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Review article

Thermochemical Energy Storage for Renewable Grids: A Critical Review of Materials, Reactor Architectures, and Integration Strategies

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A B S T R A C T

Thermochemical energy storage (TCES) has gained increasing attention as a practical pathway for achieving reliable, long-duration energy storage in systems dominated by intermittent renewable generation. Unlike conventional thermal storage, TCES relies on reversible redox and sorption reactions to store energy within chemical bonds, allowing for high energy density and negligible standing losses over extended periods. This review examines recent progress across the four principal components that shape TCES performance: thermochemical materials, reactor architectures, system-level integration, and modelling approaches. Current material candidates, including metal oxides, salt hydrates, and selected organic compounds, are evaluated in terms of reaction enthalpy, cycling stability, and techno-economic viability. Reactor concepts such as fixed-bed, fluidised-bed, and modular tubular designs are compared with respect to heat transfer characteristics, scalability, and suitability for applications ranging from concentrated solar power to industrial waste heat recovery and building-level thermal management. Key performance indicators, including gravimetric energy density, round-trip efficiency, and reaction kinetics, are reviewed alongside advances in thermodynamic, kinetic, and system-scale simulations. A distinguishing feature of this review is its integrated perspective, linking material-scale thermochemistry with reactor engineering and system-level operation to assess the practical scalability of TCES. The analysis highlights persistent barriers to deployment, particularly material degradation, limited heat and mass transfer, and the lack of standardised lifecycle assessment frameworks. Overall, while TCES presents a technically robust and versatile approach to grid-scale thermal storage, its widespread adoption will depend on coordinated advances in material development, reactor optimisation, intelligent control strategies, and pilot-scale validation across real operating environments.

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1. INTRODUCTION

The accelerating global shift toward decarbonised energy systems has intensified the deployment of renewable technologies, particularly wind and solar power. Although essential for achieving climate neutrality,

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their inherent intermittency creates persistent challenges for grid stability, operational flexibility, and long-term system reliability. Without effective long-duration energy storage (LDES), high-renewable power systems face increased curtailment, widening gaps between supply and demand, and reduced economic efficiency. Recent modelling studies for net-zero energy scenarios in the United Kingdom, for instance, demonstrate that insufficient storage capacity can significantly compromise both resilience and affordability (Cosgrove et al., 2023).

Thermal energy storage (TES) has long been explored as a practical means of mitigating these temporal mismatches. Sensible and latent heat storage systems have reached varying levels of technological maturity, with sensible heat, such as molten salt tanks, already in use within concentrating solar power (CSP) facilities. Latent heat systems employing phase change materials (PCMs) offer higher energy density and quasi-isothermal operation. Yet both approaches face intrinsic limitations. Sensible systems experience substantial long-duration heat losses, and PCMs often suffer from supercooling, phase segregation, and inherently low thermal conductivity, all of which hinder large-scale deployment and operational predictability (Wei et al., 2018; Yang et al., 2021).

Against this backdrop, thermochemical energy storage (TCES) has emerged as a next-generation alternative capable of addressing many of these constraints. By storing energy through reversible redox or sorption reactions rather than direct heat retention, TCES systems achieve minimal standing losses and substantially higher energy densities (Abdullah et al., 2024; Jarimi et al., 2019). Their ability to decouple storage capacity from insulation also makes them particularly attractive for long-duration and seasonal applications, including remote or infrastructure-limited environments (Han et al., 2022). Research into solid–gas TCES has expanded rapidly, with high-temperature redox materials such as cobalt, manganese, and copper oxides showing strong cyclic stability and energy capacities suitable for industrial heat applications. In parallel, lower-temperature materials such as magnesium chloride and lithium bromide have demonstrated promise for residential and building-scale uses due to their high gravimetric energy density and operational flexibility (Spietz et al., 2025). Despite this progress, several persistent challenges hinder commercialisation, including material degradation, slow reaction kinetics, and inefficient heat and mass transfer, particularly in fixed-bed configurations. High capital costs associated with advanced materials and reactor infrastructure further limit large-scale adoption. These barriers highlight a continuing disconnect between laboratory performance and integrated, field-tested system operation.

The present review synthesises recent developments across four core dimensions of TCES research: advances in thermochemical materials, reactor architectures and heat-transfer optimisation, system integration strategies, and performance modelling methodologies. In doing so, it identifies the principal technical and economic challenges that remain and outlines priority research directions needed to accelerate the transition from laboratory-scale innovation to commercially viable, decarbonised energy storage solutions. Unlike earlier reviews that have typically examined materials or reactor concepts in isolation, this study provides a cross-sectional perspective that links material behaviour with reactor design and system-level performance. The analysis draws on peer-reviewed literature indexed in Web of Science and Scopus from 2013 to 2025, prioritising studies with experimental validation or full-scale modelling to ensure robustness and relevance.

2. FUNDAMENTALS OF THERMOCHEMICAL ENERGY STORAGE

Thermochemical energy storage (TCES) systems operate by storing thermal energy in the form of enthalpy through reversible chemical reactions, typically involving dehydration, sorption, or redox processes. In contrast to sensible and latent heat storage, where energy is stored as temperature rise or phase change, TCES stores energy chemically, enabling long-duration storage without significant thermal losses (Padamurthy et al., 2025; Gbenou et al., 2021).

The operation of thermochemical energy storage (TCES) systems relies on reversible chemical reactions that absorb and release heat during charging and discharging phases, respectively. These reactions can be broadly represented by:

$$A + Heat \rightleftharpoons B + C \quad (1)$$

For example, in a typical salt hydration system, the reversible reaction may be written as:

$$Salt \cdot xH_2O \rightleftharpoons Salt + xH_2O\,(g) \quad (2)$$

During the charging phase, an endothermic reaction stores energy by breaking chemical bonds. Upon discharge, the reverse reaction is exothermic and releases stored heat. The total amount of energy stored can be expressed by:

$$Q = n \times \Delta H \qquad (3)$$

where Q is the stored energy (J), n is the number of moles of reactive substance, and ΔH is the enthalpy change of the reaction (Padamurthy et al., 2025).

The thermodynamic spontaneity of the discharge process is governed by the Gibbs free energy equation:

$$\Delta G = \Delta H - T\Delta S \qquad (4)$$

A negative value of ΔG indicates that the reaction proceeds spontaneously under a given temperature T, with ΔS representing the entropy change of the system (Gbenou et al., 2021).

The equilibrium behaviour of the reaction as a function of temperature can be analysed using the Van't Hoff equation:

$$ln(K) = (-\Delta H / RT) + (\Delta S / R) \qquad (5)$$

Here, K is the equilibrium constant, R is the universal gas constant (8.314 J/mol·K), and T is the absolute temperature. This equation allows prediction of the extent of reaction under varying thermal conditions and is crucial for the design of both open and closed-loop TCES systems (Padamurthy *et al.*, 2025).

In addition to reaction direction and equilibrium, energy density is a key performance metric. It is often described as:

$$\rho = Q / V = (n \times \Delta H) / V \qquad (6)$$

where ρ is the volumetric energy density (J/m^3), and V is the volume of the storage medium (Arévalo et al., 2024). High energy density is a primary advantage of TCES compared to sensible and latent heat storage systems, enabling compact and long-duration energy storage configurations.

These fundamental thermodynamic relations provide the analytical basis for assessing and optimising TCES materials and systems.

2.1 SYSTEM CLASSIFICATIONS: OPEN AND CLOSED CONFIGURATIONS

TCES systems are commonly categorised as either open- or closed-loop configurations, each offering distinct advantages and operational constraints. In open-loop systems, volatile reactants such as water vapour or ammonia are exchanged directly with the surrounding environment. This approach simplifies system architecture and reduces the need for extensive containment infrastructure. However, the reliance on ambient conditions makes system performance more vulnerable to fluctuations in humidity, temperature, and atmospheric pressure. Closed-loop configurations, by contrast, retain all reactants and products within a sealed system. This containment enables tighter control over reaction conditions, improved conversion efficiency, and more consistent material utilisation. The trade-off, however, is increased system complexity, particularly in managing pressure, sealing integrity, and long-term stability of reactive gases (Padamurthy et al., 2025; Gbenou et al., 2021). Although both architectures remain viable depending on the application context, closed-loop systems are generally favoured for high-temperature or high-efficiency applications where operational stability is paramount.

2.2 REACTOR DESIGNS AND SYSTEM INTEGRATION

The reactor serves as the functional core of any TCES system, providing the environment for reversible thermochemical reactions and mediating heat transfer between the storage medium and the external energy source. Various reactor configurations have been developed, each with characteristic strengths and limitations. Fixed-bed reactors are often selected for their structural simplicity and ease of fabrication, though they tend to suffer from restricted heat and mass transfer, leading to non-uniform temperature profiles and slower reaction rates. Fluidised-bed reactors address many of these shortcomings by suspending reactive particles in a flowing medium, thereby enhancing mixing, improving thermal homogeneity, and enabling faster charging and discharging cycles. Moving-bed reactors offer yet another alternative, permitting continuous particle flow and stable throughput, which can be advantageous for large-scale or industrial processes requiring steady operation (Padamurthy et al., 2025).

Designing effective TCES reactors requires careful optimisation of heat-transfer pathways, particle residence time, thermal conductivity, and the integration of internal or external heat exchangers. Although numerous simulation studies demonstrate promising thermal and kinetic performance across these reactor types, real-world implementation remains limited. Challenges such as maintaining material stability under cyclic operation, preventing degradation, and effectively controlling reaction kinetics have hindered large-scale deployment. As Gbenou et al. (2021) note, translating reactor concepts from numerical models to field-ready technologies will require not only improved material resilience but also advanced control strategies capable of managing fluctuating thermal and operational conditions.

2.3 COMPARISON TO SENSIBLE AND LATENT HEAT STORAGE

Unlike sensible heat storage, which suffers from thermal losses over time and requires large volume for low-density materials, TCES enables energy storage over weeks or months without insulation loss, as no actual temperature change is retained during the storage period. Latent heat systems, while denser than sensible heat systems, are constrained by subcooling and material degradation (Arévalo et al., 2024; Eppinger et al., 2020). TCES offers greater flexibility in decoupling charging and discharging in both time and location, making it suitable for seasonal storage and integration with variable renewable energy sources (Padamurthy et al., 2025).

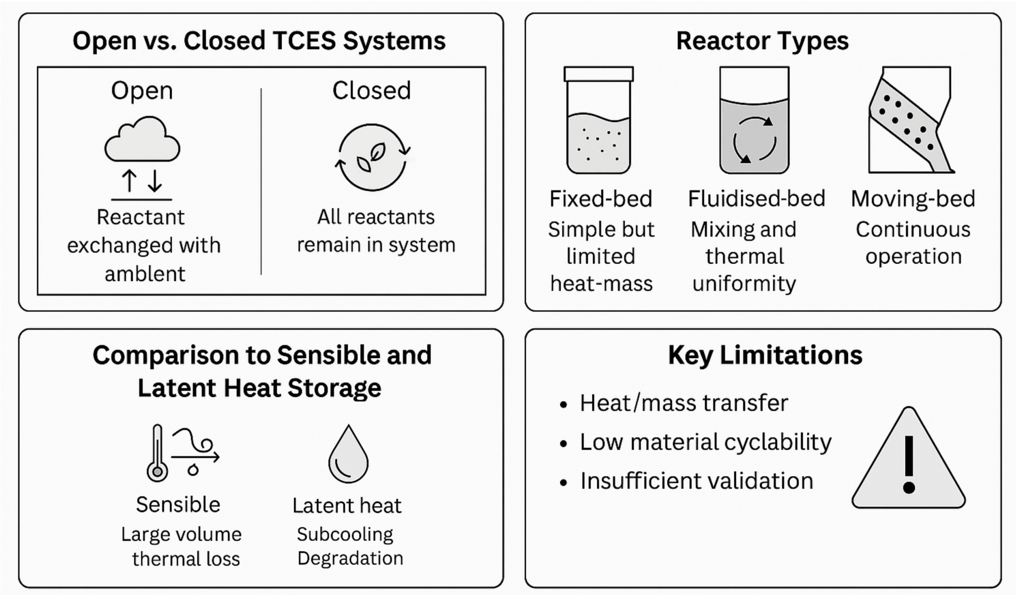

Figure 1. System concepts and operational principles.

2.4 KEY LIMITATIONS AND RESEARCH GAPS

Despite its promise, TCES remains largely pre-commercial. Limitations include poor heat and mass transfer, low material cyclability, and insufficient experimental validation of many concepts. Gbenou et al. (2021) note that many proposed systems remain conceptual or poorly validated, with simulations often disconnected from experimental reality. Similarly, Padamurthy et al. (2025) emphasise that continued material innovation, improved reactor designs, and long-term testing under real conditions are essential for technological maturity. Figure 2 provides a conceptual flow diagram of a typical TCES system, outlining the energy pathway from thermal input (e.g., solar or industrial waste heat) through chemical conversion and storage, to eventual recovery and application in heating or power generation.

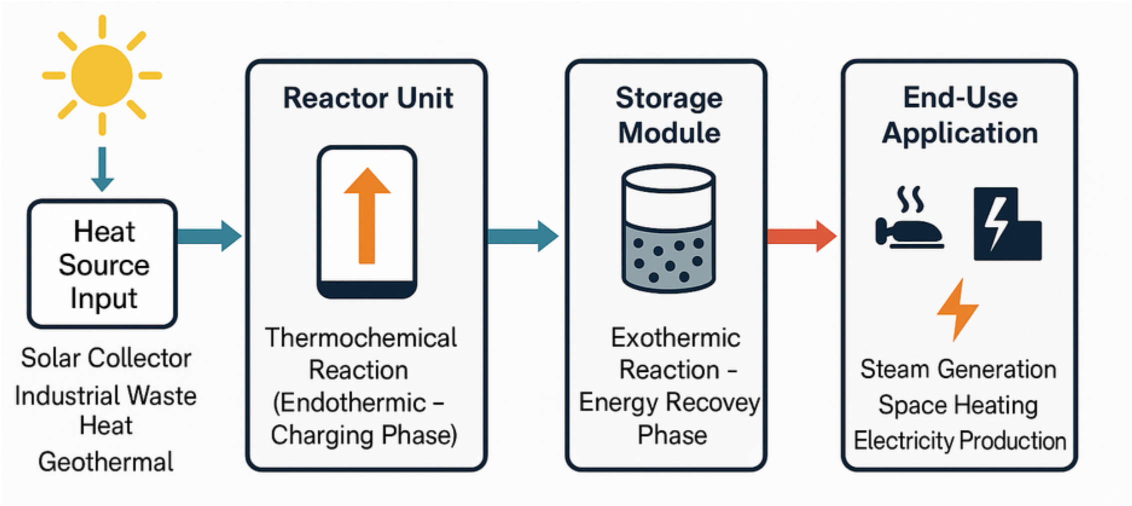

Figure 2. Conceptual flow diagram of a typical TCES system, illustrating key components including heat input source, reactor unit, energy storage module, and end-use application.

3. MATERIALS FOR THERMOCHEMICAL ENERGY STORAGE

The performance, reliability, and scalability of TCES systems depend fundamentally on the properties and behaviour of the materials employed. Beyond their intrinsic thermodynamics, these materials determine the operating temperature window, achievable energy density, cost-effectiveness, and long-term cycling stability of the storage process. Their suitability also varies widely across application domains, from residential heating and building-scale thermal management to high-temperature industrial processes and concentrated solar power (CSP) plants. This section reviews three major classes of TCES materials, metal oxides, salt hydrates, and selected organic compounds, highlighting their operational characteristics, benefits, and prevailing limitations that influence system-level performance (Carrillo et al., 2019).

3.1 METAL AND MIXED METAL OXIDES

Metal oxides represent some of the most promising candidates for high-temperature TCES applications, particularly in CSP systems where operating temperatures commonly exceed several hundred degrees Celsius. These materials store and release thermal energy through reversible redox reactions, often exhibiting high reaction enthalpies and strong thermal stability. Well-studied examples such as cobalt oxide (Co_3O_4), cerium oxide (CeO_2), and manganese oxide (Mn_2O_3), along with various perovskite-derived structures, have demonstrated favourable energy densities and reliable performance across multiple charge–discharge cycles.

Despite these advantages, metal oxides face several well-documented challenges that constrain their long-term practicality (Dizaji and Hosseini, 2018; Liu et al., 2018). High-temperature cycling can cause sintering, particle agglomeration, and structural degradation, all of which progressively reduce surface area and diminish reaction rates. These degradation mechanisms not only weaken the intrinsic reactivity of the material but also impose limitations at the reactor level. For instance, reduced porosity or uneven reaction fronts can disrupt heat and mass transfer within fixed-bed reactors, leading to local temperature gradients, slower conversion kinetics, and increased mechanical stress during repeated cycling. As a result, material instability directly affects both the efficiency and operational lifespan of TCES systems.

To mitigate these issues, recent research has shifted toward mixed metal oxides, which offer tunable redox behaviour through controlled elemental substitution. Adjusting the metal composition allows researchers to optimise reaction enthalpy, modify activation energies, and tailor operating temperatures to specific system requirements (Dizaji and Hosseini, 2018). However, identifying suitable multi-component oxides remains a complex undertaking. Promising candidates often perform well in laboratory tests but exhibit lower stability or unexpected deactivation pathways under realistic thermal cycling, fluctuating gas environments, or large-scale reactor conditions. Consequently, rigorous experimental validation at pilot and demonstration scales is essential for evaluating cyclability, cost implications, and compatibility with reactor architectures before these materials can be fully integrated into practical TCES applications.

3.2 SALT HYDRATES

Salt hydrates constitute one of the most promising classes of TCES materials for low- to mid-temperature applications, owing to their reliance on reversible hydration–dehydration reactions and their comparatively high theoretical energy densities. Common candidates such as magnesium chloride ($MgCl_2·6H_2O$), lithium bromide ($LiBr·H_2O$), sodium carbonate decahydrate ($Na_2CO_3·10H_2O$), and calcium chloride ($CaCl_2·6H_2O$) are widely available, relatively low-cost, and suitable for integration into industrial waste-heat recovery systems and building-scale thermal storage units. Their favourable operating temperature windows enable deployment in a wide range of heating and cooling scenarios (Spietz et al., 2025; Ghafurian et al., 2024).

Despite these advantages, the practical performance of salt hydrates is often constrained by a series of material-related challenges. Their hygroscopic nature makes them highly susceptible to moisture uptake from ambient air, which can trigger premature hydration, cause corrosion of containment structures, and complicate long-term storage. Additionally, many hydrates suffer from low intrinsic thermal conductivity and incomplete dehydration during charge cycles, both of which reduce reaction completeness and lead to gradual performance degradation over extended cycling. To mitigate these issues, current research is examining structural stabilisers, hydrophobic coatings, and thermally conductive additives to improve heat transfer and suppress unwanted side reactions. Ghafurian et al. (2024) report that materials such as LiOH, $MgCl_2$, and Na_2CO_3 exhibit comparatively strong cycling behaviour, low toxicity, and favourable cost-performance characteristics, reinforcing their potential for scalable TCES deployment.

3.3 ORGANIC PHASE CHANGE MATERIALS

Although organic PCMs are traditionally used in latent heat storage applications, select compounds have shown potential for thermochemical or quasi-thermochemical operation, particularly in solar-assisted cooling systems. Among the most studied candidates, d-mannitol and hydroquinone offer relatively high energy densities and strong thermal stability, making them attractive for higher-temperature regimes. Pilot-scale experiments by Gil et al. (2013) demonstrated successful integration of these materials with thermal-oil heat transfer loops, with d-mannitol showing particularly consistent cycling performance.

Nevertheless, several limitations restrict the broader use of organic PCMs in TCES. Subcooling, polymorphic transitions, and partial melting behaviour are commonly reported, introducing uncertainty into the charge–discharge process and affecting predictability of stored energy (Gil et al., 2013). While such effects did not cause severe degradation over short-term cycling, they highlight the need for more precise thermal characterisation and careful system design to manage phase transitions. These constraints suggest that organic PCMs may play a supporting rather than central role in future TCES configurations, unless further material engineering efforts address their transition irregularities and enhance compatibility with reactor environments involving high or rapidly fluctuating temperatures (Gil et al., 2013).

3.4 SUMMARY AND COMPARISON

Thermochemical energy storage encompasses a diverse set of materials, each with distinct advantages and limitations related to operating temperature, reaction enthalpy, cost, and long-term durability. Table 1 summarises representative compounds from the three major material categories discussed.

Table 1. Comparative assessment of key TCES material classes.

Material Class	Representative Compounds	Reaction Enthalpy ΔH (kJ/mol)	Operating Temperature (°C)	Stability / Cyclability	Relative Cost	Key References
Metal Oxides	Co_3O_4, CeO_2, Mn_2O_3	200–350	600–1000	Moderate to High	High	Han et al. (2022); Dizaji & Hosseini (2018); Carrillo et al. (2019)

Material Class	Representative Compounds	Reaction Enthalpy ΔH (kJ/mol)	Operating Temperature (°C)	Stability / Cyclability	Relative Cost	Key References
Salt Hydrates	$MgCl_2·6H_2O$, $LiBr·H_2O$, $Na_2CO_3·10H_2O$	50–150	30–150	Low to Moderate	Low	Ghafurian et al. (2024); Spietz et al. (2025)
Organic PCMs	d-Mannitol, Hydroquinone	200–280	160–180	Moderate	Medium	Gil et al. (2013); Arévalo et al. (2024)

A comparison of these material classes shows that none of them independently satisfies all performance requirements for scalable TCES deployment. Metal oxides offer the highest reaction enthalpies and strong thermal resilience, making them ideal for high-temperature applications such as CSP. However, their high cost and susceptibility to sintering and structural degradation under long-term cycling present notable barriers to commercialisation. Salt hydrates provide a more economical and lower-temperature alternative, but issues such as deliquescence, corrosion, and incomplete dehydration undermine their long-term reliability. Organic PCMs occupy an intermediate position: they offer moderate operational temperatures and respectable energy densities, yet their tendency toward subcooling, polymorphic transitions, and phase instability limits their applicability in conventional TCES reactors.

Across all categories, the trade-off between energy density, durability, cost, and operational complexity suggests that no single material class can deliver the full suite of characteristics required for widespread adoption. As a result, research is increasingly directed toward composite materials and hybrid formulations that combine the thermal robustness of metal oxides with the affordability and adaptability of salt hydrates and organic PCMs. Future progress will depend heavily on improving reaction kinetics under realistic cycling conditions, understanding long-term degradation pathways, and integrating these materials within scalable reactor architectures. Bridging the gap between laboratory demonstrations and full-scale system performance remains essential for transforming TCES from a promising concept into a commercially viable energy storage technology.

4. REACTOR DESIGNS AND ARCHITECTURES FOR TCES SYSTEMS

The design and configuration of reactors are central to the efficiency, scalability, and reliability of TCES systems. Beyond facilitating the core chemical reactions, reactor architecture directly influences thermal performance, operational stability, and integration potential with renewable energy sources such as concentrated solar power (CSP), industrial heat recovery, and solar-assisted cooling. Recent research efforts have aimed to optimise heat transfer dynamics, introduce modularity, and enhance system responsiveness, while simultaneously addressing persistent challenges including thermal losses, pressure fluctuations, and material degradation under cyclical operation.

4.1 FIXED-BED VS. FLUIDISED-BED REACTORS

Fixed-bed and fluidised-bed reactors represent two of the most widely studied configurations for TCES systems, each offering distinct advantages and constraints. Fixed-bed designs employ a stationary packed arrangement of reactive media through which a heat-transfer fluid is directed to drive either the endothermic charging or exothermic discharging reaction. Their mechanical simplicity, robust construction, and relatively low cost make them appealing options for early-stage development and integration into CSP or industrial heat-recovery facilities. However, fixed beds frequently suffer from non-uniform temperature profiles, limited reactive surface area, and restricted mass-transfer pathways, all of which slow reaction kinetics and reduce system responsiveness, challenges that become more pronounced during repeated cycling or when scaled to larger reactor volumes. Figure 3 compares three common reactor configurations employed in TCES systems, fixed-bed, fluidised-bed, and modular tubular reactors, highlighting key design differences in heat transfer pathways and material distribution.

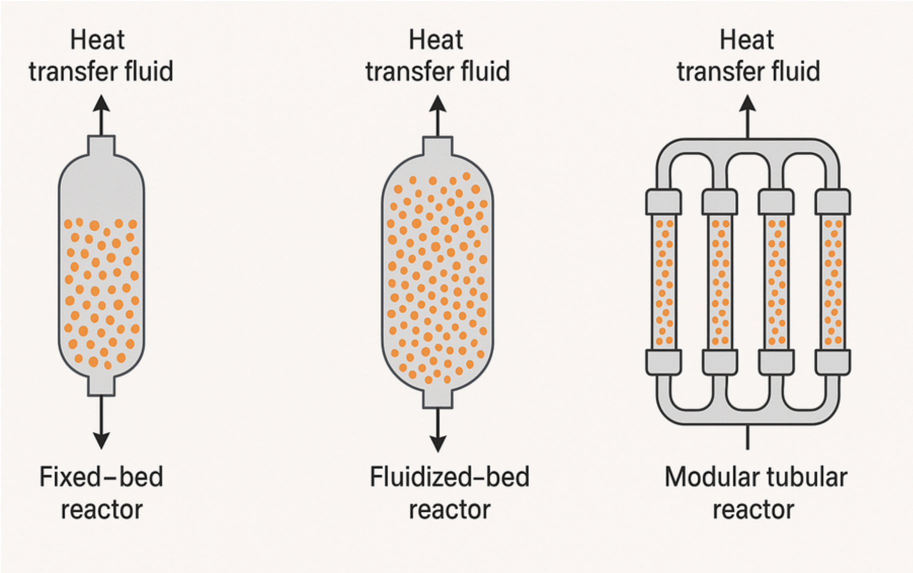

Figure 3. Comparative schematic representation of three common TCES reactor architectures: fixed-bed, fluidised-bed, and modular tubular reactors, highlighting the flow of heat transfer fluid and material configuration.

Fluidised-bed reactors, by contrast, employ a flowing gaseous medium to suspend and circulate reactive particles, continuously renewing the contact surface between the material and the heat-transfer fluid. This dynamic mixing leads to significantly improved heat and mass transfer, more homogeneous temperature fields, and faster reaction rates. These advantages translate into higher operational efficiencies and more stable performance across a range of thermal conditions. Nevertheless, fluidised beds introduce their own set of engineering challenges, including particle attrition, mechanical abrasion, and erosion of reactive solids, which can compromise material longevity and increase maintenance demands (Ren and Zhang, 2012; Jarimi et al., 2019).

Although the work of Ren and Zhang (2012) was conducted in the context of catalytic decomposition rather than TCES, their analysis provides valuable insight into fluid–solid interaction, pressure-drop behaviour, and heat-transfer pathways within both fixed-bed and fluidised-bed environments. These underlying transport phenomena directly influence the performance of TCES reactors, where achieving uniform temperature distribution, maintaining material stability, and minimising thermal gradients are essential for efficient charge–discharge cycling. Their findings therefore remain relevant in understanding how reactor geometry and fluid dynamics shape the operational limits and scalability of TCES systems.

4.2 MULTILAYERED ARCHITECTURES AND EMBEDDED HEAT EXCHANGE

Efforts to improve the thermal performance of conventional TCES reactors have increasingly focused on multilayered architectures capable of better managing internal temperature gradients and mechanical stresses. Han et al. (2022) demonstrated that stratified reactors employing calcium-based thermochemical compounds can significantly enhance heat distribution and stabilise reaction behaviour under fluctuating operating conditions. Their multiphysics simulations indicate that separating reactive layers into structured thermal zones reduces localised overheating, smooths spatial temperature gradients, and promotes more uniform conversion during repeated charge–discharge cycles. These improvements not only increase operational stability but also mitigate the accumulation of thermal stress, thereby extending reactor lifespan and reducing maintenance demands (Saeb Gilani and Morosuk, 2025).

Parallel to these architectural advances, the direct incorporation of internal heat exchangers within reactor bodies has emerged as an effective strategy for enhancing system responsiveness. Gilani and Morosuk (2025) identified several compact and high-efficiency heat exchanger configurations that can be adapted for TCES, enabling more effective heat transfer between the reactive media and the working fluid. Embedding these exchangers within the reactor wall or core reduces external heat losses, improves thermal coupling during both charging and discharging phases, and enhances reactor performance in space-constrained environments. For applications such as CSP towers or industrial retrofits, where thermal efficiency and footprint are critical, these embedded designs offer a promising route toward achieving faster reaction rates and more predictable thermal output (Han et al., 2022).

4.3 MODULAR AND TUBULAR REACTOR INNOVATIONS

Modular and tubular reactors have gained growing attention as TCES technologies expand toward distributed, mobile, and solar-driven applications. Zhang et al. (2024) introduced a tubular modular configuration specifically tailored for CSP-integrated TCES systems, in which the reactor geometry is aligned with concentrated solar flux to maximise heat absorption and transfer. The resulting design offers several advantages: reduced thermal resistance due to short conduction paths, rapid and controllable energy transfer, and improved adaptability across diverse environmental and operating conditions. An additional strength of the modular arrangement lies in its ease of assembly and maintenance; individual modules can be replaced or reconfigured without requiring shutdown of the entire system, thereby improving serviceability and reducing operational downtime (Carrillo et al., 2019).

Despite these benefits, modular tubular systems are not without unresolved challenges. Zhang et al. emphasise that thermal leakage remains a significant barrier, particularly at high operating temperatures where small inefficiencies can compound over time. Ensuring the long-term compatibility of construction materials with repeated thermal cycling is another critical concern, as is optimising the interface between tubular reactors and solar concentrators to ensure uniform irradiation and efficient heat absorption. These issues illustrate the inherent trade-off between pursuing lightweight, flexible architectures and maintaining the thermal robustness needed for practical, large-scale deployment. As a result, further research is required to refine insulation strategies, develop more durable high-temperature alloys or ceramics, and integrate advanced control approaches capable of stabilising thermal behaviour under real-world operating fluctuations.

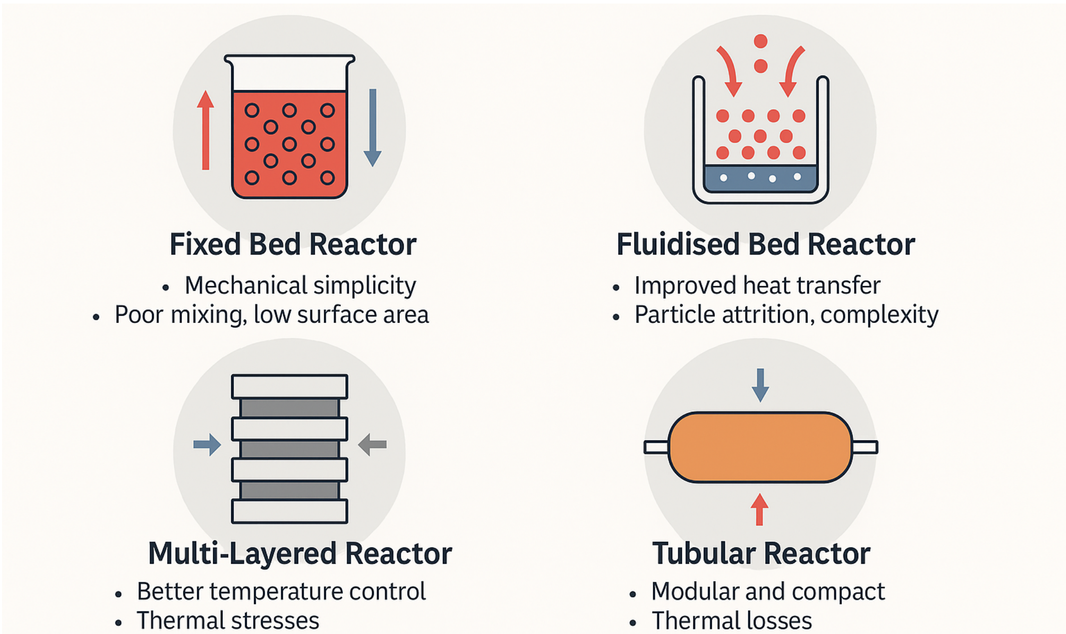

Figure 4. Reactor designs and architectures for TCES systems.

4.4 CHALLENGES AND FORWARD DIRECTIONS

Despite notable progress in the development of TCES reactor technologies, several technical challenges continue to limit their performance and scalability. One of the most persistent issues is the management of thermal stress during repeated charge–discharge cycles, particularly in high-temperature systems where rapid temperature fluctuations can deform reactor components and accelerate material degradation. Closely related is the long-term stability of thermochemical media, whose structural resilience and resistance to sintering or unwanted side reactions largely determine the operational lifespan of any reactor configuration. Achieving efficient heat transfer in compact or high-density reactors presents an additional difficulty; as systems become smaller or more integrated, maintaining uniform temperature fields and effective gas–solid contact becomes increasingly complex. Furthermore, pressure drops across closed-loop fluid systems can significantly reduce system efficiency, especially in designs where reactive beds or internal heat exchangers impose flow resistance. These thermal, mechanical, and fluid-dynamic constraints are compounded by the relatively high cost of advanced internal components such as embedded heat exchangers and modular assemblies, which remain barriers to widespread commercial adoption.

Addressing these interconnected challenges requires a coordinated, interdisciplinary approach that integrates materials science, mechanical and thermal engineering, and system-level design. One promising direction lies in the co-development of materials and reactors, ensuring that thermochemical properties, such as reaction kinetics, heat-transfer behaviour, and structural stability, are matched with reactor geometries and operating conditions from the outset. Advances in smart control strategies and real-time thermal management are also expected to play an increasingly important role, enabling reactors to adapt dynamically to fluctuating heat inputs and operational demands. Likewise, improvements in adaptive insulation, modular reactor platforms, and high-performance composite materials may provide pathways toward both centralised deployment in CSP facilities and decentralised, small-scale installations for industrial waste heat recovery or building-level energy management. Together, these developments represent essential steps toward transforming TCES reactors from laboratory-scale prototypes into robust, commercially viable components of future low-carbon energy systems.

5. SYSTEM INTEGRATION AND OPERATING MODES

The practical effectiveness of thermochemical energy storage (TCES) systems is determined not only by the performance of their materials and reactor configurations but also by the extent to which they are successfully integrated within broader energy infrastructures. System integration dictates how thermal energy is captured, transferred, stored, and ultimately dispatched across a variety of end-use environments, ranging from concentrated solar power (CSP) plants to district heating systems and building-scale thermal networks. As TCES technologies progress toward real-world deployment, understanding the interplay between operating modes, heat sources, control strategies, and downstream applications becomes essential for achieving stable, predictable, and economically viable performance. This section examines the ways in which TCES systems interface with renewable energy inputs and industrial heat streams, and how operational strategies shape their efficiency and responsiveness.

5.1 INTEGRATION WITH RENEWABLE ENERGY AND INDUSTRIAL HEAT STREAMS

TCES technologies are increasingly recognised as pivotal components in creating dispatchable renewable energy systems. Their ability to store heat when solar or other renewable resources are abundant and release it during periods of high demand enables CSP plants to operate with greater flexibility and reduced reliance on backup fuels. Peng et al. (2020) demonstrated that integrating fixed-bed TCES reactors within CSP power blocks not only improves round-trip efficiency but also enhances the operational responsiveness of the system. Their findings highlight the importance of aligning reactor thermal dynamics with both fluctuations in solar irradiance and the temporal structure of electricity demand, a coordination that becomes critical as solar penetration increases (Abdur Rehman et al., 2021; Liu et al., 2018).

Beyond high-temperature CSP applications, TCES is gaining traction in low-temperature contexts such as residential heating, district energy systems, and industrial waste-heat recovery. In these settings, the quality and consistency of the heat source vary significantly. Systems operating with solar thermal collectors or low-grade industrial heat must therefore accommodate intermittent input conditions and often tight spatial constraints. Liu et al. (2025) found that the effectiveness of sorption-based TCES for domestic use depends primarily on the synergy between material behaviour, reactor geometry, and system configuration. Their results underscore that compactness, rapid thermal response, and physical compatibility with existing building infrastructure are frequently more decisive than material selection alone.

A broader comparison across studies indicates that TCES–renewable integration faces additional systemic challenges: the mismatch between reactor thermal inertia and variable heat input, the need for predictive control algorithms to stabilise charge–discharge cycles, and the difficulty of maintaining high efficiency when temperature gradients fluctuate rapidly. These considerations emphasise that successful integration requires not only robust materials and reactor designs but also sophisticated system-level management capable of coordinating real-time thermal behaviour with dynamic energy supply conditions.

5.2 OPERATING MODES AND CONTROL STRATEGIES

All TCES systems operate through repeated cycles of endothermic charging and exothermic discharging, yet the way these cycles are orchestrated has a substantial impact on overall performance, durability, and system complexity. The choice between open- and closed-loop operation, batch or continuous flow, and passive or actively controlled modes determines how effectively the reactor can respond to changing thermal inputs and output demands (Bahr et al., 2023).

In solar-driven applications, synchronising reactor operation with the intermittency of sunlight is critical. Charging must track the temporal profile of solar irradiance, while discharge must be aligned with the thermal or electrical load. Peng et al. (2020) demonstrated that design features such as preheating zones or compartmentalised reactor segments improve temperature uniformity under fluctuating solar input, thereby stabilising reaction kinetics and reducing thermal stress. These design modifications illustrate how operational logic and reactor geometry must be co-optimised for reliable performance.

At the building scale, where thermal loads follow daily or seasonal patterns, passive control strategies leveraging natural diurnal temperature swings can reduce system complexity. Liu et al. (2025) found that such passive operation can be effective for low-temperature, sorption-based TCES systems, provided that materials and reactor geometry are well matched. Nevertheless, passive configurations often struggle to maintain responsiveness during abrupt changes in load or heat input. Incorporating active control elements, such as smart valves, airflow regulators, or thermostatic feedback systems, can markedly improve system flexibility, allow rapid adjustment of charging and discharge rates while maintain stable internal conditions.

Industrial energy systems present additional challenges due to highly variable load profiles and the economic importance of real-time optimisation. Bahr et al. (2023) proposed predictive control frameworks that use real-time sensor data and electricity market signals to schedule TCES operation in ways that minimise cost and support grid flexibility. Such intelligent, anticipatory control transforms TCES from a passive reservoir of stored heat into an active participant within the energy system, capable of adjusting operational mode, discharge timing, and reaction rates in response to external fluctuations.

Taken together, these findings underscore that effective control, whether structural, passive, or algorithmic, is essential for achieving stable, efficient, and economically viable TCES operation. As storage systems become more integrated with dynamic energy networks, advanced control strategies will increasingly define their real-world performance and long-term value.

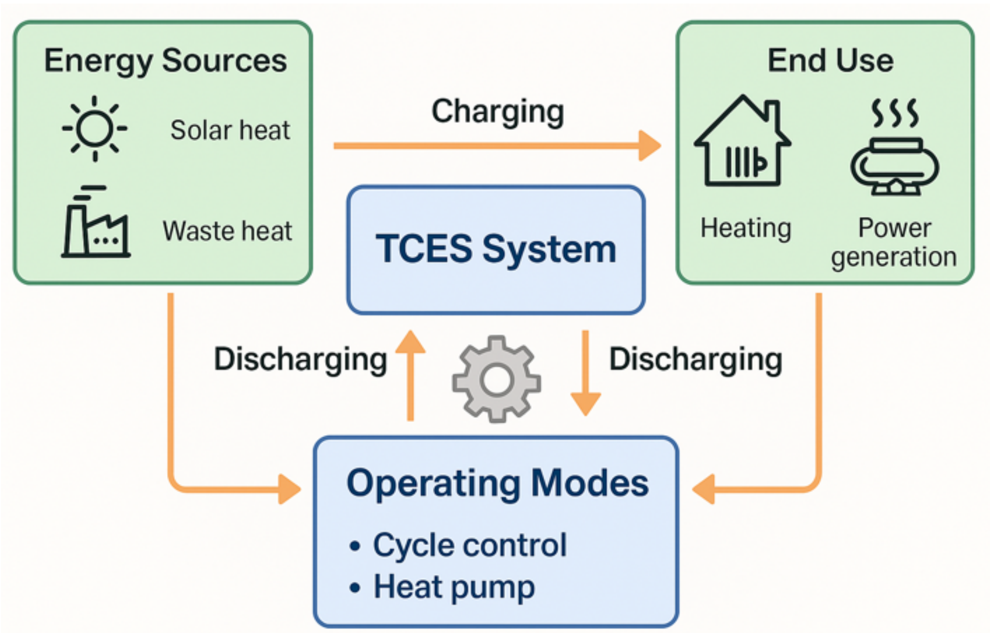

Figure 5. Integration pathways and operating modes in TCES systems.

5.3 COUPLING WITH DOWNSTREAM END-USE TECHNOLOGIES

A critical aspect of TCES deployment is the manner in which stored thermal energy interfaces with downstream technologies, as this determines both the practical value and the functional versatility of the system. In high-temperature applications, the released heat is commonly utilised to generate electricity through steam turbines or supercritical CO_2 power cycles, which demand stable thermal input and precise temperature control. At lower temperatures, TCES units can directly support domestic heating, hot water production, and advanced cooling systems such as sorption chillers (Abdullah et al., 2024).

Rehman et al. (2021) examined hybrid configurations that pair TCES with heat pumps, enabling bidirectional energy flows between thermal and electrical domains. Their study showed that such coupling allows buildings or districts to store excess heat during off-peak hours and deliver either heating or cooling depending on real-time needs. This hybridisation is particularly appealing for net-zero buildings and district-energy infrastructures, where flexibility and the ability to respond dynamically to changing conditions are central design requirements. Liu et al. (2025) likewise emphasised the retrofit potential of sorption-based TCES systems, noting that their compact form factor, low operating pressures, and compatibility with existing heat-distribution networks make them practical for both new installations and upgrades of older building stock. This adaptability strengthens the case for integrating TCES into broader energy-efficiency strategies, especially in urban environments where spatial constraints and infrastructure compatibility are limiting factors.

5.4 INTEGRATION CHALLENGES AND FUTURE PERSPECTIVES

Despite steady progress, several systemic challenges continue to impede the seamless integration and large-scale deployment of TCES technologies. One of the most fundamental issues is the temporal mismatch between the availability of heat, often intermittent and resource-dependent, and the timing of end-use demand. This discrepancy is especially problematic in hybrid systems, where multiple thermal and electrical components interact and where maintaining synchronisation requires sophisticated control logic. System complexity can escalate rapidly as additional subsystems are incorporated, increasing both capital investment and operational overhead. Thermal inertia and distribution losses, particularly in heat exchangers and transport lines, further constrain overall efficiency and complicate system sizing. Added to this are uncertainties related to modular scalability, which affect the feasibility of adapting TCES designs to diverse application scales ranging from building-level units to multi-megawatt CSP facilities.

Overcoming these integration bottlenecks calls for a holistic, systems-level design framework in which materials, reactors, heat-exchange networks, and control strategies are engineered as interdependent elements rather than isolated components. As energy markets evolve toward dynamic pricing and increasingly incorporate demand-side management, TCES systems equipped with intelligent control and forecasting algorithms may play an expanded role. Such systems could operate not only as static reservoirs of stored heat but as active, flexible thermal assets capable of shifting energy use in time, supporting peak-shaving strategies, and enhancing grid stability.

Looking forward, the value proposition of TCES is likely to grow in sectors where thermal and electrical loads coexist and where long-duration storage provides advantages over conventional electrochemical batteries. Achieving this potential will require integration frameworks that prioritise interoperability, real-time responsiveness, and practical constraints such as cost, footprint, and maintenance pathways. With these considerations in place, TCES technologies can become viable across a wide spectrum of scales, from decentralised, building-scale systems to large, utility-grade CSP installations.

6. PERFORMANCE METRICS AND MODELLING APPROACHES

Evaluating the performance of thermochemical energy storage (TCES) systems requires a multidimensional framework capable of capturing the interplay between chemical reactivity, heat and mass transfer phenomena, reactor design, and system-level operational constraints. Unlike sensible or latent heat storage technologies, where thermal gradients or phase transitions provide direct performance indicators, TCES relies on reversible chemical transformations whose efficiency and stability depend simultaneously on thermodynamic feasibility, reaction kinetics, structural evolution of the storage medium, and integration with external energy networks. As TCES technologies progress toward commercial readiness, establishing rigorous performance metrics and reliable modelling tools becomes essential for optimising design choices, guiding scale-up, and validating long-term applicability under real operating conditions.

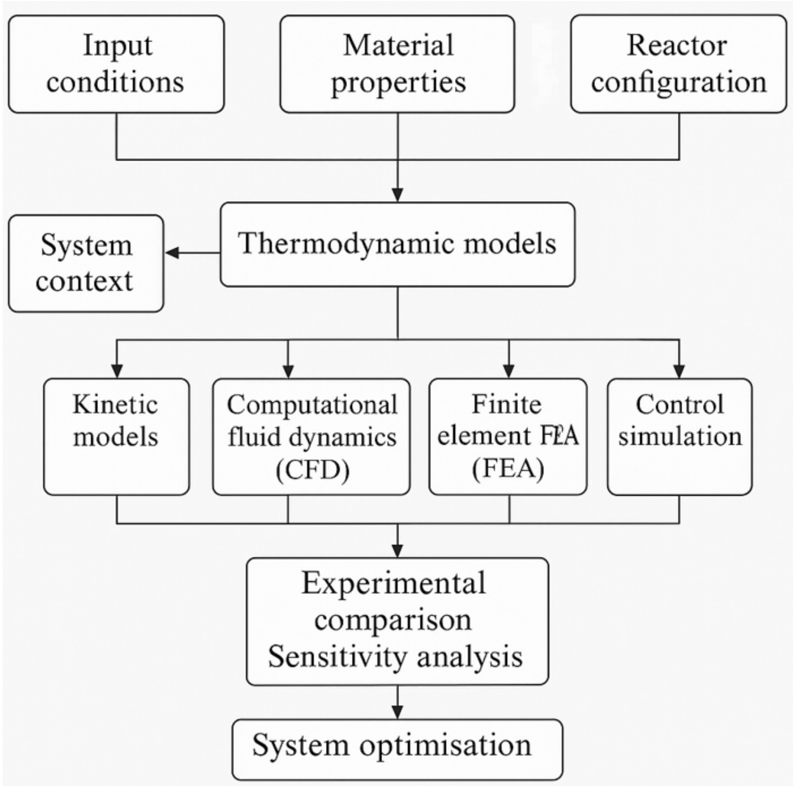

Figure 6. Performance evaluation and modelling framework for TCES systems.

6.1 KEY PERFORMANCE INDICATORS

Assessing TCES performance begins with a set of material- and reactor-level indicators that collectively describe efficiency, durability, and dynamic response. Energy density determines the compactness and storage capacity of a given material, while round-trip efficiency reflects how effectively input heat is recovered during discharge. Charging and discharging rates indicate how rapidly the reactor can respond to intermittent heat sources, an ability that is crucial for solar-integrated systems. Cyclability and thermal–chemical stability, in turn, reveal the extent to which materials preserve their structural integrity and reaction reversibility over repeated cycles.

Studies by Smdani et al. (2023) show that TCES materials often exceed conventional thermal storage media in energy density, highlighting their potential for applications where space or transport constraints are significant. Osman et al. (2020) further emphasise the value of incorporating KPI analysis into early-stage design so that material properties, reactor geometry, and heat-transfer requirements are properly aligned. Additional parameters such as reaction enthalpy, conversion efficiency, and reaction extent are commonly used to quantify chemical performance, but these metrics gain meaning only when interpreted alongside reactor-level factors such as flow configuration, temperature distributions, and thermal conductance. A comprehensive performance profile must therefore integrate both material-specific behaviour and reactor-scale characteristics to yield an accurate representation of system capability.

6.2 SYSTEM-LEVEL METRICS AND LIFECYCLE CONSIDERATIONS

Beyond material and reactor performance, broader system-level metrics play a central role in determining whether TCES can be viably deployed at commercial or utility scales. Exergy efficiency provides insight into the quality of stored energy and its potential for useful work, offering a more holistic perspective than energy-based metrics alone. Economic indicators such as the levelised cost of storage (LCOS) integrate material costs, reactor construction, operational expenditure, and projected service life, enabling fair comparison with batteries, mechanical storage, and hybrid thermal–electrical technologies.

System response time is another critical metric, particularly in grid-responsive applications where TCES units must adjust rapidly to shifts in heat or electricity demand. Sarbu and Sebarchievici (2018) argue that exergy-based evaluation frameworks capture sustainability and operational viability more effectively than conventional thermal analyses, especially when TCES interacts with district heating networks, fluctuating renewable inputs, or industrial waste-heat streams. Lifecycle assessments that incorporate maintenance, degradation, and replacement costs are equally important for understanding long-term competitiveness and ensuring that TCES meets performance expectations in real-world conditions.

6.3 MODELLING AND SIMULATION TOOLS

Given the cross-disciplinary nature of TCES systems, accurate modelling requires a combination of thermodynamic, kinetic, and transport-based approaches. Thermodynamic models identify feasible reaction pathways and equilibrium limits, offering initial estimates of energy density and reaction extent under idealised conditions. Kinetic models introduce temporal and mechanistic detail, capturing activation energies, rate limitations, and the influence of operating parameters such as pressure, particle size, and gas composition (Tirado et al., 2022).

Computational Fluid Dynamics (CFD) plays a central role in reactor-scale modelling by resolving spatial variations in temperature, species concentration, and flow fields, an essential capability for analysing fixed-bed, fluidised-bed, or multilayered reactor configurations. Finite Element Analysis (FEA) complements CFD by predicting thermal stresses, material deformation, and the structural reliability of reactor walls under high-temperature cycling. For system-level analysis, software platforms such as TRNSYS, MATLAB/Simulink, and Modelica enable dynamic simulations of TCES integration with CSP plants, district heating systems, or smart grids.

Tirado et al. (2022), though focused on renewable fuel generation, demonstrated that modelling strategies developed for multi-bed reactors, particularly those addressing spatially resolved heat transfer and pressure-drop estimation, translate directly to TCES scenarios. As modelling complexity increases, experimental benchmarking becomes indispensable. Pilot-scale and lab-scale datasets are required to calibrate assumptions, validate algorithms, and ensure that model predictions remain reliable when transferred to larger systems or real-world operating conditions.

6.4 CHALLENGES AND FUTURE RESEARCH DIRECTIONS

Despite steady progress, several challenges hinder the robustness and general applicability of TCES performance modelling. A persistent issue is the absence of standardised KPIs across research groups, which limits comparability and slows the development of universally accepted benchmarks. High-fidelity, multi-physics simulations, although powerful, remain computationally demanding and are often restricted to academic or prototypical cases rather than large-scale engineering design. Equally important is the limited availability of long-term experimental data, particularly under cyclic loading, fluctuating environmental conditions, and realistic integration scenarios. This shortage of empirical evidence constrains the validation of advanced models and reduces confidence in predictions related to degradation, stability, and operational longevity.

Addressing these challenges will require unified modelling frameworks that bridge thermodynamic, kinetic, and control-oriented perspectives within a single integrated architecture. Emerging research increasingly points toward machine learning and AI-based surrogate modelling as promising tools for real-time optimisation, fault detection, and predictive maintenance, especially when applied to systems with dynamic and uncertain input conditions. The convergence of data-driven analytics with high-fidelity simulations and validated experimental datasets is expected to form the foundation of next-generation TCES design, enabling more accurate forecasting, enhanced stability, and more efficient coupling with renewable energy systems.

A notable example of progress in this direction is the pilot-scale demonstration of a TCES system based on the $CaO/Ca(OH)_2$ reaction pair, operated within a bubbling fluidised-bed reactor. Morgenstern et al. (2024) achieved stable cyclic performance and high thermal efficiency, confirming both the feasibility of this material system and the importance of pilot-scale data for advancing model validation and guiding future system optimisation.

7. CHALLENGES AND FUTURE PROSPECTS

TCES systems continue to attract growing interest as viable solutions for applications requiring high energy density and long-duration storage. However, despite notable scientific and engineering progress, the pathway to widespread deployment remains constrained by several interconnected technical, economic, and systemic barriers. Understanding and addressing these challenges is essential for positioning TCES as a scalable and reliable component in the emerging low-carbon energy landscape.

7.1 TECHNICAL LIMITATIONS AND ENGINEERING CONSTRAINTS

A major technical challenge facing TCES systems arises from the long-term behaviour of thermochemical materials under repeated cycling. Many solid–gas reaction pairs experience progressive degradation, driven by sintering, particle agglomeration, irreversible side reactions, or structural transformations that reduce reactive surface area. Kur et al. (2023) underscore how issues such as thermal instability, low thermal conductivity, and limited compatibility between materials and reactor geometries can amplify these problems, particularly in low- to mid-temperature systems where heat transfer pathways are already constrained.

Reactor architecture introduces an additional set of engineering trade-offs. Fixed-bed reactors remain widely used due to their simplicity and relatively low manufacturing cost, yet they commonly suffer from non-uniform temperature distributions, slow thermal diffusion, and challenges in achieving efficient scale-up. Alternative configurations such as fluidised beds or modular tubular reactors offer superior heat and mass transfer and greater adaptability, but these benefits come with increased mechanical complexity, higher maintenance requirements, and limited validation outside laboratory conditions. The lack of long-term field data makes it difficult to assess how these advanced designs behave when exposed to fluctuating thermal inputs, grid-coupled operating regimes, or large-scale industrial environments (Carrillo et al., 2019; Abdullah et al., 2024).

Heat-transfer management remains another persistent hurdle, especially for TCES units coupled to renewable sources such as solar or wind, where thermal input can vary rapidly. Inefficiencies during both charging and discharging often stem from inadequate insulation, temperature overshooting, or uncontrolled energy release. The absence of advanced real-time control systems further restricts the system's ability to respond dynamically, hindering the ability of TCES to function as a flexible energy asset within increasingly complex energy networks.

7.2 MARKET BARRIERS AND ECONOMIC VIABILITY

From an economic perspective, TCES technologies face strong competition from more established storage solutions such as batteries or pumped hydro. Geng et al. (2025) highlight that these alternatives benefit from mature supply chains, declining capital costs, and widespread market familiarity, advantages that TCES technologies have not yet fully achieved. High material costs, particularly for metal oxides and advanced composite media, represent a significant barrier, as does the expense associated with designing and fabricating specialised reactor systems.

Economic constraints are especially pronounced in decentralised or building-scale applications, where installation budgets are limited and custom engineering solutions are often impractical. Compounding this is the lack of standardised economic assessment tools for TCES. Although techno-economic studies are increasing, there is still no widely accepted framework for comparing lifecycle costs or long-term performance across different TCES technologies. Kur et al. (2023) argue that this absence of uniform benchmarks undermines investor confidence, complicates technology evaluation, and slows commercialisation.

7.3 FUTURE PATHWAYS AND STRATEGIC PRIORITIES

Despite these challenges, several promising research directions suggest that TCES could evolve into a key contributor to high-temperature industrial decarbonisation and renewable energy integration. A new generation of materials, including perovskite oxides, metal–organic frameworks (MOFs), and nanostructured composites, shows considerable potential for improving thermodynamic tunability, structural resilience, and operating range. Pantaleo et al. (2024) note that such innovations may significantly broaden the applicability of TCES in sectors requiring reliable thermal buffering or continuous heat supply.

Equally transformative is the integration of TCES with intelligent, multi-vector energy platforms. When coupled with smart grids, district heating systems, or hybrid thermal–electrical networks, TCES can transition from a passive storage unit to a dynamically optimised component capable of responding to weather forecasts, market prices, or real-time load variations. Early studies using predictive control algorithms and machine learning have demonstrated that TCES systems can be scheduled and dispatched adaptively, thereby improving operational efficiency and economic value.

A particularly impactful strategy for advancing TCES capability is the adoption of a co-design methodology in which materials development, reactor engineering, and control strategies are conceived as interconnected elements rather than sequential steps. Kur et al. (2023) argue that such integrated development accelerates compatibility between chemical, thermal, and structural performance, reducing the iteration cycles needed to transition from laboratory innovation to field-ready technology.

Achieving commercial scalability will require several targeted actions. First, low-cost but thermally robust materials capable of sustained cycling must be developed. Second, large-scale demonstration projects, on the order of several megawatt-hours, are needed to validate system reliability, integration potential, and dynamic behaviour under real operating conditions. Third, the establishment of industry-wide performance benchmarks, harmonised lifecycle assessment methodologies, and standardised techno-economic metrics will be essential for supporting investment and guiding regulatory development. Finally, appropriate policy mechanisms and financial incentives will be required to reduce risk for early adopters and stimulate deployment in emerging markets.

Recent evaluations also highlight the importance of benchmarking TCES technologies against standard Technology Readiness Levels (TRL). While most material innovations remain at TRL 3–4, several reactor configurations, particularly modular tubular designs, have advanced to TRL 5–6. Progressing to TRL 8–9, where commercial deployment becomes feasible, will require coordinated pilot demonstrations, rigorous lifecycle assessments, and supportive policy frameworks that encourage long-term investment.

As energy systems evolve toward greater decentralisation, decarbonisation, and digitalisation, the niche advantages of TCES, high-temperature buffering, seasonal heat storage, and industrial load balancing, position it as a potentially indispensable technology in applications where batteries or mechanical storage options remain inadequate.

7.4 ENVIRONMENTAL AND SAFETY CONSIDERATIONS

Although TCES technologies offer clear decarbonisation benefits, their environmental footprint must be evaluated comprehensively through full lifecycle assessments, including extraction, synthesis, fabrication, operation, and end-of-life disposal of storage materials. Certain thermochemical compounds, particularly salt hydrates and metal oxides, may introduce environmental risks related to corrosion, leaching, or waste-handling requirements if not properly managed. Safety considerations are equally critical, especially in residential or industrial retrofit installations where improper handling or thermal runaway could pose operational hazards. Establishing rigorous safety standards, monitoring protocols, and environmentally responsible disposal pathways will therefore be essential as TCES systems progress from laboratory prototypes to widespread commercial adoption.

8. CONCLUSION

Thermochemical energy storage (TCES) has emerged as a promising solution for bridging the gap between variable renewable energy generation and the growing demand for long-duration, high-density storage. By relying on reversible chemical transformations rather than sensible or latent heat retention, TCES offers minimal thermal losses and high storage capacity, making it particularly attractive for medium- to high-temperature applications such as concentrated solar power and industrial waste-heat utilisation. This review has examined recent advances across four interconnected pillars of TCES development, materials, reactor architectures, system integration, and modelling frameworks, and has highlighted both the progress achieved and the fundamental challenges that persist.

Advances in material science have expanded the operational window of TCES systems, with metal oxides, salt hydrates, and emerging organic and composite materials demonstrating improved reaction performance and broader temperature compatibility. However, issues such as thermal degradation, limited conductivity, structural instability during cycling, and high material costs continue to restrict real-world applicability. The development of hybrid or nanostructured materials offers new pathways for tailoring thermodynamic and kinetic properties, though their long-term stability and cost-effectiveness remain to be demonstrated at meaningful scales.

Reactor innovation has followed a similarly promising but uneven trajectory. Fixed-bed, fluidised-bed, tubular, and multilayered reactor configurations have each shown the potential to enhance heat transfer, improve reaction uniformity, and provide modular deployment options. Yet most designs remain confined to laboratory or pilot-scale implementations, and their performance under fluctuating thermal input, field conditions, and extended cycling is still not well understood. Achieving commercial viability will require reactor concepts that balance thermal efficiency, mechanical robustness, simplicity of operation, and compatibility with renewable heat sources.

System-level integration studies reveal that TCES can play a valuable role in enabling thermal flexibility and enhancing resilience across district heating networks, hybrid thermal-electric infrastructures, and emerging smart grids. However, barriers such as high upfront investment, the absence of standardised integration guidelines, and the relative immaturity of the technology limit its adoption compared to more established storage solutions like batteries and pumped hydro. Even so, the distinct advantages of TCES, especially its capability for long-duration storage and direct heat delivery, position it as a complementary technology suited to niche applications where conventional storage options fall short.

Looking ahead, accelerating the commercialisation of TCES will require coordinated advances across multiple domains. Priority areas include the discovery of low-cost, durable materials with rapid reaction kinetics; the development of thermally efficient, scalable reactor systems; and the integration of advanced control algorithms capable of stabilising operation under real-world variability. A systems-level co-design approach, one that aligns material properties, reactor geometries, heat-exchange strategies, and predictive control, is likely to be essential for translating laboratory progress into deployable solutions.

In summary, TCES is unlikely to replace dominant energy storage systems in the near term. Yet its unique characteristics make it a strong complementary option within a diversified, low-carbon energy landscape, particularly for sectors requiring high-temperature buffering, seasonal heat storage, or industrial load balancing. Realising this potential will depend on sustained interdisciplinary collaboration, supportive policy frameworks, and targeted investment to bridge the gap between innovation and large-scale implementation.

8.1 POLICY AND COMMERCIALISATION OUTLOOK

Moving TCES technologies from laboratory experimentation to widespread commercial deployment will require supportive policy environments and targeted market incentives. Although recent advances in materials, reactor architectures, and system integration have demonstrated the technical promise of TCES, meaningful uptake will depend on reducing investment risk and accelerating demonstration at scale. Policies that prioritise pilot projects, mandate lifecycle assessment practices, and offer subsidies or tax incentives for early adopters, particularly in sectors with significant high-temperature heat demand, can help establish the foundational infrastructure needed for broader market penetration.

Toward 2030 and beyond, TCES has the potential to play a strategic role in long-duration and seasonal thermal storage, complementing battery systems, hydrogen infrastructures, and electrification pathways. Its capability to deliver stable thermal output, even under fluctuating renewable input, positions it as a valuable asset within emerging flexible thermal grids. This value proposition is especially relevant for developing economies with high solar availability, where affordable, long-duration storage can help stabilise power systems and reduce reliance on fossil-fuel-based thermal generation.

Achieving this vision will require coordinated action across policy, industry, and research domains. Standardised performance benchmarks, robust techno-economic assessment frameworks, and clear integration guidelines will be essential to building investor confidence and reducing market entry barriers. In parallel, targeted funding programs and regulatory mechanisms that reward decarbonisation, reliability, and grid flexibility can accelerate deployment in both industrial and urban settings. With these measures in place, TCES technologies can transition from promising laboratory innovations to commercially viable components of a resilient, low-carbon global energy system.

DATA ACCESSIBILITY STATEMENT

No new datasets were generated or analysed during the current study. All data supporting the findings of this review are derived from previously published sources, which are appropriately cited throughout the manuscript.

AUTHOR CONTRIBUTIONS

James Riffat conceptualised the structure of the review, conducted the literature research, performed the analysis, and wrote the manuscript. All sections were reviewed and revised by Seyed Reza Samaei to ensure consistency, accuracy, and coherence. The authors approved the final version of the manuscript.

DECLARATION OF COMPETING INTERESTS

The authors declare no competing financial or personal interests.

AUTHOR NOTE ON EDITORIAL INDEPENDENCE

The corresponding author of this manuscript, James Riffat, currently serves as an editor for *Research and Reviews in Sustainability*. To ensure full transparency and uphold the integrity of the peer review process, the handling of this submission has been delegated entirely to an independent editor who has no conflicts of interest with the authors. At no point will the submitting author be involved in the editorial or review decisions related to this manuscript.

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