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# Thermal Energy Storage for Flexible, Low-Carbon Energy Systems: Materials, Architectures, Design Metrics, and Deployment Pathways

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A R T I C L E I N F O

*Keywords:*

*Thermal energy storage; sensible heat; phase change materials; thermochemical storage; district cooling; concentrating solar power; underground thermal energy storage; heat exchangers; energy flexibility; techno-economic metrics*

A B S T R A C T

Thermal energy storage (TES) is a cornerstone technology for decarbonizing heating and cooling, increasing renewable penetration, and improving grid flexibility by shifting thermal demand in time. This review consolidates TES fundamentals and deployment practice across sensible, latent, and thermochemical pathways, emphasizing how material properties and system architectures translate into practical metrics such as energy density, power density, round-trip efficiency, cycling durability, and levelized cost. Sensible TES remains the most mature and widely deployed, ranging from chilled-water tanks and ice storage in buildings to packed-bed rock, concrete, and molten-salt systems for industrial heat and concentrating solar power. Latent TES (phase change materials, PCMs) enables quasi-isothermal operation and compactness but is constrained by low thermal conductivity, phase segregation, subcooling, and packaging complexity. Thermochemical TES offers the highest theoretical energy density and the possibility of long-duration storage with limited standing losses, yet faces challenges in reactor/contactor design, kinetics, cycling stability, and integration. The review proposes a consistent framework for material screening, component sizing, and system-level evaluation, and summarizes emerging enhancement strategies including encapsulation, finned heat exchangers, metal foams, graphite additives, and cascading temperature stages. Six illustrative figures and three design-oriented tables are provided to connect key concepts: technology classification, energy-density ranges, temperature signatures, PCM property trade-space, suitability scoring, and multi-criteria comparison.

## 1. Introduction

Thermal energy storage is the intentional capture of thermal energy—either as heat or cold—during periods when it is abundant or inexpensive, with subsequent release when it is needed to deliver a service such as space cooling, space heating, domestic hot water, industrial process heat, or power generation support. The relevance of TES is expanding rapidly because modern energy systems are increasingly shaped by variable renewable electricity, electrification of end-uses, constraints on generation and network capacity, and the need for resilience and peak shaving. Unlike electrical storage, TES can be extraordinarily cost-effective when the end-use is inherently thermal, because it stores the "right form" of energy and can use inexpensive media such as water, rock, concrete, or salts. TES also reduces curtailment of renewables and enables sector coupling by allowing electricity to be converted to heat or cold and stored with high efficiency in appropriate temperature bands. These system-level motivations, combined with advances in materials and heat exchanger design, have made TES a central enabling technology for flexible energy infrastructure. [1–3]

A first principle for TES is that thermal services have characteristic temperature levels and temporal profiles. Buildings demand cold in hot climates and heat in cold climates, both of which are daily-cycling loads that align well with diurnal storage. Industrial processes often require higher temperatures and may demand longer-duration, multi-shift, or seasonal storage. In concentrating solar power (CSP), TES is used to decouple solar collection from power block operation, enabling dispatchability that resembles conventional generation. For district heating and cooling, TES supports network stability, plant optimization, and demand shifting across hours to seasons. Because thermal loads span temperature regimes from below-freezing cold storage through low-temperature heating to high-temperature process heat, TES technologies naturally segment by operating temperature, allowable temperature glide, and integration constraints. This segmentation is essential for rational technology choice and for meaningful comparison across TES options. [1,4,9]

At the technology level, TES is commonly grouped into sensible heat storage (SHS), latent heat storage (LHS), and thermochemical storage (TCS). Sensible storage relies on raising or lowering the temperature of a medium, with stored energy proportional to mass, heat capacity, and temperature change. The advantages are simplicity, low cost, and long life, but the disadvantage is that the delivery temperature varies as the store charges and discharges. Latent storage relies on phase transition, typically solid–liquid melting/freezing, providing high effective heat capacity around a nearly constant phase change temperature. This quasi-isothermal behavior can reduce exergy losses and simplify process control, yet practical systems are often limited by heat transfer rates and material stability. Thermochemical storage stores energy in reversible chemical reactions or sorption processes, providing potentially high energy density and low standing losses, but demanding more complex reactors, robust kinetics, and stable cycling under realistic conditions. A complete view of TES thus spans a continuum of maturity, from ubiquitous chilled water tanks to emerging chemical looping and sorption-based systems. [1,4,5,11,13].

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**Nomenclature**

Abbreviation
TES — Thermal Energy Storage
SHS — Sensible Heat Storage;
LHS — Latent Heat Storage
TCS —Thermochemical Storage
PCM — Phase Change Material
CSP — Concentrating Solar Power
ATES —Aquifer Thermal Energy Storage
BTES—Borehole Thermal Energy Storage
HVAC —Heating, Ventilation, and Air Conditioning

*Symbol*
Q — stored/released thermal energy (J);
m — mass (kg);
*cp*—specific heat capacity (J/ kg/K)

Materials are the "engine" of TES, but they are not sufficient on their own. A TES system is a coupled problem of material thermodynamics, heat and mass transfer, containment, and integration into the host energy system. A phase change material with high latent heat may still perform poorly if it is packaged in a geometry that throttles conduction, or if volume changes and phase segregation degrade performance over cycles. Similarly, thermochemical pairs with attractive reaction enthalpies can fail in practice if kinetics are slow at required operating conditions, if side reactions occur, or if the reactor design introduces unacceptable pressure drop or parasitic power consumption. Therefore, TES design should begin with a service definition—temperature, power, capacity, charge/discharge time, and lifetime—followed by material and architecture screening using metrics that relate directly to delivered service. These metrics include volumetric and gravimetric energy density, thermal conductivity and effective heat transfer coefficient, permissible temperature lift, round-trip efficiency, cycle life, and safety. [1,2,6,12]

A core challenge in TES evaluation is that "energy stored" and "useful energy delivered" are not identical. For example, storing heat at high temperature may be energetically dense, yet the usefulness depends on the required delivery temperature and the thermal match between the store and the load. The second-law perspective highlights that temperature levels matter: a store that discharges with large temperature glide may deliver less useful energy if the downstream process requires near-constant temperature. Conversely, a PCM store that holds temperature nearly constant can deliver high-quality heat within a narrow band but may be impractical if heat transfer is too slow or if the PCM's melting range is too broad. Thus, exergy and pinch-based integration become essential when TES interfaces with power cycles, industrial heat recovery, or cascaded temperature networks. This review adopts an application-oriented lens, consistently translating material and component properties into system performance. [1,3,9,16]

The literature on TES is extensive, spanning building-scale cooling storage, district energy, CSP, industrial heat management, and seasonal underground storage. Foundational contributions have documented PCM behavior and system modeling, including phase change kinetics, subcooling, and long-term degradation. Reviews have established how enhancement techniques—fins, metal foams, graphite composites, nano-additives, and encapsulation—can improve effective heat transfer, but often at cost, manufacturability, or stability trade-offs. Meanwhile, high-temperature TES in CSP has matured around molten nitrate salts, while solid-media systems and thermochemical pathways continue to develop for higher temperature, higher density, and longer duration. Underground TES, including borehole and aquifer storage, offers seasonal shifting potential but requires careful geotechnical characterization and coupled hydro-thermal modeling. The field therefore demands synthesis that unifies these strands into design principles and decision frameworks. [2,4,5,8,13,14,18]

This paper contributes a structured, engineering-centered review that (i) organizes TES by service temperature and operational objective, (ii) provides a consistent set of metrics and equations for preliminary design, (iii) consolidates practical architectures used in buildings, districts, CSP, and industrial systems, and (iv) identifies cross-cutting gaps in performance characterization, durability modeling, and integration/control. Six illustrative figures are included to support conceptual clarity and technology comparison, and three tables are provided to translate literature insights into actionable screening and sizing steps. While the review emphasizes broad applicability, the approach is particularly useful for real-world engineering decisions where constraints such as footprint, parasitics, safety, supply chain, and maintenance govern technology choice as much as raw energy density. [1–20].

## 2. Methodology

This review follows an engineering synthesis methodology that integrates material-property screening, architecture mapping, and metric-based comparison. First, TES applications are categorized by service temperature band (cold storage below ~15°C, low-to-mid temperature heating ~15–120°C, and high temperature above ~120°C), because temperature level governs both feasible materials and system integration constraints. Second, within each band, TES options are classified into SHS, LHS, and TCS, and then further into realizable architectures such as tanks (stratified or mixed), packed beds, embedded heat exchangers, encapsulated PCM modules, and reactor-based chemical or sorption systems. Third, performance is compared using a consistent set of metrics: energy capacity, charge/discharge power, round-trip efficiency, response time, cycle life, and cost drivers. Fourth, common degradation and non-idealities are mapped to measurable indicators, enabling apples-to-apples interpretation of data across studies. Finally, the paper consolidates design equations used in early-stage sizing, recognizing that detailed design ultimately requires transient modeling and experimentally validated effective properties. [1–3,5,6,8,9,11,13,14,16,18]

Material screening begins by matching the required operating temperature and temperature glide to candidate media. For SHS, the selection emphasizes high heat capacity, low cost, chemical compatibility, low vapor pressure, and acceptable pumping/containment requirements. For LHS, the selection additionally requires an appropriate phase change temperature, narrow melting range, minimal subcooling, stable cycling without segregation, low volume-change stress, and manageable flammability/toxicity. For TCS, screening is dominated by reaction enthalpy, equilibrium temperature/pressure, kinetics, cycling stability, reactor pressure drop, and practical separability of products when applicable. In all cases, the "effective" properties at the component level—effective conductivity, effective heat transfer coefficient, and usable fraction of stored energy—are more decisive than ideal bulk values, so enhancement methods and packaging constraints must be considered from the start. [4,7,10,12,13,15,19,20]

**Table 1.** Application-led screening checklist for TES selection (design-oriented synthesis)

| Design input | Why it matters | SHS typical decision | LHS (PCM) typical decision |
|---|---|---|---|
| Service temperature & allowable glide | Determines exergy match and feasible media | Wide glide acceptable | Prefer narrow band near load temperature |

| | | | |
|---|---|---|---|
| Required duration (hours–months) | Governs standing losses & scale | Tanks/packed beds for hours–days | Modules for hours–days |
| Power requirement (kW–MW) | Heat exchanger sizing & parasitics | High power feasible with HX area | Limited by conductivity unless enhanced |

**Table 2.** pical property ranges used for preliminary TES comparisons (illustrative ranges compiled from literature)

| TES type | Typical temperature band | Key property range (illustrative) | Common constraints |
|---|---|---|---|
| Water SHS | 0–100°C | high (c_p), low cost | tank volume, stratification control |
| Rock/concrete SHS | 30–500°C | moderate (c_p), low cost | thermal stress, contact resistance |
| Molten salt SHS | 200–600°C | good stability in CSP band | freezing risk, corrosion control |

## 3. Results

Thermal energy storage technologies exhibit distinct performance signatures once they are translated from bulk material properties into system-level delivery metrics. A fundamental observation is that TES performance is shaped by the coupled triad of capacity, power, and losses. Capacity depends on energy density and total storage volume; power depends primarily on heat transfer area, effective thermal conductivity, and allowable driving temperature difference; and losses depend on insulation, standing time, and integration temperature mismatch. Consequently, two systems with similar theoretical energy density can differ greatly in delivered service. For example, PCMs can store substantial latent heat in compact volumes, but practical charge/discharge rates may be limited unless enhancement strategies are implemented, while sensible systems can deliver high power readily but at the cost of temperature glide. Thermochemical storage promises compactness and long duration, but its delivered power is governed by reaction kinetics and reactor mass/heat transfer rather than by the bulk thermodynamics alone. The results below consolidate these distinctions through an application-driven comparison across TES families. [1–6,8–14,16,18–20]

Figure 1 provides a technology map that organizes TES by fundamental mechanism and by common implementation routes. This map is useful because it makes explicit that "TES choice" is never only about material; it is equally about packaging (tanks vs modules vs packed beds vs reactors) and about the nature of the heat transfer interface (direct contact, embedded coils, plate-fin heat exchangers, encapsulated particles, or sorption contactors). In practice, architecture selection can dominate manufacturability, maintenance, and parasitic power. For example, a packed-bed rock system can be robust and low cost, but it introduces pressure drop and requires fan or blower work when used with air as the heat transfer fluid. A water tank can be extremely efficient but may require large volume and careful stratification control. Encapsulated PCM designs can be modular and scalable but may face long-term leakage or shell fatigue under cycling. Thermochemical systems can minimize standing losses but demand valves, seals, and thermal management to maintain reaction conditions. The classification diagram therefore functions as a design decision entry point. [1–3,5,9,11,13,18]

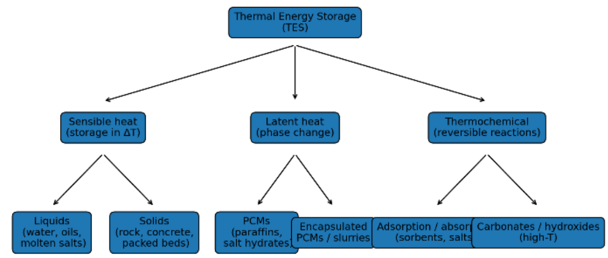


**Fig. 1**. Classification of TES technologies and representative implementation routes.

Capacity comparisons are often made using volumetric energy density, but meaningful ranges must specify temperature lift for sensible systems and the usable latent fraction for PCMs. Figure 2 shows illustrative volumetric energy-density ranges, highlighting that sensible storage spans a broad range depending on $\Delta T$ and medium, that PCMs often sit in a mid-to-high band due to latent contribution, and that thermochemical storage can offer substantially higher theoretical density when reactions can be fully utilized. However, the practical advantage of thermochemical pathways is frequently reduced by incomplete conversion, additional inert mass in reactors, and heat transfer limitations. Similarly, PCM energy density is frequently reduced at the module level because encapsulation adds non-storage mass and volume, and because a fraction of the PCM may not fully melt/solidify under operational temperature differences. On the other hand, sensible systems may realize a large fraction of theoretical capacity because their design is simpler and easier to fully utilize, particularly in well-mixed tanks or in properly designed stratified tanks with controlled inlet diffusers. For building-scale storage, chilled-water tanks and ice storage remain dominant because the required temperature levels are well matched to refrigeration systems and the architectures are mature. For CSP and industrial heat, molten salt and solid-media sensible storage remain leading options due to stability and scalability, while thermochemical systems are actively researched for higher temperature and longer duration. [1,2,4,5,8,9,11,13,16,18].

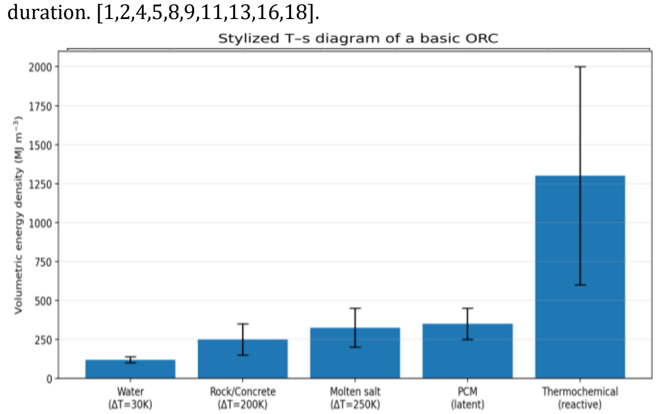


**Fig. 2**. Illustrative volumetric energy-density ranges across TES options (representative ranges synthesized from literature).

The temperature-time signature during charging and discharging is a critical operational result because it governs integration losses, heat exchanger sizing, and controllability. Figure 3 contrasts typical sensible and PCM behavior. Sensible storage generally shows monotonic temperature rise during charge and monotonic fall during discharge, with the delivery temperature varying as state of charge changes. This temperature glide can be acceptable when the downstream process tolerates variable inlet temperature (for example, preheating or precooling), but it can be detrimental when the process requires a narrow temperature band. PCM storage, by contrast, exhibits a plateau near the melting temperature during both charge and discharge, reflecting the dominance of latent heat. This quasi-isothermal behavior can improve the temperature match and reduce exergy destruction, especially when the load is itself near-isothermal (as in some HVAC heat exchanger processes). Yet, the plateau also reveals a challenge: if heat transfer is limited, the PCM can develop internal temperature gradients and partial melting, producing an apparent plateau at the interface while substantial PCM mass remains unmelted. Enhancement methods such as fins, metal foams, high-conductivity additives, and reduced characteristic length scales are thus directly tied to achieving usable power. From a system standpoint, sensible systems tend to excel in power density, while PCM systems excel in temperature stability and compactness when enhanced properly. [1,3–7,10,12,15,16,19].

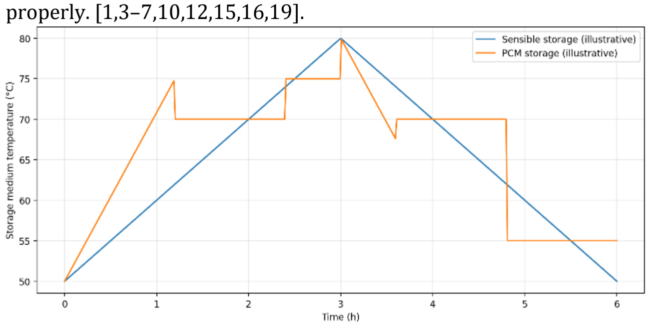


**Fig. 3**. Typical charging/discharging temperature signature comparing sensible storage and PCM storage (illustrative).

For latent TES, the material-property trade-space is central because not all PCMs provide the same balance of latent heat, conductivity, stability, and safety. Figure 4 visualizes an illustrative scatter of thermal conductivity versus latent heat for three common PCM families: paraffins, fatty acids, and salt hydrates. While organic PCMs (paraffins and fatty acids) tend to offer favorable cycling stability and chemical compatibility in many low-temperature applications, they often suffer from low thermal conductivity, which limits charging/discharging rate unless thermal pathways are engineered. Salt hydrates can offer higher conductivity and high latent heat, but they commonly face challenges such as phase segregation, incongruent melting, and subcooling, which can reduce effective capacity over repeated cycles. These limitations are not universal—careful formulation, additives, and encapsulation can mitigate them—but they demonstrate why PCM selection cannot be made purely on latent heat value. A robust selection must incorporate melting range, hysteresis, cycling tests, corrosion compatibility with container materials, and safety considerations. In addition, module-level performance often depends more on heat exchanger geometry than on the marginal difference in latent heat between two candidate PCMs. [4–7,10,11,12,15,19,20].

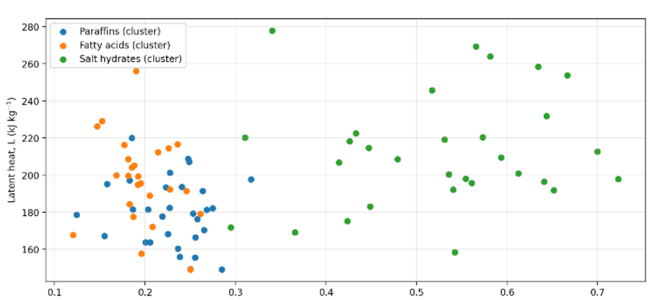


**Fig. 4**. Illustrative property space for common PCM families (clustered representation).

When TES is viewed across applications, suitability is multi-dimensional and cannot be captured by a single metric. Figure 5 provides an illustrative normalized scoring across temperature bands and system-level considerations such as capital intensity and round-trip efficiency. Cold storage is dominated by chilled-water and ice systems, with ice providing high effective energy density for cooling but requiring careful refrigeration integration and potentially higher compressor lift. For low-to-mid temperature heat, water tanks, packed beds, and PCM modules can all be viable depending on footprint, required power, and temperature stability. For high-temperature TES, molten salts have demonstrated commercial maturity in CSP, but freezing risk and corrosion control are key design constraints. Solid-media systems (rocks, concrete, ceramics) offer potential for higher temperature capability and lower cost, but require careful management of thermal stresses and contact resistances. Thermochemical systems show promise for long-duration and high density, but their current suitability is constrained by system complexity and the need for reliable, scalable reactors with stable cycling. A key result is that maturity often correlates with simplicity and supply chain readiness, while the highest theoretical performance often correlates with increased component complexity. [1–3,8,9,11,13,14,16,18].

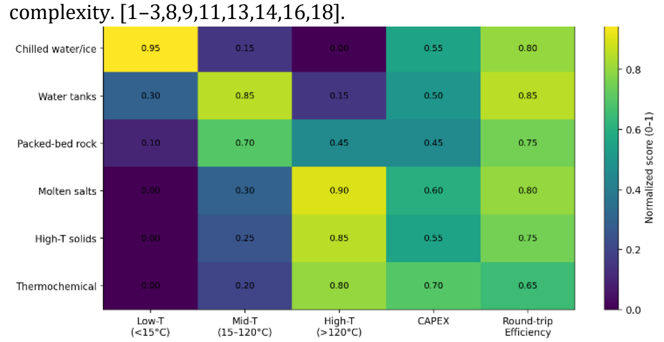


**Fig. 5**. Illustrative TES option suitability and performance scoring across temperature bands and system criteria.

Finally, decision-making in TES frequently requires balancing competing priorities, including cost, safety, maturity, and performance under realistic duty cycles. Figure 6 shows an illustrative radar comparison across multiple criteria, capturing the typical narrative that sensible TES is mature, low cost, and robust; latent TES improves temperature stability and compactness but requires enhanced heat transfer and careful durability design; and thermochemical TES can offer high energy density and long duration but remains less mature at large scale due to reactor and material stability challenges. Although the specific scoring will vary by application, the radar format is useful because it forces explicit weighting of criteria rather than implicit preference based on a single number. For example, in district cooling, safety, maturity, and efficiency may dominate, leading to chilled-water tanks or ice storage. In CSP, high-temperature compatibility and dispatchability dominate, supporting molten-salt sensible storage today while motivating research into higher-temperature solids and thermochemical options. In industrial decarbonization, integration constraints, temperature levels, and availability of waste heat can strongly shift the optimal TES choice. [1–3,8,9,11,13,16,18].

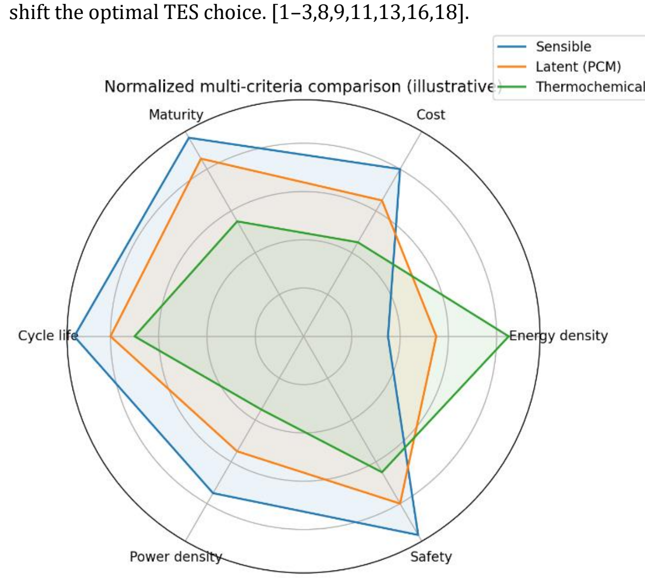


**Fig. 6**. Normalized multi-criteria comparison of TES families (illustrative).

Across these results, several cross-cutting quantitative insights emerge. The first is that effective heat transfer is a universal bottleneck for compact TES and is often the limiting factor in PCM and thermochemical systems. The second is that the best "technology" depends on the service definition; in many cases, an inexpensive, lower-density store outperforms a high-density store if it integrates better and delivers usable power and temperature at lower parasitics. The third is that module- and system-level non-idealities—encapsulation fraction, heat exchanger dead volume, stratification mixing, pressure drop, and degradation—must be included early in performance projections, otherwise designs can be systematically over-optimistic. The fourth is that standardized reporting of cycling conditions, thermal losses, and usable capacity is essential for comparing options across studies. These insights, while broadly known, are often underapplied in early-stage design; consolidating them into a consistent framework can significantly reduce technology risk and accelerate deployment. [1–20].

## 4. Discussion

The synthesized results highlight that TES should be treated as an integration technology rather than a standalone component. A recurring reason for performance shortfalls in practice is that material selection is performed without simultaneously constraining architecture, heat exchanger geometry, and control strategy. For sensible systems, the dominant practical issue is often not the storage medium but the management of stratification and losses. Stratified tanks can achieve high exergy efficiency when thermal layers are preserved, but real installations can degrade due to inlet jet mixing, improper diffuser design, or operational control that repeatedly disrupts stratification. Similarly, packed-bed systems can offer low-cost scalability, but the choice of heat transfer fluid (air, oil, steam) and the allowable pressure drop strongly influence parasitics and hence round-trip efficiency. For molten salt systems in CSP, freezing avoidance becomes a primary operational constraint that shapes pipe heat tracing, start-up procedures, and minimum temperature control, often affecting both CAPEX and OPEX. These integration details can dominate the levelized cost of stored energy more than small differences in bulk material heat capacity. [1–3,8,9,16,18]

For latent TES, the discussion pivots around a central tension: PCMs are attractive because they store and deliver at nearly constant temperature, yet the same phase change that provides this advantage introduces heat transfer challenges and complex multiphase behavior. Low conductivity leads to long charge/discharge times unless the characteristic length scale is reduced or high-conductivity pathways are introduced. However, aggressive enhancement (dense fins, metal foam) increases cost, adds mass that does not store energy, and can reduce the apparent energy density at the module level. Moreover, long-term cycling introduces failure modes such as container fatigue, leakage, chemical incompatibility, and property drift, which can reduce usable latent heat. Salt hydrates in particular can suffer from phase segregation and subcooling; addressing these typically requires nucleating agents, thickening additives, or microencapsulation, each of which may introduce new durability questions. Therefore, successful PCM deployment is rarely about identifying a “best PCM” in the abstract; it is about optimizing a PCM–container–heat exchanger ensemble for a defined duty cycle and cost target. [4–7,10,12,15,19,20]

Thermochemical TES offers a different value proposition: higher theoretical energy density and potentially low standing losses, enabling longer duration storage. Yet the gap between theory and deployment is often widest here, because reaction systems require stable kinetics and robust reactor designs. Reversible reactions and sorption processes can become diffusion-limited, heat-transfer-limited, or limited by side reactions and sintering over cycling, particularly at high temperature. Additionally, reactor designs must manage pressure drop, maintain uniform temperature, and control reactant distribution; otherwise, partial conversion reduces effective storage capacity and introduces hot spots that accelerate degradation. From a systems viewpoint, thermochemical storage can be compelling when long duration is valuable, when transportability of the stored “chemical potential” is beneficial, or when heat must be stored with minimal loss over time. Even in such cases, integration complexity and material stability remain decisive barriers, and near-term progress will likely be driven by engineering advances in reactor/contactor designs, standardized cycling protocols, and scale-up demonstrations that quantify performance retention over thousands of cycles. [11,13,16,18,19]

A unifying theme across SHS, LHS, and TCS is that performance should be evaluated using delivered service metrics. Round-trip efficiency must include not only thermal losses but also parasitic electricity for pumps, fans, valves, and controls. Capacity should be reported as usable delivered energy within the required temperature band, not merely theoretical stored energy. Power capability must account for degradation over state of charge and over cycles, especially for PCMs where melting fraction and heat transfer coefficients evolve during operation. Cost comparison requires consistent boundary conditions, including containment, insulation, heat exchangers, installation, and maintenance. Without such consistent accounting, technology comparisons can be misleading and can bias decisions toward options with optimistic laboratory-level numbers that do not survive module- and system-level realities. [1–3,6,8,9,16,18]

From a deployment perspective, the discussion suggests a pragmatic pathway. For cold and low-temperature building applications, sensible storage (water tanks) and ice storage will remain workhorses because they are proven, reliable, and supported by mature supply chains, while PCM solutions will expand in niche cases where footprint or temperature stability provides clear value. In district energy, large sensible storage and, where appropriate, underground seasonal storage can provide significant flexibility if planning and subsurface characterization are done carefully. For CSP and high-temperature heat, molten salt sensible storage remains dominant in current commercial practice, but higher-temperature solid media and emerging thermochemical approaches represent the likely next steps to push efficiency and reduce cost for long-duration dispatchability. For industrial decarbonization, the most impactful opportunities may come from integrating TES with waste heat recovery and electrified heating, where TES can reduce peak electrical demand and enable smaller, cheaper upstream equipment. Across all these applications, improvements in standardized testing, modular manufacturing, durability characterization, and controls that preserve performance over time will likely yield larger real-world gains than marginal improvements in intrinsic material properties alone. [1–20].

## 5. Conclusion

Thermal energy storage is a mature-and-evolving technology family that enables flexible, efficient, and lower-carbon energy systems by shifting thermal services in time. Sensible TES offers the strongest combination of maturity, cost-effectiveness, and durability, and will continue to dominate many near-term deployments in buildings, district energy, and high-temperature applications such as CSP via molten salts and solid media. Latent TES offers quasi-isothermal operation and compactness, but its system performance is frequently limited by heat transfer and long-term stability, making integrated design of PCM, packaging, and heat exchanger essential. Thermochemical TES provides high theoretical energy density and low standing losses, offering a pathway to long-duration storage, but requires breakthroughs in reactor design, kinetics management, and cycling stability to achieve scalable deployment. A consistent application-led framework—starting from service temperature, power, duration, and integration constraints—remains the most reliable route to selecting and designing TES. The most actionable near-term priorities are standardized performance reporting, robust degradation models linked to measurable indicators, manufacturable enhancement strategies, and integration-ready control schemes that preserve efficiency and capacity over lifetime. [1–20].

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