ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XIV, Issue VII, July 2025

Improved CSP Efficiency: Innovations and Challenges in Thermal Energy Storage Systems

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DOI: https://doi.org/10.51583/IJLTEMAS.2025.1407000005

Abstract: This review article examines the current state and future prospects of systems for storing thermal energy in concentrated solar power (CSP) plants. CSP technology has drawn a lot of interest as a renewable energy source, but its intermittent nature necessitates efficient energy storage solutions. The paper provides a comprehensive overview of various TES technologies, including thermochemical, latent, and sensible storage methods, analyzing their performance, cost-effectiveness, and scalability. Key challenges such as material degradation, heat transfer efficiency, and system integration are discussed. Recent advancements in novel storage materials, heat transfer fluids, and system designs are evaluated, with a focus on their potential to enhance overall plant efficiency and reduce levelized cost of electricity. The review also explores emerging trends, such as high-temperature storage systems and hybrid configurations, assessing their potential impact on the future of CSP technology. Finally, the paper identifies critical research gaps and provides recommendations for future developments to improve the viability and competitiveness of CSP plants with integrated systems for TES.

Keyword: TES, CSP, PCM, thermal fluid

Overview

CSP uses the sun as a sustainable energy source that is accessible locally. It might be feasible to improve access to financing and reduce overall system costs by reducing the uncertainty surrounding future generating costs. When compared to solar photovoltaics, thermal energy storage (TES) combined with CSP, may be able to function more freely and for longer periods of time [2]. To support social progress and the expansion of the local economy, CSP offers free services and benefits. Concentrated solar power plants have advanced significantly since 1878 and are becoming more and more popular because of their low operating costs and lack of reliance on fossil fuels [3].

Linear Fresnel Reflector (LFR), Solar Power Tower (SPT), Parabolic Trough Collector (PTC), and Parabolic Dish Collector (PDC) are the four most advanced CSP technology categories [1]. Focused sunlight is directed onto a linear receiver employing line-focus CSP collectors like PTC and LFR, which have a somewhat lower concentration ratio. Despite being point focus types, SPT and PDC can achieve a concentration ratio of 300–3000, which is significantly higher [5]. While the PDC is advised for smaller generating capacities between 0.01 and 0.4 MW, the PTC, LFR, and SPT are most appropriate for power generation capabilities in the 10-200 MW range [4].

Compared to most energy-generating technologies, including solar photovoltaic (PV) technology, CSP is a relatively young technology. In late 2011, the total installed CSP capacity globally surpassed 1000 MW (IRENA, 2012a). It more than quadrupled to almost 3000 MW by the end of 2013 (NREL, 2013), and by the end of 2015, it had nearly reached 4800 MW (REN21, 2016). PV, in contrast, has experienced sustained expansion over a longer duration; by the end of 2015, its installed capacity has grown to approximately 227 GW (REN21, 2016), surpassing 67 GW globally in 2011 (IRENA, 2012b) [1].

Advanced thermal energy storage (TES) systems in concentrated solar power (CSP) plants represent a significant leap forward in renewable energy technology. The most advanced TES systems in CSP plants utilize a combination of innovative materials, designs, and integration strategies to maximize efficiency and extend operational hours. These systems usually use molten salt as a storage medium and heat transfer fluid, capable of maintaining temperatures up to 565°C [3]. Some cutting-edge designs are exploring even higher temperature ranges, potentially reaching 700°C or more, using novel materials such as ceramic particles or liquid metals. Advanced TES systems also incorporate multi-tank configurations, allowing for better temperature stratification and more flexible operation [1]. Additionally, thermocline systems with single-tank designs are being developed to reduce costs while maintaining high efficiency. These advanced systems often integrate phase change materials (PCMs) or thermochemical storage methods to increase energy density and storage capacity [1]. Sophisticated heat exchangers and advanced control systems further enhance the performance of these TES systems, enabling rapid response to grid demands and seamless integration with the CSP plant's power block [3]. As research continues, these advanced TES systems are pushing the boundaries of energy storage capabilities, aiming to make CSP a more competitive and reliable source of renewable energy [5].

INTERNATIONAL JOURNAL OF LATEST TECHNOLOGY IN ENGINEERING,
MANAGEMENT & APPLIED SCIENCE (IJLTEMAS)
ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XIV, Issue VII, July 2025

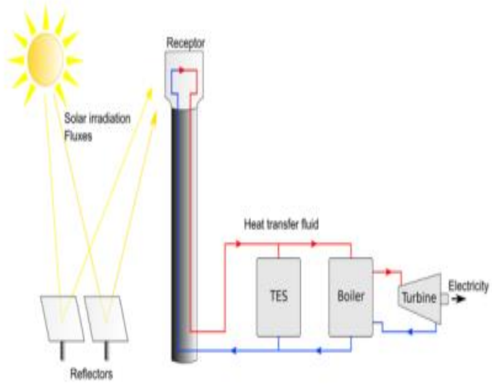

Fig. 1 Schematic of a Concentrated Solar Power (CSP) Plant with Integrated Thermal Energy Storage (TES) System

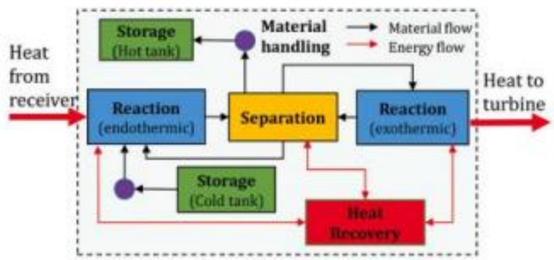

Fig. 2 Schematic of a Thermochemical Energy Storage (TCES) System in a CSP Plant

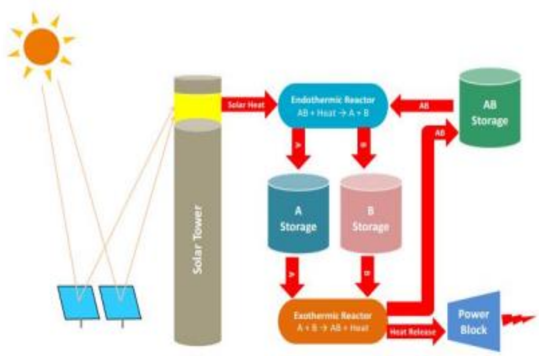

Fig. 3 Schematic of a solar thermochemical energy storage system.

TES Design Observation

To guarantee the best storage dynamics and endurance, a number of factors must be taken into account, depending on the type of storage. The following important performance indicators must be taken into account when weighing cost-benefit analysis, technical requirements, and environmental requirements.

Cost: describes the storage system's power ($/kW) or capacity ($/kWh). It is also known as the thermal or electric cost, and it typically consists of the cost of the enclosure or space for the TES, the heat exchanger for charging and discharging the system, and the storage material itself.

The energy stored in a system is defined by its capacity [MWh], which is dependent on its size, medium, and storage method. Time needed to charge or discharge the system is specified by the charge and discharge times [h].

Efficiency [%]: the proportion of energy required to charge the storage system to energy delivered upon discharge. It takes into consideration the energy loss that occurs throughout the charging and discharging cycles as well as during storage.

The storage material's high energy density (per unit mass or per unit volume).

The storage material's mechanical and chemical stability compatibility of HTF, heat transfer apparatus, and storage with low thermal losses.

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XIV, Issue VII, July 2025

Minimal impact on the environment.

Controllability.

Temperature drop per unit time of the molten salt and/or storage tank/material melting (typically below 1°C every 24 h) [5].

TES categories

Thermal Energy Storage (TES) systems fall into two primary categories: circulation nature and storage mechanism. These groups can be further separated according to a number of attributes [2].

Storage mechanism classification In SHS systems, by altering the storage medium's temperature, energy can be stored or released without undergoing a phase shift or chemical reaction. Sensible storage works on the basis of the idea that a substance's energy content increases with temperature, and that the stored energy is released when the material cools [4]. SHS systems are the most established and commonly used in industrial applications [3].

Table 1: Comparison of Sensible, Latent, and Thermochemical Energy Storage Systems for CSP Applications

Characteristic	SHS	LHS	TCS
Storage mechanism	Energy stored as temperature difference in solid (e.g., concrete, rock, sand) or liquid media (molten salt)	Energy stored using phase change materials (i.e. isothermal phase transition)	Energy stored in chemical bonds (reversible chemical reactions)
Storage temperature (°C)	400–600	700–1500	200–250
Energy density (MJ/m^3)	Low (~200 for 200 °C temperature differential)	Medium (300–600)	High (500–4000)
Lifetime (years)	20	5	2
Heat loss	Significant heat loss over time	Significant heat loss over time	Small heat loss
Power density	Small ~50 kWh/m^3	Medium ~100 kWh/m^3	High (500 kWh/m^3)
Maturity	Commercially available	Pilot scale	Laboratory stage
Storage period	Hours to days (limited due to thermal losses)	Hours to days (limited due to thermal losses)	Theoretically unlimited
Technical complexity	Simple	Medium	Complex
Advantage	Low cost and mature technology; Relatively simple system, easy to control; Reliable.	Small volume and short distance transport possibility; Good for isothermal or low ΔT applications; Provide thermal energy at constant temperature; Can provide large energy density with combined sensible and latent heat storage	Highest energy density, Negligible heat losses; Potential for long-term storage; Compact storage system;
Disadvantage	Low energy density; Self-discharge & heat losses problem; High cost of site construction; Geological requirements	Lack of thermal stability; Small heat conductivity; Crystallization; Materials Corrosion; High cost of storage material	Poor heat and mass transfer property under high-density condition; Uncertain cyclability; High cost of storage material; Technically complex
Challenges	Requires insulation to mitigate heat losses; Lower energy density requires larger volumes; Molten salts freeze at ~200 °C.	Potential for corrosion; For larger ΔT, may need cascaded systems (adds costs and complexity); Low maturity	Higher complexity; Low maturity; Higher capital costs; May require storage of gaseous products
Future work	Optimization of control policy to advance the solar fraction and reduce the power consumption; Optimization of storage temperature to reduce heat losses; Simulation of ground-/soil-based system with the consideration of affecting factors (e.g., underground water flow)	Screening for better suited; PCMs with higher heat of fusion; Optimal study on store process and concept; Further thermodynamic and kinetic study, noble reaction cycle;	Optimization of the particle size and reaction bed structure to get constant heat output; Optimization of temperature level during charging/discharging process; Screening for more suitable & economical materials; Further thermodynamic & kinetic study
Maturity	High	Low	Low
Cost	~$1/kg for molten salts and ceramic particles; ~$0.1/kg for rock and sands; ~$1/MJ–$10/MJ (system capital cost)	~$4/kg–$300/kg; ~$10/MJ–$100/MJ (system capital cost)	~$10/MJ–$100/MJ (system capital cost)

Heat storage that is sensible (SHS)

Without undergoing a phase shift or chemical reaction, energy is stored or released in SHS systems by varying the temperature of the storage medium [2]. The idea behind sensible storage is that a substance's energy content increases with temperature, and that the stored energy is released as the material cools. SHS systems are the most established and commonly used in industrial applications [4].

Storage of latent heat (LHS)

Latent TES systems make use of the significant amount of latent heat that can be discharged or stored during phase transitions, typically from solid to liquid. This approach has garnered significant interest for CSP applications in recent years [5]. The materials employed in Phase Change Materials (PCM) are materials that store heat latently. Despite having a higher energy density, LHS technology performs poorly in heat transfer because of the materials' incredibly low thermal conductivity [2]. Currently, LHS technology is not yet commercially viable and is transitioning starting with lab studies and ending with commercial demonstration, facing numerous challenges. The main goals of recent research on LHS systems are to improve performance stability, minimize supercooling, and lower costs for thermal storage applications in CSP facilities [3]. Notwithstanding significant scientific contributions in articles and patents, technical obstacles have impeded the advancement of LHS technology compared to other methods, such as Sensible Heat Storage (SHS) [1].

Thermochemical storage.

CSP plants can store thermal energy as chemical energy via fuel oxidation reactions that are endothermic. Thermochemical storage (TCS) systems have drawn interest recently as a possible energy storage option because of their high energy density and lack of energy loss during storage [4]. Among all thermal energy storage (TES) systems, TCS offers most energy-dense, almost five to ten times more than sensible heat storage (SHS) and latent heat storage (LHS), respectively. A TCS system's general structure consists of five primary tasks, as seen in Fig. 4. [3].

i. process includes both the reverse exothermic process, which produces heat for power generation, and an endothermic reaction driven by focused sunlight.

ii. Storage: Exothermic reaction products are kept in a "cold" tank, whereas endothermic reaction products are retained in a "hot" tank for usage at night.

iii. Separation (optional): to maximize conversions and purity in storage tanks, unreacted reactants from endothermic and exothermic reactions are separated from products. However, if separation is challenging, the process may be more cost-effective

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XIV, Issue VII, July 2025

without it.

iv. Material handling: ensures the maintenance of material moves through the process (for example, with the use of compressors and pumps).

v. Heat recovery: meets heating and cooling needs by using a network of heat exchangers [5].

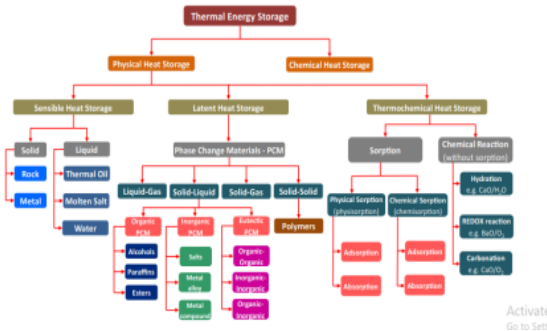

Fig. 4 Classification of thermal energy storage (TES) systems

Heat Storage-Based Thermal Energy Storage (TES) Systems Mechanisms

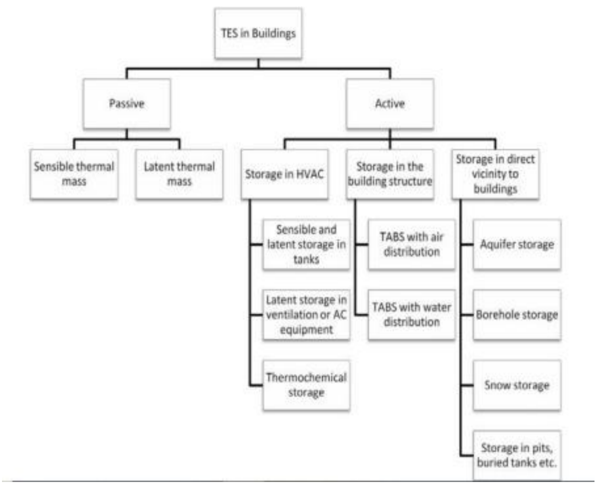

Fig. 5 Classification of thermal energy storage (TES) applications in buildings

Passive Systems

Passive systems operate without external inputs such as pumping during charging and discharging processes [6]. These systems utilize phenomena such as natural convection and thermal inertia to fulfil their intended function. Applications of temperature control in buildings, cars, textiles, and the transportation of food and medications are examples of passive TES approaches.[6] Figure 16 illustrates the operational idea behind passive TES systems. Using a Phase Change Materials (PCM) latent heat to increase thermal inertia, the overall strain on HVAC systems can be decreased by minimizing temperature changes within thermal comfort bounds. [10]

TES in Buildings

Figure depicts various TES systems used in structures. The use of passive TES technology increases the thermal mass of buildings through the use of innovative building composite PCMs (BCPCMs). Table provides an overview of different building composites investigated in previous studies [6].

Vehicles:

Jamekhorshid et al. [89] calculated that 755 g of PCM (n nonadecane) would be required to regulate the temperature in a car's interior compartment when exposed to sunlight. Their approach had a thin layer of PCM within a pouch that was inserted into the ceiling of the vehicle. Without PCM, on a July day, the cabin temperature peaked at 68.5°C at 13:50 h and dropped below 30°C at night [7]. The maximum temperature was kept at about 35°C by the passive temperature control system using 755 g of PCM (melting point: 32°C). In a different application, Gumus et al. [90] used $Na_2SO_4 \cdot 10H_2O$ as the PCM to create an experimental 2 MJ capacity TES system for preheating internal combustion engines. The TES system assisted in keeping the engine's average temperature at 17.4°C under 2°C ambient circumstances. At 57.5% thermal efficiency, the TES system released heat during

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XIV, Issue VII, July 2025

discharge (engine off for 12 hours, followed by preheating before cold start) after storing 2.27 MJ of heat during charging (engine run period) [8]. In colder climates, this technology reduces engine emissions. Because catalytic converter performance is low during cold starts, emissions of harmful gases like CO and HC can be decreased by preheating the engine with heat stored in a passive TES system [9].

Systems in Action

During charging and discharging, active systems use pumping work to move a heat transfer fluid (HTF). Vast pipe networks and viscous HTFs cause huge pressure head dips in large-scale TES systems. Rapid heat transfer rates with increased mass flow through forced convection are required in high-temperature and high-heat flux environments. For these variables, HTF circulation by pumping is necessary [8].

Systems for Tanks

The main heat storage medium in tank systems is heat transfer fluid, which is kept in one or two insulated tanks [10]

System of packed beds

The main heat storage medium in packed bed thermal energy storage (TES) systems is a stationary bed of filler material housed in an insulated tank. A heat exchanger is not necessary because the heat transfer fluid (HTF) charges and discharges the packed bed through direct surface contact, as shown in Fig. 18. Efficiency is increased by the large contact surface area that this direct engagement offers for heat transfer [7]. A notable characteristic of packed bed systems is the effect of temperature stratification along the bed. A variation of the packed bed system is the stratified liquid thermocline system with filler, which is covered in section 5.2.1.3.2. With fillers organized in a packed bed pattern, thermocline systems use liquid as HTF. The liquid also stores some of the total thermal energy. Gaseous HTFs, such as air, can also be used in packed bed systems; these HTFs serve just as heat transfer agents, with the packed bed's filler storing all of the thermal energy [9].

Common HTFs include gases including supercritical CO2, water, air, and thermal oils. Rocks, pebbles, gravel, sand, gypsum, soil, metal blocks, microencapsulated PCM containers, clay brick, porcelain balls, zirconium oxide pellets, and irregular solid particles of iron ore, coke, limestone, coal, blast furnace charge, copper slag, iron slag, and aluminium slag are examples of common bed filler materials [9][8]. The filler material's thermal stability limits the TES operating temperature range. The most widely employed fillers are earth materials, such as pebbles, gravel, and sand, and these systems usually function in the medium temperature range of 50 to 300 °C [5]. Heat is often stored as sensible heat in fillers in packed bed TES systems. But in PCM container beds that are microencapsulated, The PCM stores heat as latent heat [5]. Sensible heat bed materials in packed bed TES systems allow for variable outlet temperatures. Variable HTF temperatures at the solar collector outlet are caused by daily variables such as load, insolation, ambient temperature, and HTF temperature at the solar collector intake for solar air heaters [4]. The packed bed is charged by this hot HTF from the solar collector outlet, and the temperature at which it is heated varies based on these elements as well. Additionally, the bed temperature rapidly drops during discharge. Thermal ratcheting is another operating difficulty with filled beds [6]. Uneven thermal expansion and contraction between bed materials like rock and container materials like steel is caused by repeated heat cycles, which gradually accumulates plastic strains, especially [8].

A review paper on current research on packed bed TES systems was published by Singh et al. [9][8]. HTF mass flow rate, gravel to container size ratio, HTF pressure drop over the bed, bed porosity, and bed dimensions are important factors that affect a packed bed TES system. Solar air heaters, underground pit seasonal TES systems, and waste heat recovery from exhaust gasses used for preheating are examples of common uses for packed systems [7].

TES system performance and design parameters

Size and capacity

This is the most thermal energy that is able to be billed to the TES system, expressed in kWh or MJ. The capacity of TES containers causes their size to rise. It is the result of multiplying the volume of the container by the volume of heat storage capacity of the chosen thermal storage material [10].

Power: This is the TES system's discharge/charging rate, measured in kW.

Range of operating temperatures

TES systems typically function in the temperature range of 40 to 600ºC. The materials used for TES and containers ought to be thermally, chemically, and physically stable within this range of temperatures. The charging and discharging temperatures of chemical sorption materials may vary. The following are examples of discharge temperature control situations [10].

Using sensible materials for heat storage

High temperature TES systems in CSP installations have a broad operating temperature range. When employing sensible heat storage materials in tiny TES systems, the discharge temperature fluctuates a lot and drops very quickly [9].

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XIV, Issue VII, July 2025

Using PCM

Near the phase transition temperature, materials used for latent heat storage operate in a certain range. The HTF output temperature is almost constant, and heat is released steadily [9].

With several PCM

Arranging many PCM along the discharge line in the rate of heat transmission is enhanced when they are arranged in increasing order of their melting points [117]. Even when the HTF temperature rises as it flows down the discharge channel, the maximum temperature differential between the HTF and PCM may be preserved [9].

Storage duration

The operating temperature of short-term diurnal TES systems are smaller and have a larger capacity. Sensible heat storage materials that work at very high temperatures, including molten salts and liquid metals, are great choices for short-term storage. For long-term seasonal TES systems to store heat at low temperatures below 80°C, a sizable amount of storage material and a very large capacity are required [10].

Given the sheer volume, long-term seasonal storage uses affordable, naturally existing sensible heat storage materials like rock, sand, and water because of their affordability, environmental friendliness, and storage material requirements. Chemical storage materials are appropriate for long-term heat storage since, in theory, they lose no heat [6].

Effectiveness

It is the proportion of amount of energy released to the end user compared to the total energy supplied to charge the TES system. The overall amount of heat lost while charging, storage time, and discharging will be the difference between the total heat generated during charging as well as the overall heat discharged to the end user [7].

Price

Both the original capital expenditures and ongoing operating costs are included in the how much a TES system costs. First expenditures include those associated with planning and building the storage tank, purchasing equipment, instrumentation, insulation, pipelines, fittings, and labour for installing and commissioning the TES unit [8]. Costs associated with parasitic loads, such as pumping, electric trace heating, restocking storage supplies, etc., are included in operation and maintenance expenses. The System Advisor Model (SAM) of the National Renewable Energy Laboratory (NREL) software now offers pre-made financial models for renewable energy projects at the residential, commercial, and utility scales. One of the most crucial cost metrics for these kinds of projects is the levelized cost of energy (LCE), which is stated in $/kWh (G. Alva et al., Energy 144 (2018) 341e378 373) [7].

The cost of containers

The capital cost is significantly impacted by the choice of container design. Costly designs include shell and tube, two tank systems, packed bed of encapsulated PCM, fluidized bed, etc. The less costly Solutions include hard solid concrete blocks, a single tank thermocline liquid storage, and a packed bed of pebbles and sand [10]. Because of their massive storage capacity needs, seasonal thermal storage tanks demand a significant capital investment. Reinforced concrete and stainless steel are common materials for containers [10]. Insulation costs are covered by the container cost component. Fiber glass is a common material for insulation. Storage media having a low volumetric energy storage density raises container costs since smaller containers are less expensive. Higher storage medium vapor pressure results in larger walls and higher expenses [6].

Cost of materials for storing

Among other things, thermochemical, organic PCM, thermal oil, metals, and refrigerants used in gas hydrates are more costly storage materials than water, salts, rock, sand, and concrete [7]. The cost per unit mass of thermal energy storage material, represented in $/kg, can be used to evaluate the total cost of storage materials. prices associated with enhancing heat conductivity, such as micro-encapsulation or composite preparation, may also be included in storage material prices [9].

Cost of overhead

Miscellaneous expenses like electrical, instrumentation, plumbing, valves, fittings, etc. are typically included in the overhead cost component. 10% of the total cost might be used to simplify the estimation process [2].