" An Analysis of Thermal Energy Storage Technologies for Solar Power Applications "

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ABSTRACT

High-temperature thermal energy storage (TES) is a key enabler in the shift toward cleaner and more efficient energy systems. It allows surplus thermal energy—sourced from heat or cold environments—to be stored and retrieved when needed, enhancing energy management flexibility. This approach is particularly advantageous for harnessing solar energy on a large scale, especially in concentrating solar power (CSP) plants, where excess heat can be stored during periods of high solar radiation and utilized during low-sunlight hours to maintain continuous energy output.

With the increasing integration of intermittent renewable energy sources and the global push for carbon-neutral energy systems, TES technologies are gaining momentum. Among the different TES methods, latent heat storage using phase change materials (PCMs) is notable for its high energy storage density and ability to operate with minimal temperature variation. Likewise, thermo-chemical storage systems, which rely on reversible chemical reactions, offer high energy capacity and long-duration storage potential. This study investigates the latest developments in high-temperature TES, focusing on latent and thermo-chemical storage mechanisms, while also considering sensible heat storage and hybrid configurations that combine multiple storage strategies for improved performance and efficiency.

By exploring material properties, storage principles, and system configurations, this research aims to contribute to the advancement of high-temperature TES technologies as a cornerstone for future sustainable and low-carbon energy infrastructure.

Keywords: *Thermal Energy Storage (TES), High-Temperature Storage, Latent Heat Storage, Thermo-Chemical Energy Storage, Phase Change Materials (PCMs), Sensible Heat Storage, Renewable Energy Integration, Concentrated Solar Power (CSP), Energy Efficiency, Low-Carbon Technologies.*

1. Introduction

In recent years, governments across the globe have increasingly prioritized energy sustainability, environmental protection, and long-term development goals. This shift in focus is largely driven by the adverse consequences of prolonged dependence on fossil fuels, which include environmental degradation, intensification of the greenhouse effect, global warming, and the exhaustion of non-renewable resources—all of which threaten ecological balance and human progress [1].

Amid these concerns, renewable energy sources—such as solar, wind, hydro, and geothermal—are gaining significant attention due to their environmentally friendly and inexhaustible nature. Among these, solar energy is particularly promising owing to its abundance and universal accessibility [2]. However, the intermittent nature of solar irradiance leads to fluctuating power outputs, making it necessary to develop reliable energy storage systems that can balance the mismatch between energy generation and consumption.

To address this challenge, various energy storage technologies have been proposed and investigated, including compressed air energy storage, pumped hydroelectric storage, flywheels, electrochemical batteries, hydrogen storage, and thermal energy storage (TES) [3]. Each of these storage approaches exhibits unique advantages and is suitable for different applications depending on the operational and economic requirements.

Thermal energy storage, in particular, stands out for its economic feasibility and wide range of practical uses. TES functions by retaining thermal energy in a medium through either heating or cooling for subsequent utilization. Its applications are diverse, encompassing district heating networks, residential climate control systems, concentrated solar power (CSP) facilities, industrial processes, and even sectors like food preservation. Integration of TES systems within energy infrastructures can significantly enhance system efficiency, dependability, cost-effectiveness, and environmental performance by reducing greenhouse gas emissions and pollutant discharge [4].

To enable uninterrupted 24-hour operations in TES systems, ongoing research focuses on the development of advanced materials with superior thermophysical properties. A key aspect of this research is improving energy density, which in turn influences the solar fraction, system efficiency, and heating or cooling demand. Latent heat storage materials—particularly phase change materials (PCMs)—are of considerable interest due to their ability to increase energy density while minimizing storage volume. This enhancement allows either an increase in solar fraction for a fixed tank size or a reduction in tank volume for a desired solar contribution [5].

Extensive studies have been dedicated to both sensible and latent heat storage mechanisms. Innovations span from solar thermal collectors and TES systems for solar heating to ice-based storage for cooling and the use of PCMs for cold retention in domestic refrigeration units. Overall, the incorporation of thermal energy storage technologies—especially those employing latent heat and thermo-chemical storage mechanisms—presents a viable and effective solution to energy intermittency challenges. These systems not only contribute to improved energy utilization but also align with global objectives for sustainable and resilient energy futures.

2. High-Temperature Thermal Energy Storage Technologies

The intermittent and unpredictable nature of solar energy underscores the importance of thermal energy storage (TES) in advanced thermodynamic systems. TES plays a pivotal role in enhancing system efficiency and thermal dependability by bridging the gap between energy generation and consumption. Consequently, the development of TES systems that are not only efficient but also economically viable has become a central research focus.

Despite its advantages, the integration of TES technologies into solar thermal power plants remains limited. Ongoing investigations continue to explore the design and deployment of TES solutions for a variety of residential and industrial solar applications. Among the tools aiding in this optimization process, computational fluid dynamics (CFD) techniques have emerged as essential. Specifically, ANSYS FLUENT is widely used to simulate thermal behavior and streamline system designs across engineering domains.

Figure 1 depicts the various TES technologies applicable to different energy sources, encompassing sensible, latent, and thermo-chemical storage types. Key performance indicators such as storage capacity, power output, energy efficiency, retention time, and charge/discharge dynamics are typically used to classify and evaluate these systems. Notably, an inverse relationship may exist between power and storage capacity in certain configurations.

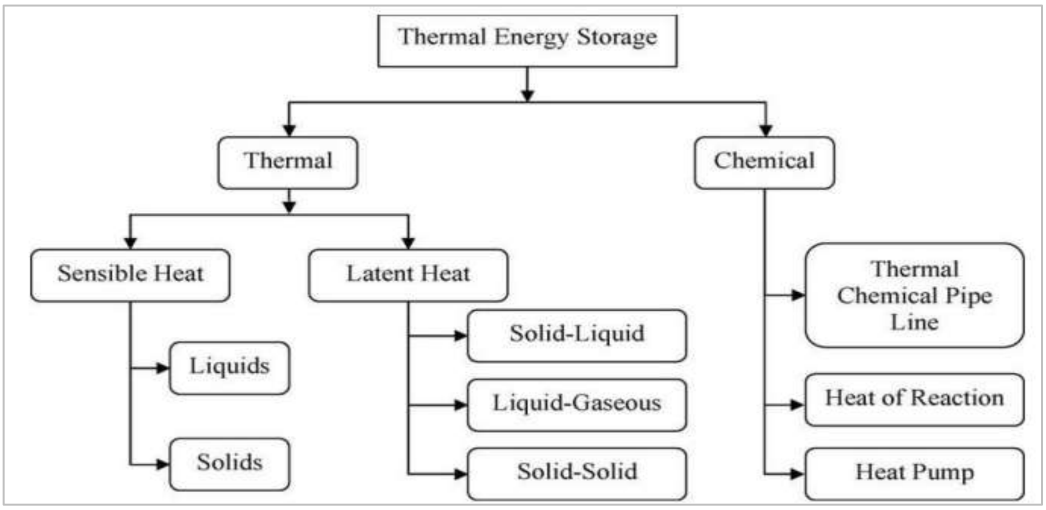


Figure 1: Solar thermal energy storage types

Table 1 outlines the standard parameters and operating characteristics of typical high-temperature TES systems, offering a comparative view of their potential in large-scale applications.

Table 1: The three TES methods are compared with their typical values

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

Sensible Heat Storage (SHS) represents the most straightforward form of thermal energy retention, wherein energy is stored by altering the temperature of a storage medium without inducing any phase transformation. As illustrated in Fig. 2, Sensible Heat Thermal Energy Storage (SHTES) systems operate by absorbing and releasing heat through heating and cooling cycles of the medium. The mechanism relies on the material's intrinsic thermal capacity and its ability to undergo temperature fluctuations during charging and discharging phases [8].

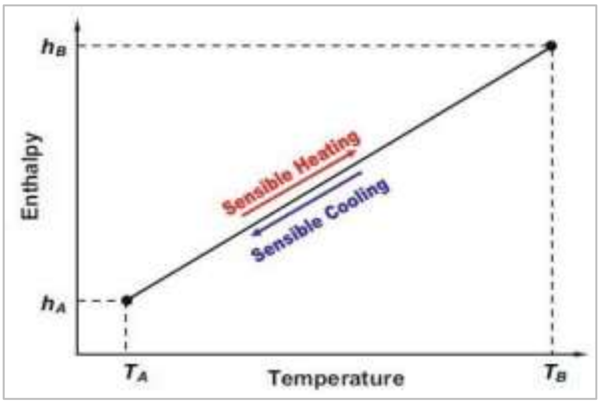


Figure 2: Changes in medium enthalpy because of sensible heating and cooling

A typical SHS setup comprises a storage material, a containment unit, and inlet/outlet ports for thermal exchange. Minimizing energy losses and safeguarding the storage substance from environmental effects are critical for system efficiency [9]. Various factors influence the performance of SHS systems, including the thermal properties of the medium, the operating temperature boundaries, inlet/outlet design, thermal stratification, mixing phenomena during operation, and insulation effectiveness [24].

In SHS, either a solid or liquid material is heated across its operational temperature range to retain thermal energy. Water is frequently utilized due to its high specific heat capacity, affordability, and non-toxic nature. Water tanks remain a popular choice for practical and economic reasons. However, for applications requiring higher temperature thresholds and greater energy density, advanced materials such as molten salts and liquid metals are increasingly adopted [10].

Sensible heat can also be stored using subsurface methods like borehole thermal energy storage (BTES) with vertically-aligned U-pipes or shallow trench systems. These underground thermal energy storage (UTES) configurations offer viable options for long-term energy retention. The total thermal energy stored in an SHS system can be estimated using the equation:

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

where Qs denotes the energy stored (in Joules), mmm is the mass (in kilograms), c_p is the specific heat capacity (in J/kg·K), t_i is the initial temperature, and t_f is the final temperature.

2.1.1 Sensible Heat Storage Using Water Tanks

Due to its high specific heat capacity and affordability, water remains a widely utilized medium for sensible heat storage systems. Water tanks are commonly implemented in thermal energy storage (TES) setups, offering a cost-effective and efficient means of conserving thermal energy. While suitable for low- to moderate-temperature applications, water's limitations become apparent in high-temperature scenarios, where alternative materials such as molten salts or liquid metals are preferred due to their superior thermal stability and energy density.

In some systems, Underground Thermal Energy Storage (UTES) is employed, where water tanks or heat transfer fluids (HTFs) circulate through U-shaped piping configurations placed within vertical boreholes or horizontal trenches to store energy below ground level. These systems are particularly beneficial for seasonal thermal energy storage in combination with solar or cogeneration technologies.

Conventional hot water tanks have long served as a practical solution for thermal storage, especially in residential and commercial heating systems. Their economic viability continues to be affirmed in contemporary energy projects. Enhancements in thermal performance are achieved through advanced stratification techniques—where temperature layering is maintained inside the tank—and by employing high-efficiency insulation materials.

Recent research has explored innovations such as evacuated super-insulation, which demonstrates exceptionally low thermal conductivity values (e.g., 0.01 W/(m·K) at 90°C under a vacuum of 0.1 mbar), thereby significantly minimizing heat loss. Figure 3 illustrates a typical configuration of a water-based heat storage unit.

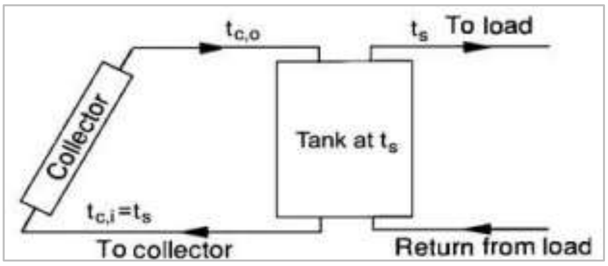
When water or any other liquid medium is uniformly mixed (i.e., without thermal stratification), its thermal storage capacity can be calculated using the following equation:

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

Where:

- Q_u and Q_L are the rates of thermal input from the collector and output to the load, respectively.
- U_s denotes the overall heat loss coefficient of the storage tank.
- A_s is the surface area through which heat loss occurs.
- t_i and t_a represent the internal tank temperature and ambient temperature, respectively.

Storage efficiency and energy retention are closely tied to tank sizing and insulation quality, particularly in systems aiming to support higher-temperature applications.



2.2 Latent Heat Storage

Phase Change Materials (PCMs) are categorized as latent heat storage media due to their capability to absorb or discharge thermal energy during phase transitions. As illustrated in Figure 4, a reduction in the volume of latent heat storage systems generally results in an increase in energy density [13]. This energy is stored by leveraging the latent heat associated with the material's phase change, which occurs at a nearly constant temperature. PCMs serve as the fundamental components for latent heat-based thermal storage systems, offering an effective means to store thermal energy.

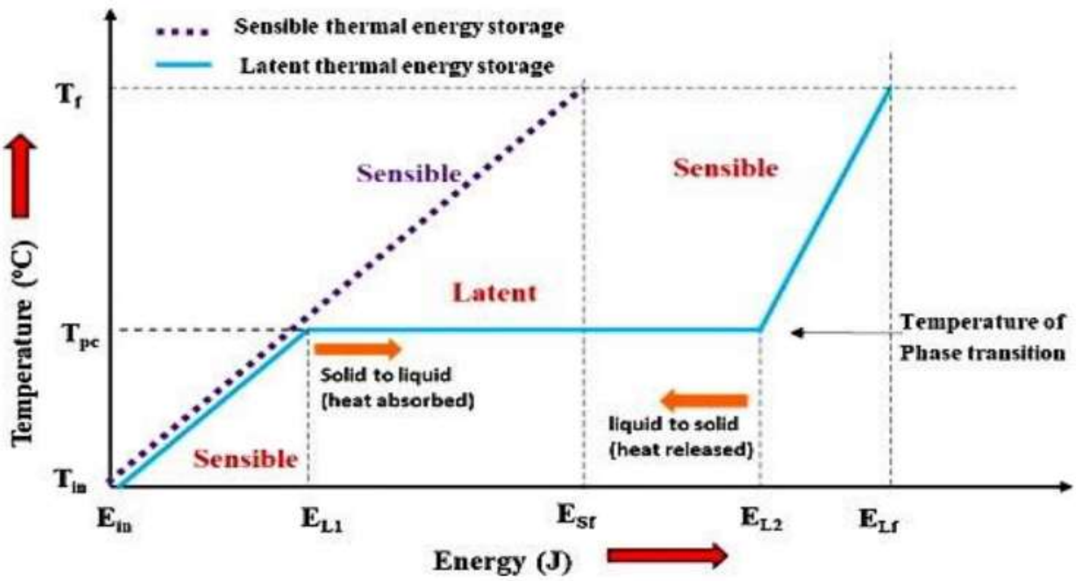


Figure 4: Enthalpy variation of a medium during charging– discharging periods of an LHTES unit

One of the key advantages of Latent Heat Storage (LHS) over Sensible Heat Storage (SHS) is its ability to maintain a nearly constant internal temperature while energy is being stored or retrieved [14]. Initially, as the enthalpy of the system increases linearly with temperature, LHS materials behave similarly to conventional SHS media [26]. However, during the phase change process—such as melting or solidifying—LHS materials absorb or release substantial amounts of energy without a significant change in temperature. This thermal behavior provides greater efficiency and precision compared to SHS systems, where temperature continuously varies throughout the storage cycle [15].

The heat storage capacity of a PCM system can be expressed as:

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

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

Where:

- Q_s represents the total stored heat energy,
- c_{ps} and c_{pl} denote the specific heat capacities of the PCM in solid and liquid states, respectively,
- Δq is the latent heat of fusion,
- t_i and t_f are the initial and final temperatures of the storage cycle, and
- t_m is the melting point of the PCM.

This model highlights the multi-phase contribution to thermal storage, making LHS an attractive option for high-temperature thermal energy applications where phase stability and efficiency are crucial.

2.2.1 Phase Change Materials (PCMs)

In recent developments, solid-liquid phase change materials (PCMs) have emerged as viable alternatives to traditional sensible heat storage media, especially in the context of latent thermal energy storage. Unlike sensible heat systems that rely on temperature rise for energy accumulation, PCMs store and release thermal energy at their transition temperatures. This allows for minimal temperature gradients between the heat charging and discharging cycles, thereby improving efficiency. Figure 5 illustrates the diverse classifications of PCMs applied in thermal energy storage (TES) systems [23].

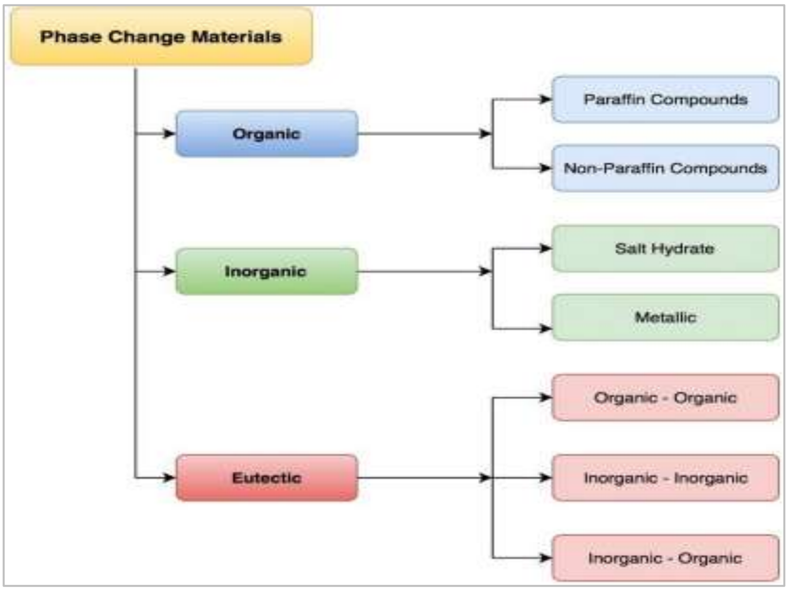


Figure 5: PCMs (phase-change materials) categorization

Organic PCMs

Organic PCMs, particularly eutectic blends, are commonly employed in a range of applications including space heating, power generation, HVAC systems, solar heating (both air and water), textiles, automotive systems, and food preservation. Among these, paraffin waxes — primarily composed of straight-chain n-alkanes such as CH_3-(CH_2) n-CH_3 — are widely studied. These compounds exhibit high latent heat release during crystallization processes. The melting temperature and enthalpy of fusion are directly proportional to the length of the carbon chain, which is why only high-purity paraffin grades are utilized in advanced TES applications.

Paraffin waxes offer several desirable attributes: they are chemically stable, non-corrosive, cost-effective, and commercially available across a broad temperature range up to approximately 80°C [17]. However, the spectrum of organic PCMs extends beyond paraffins, including materials such as esters, fatty acids, alcohols, and glycols. These substances typically possess high latent heat capacities due to their molecular structure and purity. Nevertheless, they face challenges such as low thermal conductivity (typically in the range of 0.1 to 0.35 W/m·K), flammability, thermal degradation at elevated temperatures, and low ignition points [25]. Despite these drawbacks, the chemical inertness of organic PCMs contributes to long-term stability and resistance to degradation [18].

Inorganic PCMs

In contrast, inorganic PCMs present a different set of characteristics, generally outperforming organic counterparts in specific aspects. They offer higher volumetric energy densities, improved thermal conductivities, and greater thermal resilience — enabling their use in high-temperature applications [28]. Examples include salt hydrates and various inorganic salts. However, these materials are often corrosive to metals, which can reduce the lifespan and reliability of storage systems, thus increasing operational and maintenance costs [19].

One of the limitations of inorganic PCMs is their tendency for phase separation and supercooling, which can hinder reversibility and affect thermal storage performance. To address these challenges, metal alloys and pure metals are under investigation as advanced alternatives, particularly due to their high-temperature compatibility and corrosion resistance [20]. Inorganic salts — often represented by compounds such as AxB and AxByn(H_2O) — feature diverse anionic groups (e.g., carbonates, sulfites, phosphates, chlorides) and varying hydration levels. These salts are typically more affordable, non-flammable, and abundant compared to organic PCMs, while also delivering superior thermal properties [21].

Eutectic Mixtures

Eutectic materials are unique blends of two or more components that melt and solidify congruently at a specific composition, producing a homogeneous crystalline structure. Both organic and inorganic eutectics have been extensively examined for their role in thermal storage applications. One key advantage of eutectics lies in their resistance to phase segregation, allowing for more uniform performance and enhanced thermal stability during repeated thermal cycling. Compared to conventional PCMs, eutectics often display improved reliability, especially in high-temperature latent heat storage systems [22].

Table 2: Various materials' operating temperatures and enthalpy changes

Materials	Enthalpy Change due to Chemical Reaction	Range of Temperature (°C)
Ammonia	67KJ/mol	401-501
Calcium Carbonate	4.4e+9J/m³	802-901
Metal Hydrides	4e+9J/m³	199-299
Hydroxides	3e+9 J/m³	500.5
Iron Carbonate	2.6e+9 J/m³	179.5

3. Conclusion

This research delves into high-temperature thermal energy storage (TES), with a particular emphasis on latent heat storage using phase change materials (PCMs) and the emerging potential of thermochemical storage systems. While a range of TES technologies is discussed, the study highlights composite PCMs as an innovative and promising advancement over conventional materials such as paraffin wax. These composites exhibit superior thermal properties—including enhanced conductivity, greater latent heat of fusion, increased density, and tailored melting points—making them ideal candidates for next-generation TES applications.

Latent heat storage systems demonstrate a significantly higher energy density compared to sensible heat storage, with the ability to retain up to 14 times more heat. This makes them an attractive option for achieving compact, efficient, and reliable thermal storage. Furthermore, integrating thermal functions such as heating, cooling, and dehumidification within a single TES framework enables versatile poly-generation solutions.

Thermochemical energy storage, though still under active investigation, offers considerable promise for long-duration and high-capacity thermal management. Processes like adsorption and reversible chemical reactions can be employed not only for heat and cold storage but also for climate control functionalities. However, both PCM-based and thermochemical TES systems require continued research to overcome current limitations in cost, material stability, and scalability.

In summary, latent and thermochemical heat storage systems present transformative potential for sustainable energy infrastructure. Advancements in composite materials and chemical storage methods are essential for unlocking their full utility, and ongoing R&D efforts will be pivotal in transitioning these technologies from experimental stages to practical, commercial deployment.

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