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A Comprehensive Review of Advanced Materials, System Design, and Applications

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High Temperature Thermal Energy Storage:
A Comprehensive Review of Advanced Materials, System Design, and Applications

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Abstract:
High-temperature thermal energy storage (HT-TES) is essential for meeting and balancing of the expanding global demand for sustainable, efficient and reliable energy systems. Some of the most significant applications are: concentrated solar power, industry decarbonization and waste-heat recovery and advanced nuclear plants. Despite advances in material and system design that have

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improved HT-TES potential, chronic challenges remain in achieving high energy density, cost-effectiveness, and reliable long-term performance under the operational conditions. This review synthesizes recent progress across three interrelated areas: materials (sensible, PCM and thermochemical materials), system design and applications. The authors identify key technical barriers, including material degradation and low PCM thermal conductivity, and propose research priorities pathways to develop high-performance HT-TES for decarbonized energy systems.

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Keywords: Thermal Energy Storage, High Temperature TES, Storage Materials, HT-TES System Design, Concentrating Solar Power

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الخزانات الحرارية ذات درجات الحرارة المرتفعة: مراجعة شاملة للمواد المتقدمة، تصميم الأنظمة، والتطبيقات

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الملخص:

تعد تقنيات تخزين الطاقة الحرارية ذات درجات الحرارة العالية (HT–TES) ركيزة أساسية لتلبية الطلب العالمي المتزايد على مصادر طاقة مستدامة، وفعالة، وموثوقة. وتبرز أهمية هذه الأنظمة في تطبيقات مهمة مثل محطات الطاقة الشمسية المركزة، وتقنيات تخفيض الانبعاثات الكربونية واسترداد الحرارة في القطاع الصناعي. ورغم التطور الملحوظ في تصميم المواد والأنظمة الذي عزز من كفاءة هذه التقنيات، إلا أنها لا تزال تواجه تحديات

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مستمرة في الوصول إلى مستويات مثالية من كثافة الطاقة، والجدوى الاقتصادية، والموثوقية التشغيلية على المدى الطويل في الظروف التشغيلية. في هذه المراجعة نسلط الضوء على أحدث التطورات العلمية في ثلاثة مسارات تتعلق بخزانات الطاقة الحرارية مرتفعة الحرارة: مواد التخزين (للحرارة المحسوسة، والمواد متغيرة الطور PCM ، والمواد الكيميائية الحرارية)، وتصميم النظم، ومجالات التطبيق. كما نحدد أبرز العوائق التقنية مثل: تراجع الكفاءة الحرارية للمواد، وضعف الموصلية الحرارية لمواد متغيرة الطور، ويطرح الباحثون رؤية بحثية استشرافية تهدف إلى تطوير أنظمة تخزين طاقة حرارية عالية الأداء، بما يخدم التحول نحو أنظمة طاقة خالية من الانبعاثات الكربونية.

وقد تم عرض هذه الورقة العلمية في جلسات المؤتمر الدولي للطاقة المتجددة والنفط والغاز وتغير المناخ "أيريقو" في الفترة 25-27 ابريل 2026م. طرابلس – ليبيا

الكلمات المفتاحية :تخزين الطاقة الحرارية، خزانات الطاقة الحرارية ذات درجات الحرارة العالية، مواد التخزين الحراري، تصميم أنظمة HT-TES ، المركزات الشمسية.

Introduction

The increasing global demand for sustainable and efficient energy systems has driven significant interest in thermal energy storage (TES) as a key technology for bridging the gap between energy supply and demand[1]. High-temperature thermal energy storage (HT-TES) systems, in particular, play a pivotal role in enhancing the efficiency and reliability of concentrated solar power (CSP), industrial waste heat recovery, and advanced nuclear energy systems[2]. Despite substantial advancements in TES materials and system design, critical challenges remain in optimizing energy density, thermal stability, cost-effectiveness, and long-term performance under extreme operating conditions [3].

Among various TES technologies, HT-TES stands out due to its ability to store and discharge thermal energy at elevated temperatures, making it a crucial component in advanced energy applications. Typically defined as systems operating above 400°C

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(though interpretations may differ), HT-TES involves capturing thermal energy at high temperatures for later use [4].

Recent literature highlights significant progress in advanced materials such as molten salts, phase change materials (PCMs), and ceramic-based composites for HT-TES applications[5]. However, gaps persist in understanding the degradation mechanisms of these materials under cyclic thermal loading, the scalability of system designs, and the integration of HT-TES with next-generation power cycles [6]. Furthermore, while numerous studies have explored individual components of HT-TES, a comprehensive review of the synthesizing material innovations, system-level optimization strategies, and emerging applications is lacking. This gap hinders the development of standardized design protocols and limits the widespread adoption of HT-TES technologies [7].

However, thermal storage could be classified, by the system operating temperature, into three types: Low, Medium and High temperature thermal energy storage [8]. The low-temperature TES is widely used in domestic water heating and HVAC systems in the building sector, where sensible heat aqueous materials and packed beds are mostly used. Low-temperature PCMs, such as paraffin wax, are available but not preferred due to their high cost and low thermal conductivity. Despite that, high-temperature applications are mainly conducted for nuclear energy and solar thermal electricity production by CSP. Recently, high-temperature TESs have been suggested to work as high-capacity batteries, whereas conventional chemical batteries have a much lower lifespan and cost.

Therefore, high temperature applications that involve electricity production are significant for nowadays power networks to maintain high reliability and sustainability. Many studies, recently, have conducted concentrated experimental work on new materials for thermal energy storage, such as sand, high-temperature thermoclines, sorption and molten salts. Where Diego et al. [9] and Diego et al. [10] have discussed the feasibility of sand implementation as a TES fluid. It is found that the sand is thermally

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stable even at a temperature of 1100 °C. While some changes in sand composition occurred during the first charge due to the CO_2 release.

This study aims to provide a systematic and critical review of the state-of-the-art in high-temperature TES, addressing three primary research questions: *material innovations:* what are the most promising advanced materials for HT-TES, and how do their thermophysical properties, durability, and cost compare?, s*ystem design:* what are the key engineering challenges in HT-TES system design, and how can novel configurations improve efficiency and scalability? and *applications and Integration:* How can HT-TES be effectively integrated into existing and future energy systems to maximize economic and environmental benefits?. By consolidating and analyzing recent advancements, this review seeks to identify critical research directions, highlight unresolved technical barriers, and propose pathways for commercialization. The methodology involves a rigorous bibliometric analysis coupled with a qualitative assessment of experimental and computational studies on HT-TES materials and systems. The findings are expected to guide researchers, industry stakeholders, and policymakers in accelerating the deployment of high-performance HT-TES solutions.

The remainder of this paper is structured as follows: Section 2 reviews advanced materials for HT-TES, Section 3 examines system design and integration strategies, Section 4 discusses applications and Section 5 concludes with future research directions and recommendations. Through this comprehensive analysis, we aim to contribute to the ongoing discourse on sustainable energy storage and facilitate the transition toward decarbonized energy systems.

Advanced Materials for High-Temperature TES

High-Temperature Thermal Energy Storage (HT-TES) systems critically depend on the effective selection and development of advanced materials capable of enduring extreme temperatures and facilitating efficient heat transfer and storage. The performance, lifespan and economic feasibility of any HT-TES solution are inherently linked to the thermophysical properties, stability, and

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cost-effectiveness of the storage medium. This section comprehensively reviews the diverse array of materials employed in HT-TES. As shown in Figure 1, TES could be categorized into sensible heat storage materials, latent heat storage materials (Phase Change Materials or PCMs), and thermochemical energy storage (TCES) materials, highlighting their respective advantages, limitations, and recent advancements aimed at maximizing energy density, thermal stability, and overall system efficiency. [8], [12], [13], [14]

Sensible Heat Storage Materials

In the evolving landscape of renewable energy technologies, sensible heat storage (SHS) materials such as rocks, sands, molten salts, and metals have been widely explored for high-temperature thermal energy storage (TES) systems. (See figure (1)).

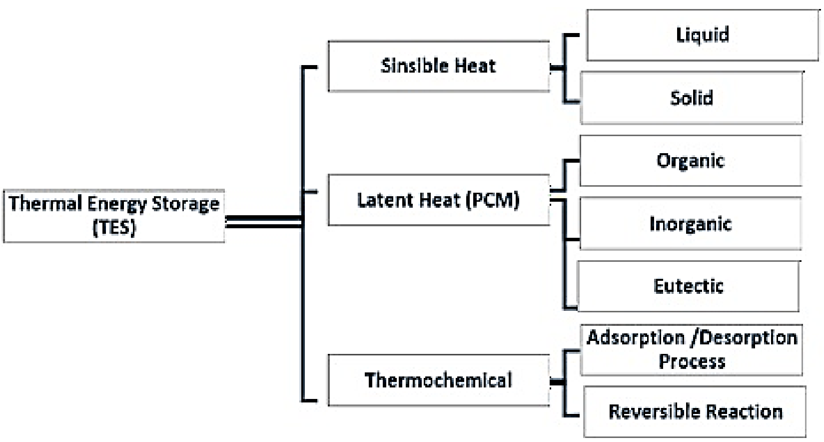

Figure 1: Thermal Energy Storage classifications[8], [85][17]

They store and release thermal energy through temperature changes without undergoing a phase change, making them reliable and operationally simple for industrial and CSP applications. Their performance is primarily assessed by specific heat capacity, density, and thermal stability at high temperatures [1]. These materials are

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suitable for applications requiring gradual and stable heating or cooling. Their efficiency depends on specific heat capacity, density, and long-term thermal stability.

To achieve high performance in TES systems, materials must exhibit the following: high specific heat capacity, high density, thermal and chemical stability at high temperatures, high thermal conductivity to ensure efficient heat transfer during charging and discharging, availability and economic feasibility.

The International Energy Agency [15], also recommends considering environmental safety, material corrosiveness to storage containers, and ease of maintenance.

Molten Salts

Although primarily used in phase change applications, certain salts such as sodium nitrate ($NaNO_3$) and potassium nitrate (KNO_3) are also employed as sensible heat storage media due to their high melting points and thermal stability within the 250–600°C range. These salts are foundational in CSP systems, as seen in Spain's Gemasolar project. In addition, Bauer et al. [16] has reported that a $NaNO_3/KNO_3$ eutectic mixture can store up to 300 kWh/m^3 with consistent performance over more than 1000 thermal cycles.

As reported by *the International Renewable Energy Agency (IRENA), by* 2020, molten-salt thermal energy storage (TES) represented the predominant form of installed TES capacity within the power sector, primarily due to its integration with concentrated solar power (CSP) plants. This technology plays a crucial role in enabling CSP facilities to store excess thermal energy for later use, thus ensuring a more stable and continuous power supply. At the time, the global installed capacity of molten-salt storage had exceeded 21 GWh by 2020, while more than 140 GWh is planned to join the market by 2030, highlighting its significance in advancing renewable energy solutions. [17].

Packed bed

Sensible heat TES materials could be classified into liquids and solids. Whereas molten salts as liquids are used for energy storage, solids could be arranged in packed beds with low porosity to extract heat from the gaseous HTF. These systems typically consist of a

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container filled with a solid storage material, such as rocks, glass or mineral babbles, through which the heat transfer fluid (HTF) flows. The fundamental principle involves transferring thermal energy between the HTF and the solid packing material. many significant characteristics are studied in research, such as pressure drop, the amount of thermal energy absorbed by the media and the time constant. The governing equations have demonstrated the viability of packed-bed TES for high-temperature applications, with the structured design are offering superior pressure-drop performance. [18] However, only a one-dimension model is conducted in the study. Mohammad et al. [19] have investigated the performance of a Hi-Temperature rock bed thermal energy storage in 2-Dimension by a CFD model simulation of a 1 MWh pilot-scale TES unit and validated using experimental data, focusing on parameters such as rock size, flow rate, and storage material to optimize efficiency. The results illustrated charge efficiencies ranging from 77% to 94%, with magnetite outperforming diabase due to higher thermal conductivity and heat capacity. (see Fig.2.)

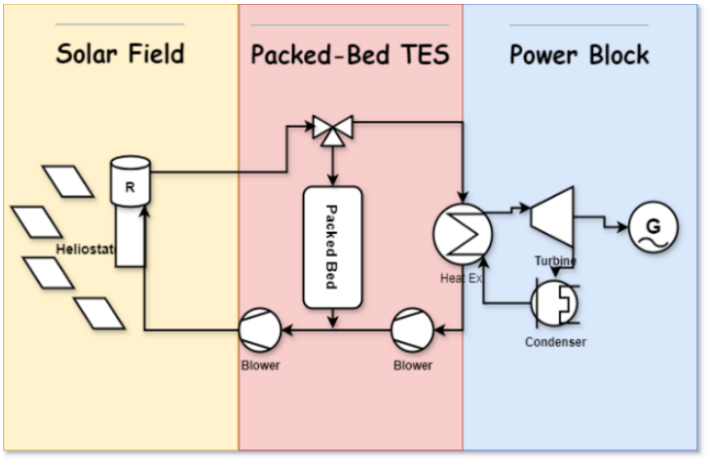

Figure 2: Schematic diagram for a packed bed TES integration in CSP application

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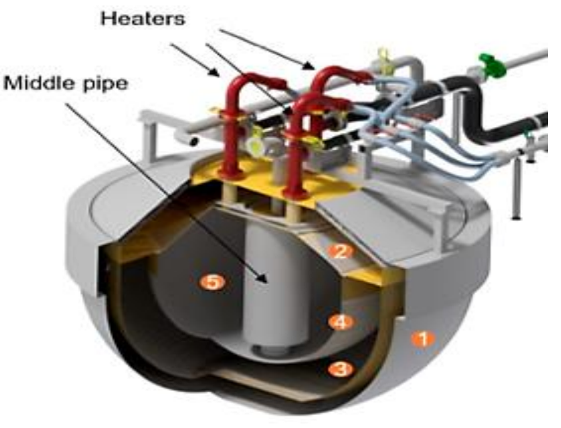

Figure 3 A design of a Rock Bed HT-TES investigated for industrial purposes by [19]

Ceramics and Refractory Materials

This category includes stable metal oxides such as aluminum oxide (Al_2O_3) and magnesium oxide (MgO), which tolerate temperatures exceeding 1000°C. Known for chemical inertness and corrosion resistance, ceramics are favored in high-temperature industrial and ultra-high-temperature solar applications [20],[21]. Esence et al. [22] have tested a ceramic-plates packed bed and compared it to a natural-rocks filled packed bed. The results demonstrated a 54% lower pressure drop in the ceramic plates. However, the thermal performance of both packed beds was close. Both packed beds have illustrated high charge/discharge thermal stability under a hundred cycles with a temperature range of 80°C to 800°C for various flow rates. Furthermore, Zhang et al. [1] has identified ceramics as strategic materials for future TES applications requiring high energy density and long-term thermal stability.

Concrete

While materials like molten salts offer excellent heat capacity, they suffer from drawbacks including high cost and corrosiveness. Vigneshwaran et al. [23] have investigated the feasibility of

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concrete as a cost-effective and durable alternative for high-temperature TES. The study presents the design, modeling, and experimental validation of a Concrete-based Thermal Energy Storage (CTES) system operating with air as the heat transfer fluid (HTF) up to 500 °C. Results from both 3-D and 1-D numerical simulations validated with experimental data and demonstrated efficient heat charging and discharging behavior, with reduced times (up to 48% and 29%, respectively) achieved by increasing inlet temperature. The concrete TES system demonstrated radially uniform heat transfer and long-term mechanical integrity over more than 300 thermal cycles. Despite these promising findings, certain limitations were noted: the 3-D model lacked real-time adaptability to variable inlet conditions, and minor cracking was observed near the inlet section due to thermal stress after prolonged use. Nevertheless, the concrete could be a viable SHS medium with a compelling balance of thermal performance, mechanical resilience, and cost, especially suited for applications such as steam generation and industrial process heat, where integration with renewable energy sources is critical.

Furthermore, the potential of a specific type of concrete, which is the geopolymer concrete, is explored by [24] to be utilized as a medium for high-temperature sensible heat thermal energy storage (TES). Employing numerical simulations conducted via COMSOL Multiphysics, the research examines how variations in design parameters, particularly the number and spatial arrangement of heat transfer fluid (HTF) tubes, influence the system’s thermal efficiency.

The results suggest that geopolymer concrete demonstrates favorable thermal characteristics and that strategic optimization of HTF configurations can substantially enhance heat storage and retrieval performance. Nonetheless, the investigation is constrained by the absence of experimental validation, limited assessment of long-term thermal and mechanical durability, and a lack of techno-economic or scalability analysis. The study thus contributes to addressing critical questions regarding the viability and optimization of geopolymer concrete for integration into

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concentrated solar power and other high-temperature TES applications.

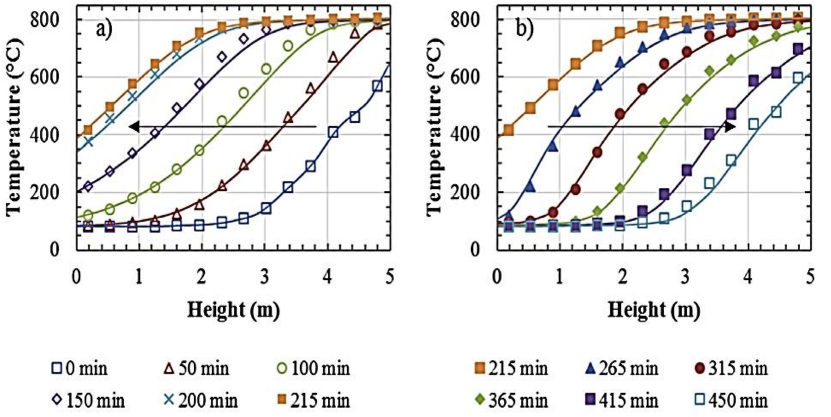

Figure 4: Typical Packed bed temperature profile during charge and discharge phases, numerically and experimentally

Sand

Traditional TES materials such as molten salts, while effective, suffer from high costs and environmental concerns. This has prompted the exploration of more abundant and low-cost alternatives. Sand, with its high thermal stability and natural abundance, presents a compelling solution for large-scale thermal storage, especially in arid regions rich in solar energy. [10] have investigated the viability of using naturally abundant desert sand as a medium for thermal energy storage (TES) in concentrated solar power (CSP) systems. It presents a comprehensive analysis of the thermal, physical, and chemical properties of desert sand, including thermal conductivity, specific heat capacity, and thermal stability under cyclic heating. The study reveals that desert sand exhibits promising thermal performance, cost-effectiveness, and environmental sustainability. In addition, Nei et al, [25] have conducted numerical and experimental work testing a novel solar

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receiver that utilizes grey ceramsite sand as a heat transfer and storage medium. The study focuses on optimizing the thermal performance of this receiver, which is a crucial component in systems that aim to implement sand-based thermal energy storage. On the other hand, the article does not delve into the long-term material stability, degradation, or thermal cycling properties of the specific grey ceramsite sand used, which are critical for TES system durability. Furthermore, the paper does not address general operational challenges such as dusting, particle agglomeration, or erosion that are inherent to solid particle systems. However, the thermal conductivity of sand is low. Thus, Tetteh, et al [26] have investigated the use of metallic chips and sand mix instead of pure sand and compared them experimentally. Subsequently, the lab results demonstrated that mixing sand with 20% (volumetric basis) of aluminum chips significantly improved the heat rate by 1.7 times compared to pure sand, offering a cost-effective solution for more efficient TES applications essential for integrating renewable energy into the modern grid.

Latent Heat Storage Materials

Latent Heat Storage (LHS) materials store significant energy at nearly constant temperatures through phase changes, usually between solid and liquid states. During phase transitions, these materials absorb or release large amounts of latent heat with minimal temperature variation, making them ideal for applications requiring precise thermal regulation. They are widely used in CSP systems and industrial thermal networks, offering higher energy density compared to SHS materials and improving the efficiency and compactness of storage systems [27].

These include paraffins, salt hydrates, and selected oxides such as calcium oxide (CaO). Their main advantage lies in storing or releasing large amounts of heat at melting or freezing points. However, organic PCMs often suffer from low thermal conductivity and instability at elevated temperatures, necessitating material enhancement [27]. Rear, J. and others [28], have investigated the use of aluminum-silicon alloy as a phase change material (PCM) for

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storing and releasing heat. They have demonstrated the viability of using metal alloys like aluminum-silicon for high-temperature, modular thermal storage systems suitable for small-scale solar power generation, potentially lowering costs and improving system dispatchability. The system maintained a uniform temperature (within 5 °C) across the storage tank. In addition, minimal temperature drops were observed at system interfaces, ensuring efficiency.

Nano-Enhanced PCM

Nano-enhanced Phase Change Materials (NePCMs) significantly contribute to Latent Heat Thermal Energy Storage (LHTES) systems by addressing the inherent low thermal conductivity of traditional Phase Change Materials (PCMs). This enhancement is crucial for improving the efficiency of solar energy storage and other applications where LHTES systems are utilized. Fine metallic particles, including aluminum, copper, titanium, and zinc oxides, were tested alongside non-metallic powders such as silicon carbide. These additives demonstrated promising results in enhancing the thermal properties of PCMs. However, incorporating nano-additives slightly reduces the overall storage thermal capacity, as they occupy a portion of the PCM volume [29] In addition, they have been shown to reduce solidification time, primarily due to an increase in thermal conductivity, with various NPs such as Al_2O_3, ZnO, CuO, and SiO_2 demonstrating this effect. Furthermore, NPs can enhance the thermal stability of PCMs at elevated temperatures and improve thermal diffusivity. In certain applications, NPs can also beneficially adjust the onset and overall melting temperatures of PCMs. While some studies have reported a decrease in latent heat with NP inclusion, others have
indicated an increase in both specific heat and latent heat of fusion.[30][31][32]

Recent research has focused on integrating nanoparticles, such as carbon nanotubes (CNTs) and graphene oxide (GO), into PCMs to enhance thermal conductivity. These enhancements have been shown to improve heat charging/discharging rates and increase heat

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transfer efficiency without significantly affecting melting temperatures[34], [35], [36], [37]. (Figure .5)

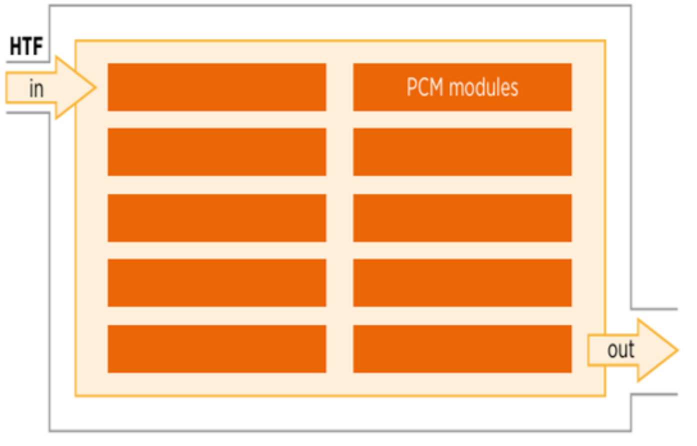

Figure 5: Encapsulated PCM heat storage system [33]

Encapsulated PCM

Micro-encapsulation of PCMs in micron-sized containers, as illustrated in **خطأ! لم يتم العثور على مصدر المرجع.**, minimizes energy loss, prevents interaction with external environments, and extends material lifespan. It also enables multi-layered system designs for flexible thermal responses in industrial settings (See figure 6). [38]

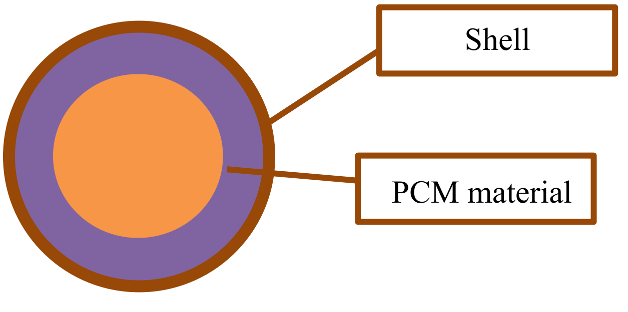

Figure 6: Encapsulated PCM material

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Thermochemical Heat Storage Materials

This method utilizes reversible chemical reactions (endothermic/exothermic) to store and release energy. It offers high energy density and minimal heat loss over long durations. A prominent example is the CaO/CO_2 reaction forming calcium carbonate ($CaCO_3$). This system enables energy storage at temperatures up to 650°C, with easy reversibility using concentrated solar heat [39], [40].

Furthermore, iron and manganese oxides exhibit excellent dynamics for TES through redox reactions, maintaining performance over hundreds of cycles, thus making them suitable for long-term, cyclic operation[41][42]. On the other hand, A key factor in thermochemical TES is reaction reversibility and rate under operating conditions. Studies show some systems can achieve energy conversion efficiencies exceeding 80% when temperature and gas pressure are well controlled [43], [44].

System Design and Integration

TES System Configurations

With growing global emphasis on energy sustainability and decarbonization, Thermal Energy Storage (TES) systems have become increasingly vital in supporting the efficient use of renewable energy resources. As the penetration of variable renewable energy sources, such as solar and wind, continues to rise, the ability to store excess thermal energy and dispatch it on demand is critical to maintaining grid stability, enhancing energy efficiency, and reducing greenhouse gas emissions. TES systems not only bridge the temporal mismatch between energy generation and consumption but also enable greater flexibility across a wide spectrum of applications, including industrial processes, grid integration, and building-level energy management. This section explores the design principles, technological configurations, and integration strategies of TES systems, with particular emphasis on direct versus indirect storage methods, modular scalability, concentrated solar power (CSP) coupling, waste heat recovery, and

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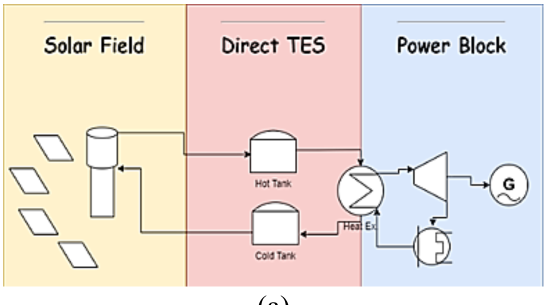
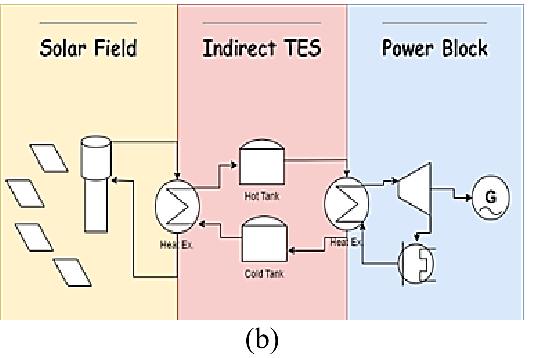
grid load-shifting. The discussion is supported by recent advancements in materials science, digital control, and economic assessments, highlighting the pivotal role of TES in shaping next-generation energy infrastructure.

Direct Vs. indirect systems

Thermal energy storage (TES) systems are categorized as direct or indirect, each with distinct operational features, as demonstrated in **خطأ! لم يتم العثور على مصدر المرجع.**. Direct systems use the same medium for heat transfer and storage, such as water, offering high thermal efficiency and simple design, with fast charge/discharge rates governed by fluid flow. However, they have low energy density, require large volumes, and experience higher losses in small-scale setups.



(a)



(b)

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Figure 7 schematic diagram of the (a) Direct TES and (b) Indirect TES

Indirect systems, in contrast, separate the transfer and storage media, often incorporating phase change materials (PCMs) or borehole storage with heat exchangers. This leads to higher energy density and reduced space requirements, though at the cost of system complexity, heat exchanger limitations, and increased capital expense. While direct TES can discharge up to 98% capacity per hour, indirect options are slower (around 25%) but provide better thermal regulation and control. Economically, direct TES is cost-effective but spatially demanding, while indirect systems offer compactness, up to 25% space savings, at higher upfront costs [45]. Despite their differences, both systems yield similar annual storage efficiency and have shown performance improvements when integrated with solar thermal systems. Their application ultimately hinges on project-specific needs such as space, flexibility, and budget [46], [47].

Modular and Scalable Thermal Energy Storage (TES) Systems:

Modular TES systems have emerged as a critical solution for addressing the variability of renewable energy sources, offering flexible and scalable storage through standardized units such as PCM capsules, molten salt tanks, and hybrid modules[48], [49]. These systems enable adaptable deployment across scales, from residential to utility-level applications, by supporting horizontal (capacity) and vertical (functionality) scalability. **خطأ! لم يتم العثور على مصدر المرجع.** represent encapsulated PCM that could be arranged in modules as illustrated in **خطأ! لم يتم العثور على مصدر المرجع.** [50]. PCM modules are efficient in compact systems due to their high energy density, but face challenges like cycling degradation and cost. Molten salts, by contrast, are better for high-temperature applications, offering durability and long-duration storage, though they require careful management to mitigate issues like corrosion and freezing [51]. New developments are recently investigated include *3D-printed PCM modules* that show 40% faster thermal response [7], Guo et al. [52] have conducted that the use of 3D

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printed lattice structure plates with PCM could enhance the thermal conductivity 13 times.

Thermal energy storage is a main part of the CSP solar power generation, where material selection is critical for TES utilized for CSP plants. Properties like thermal conductivity, phase transition temperature, and chemical stability influence performance [11]. The match between TES and the type of CSP (e.g., towers vs. troughs) also affects outcomes. From the Techno-economic side, assessments show that CSP+TES systems can reach LCOEs as low as $0.0763/kWh when combining solar towers with enhanced PCMs [53]. The International Renewable Energy Agency (IRENA) [33] has demonstrated the targeted characteristics of TES technologies in 2030, including the expected LCOE shown in **خطأ! لم يتم العثور على مصدر المرجع.**

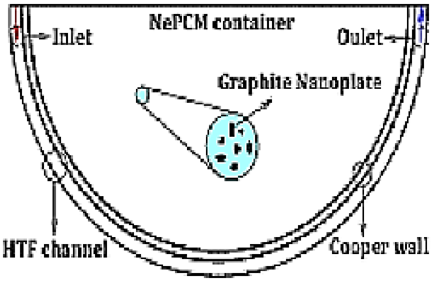

Figure 8: represent encapsulated PCM that could be arranged in modules

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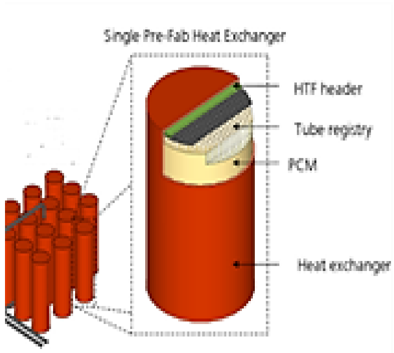

Figure 9: A schematic diagram for a Nano-enhanced PCM design [117]

Table 1: Technology Objectives by 2030 for TES systems[33]

Attribute	Sensible		Latent		Thermochemical	
	2018	2030	2018	2030	2018	2030
Cost (USD/kWh)	25–30	< 15	25–90	25–35	Research level	Pilot scale, 80–160
Efficiency (%)	>90	>92	>90	>92	40–50	N/A
Energy Density (kWh/m³)	70–200	Material selection dependent	30–85		800–1200	
Lifetime (years/cycles)	< 10,000	> 10,000	3,000–5,000	4,000–5,000	< 100	500–1,000
Working Temp (°C)	< 565	600–700	< 600	600–750	500–900	

Applications of High-Temperature TES

HT-TES technology has a growing potential to be used in a wide range of applications such as: Concentrated Solar Power (CSP) plants, wind and solar hybrid systems, industrial processes and chemical processing. Furthermore, various emerging applications are being developed, including thermal management in electronics, as well as potential uses in transportation and mobile energy storage.

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5.1. Renewable Energy Integration

The integration of VRES into existing energy grids necessitates effective storage solutions to manage their intermittency and ensure a stable power supply. HT-TES provides a compelling pathway, particularly for solar thermal energy and for stabilizing grids with high wind and photovoltaic (PV) penetration.

5.1.1. Concentrated Solar Power (CSP)

Concentrated Solar Power (CSP) technology uses mirrors to concentrate sunlight onto a receiver, heating a fluid (e.g., thermal oil, molten salt, air) to high temperatures, which then drives a conventional power cycle (typically a steam Rankine cycle) to generate electricity [54].

The primary function of HT-TES in CSP is to absorb the excess of solar heat during the day and drive the power block beyond daylight hours and during transient cloud cover [11]. This significantly increases the plant's capacity factor (the ratio of actual energy generated over a period to the theoretical maximum) and enhances its dispatchability, allowing CSP plants to provide firm power capacity similar to conventional thermal power plants [6]. Molten salt mixtures, typically a binary blend of sodium nitrate ($NaNO_3$) and potassium nitrate (KNO_3), are the most widely deployed HT-TES medium in commercial CSP plants, operating in a temperature range of approximately 290°C to 565°C, where a two-tank system is used; one relatively cold (290 ℃ approx.), while the other is hot (around 565 ℃ [55]. This sensible heat storage approach has proven its reliability and cost-effectiveness in numerous large-scale projects globally, such as the Gemasolar plant in Spain, which pioneered 24/7 operation using molten salt storage [56] , and the Noor Ouarzazate complex in Morocco [57]. On the other hand, [58] have investigated the use of many PCM materials and compared their TRNSYS simulation results with a reference CSP plant that is equipped with a typical indirect molten salt TES.
Another approach to enhance the performance of the CSP, is to use air or gases such as supercritical CO_2 as a HTF, which requires

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higher temperature TES [59], [60]. Alternative sensible heat storage materials like rock-beds or industrial ceramics are being investigated for their lower cost and potential for higher temperature operation, particularly when coupled with air or gas as the heat

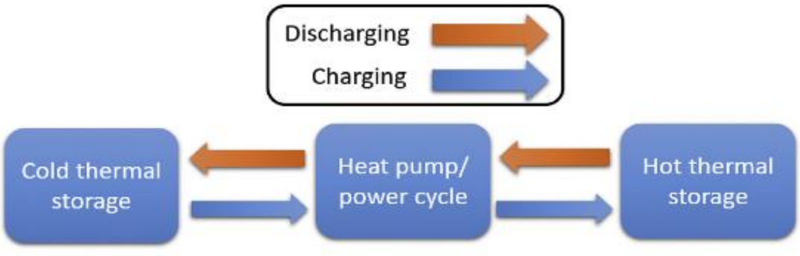

Figure 5 Working Principles of Pumped Thermal Energy System (PTES) as a Carnot Battery

transfer fluid [18], [61], [62], [63], [64], [65]. Latent heat storage using Phase Change Materials (PCMs) offers the theoretical advantage of higher energy density and isothermal operation. [5], [36], [37], [57], [66], [67], [68], [69], [70]
In summary, the integration of thermal energy storage (TES) into concentrated solar power (CSP) plants plays a crucial role in ensuring a more stable and reliable energy supply by aligning power generation with grid demand. This adaptability underscores the importance of TES technology in advancing sustainable energy solutions. [71]

5.1.2. Wind and Solar Hybrid Systems

Although CSP typically includes thermal storage, most renewable energy capacity comes from wind and solar PV, which are intermittent and can lead to energy curtailment when supply exceeds demand [72]. High-Temperature Thermal Energy Storage (HT-TES) is a promising approach to store surplus electricity from wind and PV, converting it into heat and later back into power or using the heat directly.

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Known as Power-to-Heat-to-Power (P2H2P) or Carnot Batteries, these systems use electricity to charge high-temperature media via heat pumps or resistive heating, then retrieve energy using cycles like Rankine or Brayton [49], [73], [74]. The key benefits include high capacity, long duration, geographic flexibility, and potentially lower costs than batteries on a large scale [75]

Packed bed systems using air and ceramics are favored for their low cost and thermal resilience [74], [76]. These systems could enhance renewable integration, reduce fossil fuel use, and offer thermal energy for industrial or district heating [77], [78]. Challenges include optimizing cycles, capital cost reduction, and long-term reliability [79].

5.2. Industrial Processes

Industry consumes a large share of global energy and emissions, particularly in high-temperature processes, which represent around 48% of the total industrial energy load [80]. HT-TES can improve efficiency, reduce fossil dependence, and integrate sustainable energy. [19] have highlighted the potential of rock-based TES as a cost-effective and scalable alternative to pressurized water systems for medium-temperature industrial processes (100–250 °C), reducing reliance on fossil fuels. The model demonstrated in **خطأ! لم يتم العثور على مصدر المرجع.** is utilized to study a 330 MWh TES system on an industrial scale, focusing on the ability to provide constant power output by adjusting flow rates during discharge.

Furthermore, sectors like cement, steel, and aluminum generate significant waste heat [81]. HT-TES can capture and reuse this heat for drying, power, or process stabilization [19], [82], [83], [84]. Moreover, steel production could offer heat recovery opportunities for steam or metal preheating [85], [86]. Ceramic-packed beds or high-temperature phase change materials are common storage options. [87], [88]

5.2.1. Chemical Processing

The chemical industry uses high-temperature heat for reactions, drying, and distillation [89]. HT-TES supports heat recovery from

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exothermic processes, enhancing efficiency [90]. It also buffers fluctuating heat inputs to maintain process stability [91]. The potential applications include steam methane reforming and solar-driven hydrogen production [92].

5.3. Emerging Applications

While HT-TES is primarily geared toward renewable energy integration and industrial use, research is extending into emerging fields like electronics thermal management and mobile energy storage.

Thermal Management in Electronics

Effective heat dissipation is vital in high-power electronics and computing, especially under transient loads or elevated temperatures [93]. Although most electronics operate below 100°C, advanced devices using wide-bandgap semiconductors such as SiC or GaN can exceed 200°C [94]. Traditional cooling often fails in high-temperature or harsh environments, such as: aerospace or drilling, prompting interest in HT-TES solutions using latent heat materials to buffer short-term thermal pikes. [95], [96]

Transportation and Mobile Energy Storage

High-temperature thermal energy storage (HT-TES) is being explored for auxiliary power and potential propulsion in large-scale transport systems such as trains and ships, using technologies like Stirling engines or thermochemical storage [98], [99]. Although thermochemical systems offer high energy densities, practical challenges, such as: slow reaction kinetics, complex material handling, and safety risks limit their viability [27], [100]. Currently, HT-TES applications in transportation remain experimental, with a focus on thermal buffering rather than propulsion.

Pumped Thermal Energy Storage (PTES)

Pumped Thermal Energy Storage (PTES), which can be classified as a Carnot Battery, is an innovative physical energy storage solution essential for the effective integration of intermittent renewable energy sources, such as solar and wind, into the electrical

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grid. The increasing penetration of these variable renewable energy sources (VRES) creates a significant mismatch between energy supply and demand, leading to the necessity for robust, Long-Duration Energy Storage (LDES) systems that can mitigate curtailment and ensure grid stability. The fundamental principle of PTES is the conversion of surplus electricity into thermal energy, which is then stored in thermal reservoirs and later converted back to electricity upon demand. The process involves a charging phase where a heat pump uses electrical energy to transfer heat from a cold reservoir to a hot reservoir, followed by a discharging phase where the stored thermal energy drives a heat engine to generate electricity. This technology is highly attractive for its low environmental impact and ability to be installed across different scales and almost anywhere, without the specific geographical restrictions that limit conventional pumped hydro storage [101], [102].

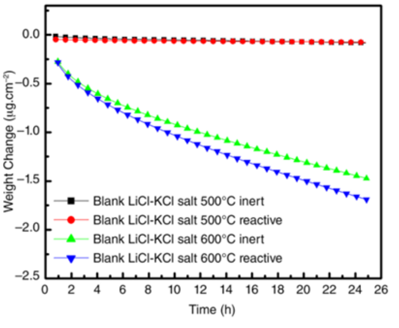

Figure 6: Mass loss in the molten salt in temperatures (500℃ and 600℃)[97].

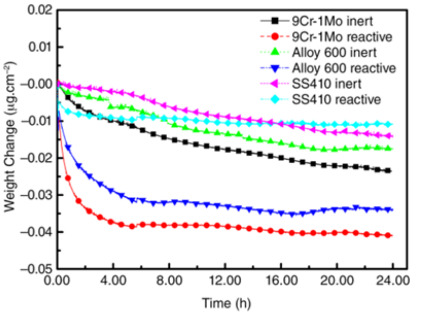

Figure 7:Storage material alloy degradation due to sever corrosion (SS410 steel, Nickle Alloy and Chromite Alloy)[97].

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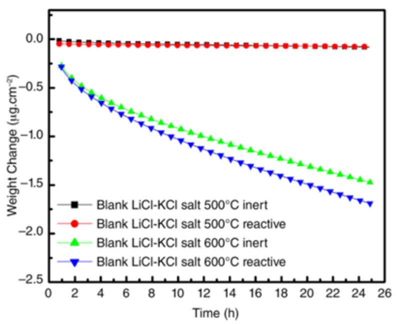

Figure 8: Mass loss in the molten salt in temperatures (500°C and 600°C)[97].

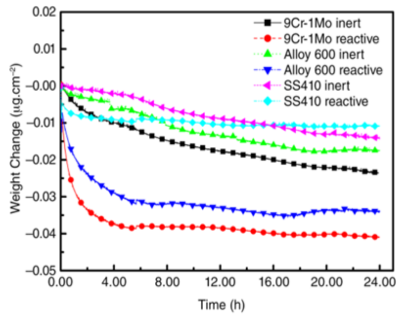

Figure 9:Storage material alloy degradation due to sever corrosion (SS410 steel, Nickle Alloy and Chromite Alloy)[97].

The thermodynamic performance of PTES relies heavily on the selection of the working fluid, the operating cycle, and the thermal storage medium. While fluids such as air, argon, and helium are employed, often operating up to 1000 ^{0}C with round-trip efficiencies (RTE) around 60%, carbon dioxide CO_2 is particularly promising due to its excellent heat transfer properties, high energy density, and non-toxic nature. CO_2-based systems can utilize various thermodynamic cycles, including supercritical Brayton and trans-critical Rankine cycles, which operate over a wide temperature range, thereby maximizing energy storage capacity and overall efficiency [102], [103].

Beyond stand-alone systems, advanced PTES research explores integrated and hybrid concepts to improve system flexibility and increase value streams. One key area is the integration with Concentrating Solar Power (CSP) to create hybrid systems, such as the "Solar Top-Up" and "Dual-Mode" devices, which share components to reduce capital costs. For instance, using solar heat to increase the maximum operating temperature in a "Solar Top-Up" configuration can significantly boost the RTE from 41% to 62% and triple the specific work output. Furthermore, PTES systems based on CO_2 heat pumps are being designed for applications in multi-

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energy storage systems that combine cold, heat, and power generation (CCHP). This diversification is intended to achieve a more efficient utilization of renewable energy, supporting multiple services for commercial and residential buildings. [101], [102], [104]

Challenges and Future Perspectives

According to the reviewed literature, it is identified that several persistent challenges are currently hindering the wider adoption of High-Temperature Thermal Energy Storage (HT-TES) technologies.

The primary challenges can be categorized into material limitations and system-level complexities. A significant barrier is the inherent trade-off in material properties. For instance, Phase Change Materials (PCMs) offer high energy density but suffer from low thermal conductivity, which reduces heat transfer rates and necessitates complex enhancement strategies like nano-additives, which in turn can reduce overall storage capacity[30], [105]. Similarly, while molten salts are commercially established, they present challenges of high cost, corrosiveness to containment materials, as shown in Figure 6 and Figure 7, and management issues like freezing. For thermochemical storage (TCES), the viability is constrained by challenges in achieving reliable reaction reversibility and sufficient reaction kinetics under operational conditions, coupled with complex material handling and safety concerns[106], [107].

From a system design perspective, a major challenge is the scalability and long-term durability of solutions proven at a lab or pilot scale. The reviewed research have highlighted that many studies, particularly on novel materials like geopolymer concrete or ceramsite sand, are constrained by a lack of experimental validation and assessment of long-term thermal and mechanical durability over thousands of cycles [108], [109]. Furthermore, issues such as material degradation, thermal cycling fatigue, and mechanical wear are noted as critical barriers to operational lifespan that require further investigation [110].

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Finally, techno-economic barriers remain substantial. The high capital expenditure and system complexity associated with indirect TES and advanced concepts like Carnot Batteries are significant hurdles. The text explicitly notes a common gap in the literature: a lack of techno-economic or scalability analysis for many proposed novel materials and systems. This indicates a challenge in transitioning from promising laboratory results to cost-effective, commercially viable solutions that can compete on a levelized cost of energy (LCOE) basis [111].

On the other hand, the future trajectory of thermal energy storage (TES) materials and technologies is characterized by a strategic shift towards enhanced performance, economic viability, and deeper system integration. The evolution of sensible heat storage will prioritize the development of low-cost, abundant solid media such as rocks, ceramics, and sand, often enhanced into composite materials to overcome inherent limitations like low thermal conductivity [10], [18], [26]. Concurrently, latent heat storage will focus on advanced phase change materials (PCMs), particularly through nano-enhancement and encapsulation techniques to rectify low conductivity issues and improve modularity [29], [33], [34], [38]. For higher energy densities and long-duration storage, research will intensify on thermochemical materials, with a critical focus on improving reaction kinetics and cyclability [41], [42], [43], [44].

A paramount trend is the move towards modular and scalable system architectures. This encompasses standardized units like packed beds and encapsulated PCM modules [48], [49], [50] , facilitated by innovations such as 3D-printed structures to optimize thermal performance [7], [52], [22], [112]. This design philosophy supports flexible deployment across applications and scales. Furthermore, TES will transcend its traditional role in concentrated solar power (CSP) to become a crucial enabler for Power-to-Heat-to-Power (P2H2P) systems, or Carnot Batteries, which convert excess electricity from variable renewables into storable heat, thereby providing critical grid-balancing services [49], [73, [75].

The application landscape for high-temperature TES is also expanding significantly. A major growth vector is the

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decarbonization of industrial process heat, where TES facilitates waste heat recovery and the integration of renewable thermal energy[19], [63], [83], [84], [113], [114], [115], [116]. While utility-scale renewable integration remains a core application, emerging uses in thermal management for high-power electronics and mobile energy storage represent nascent areas of experimental development [1].

Improving the fundamental performance metrics remains a constant and comprehensive focus that reinforces these trends in materials and technologies. This includes maximizing energy density and charge-discharge rates, demonstrating long-term durability over thousands of cycles, and ultimately achieving significant cost reduction to improve techno-economic viability and market adoption. The future TES landscape will thus be a diversified portfolio of solutions tailored to specific temperature requirements and application niches.

Conclusion

This piece of research presents a comprehensive review of the state-of-the-art in High-Temperature Thermal Energy Storage (HT-TES), addressing key advancements and persistent challenges across material innovations, system design and diverse applications. Significant progress has been made in advanced materials, including sensible heat storage media like molten salts (e.g., $NaNO_3/KNO_3$, foundational in CSP systems for their high thermal stability and prevalence), beds of rocks, sand, and ceramics, and enhanced concrete. Latent heat storage has seen improvements through the use of nano-enhanced and encapsulated Phase Change Materials (PCMs) to enhance thermal conductivity and stability. Furthermore, thermochemical heat storage, utilizing reversible gas-solid reactions (e.g., CaO/CO_2) and metal oxides, shows promise for high energy density and minimal heat loss over long durations.

In terms of system design, the review highlighted the operational features of direct and indirect systems and underscored the emergence of modular and scalable TES solutions, crucial for integrating variable renewable energy sources. Innovations such as

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additive manufacturing, nested cascaded architectures, and digital integration are enhancing efficiency and adaptability.

HT-TES technology is pivotal for enhancing the efficiency and reliability of Concentrated Solar Power (CSP) plants by extending dispatchability beyond daylight hours. Its application in wind and solar hybrid systems, often referred to as Carnot Batteries, offers a compelling pathway for storing surplus electricity and managing grid intermittency. Beyond grid-scale applications, HT-TES is crucial for improving energy efficiency and decarbonizing energy-intensive industrial processes, including waste heat recovery and chemical processing. Emerging applications in electronics thermal management and transportation also show potential.

Despite these advancements, critical challenges remain that hinder widespread adoption. These include material compatibility and degradation, particularly corrosion in molten salts and the inherent instability of some PCMs at elevated temperatures. Issues such as the low thermal conductivity of PCMs, the economic feasibility and long-term performance under extreme conditions, and the scalability of systems from pilot to full industrial scale need further investigation. Future research should focus on developing novel, durable, and cost-effective materials, optimizing system configurations through advanced thermal management, and establishing universal interface standards. Continued efforts in these areas are essential to overcome technical and economic barriers and accelerate the commercialization of high-performance HT-TES solutions.

In terms of technological maturity, sensible heat storage remains the most established option, offering high efficiency and cost-effectiveness despite relatively low energy density. Latent heat storage represents a mid-level solution, balancing efficiency and cost improvements with moderate density and lifespan limitations. Thermochemical storage, while still in early development, stands out for its superior energy density and high-temperature capabilities, though current limitations include low efficiency, high costs, and limited durability.

High Temperature Thermal Energy Storage:
A Comprehensive Review of Advanced Materials, System Design, and Applications

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Above all, by addressing these challenges and leveraging ongoing innovations, HT-TES can play a transformative role in balancing energy supply and demand, enhancing grid stability, and facilitating the global transition towards sustainable and decarbonized energy systems.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work, the authors used Chat-GPT and Gemini in order to paraphrase quotations and search for references. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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