheel energy storage, thermal energy storage, electrochemical energy storage, and hydrogen storage [3]. Each of these methods offers unique energy storage characteristics, and they find applications in various domains.

TES is particularly noteworthy for its cost-effectiveness and practical applications. TES involves storing thermal energy by heating or chilling a medium for later use. It has found use in diverse applications, including district heating, household heating and cooling, concentrated solar plants (CSP), industrial processes, and the food industry. Adopting TES in energy systems brings advantages such as improved overall efficiency, reliability, economics, and reduced environmental pollution, including lower greenhouse gas emissions [4]. To achieve efficient 24-hour operation in TES systems, researchers explore new materials with enhanced thermo-physical characteristics. Storage density— optimization of solar ratio, appliance efficiency, and heating and cooling energy use may all be achieved by increasing energy density. By decreasing solar storage volume for a given solar percentage or increasing solar fraction for a given accessible volume, phase-change materials (PCMs) may improve energy density in small water storage tanks [5]. There has been a lot of work done to find ways to store thermal energy (both sensible and transformative). Many different aspects of solar energy have been the subject of study, such as solar collectors and thermal energy storage systems for solar thermal applications, ice storage for air conditioning, and the use of phase change materials (PCMs) for cold storage in home refrigeration appliances. In conclusion, implementing thermal energy storage systems, particularly those using phase-change materials, provides a practical and efficient means of coping with the difficulties posed by energy fluctuation, boosting system efficiency, and advocating for future sustainable energy solutions.

2. Thermal energy storage technologies

The variable and sporadic character of solar radiation makes TES an invaluable component of thermodynamic systems. Increased system performance and thermal reliability are two further benefits of TES's capacity to close the supply-and-demand performance gap [6]. As a result, it is essential to create TES systems that are both effective and affordable. However, there has not been widespread use of TES in solar thermal facilities. Furthermore, there is ongoing research focused on planning TES systems for various residential solar applications. Computational fluid dynamics (CFD) techniques are commonly employed to optimize TES systems and avoid unnecessary expenses. The FLUENT software, in particular, has proven effective for various engineering applications [7]. Fig.1 illustrates the diverse range of thermal energy storage options available for other forms of energy. Capacity, power, efficiency, storage duration, charging and discharging times, cost, and other factors may all be used to characterize an energy storage system. Time, power, and capacity are all related to the discharge process. Some storage systems may have an inverse relationship between capacity and power. Table.1 displays typical TES system specifications [22].

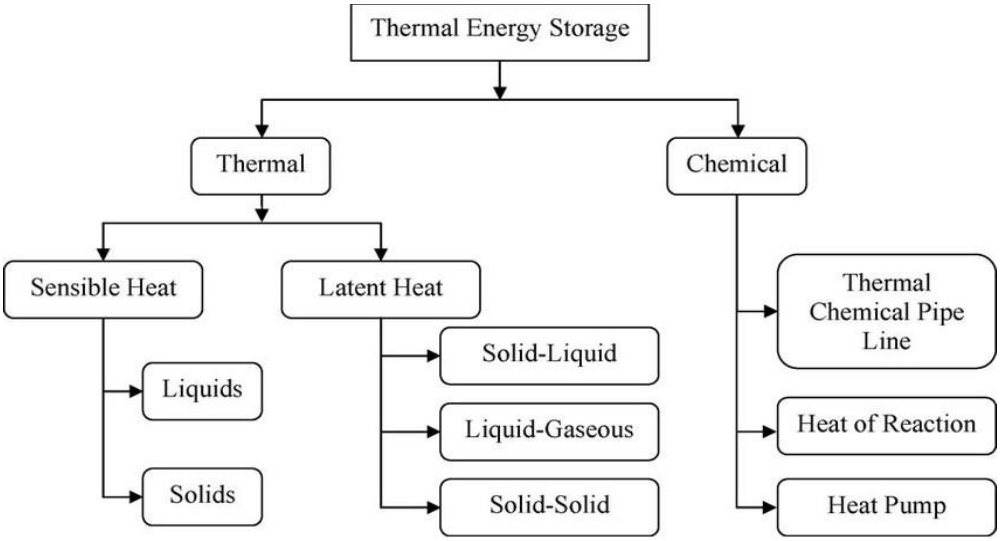

Fig. 1: Types of solar thermal energy storage

Table. 1: Typical values for three TES methods are compared.

TES System	Capacity (kWh/t)	Power (MW)	Efficiency (%)	Storage Period	Cost (/kWh)
Sensible (hot water)	10–50	0.001-10.0	50–90	days/months	0.1–10
Phase-change material (PCM)	50–150	0.001-1.0	75–90	hours/months	10–50
Chemical reactions	120–250	0.01-1.0	75–100	hours/days	8–100

2.1. Sensible Heat Storage

The most fundamental thermal energy storage method, "sensible heat storage" (SHS), involves raising or lowering a medium's temperature to store heat. Fig.2 shows how SHTES systems heat and cool. When the storage medium is being charged and discharged, the SHS system makes advantage of the inherent heat capacity and temperature changes [8].

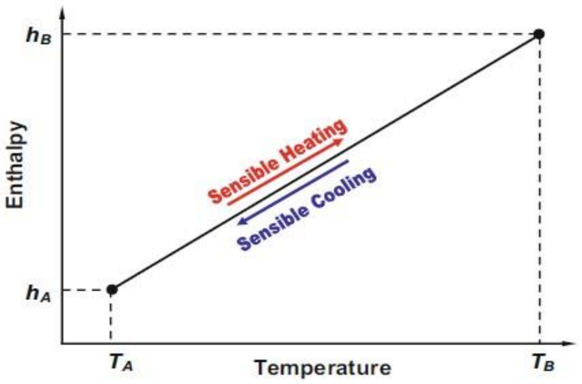

Fig. 2: Medium enthalpy fluctuation during sensible heating or cooling

The components of the system are the storage medium, the enclosure, and the input/output ports. It is important to limit heat energy losses and protect the storage medium [9]. The thermal capacity of the fluid, the operating temperature range, the design and geometry of the inlet and outlet ports, mixing effects during charge and discharge cycles, thermal losses from the storage device, and thermal stratification within the storage medium all affect SHS system efficiency [24]. SHS heats a solid or liquid over its working temperature to store heat energy. Water is often used because of its great heat capacity, cheap cost, and excellent safety. Water tanks are extensively utilized because they are inexpensive and practical. Higher temperatures and larger storage capacities are possible with the use of materials such as molten salts or metals [10]. Heat may also be stored in a network of vertically organized U-shaped pipelines (boreholes) or horizontally oriented trenches, as part of underground thermal energy storage (UTES). Using proper methodologies and considerations based on the individual system features and design, the total quantity of heat stored in the SHS system may be determined.

$$Q_s = \int_{t_i}^{t_f} mc_p dt = mc_p(t_f - t_i) \qquad (1)$$

Q_s is measured in Joules and m in kilogrammes. specific heat c_p is expressed in Joules per kilogramme degrees Kelvin, initial temperature t_i is expressed in degrees Celsius, and final temperature t_f is expressed in degrees Celsius.

2.1.1 Water tank storage

Water's large heat capacity (and inexpensive price) make it a popular choice for thermal storage [26]. Thermal energy is often stored in water tanks because they are inexpensive and efficient. However, materials like molten salts or metals may be employed for higher temperature applications, allowing for additional storage space. Underground thermal energy storage (UTES) systems, employing tanks or heat-transfer fluid (HTF) circulating through U-shaped pipes in vertical boreholes or horizontal trenches, also provide a means of energy storage [11]. Hot water tanks have been used for a long time to store thermal energy, and they're especially useful when used with solar and co-generation systems to heat water. Water tank storage has been shown to be cost-effective in modern projects [27]. Among the many strategies for increasing efficiency are the stratification of water inside the tank and the use of very effective thermal insulation. Current research focuses on optimizing system integration and developing new technologies, such as evacuated super-insulation, which has a thermal conductivity of 0.01 W which conducts 0.01 W/(mK) at 90°C and 0.1 mbar. Figure 3 shows a typical heat-storage water tank. /(mK) at 90°C and 0.1 mbar. Figure 3 depicts a typical setup for storing heat in the form of a water tank [12].

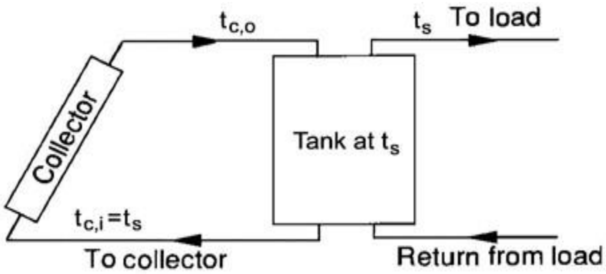

Fig. 3: A typical system using water tank storage

If the liquid is uniformly mixed (not stratified), Equation (1) may be used to compute the energy-storage capacity of a water (or other liquid) storage device operating in a restricted temperature range.

$$Q_s = mc_p\Delta t_s$$

In most cases, the process requirements dictate the lowest possible operating temperature for such a device. The process, liquid vapour pressure, and collector heat loss may limit your height. Non-stratified tank energy balance

$$mc_p\frac{dt_s}{d\tau} = Q_u - Q_L - U_sA_s(t_i - t_a)$$

Where, the energy input Q_u and output Q_L rates are represented by the collector and load input and output rates. The heat loss coefficient of a storage tank is indicated by U_s. Size of storage area matters much. The temperature in the tank at all times is t_a, and t_i is the desired temperature in degrees Celsius.

2.2. Latent heat storage

PCM are classified as Latent Heat Storage materials due to their ability to store or release energy during a phase transition. Figure 4 demonstrates that when latent heat storage decreases in volume, the energy density increases [13]. This process stores heat via the phase transition, which is connected to latent heat and occurs at a constant temperature. PCMs are ideal building blocks for Latent Heat Storage systems, which efficiently store thermal energy. Since latent heat storage (LHS) can keep its internal temperature stable while storing heat, it has an advantage over sensible heat storage (SHS) [14]. Assuming a linear temperature increase with increasing system enthalpy, LHS materials initially behave in the same way as typical SHS materials [26]. However, during a phase change, such as melting or solidification, the LHS materials absorb or release heat at virtually constant temperature. This characteristic allows for more efficient and precise heat storage compared to SHS, where the temperature varies throughout the storage process [15].

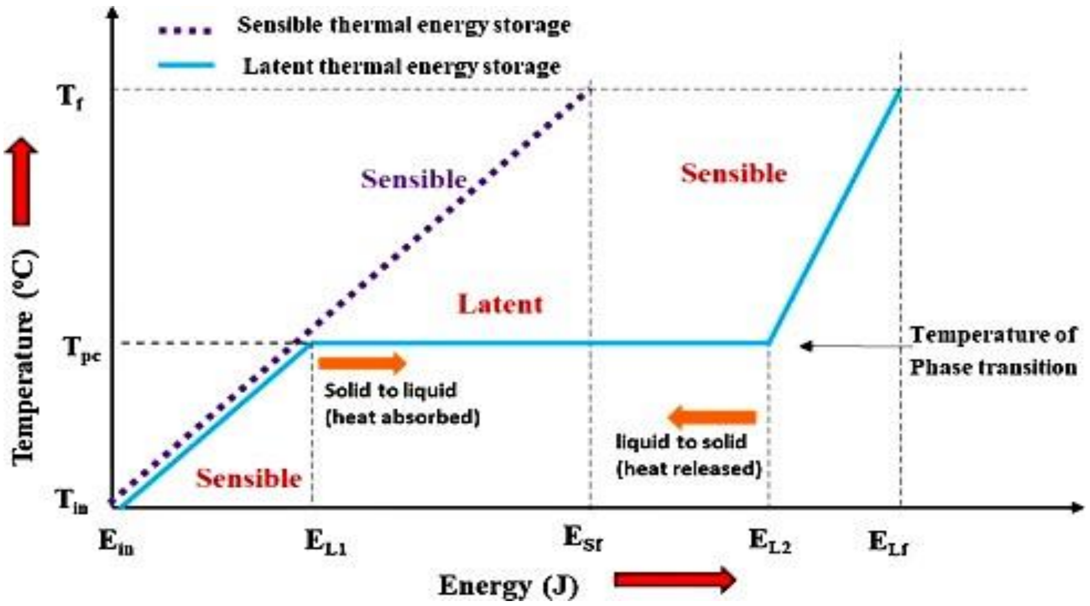

Fig. 4: Enthalpy variation of a medium during charging– discharging periods of an LHTES unit

$$Q_s = \int_{t_i}^{t_m} mc_p dt = mf\Delta q + \int_{t_m}^{t_f} mc_p dt$$

$$Q_s = m\left[c_{ps}(t_m - t_i)\right] + f\Delta q + c_{pl}(t_f - t_m)$$

Where, the heat capacity, or Q_s , is the quantity. Specific heats of PCMs in solid and liquid states, denoted by c_{ps} and c_{pl}, respectively. The latent heat of fusion denoted by q, melting point fraction, or t_i and t_f represent the storage materials' starting and ending temperatures. t_m refers to the melting point.

2.2.1. Phase change materials

Recently, solid liquid PCMs have been considered as an alternative to sensible TE) materials. Unlike sensible heat storage materials, PCMs may be used at their phase change temperature, therefore the difference between charging and discharging temperatures is low. Fig. 5 shows the various PCM families utilized for TES [23].

ORGANIC PCMs

Eutectic mixes of organic PCMs are used in space heating, energy generation, refrigeration and air conditioning, solar air and water heating, textiles, cars, food processing, and space. Straight-chain n-alkenes like CH_3-(CH_2)-CH_3 dominate paraffin waxes. Chains release latent heat during crystallization [16]. Melting temperature and latent heat of fusion increase with paraffin wax chain length. Therefore, only the highest-grade paraffin waxes are employed as PCMs in these systems. Paraffin waxes have several positive qualities as PCMs, including being non-corrosive, inexpensive, readily accessible from room temperature to temperatures as high as 80 degrees Celsius, and more [17]. However, there are a wide variety of organic PCMs beyond paraffin waxes with their own unique properties. Esters, fatty acids, alcohols, and glycols are all examples of organic PCMs that have received a lot of research [25]. These organic compounds have a high heat of fusion, but they are also unstable at high temperatures, combustible, poorly thermally conductive, and have low flash points. Within certain temperature ranges, the latent heat capacity of organic PCMs is high because of their purity and unique compositions. They may last indefinitely due to their chemical inertness [18]. However, their usefulness is limited by their poor thermal conductivities (0.1 to 0.35 W/mK).

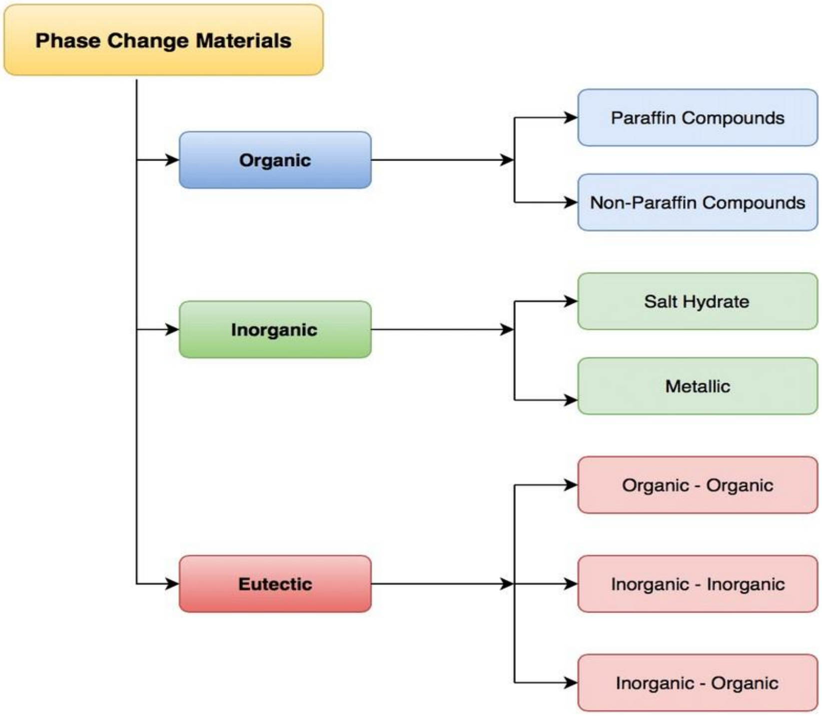

Fig. 5: Classification of phase-change materials (PCMs)

INORGANIC PCMs

Inorganic phase change materials (PCMs) have distinct advantages over organic PCMs, including approximately doubled heat storage densities, higher thermal conductivities, and the ability to withstand higher working temperatures [28]. However, there are some drawbacks associated with inorganic PCMs. One major issue is their tendency to corrode metals, leading to shortened service life and higher failure rates of the storage systems. This, in turn, results in increased maintenance costs [19].

Typical examples of inorganic PCMs are salt hydrates and inorganic salts. Inorganic PCMs have difficulties in reversibility and energy storage capacity due to phase segregation and supercooling. Because of their resilience to corrosion at high temperatures, metallic alloys and metals being studied as possible PCM alternatives for these uses [20]. Compounds of the form AxB and $AxByn(H_2O)$, where AxB is a metal and $AxByn(H_2O)$ is water, are known as inorganic salts. The number of water molecules is represented by the n value, which might be carbonate, sulfite, phosphate, nitrite, acetate, or chloride. While organic PCMs offer advantages such as non-corrosiveness and improved thermal conductivity, they also have limitations such as combustibility and lower heat storage capacity [21]. In contrast, inorganic PCMs are generally less expensive, more abundant, nonflammable, and possess high heat storage capacity and thermal conductivities.

EUTETIC

Eutectics are specific combinations of two or more components that exhibit a minimum-melting point and undergo congruent melting and solidification. This process leads to the formation of a mixture of component crystals. Both inorganic and organic eutectics have been identified and studied for their potential applications in thermal energy storage. Compared to conventional inorganic phase change materials (PCMs), eutectics often demonstrate superior properties, particularly in terms of segregation. This means that eutectics have the ability to maintain a more homogeneous mixture during phase transitions, resulting in enhanced performance and stability in thermal energy storage systems [22].

2.3. *Chemical energy storage system*

By breaking or establishing certain chemical bonds during endothermic or exothermic events, specialised compounds may absorb or release a considerable quantity of thermal energy, making chemical heat storage a viable option. These features inspired the development of this strategy [23]. Chemical heat storage may be utilised for organic or inorganic substances that absorb and release a lot of heat [24]. A chemical storage system should have good chemical reversibility, a substantial chemical enthalpy change, and simple reaction conditions. Table.2 displays useful information for choosing appropriate materials and building chemical heat storage systems, including the operating temperature and enthalpy change for different materials.

Table.2: Operating temperature, enthalpy change for various materials

Materials	Enthalpy Change due to Chemical Reaction	Range of Temperature (°C)
Ammonia	67KJ/mol	401-501
Calcium Carbonate	4.4e+9J/m^3	802-901
Metal Hydrides	4e+9J/m^3	199-299
Hydroxides	3e+9 J/m^3	500.5
Iron Carbonate	2.6e+9 J/m^3	179.5

3. Conclusion

The study focuses on phase change material (PCM) TES units, although it also covers various types of storage devices. Composite PCMs are proposed as a novel class and their characteristics are described in this study, which also compares and contrasts traditional PCMs. Composites have far better thermal conductivity, heat of fusion, density, and melting points than pure PCMs like paraffin wax. As a result, prioritizing composite PCMs might allow for the development of more potent and efficient TES units. If you need to store thermal energy, look no further than latent heat storage systems, which can store up to 14 times as much heat than sensible heat storage systems. Our research led us to the conclusion that latent heat thermal energy storage offers a more secure infrastructure for the dependable and cost-effective distribution of energy. The ability to include heating, cooling, and dehumidification into a single TES system facilitates poly-generation. Thermo-chemical energy storage is yet to be fully explored, and PCMs need to be developed further for more cost-effective use. Thermo-chemical processes, such as adsorption, may be used to store and release heat and cold and regulate humidity levels in combination with a wide variety of chemical reactants. While thermo-chemical storage (TCS) and PCM-based TES systems are still in the early phases of research, sensible heat-based TES systems are currently on the market. Additional research and development are necessary to fully exploit the potential and cost-effectiveness of these complex TES systems.

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Conflict of Interest

The authors declare “No conflict of interest”

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