

Thermal Energy Storage Systems: Advancements, Materials, and Applications

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ABSTRACT

This document presents a comprehensive review of Thermal Energy Storage (TES) systems, analyzing their critical role in the global energy transition characterized by the increasing penetration of intermittent renewable energy sources. The review categorizes TES into Sensible Heat Storage (SHS), Latent Heat Storage (LHS), and Thermo chemical Energy Storage (TCES), providing an exhaustive analysis of the thermo physical properties, mechanisms, and technological maturity of each. Particular emphasis is placed on advancements recorded during the 2024–2025 period, including the commercial deployment of sand-based storage systems, the development of bio-based and nano enhanced Phase Change Materials (PCMs), and emerging thermo chemical reactors. The paper evaluates the integration of these technologies in Concentrated Solar Power (CSP) plants, industrial process heat decarbonization (100–300 °C), and building thermal management. Furthermore, it addresses the techno-economic barriers, such as the low thermal conductivity of PCMs and the cycling stability of chemical sorbents, while highlighting the transformative potential of Artificial Intelligence (AI) in system optimization. By synthesizing recent data on energy density, efficiency, and cost specifically noting the cost competitiveness of thermal storage at approximately \$232/kWh for long-duration applications this review aims to serve as a definitive reference for researchers and policymakers navigating the complex landscape of thermal energy storage.

Keywords:- Thermal Energy Storage, Phase Change Materials, Thermo chemical Storage, Sand Battery, Artificial Intelligence etc

I. INTRODUCTION

The global energy paradigm is currently navigating a critical inflection point, driven by the dual imperatives of meeting rising energy demand and mitigating the catastrophic impacts of anthropogenic climate change. In 2024, global energy consumption witnessed a notable surge of 2.2%, a rate significantly higher than the decadal average of 1.3%, underscoring the relentless growth in human energy needs.¹ Concurrently, the deployment of renewable energy sources (RES), primarily solar photovoltaics (PV) and wind energy, has accelerated. However, the inherent intermittency of these sources dictated by diurnal cycles, weather patterns, and seasonal variations—creates a substantial mismatch between energy generation and consumption profiles. This "temporal gap" necessitates the deployment of robust Energy Storage Systems (ESS) capable of decoupling supply from demand, thereby ensuring grid stability and reliability.² While electrochemical energy storage, dominated by lithium-ion batteries, has captured significant market share for short-duration applications, it faces formidable challenges regarding scalability and cost-effectiveness for Long-Duration Energy Storage (LDES). In this context, Thermal Energy Storage (TES) emerges not merely as an alternative, but as a complementary solution. Recent data indicates that thermal energy storage is among the least expensive LDES technologies, with capital costs estimated at \$232 per kWh, compared to higher costs for battery systems.³ This review paper examines the state-of-the-art in TES technologies as of late 2025, specifically highlighting the commercial breakthrough of sand batteries and the integration of Artificial Intelligence (AI) in material science.⁴

Objective

- To store excess thermal energy (heat or cold) for use at a later time.
- To improve overall energy efficiency by balancing energy supply and demand.
- To reduce peak energy consumption and lower operating costs.
- To utilize waste heat or surplus renewable energy effectively.
- To ensure a continuous and reliable thermal energy supply during demand fluctuations.
- To enhance system performance in heating, cooling, and industrial processes.
- To minimize environmental impact by reducing fuel consumption and emissions.

- To support load management and stabilize thermal systems in power plants and HVAC applications.

II. CLASSIFICATION AND MECHANISMS OF TES

Thermal Energy Storage systems are fundamentally categorized based on the physical or chemical mechanism utilized to retain thermal energy: Sensible Heat Storage (SHS), Latent Heat Storage (LHS), and Thermochemical Energy Storage (TCES).

2.1 Sensible Heat Storage (SHS)

Sensible Heat Storage is the most technologically mature and widely deployed form of TES. It involves the storage of energy by raising the temperature of a solid or liquid storage medium without inducing a phase change. While liquid media like molten salts have been the standard for Concentrated Solar Power (CSP) 6, the 2024–2025 period has witnessed a renaissance in solid-state storage. A definitive highlight is the commercial deployment of "Sand Batteries." On June 11, 2025, the Finnish startup Polar Night Energy commissioned the world's largest commercial sand battery in Pornainen, Finland.⁴ The system delivers 1 MW of thermal power and has a storage capacity of 100 MWh. It utilizes approximately 2,000 tons of crushed soapstone, a byproduct from a local fireplace manufacturer, effectively replacing oil in the local district heating network.⁴ This technology offers a low-cost pathway for decarbonization, with pilot projects in the US targeting a Levelized Cost of Storage (LCOS) of roughly \$30/kWh for long durations.⁷

2.2 Latent Heat Storage (LHS)

Latent Heat Storage systems leverage the energy absorbed or released during a material's phase transition. These Phase Change Materials (PCMs) offer higher energy densities than SHS (approximately 90 kWh/m³) and isothermal operation.⁸ Recent innovations focus on overcoming the low thermal conductivity of PCMs. A 2025 study demonstrated that incorporating 7 wt% of optimized Expanded Graphite (EG) into paraffin wax resulted in a 153% improvement in thermal conductivity, significantly enhancing charging rates.⁹ Furthermore; there is a marked shift towards sustainable, bio-based PCMs derived from fatty acids and stabilized with biochar to reduce environmental impact.¹⁰

2.3 Thermochemical Energy Storage (TCES)

Thermo chemical Energy Storage represents the frontier of TES technology, utilizing reversible chemical reactions to store heat. TCES systems offer the highest energy densities, ranging from 200 to 500 kWh/m³, and the ability to store energy loss-free for seasonal durations.⁸ Current research in 2025 has highlighted materials such as salt hydrates and metal oxides. A review in *Materials Horizons* (2025) emphasizes the potential of these materials for low-temperature applications like domestic heating, although challenges related to reaction kinetics and cycle life persist.¹¹ Fluidized bed reactors are being developed to improve heat transfer and prevent particle agglomeration in these systems.¹²

III. APPLICATIONS AND FUTURE TRENDS

3.1 Concentrated Solar Power (CSP)

CSP remains a primary driver for high-temperature TES. In 2024, China solidified its position as the global leader, connecting 350 MW of new capacity and maintaining a pipeline of 8.1 GW.¹³ These projects increasingly utilize advanced TES to provide dispatchable base load power, differentiating them from PV.

3.2 Artificial Intelligence and Digitalization

The integration of Artificial Intelligence (AI) is transforming TES from a passive component to a smart grid asset. AI and Machine Learning (ML) algorithms are now used to predict the thermo physical properties of new PCM composites and to optimize the real-time operation of storage systems.⁵ These digital tools can forecast demand and weather patterns, optimizing charge/discharge cycles to maximize revenue and grid stability.¹⁴

IV. ADVANTAGES & DISADVANTAGES

Advantages:

- Improves energy efficiency
- Reduces peak energy demand
- Lowers operating and energy costs
- Utilizes waste heat effectively
- Reduces fuel consumption and emissions
- Provides reliable backup thermal energy
- Supports load balancing

Disadvantages:

- High initial installation cost

- Requires large space for storage
- Thermal losses during storage
- System complexity in design and control
- Maintenance requirements
- Limited storage duration depending on material.

V. CONCLUSION

The 2024–2025 period marks a transition for Thermal Energy Storage from research to industrial deployment. Sensible heat storage has achieved commercial scalability with giga watt-scale sand battery projects. Latent heat storage is overcoming conductivity limitations through nano-enhanced composites, and Thermo chemical storage holds the transformative potential for seasonal energy storage. With the support of AI optimization and robust market growth, TES is poised to play a central role in the decarbonized energy grid of the future.

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