# Critical review of Design and Material Modifications in Thermal Energy Storage Systems

Submitted by: **Soumya Raj** (2K22/ME/254) **Aagam Doley** (2K22/ME/01)
**Alluri Sumedh Narayana** (2K22/ME/28)

Under the supervision of:
**Prof. (Dr.) Pushpendra Singh**

DEPARTMENT OF MECHANICAL ENGINEERING DELHI TECHNOLOGICAL UNIVERSITY
(Formerly Delhi College of Engineering) Bawana Road, Delhi-110042

## 1. ABSTRACT

TES systems are increasingly recognized as essential components for enhancing the flexibility, reliability, and efficiency of renewable-energy-dominated power networks. However, their widespread adoption continues to be constrained by intrinsic material and design limitations: among other problems, low thermal conductivity, substantial cycling degradation, phase separation, leakage in latent-heat media, and slow heat-transfer dynamics limit charge-discharge efficiency. In response, this paper provides an extensive critical review of state-of-the-art design and material modifications developed to advance the performance of sensible, latent, and thermochemical TES systems.

On the design side, great interest has been focused on the enhanced heat-transfer structures of extended-surface fin geometries, spiral and helical heat-exchanger coils, metal-foam matrices, and internal conductive networks, while cascaded multi-temperature PCM configurations collectively enhance temperature uniformity, charging rates, and overall exergy utilization. These recent developments have yielded impressive experimental and numerical performance gains; however, they often rely on increased mechanical complexity, higher fabrication expense, and an uncertain reliability upon long-term cycling. In addition, encapsulation technologies, from macro-capsules to microencapsulation and microfluidic shell-formation techniques, have arisen as effective solutions for mitigating PCM leakage and thermal instability but create challenges for shell integrity, thermal contact resistance, and scalability in manufacturing.

Material-level modifications have also come to the fore. Nano-Enhanced PCMs with metallic, oxide, carbon-based and hybrid nanoparticles have shown notable improvement in effective thermal conductivity and heat-storage density. Similarly, composite PCMs with graphite foams, expanded graphite matrices, carbon nanotubes, or embedded metal structures have shown improved charge-discharge performances. On the other hand, thermochemical materials modified by using appropriate stabilizers or dopants or composite supports also exhibit improved reversibility and reduced cyclic degradation. Despite their promise, these materials pose a number of challenges in the form of nanoparticle agglomeration, increase in viscosity and sedimentation effects, long-term thermal instability, and environmental concerns during material synthesis and disposal.

**Keywords:**
Phase Change Materials, Nano-Enhanced PCMs, Heat-Transfer Enhancement, Encapsulation, Composite Materials, Exergy Efficiency, Molten Salt, Thermochemical Storage.

## 2. INTRODUCTION

As renewable-energy systems continue to expand globally, the need for reliable and flexible energy-storage technologies has become increasingly important. Thermal Energy Storage (TES) systems play a key role in this transition by storing excess thermal energy during periods of low demand and releasing it when energy demand rises, thereby stabilizing renewable-dominated energy networks [1], [2]. TES technologies are now widely investigated for applications such as concentrated solar power (CSP), building heating and cooling, industrial waste-heat recovery, and district-energy systems [3].

Despite their benefits, the practical performance of many TES systems remains limited by material and structural challenges. Latent heat storage systems using phase change materials (PCMs) often suffer from low thermal conductivity, leakage, phase segregation, and degradation after repeated cycling [1], [4], [6]. Sensible heat storage requires large storage volumes, while thermochemical storage systems face slow reaction kinetics and limited reversibility. These issues reduce energy- storage efficiency and long-term reliability, restricting the large-scale deployment of TES technologies [5].

To overcome these limitations, researchers have proposed a wide range of design-related and material-focused modifications. Design improvements such as extended-surface fins, spiral and helical heat-exchanger coils, and metal-foam matrices significantly enhance heat-transfer performance and temperature uniformity [3]. Similarly, cascaded PCM systems with multiple melting-point materials improve charging rates and exergy utilization. Encapsulation techniques— including macro-capsules, microencapsulation, and microfluidic shell-formation methods—have been developed to prevent PCM leakage and enhance thermal stability, though challenges remain regarding shell integrity, thermal resistance, and large-scale manufacturability [7].

Material-level advancements have also gained substantial attention. Nano-enhanced PCMs (Ne PCMs), formed by dispersing metallic, oxide, carbon-based, or hybrid nanoparticles, have shown considerable improvements in thermal conductivity, heat-storage density, and melting/solidification response [1], [2], [4], [6]. Composite PCMs using graphite foams, expanded graphite structures, carbon nanotubes, or metal reinforcements further improve charge-discharge performance [5]. Thermochemical materials modified with stabilizers, dopants, or composite supports exhibit improved reversibility and reduced cycling degradation. Despite these promising outcomes, several issues remain, including nanoparticle agglomeration, increased viscosity, sedimentation, long-term instability, and environmental concerns related to material processing and disposal [4], [6], [7].

Given the rapid progress and remaining limitations, a comprehensive and critical review is needed to evaluate the true effectiveness of these innovations. The main objectives of this paper are to (1) review recent design and material modifications in TES systems, (2) assess their performance benefits and limitations, (3) compare results across different TES categories, and (4) identify key research gaps that must be addressed to enable durable, scalable, and cost-effective TES deployment.

## 3. LITERATURE REVIEW

Over the past four decades, TES has been studied extensively, with an accelerating pace in recent years due to the shift toward renewable energy worldwide. This is manifested in studies covering a wide spectrum of topics pertaining to material science, thermodynamics, enhancement of heat transfer, reactor design, encapsulation, and system-level integration. This review synthesizes findings from over 20 key studies and is organized into five major sections:

1. Fundamentals of TES
2. Sensible Heat Storage
3. Latent Heat Storage
4. Thermochemical Energy Storage

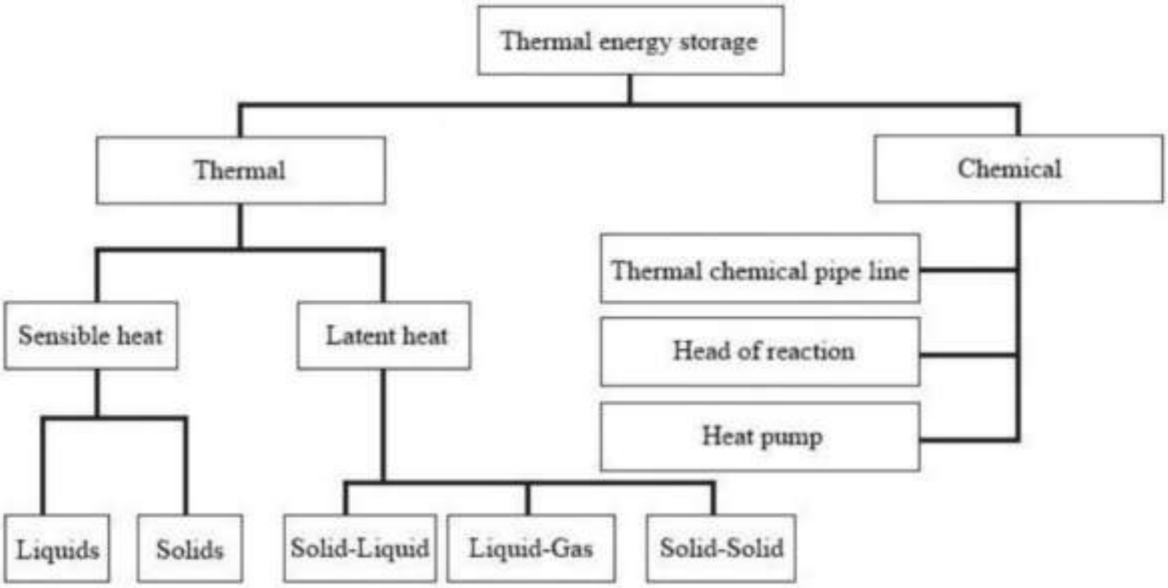

**Fig. 1.** Types of solar thermal energy storage (TES). [4]

## 4.1 Fundamentals of TES Technologies

There are three major categories of TES technologies: sensible heat storage, latent heat storage, and thermochemical heat storage. While each category presents some unique advantages, it also involves major scientific and engineering limitations.

The sensible storage materials, like water, molten salts, packed beds, or rocks, store energy by raising their temperature. They are reliable and low cost but usually suffer from the drawbacks of low energy density and large volume requirement [8].

Latent heat storage, using phase change materials, stores thermal energy during a solid-liquid transition. PCMs have higher energy density than sensible heat materials, nearly isothermal behavior, and broad applicability. However, other persistent challenges are the low thermal conductivity of materials, leakage of the materials in their molten state, phase segregation, and thermal degradation [1], [4], [9].

Thermochemical energy storage is based on reversible chemical reactions. It provides the highest theoretical energy density and long-term storage possibility. The big disadvantages, however, are the low reaction kinetics, partial reversibility, stability issues, and material cost, limiting the current applications [10, 11].

All the articles reviewed, regardless of category, point out that TES is critical to enhance renewable penetration, stabilize energy systems, and decrease peak demand; however, significant scientific breakthroughs in materials and design remain to be achieved for commercial reliability [12], [13].

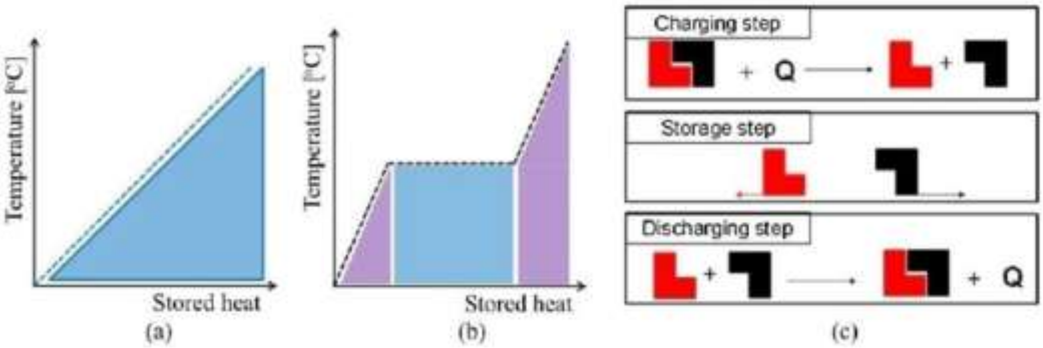

**Fig. 2.** Methods of TES (a) sensible heat; (b) latent heat; (c) thermos-chemical reactions. [23]

## 4.2 Sensible Heat Storage (SHS)

### 4.2.1 Overview and Materials

The oldest and most widely implemented category of TES is sensible heat storage. A number of materials have been studied and tested in depth, including molten nitrate salts, oils, concrete, rocks, and high-temperature ceramics [8], [14].

Molten salts like sodium nitrate, potassium nitrate, and their eutectic mixtures are the standards in CSP plants. Their advantages are:

- thermal stability up to ~565°C
- good heat-transfer properties
- low material cost

However, molten salts suffer from corrosion and freezing at high temperature, besides non- uniform degradation upon cycling [15].

Low-cost thermal storage can be provided by packed-bed sensible storage systems, using either rocks or ceramic pellets; however, heat-transfer limitations and non-uniform flow distribution reduce charging efficiency [16].

**TABLE I**

List of selected solid-state materials for sensible heat storage. [6]

| Storage Materials | Working Temperature (°C) | Density (kg/m$^3$) | Thermal Conductivity (W/(m·K)) | Specific Heat (kJ/(kg·°C)) |
|---|---|---|---|---|
| Sand-rock minerals | 200–300 | 1700 | 1.0 | 1.30 |
| Reinforced concrete | 200–400 | 2200 | 1.5 | 0.85 |
| Cast iron | 200–400 | 7200 | 37.0 | 0.56 |
| NaCl | 200–500 | 2160 | 7.0 | 0.85 |
| Cast steel | 200–700 | 7800 | 40.0 | 0.60 |
| Silica fire bricks | 200–700 | 1820 | 1.5 | 1.00 |
| Magnesia fire bricks | 200–1200 | 3000 | 5.0 | 1.15 |

### 4.2.2 Design Enhancements in SHS

Recent sensible heat storage research efforts have been increasingly oriented towards the geometric and material configuration for improved internal heat transfer behavior of the systems. It is pointed out that internally finned tubes are important to increase the effective surface area, enhancing conduction and thus producing more uniform temperature fields for charge-discharge cycles. In this regard, other researchers focus on the use of porous media fillers to enhance the conductive pathways such that heat can penetrate the storage medium with greater rapidity while maintaining structural stability during repeated thermal cycling. Another main direction involves high-performance insulation to reduce standby thermal losses, especially when storing energy over relatively long periods. Complementary to these strategies, a number of researchers have tested metal-foam-based heat exchangers because their highly conductive, open-cell structure significantly enhances thermal uniformity. However, as discussed in [3], [17], such benefits come at the expense of higher material cost and possible long-term durability issues associated with large-scale deployment, notwithstanding their strong performance in the laboratory.

### 4.2.3 Gaps and Future Directions for SHS

Despite commercial maturity, research gaps in SHS still include:

- high-temperature corrosion-resistant materials
- low-cost thermal oils with expanded operating ranges
- design strategies to reduce thermal gradients and material aging
- long-term reliability modeling under cyclic operation

Advanced alloys, improved insulation, and integration with hybrid PV-thermal systems are being considered for future SHSs [18].

## 4.3 Latent Heat Storage (PCM-Based TES)

Latent heat storage is the most widely researched TES category due to its compactness, high energy density, and near-isothermal operating behavior.

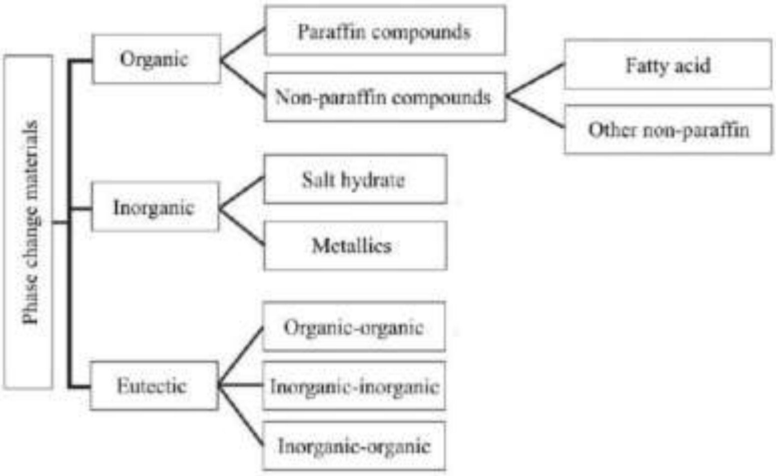

**Fig 3.** Classification of phase change materials. [2]

### 4.3.1 PCM Materials and Challenges

PCMs are classified as:

- organic PCMs (paraffins, fatty acids)
- inorganic PCMs (salt hydrates)
- eutectic mixtures

The organic PCMs have chemical stability and repeatability but at the cost of very low thermal conductivity (~0.2 W/mK) that significantly delays the melting and solidification processes. Inorganic PCMs have advantages of higher thermal conductivity and larger volumetric heat storage capacity but generally exhibit supercooling, phase segregation, and corrosive interaction with containment materials [9], [19]. All these factors may lead to a deteriorated thermal performance with repeated cycling and also limit their applications in higher temperature systems. A common conclusion found in the recent literature is that low thermal conductivity now represents the key bottleneck to better PCM performance: melting times unenhanced are between two and up to five times greater than what is needed practically by any TES application [1], [2], [20]. This has driven extensive research into conductivity- enhancement techniques, including nanoparticles, composite scaffolds, and improved enclosure geometries, all aimed at improving thermal responsiveness and system efficiency.

### 4.3.2 Nano-Enhanced PCMs (NePCMs)

Nano-enhanced PCMs have emerged as a promising method to improve the conductivity of PCMs by adding small amounts of nanoparticles that create effective pathways for heat transfer.

Common nanoparticles include:

- $Al_2O_3$
- CuO
- $SiO_2$
- Carbon nanotubes (CNTs)
- Graphene and graphene oxide However, challenges include:
- agglomeration of nanoparticles
- sedimentation and phase separation
- viscosity increase leading to slower convection
- high cost of nanoparticle production
- unclear long-term environmental impacts [4], [6], [22]

These disadvantages indicate the development of complex dispersion methodologies and stabilizing agents. Most of the literature indicates that a nanoparticle loading below approximately 0.5–3 wt.% is effective to optimize the enhancement in conductivity while considering viscosity within acceptable limits [6], [21]. Beyond this, the thermal advantage decreases and the demand for pumping is enhanced, thereby affecting overall system efficiency.

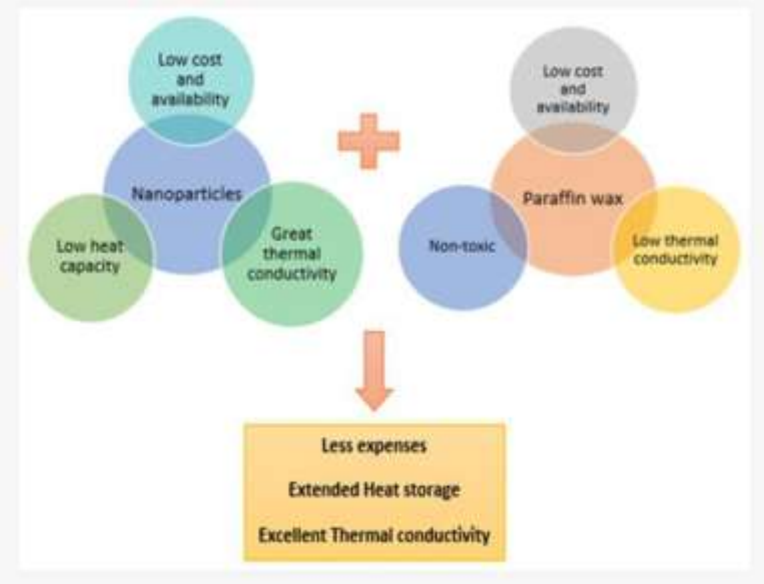

**Fig. 4.** Nano enhanced phase change materials advantages. [22]

### 4.3.3 Composite PCMs

Composite PCMs incorporate conventional PCMs into porous, conductive matrices, which provide structural reinforcement and pathways for improved heat transfer.

Common supporting matrices include:

- Expanded graphite
- Graphite foam
- Metal foams
- Carbon-based skeletons
- Polymeric scaffolds

These matrices create continuous conduction channels through the PCM, enhancing the melting and solidification processes, sometimes as high as 20–60× effective thermal conductivity when compared to pure PCMs [5], [17]. The composite PCMs still offer improved shape stability and reduced leakage risk, which makes them highly attractive for medium-to high-temperature storage and building applications.

Limitations of the composite PCMs include:

- Lower latent heat capacity because of the volume of the solid matrix
- Manufacturing and infiltration challenges
- Interfacial bonding inconsistencies between PCM and matrix

Recently, bio-based composite PCMs using natural fibers or wood-derived porous networks have attracted attention because of their environmental benefits. While promising, the long-term structural and moisture stability of these materials need further validation for industrial-scale TES applications.

### 4.3.4 Design Enhancements for PCM Systems

On top of these material improvements, system-level design modifications have profound impacts on TES performance as they optimize heat-transfer paths and thermal gradients.

Common design improvements include:

- Finned heat-exchanger tubes
- Helical or spiral heat-exchanger coils
- Metal-foam matrices integrated within PCM enclosures
- Cascaded PCM multi-layer configurations

These structural improvements serve to increase surface area, enhance conduction and convection, and decrease thermal resistance in latent heat units. Interconnected conduction pathways created by metal-foam reinforcement further hasten the distribution of heat within the storage. Cascaded PCMs improve exergy efficiency by matching their melting points to the thermal profile of the heat transfer fluid passing over them and reduce irreversibility in operation. These enhancements, taken together, support faster cycling and improved thermal stratification, thereby better preparing PCM-based storage for use in renewable energy systems and industrial heat management.

### 4.3.5 Encapsulation Techniques

Encapsulation has conventionally provided a reliable method of containing phase change materials within a protective shell or matrix that inhibits leakage into the environment during melting, while enhancing mechanical and thermal stability. In encapsulation, the PCM is enclosed by a solid barrier-usually a polymer, ceramic, or inorganic shell-so as to permit the safe phase transition of the former without loss of shape or containment. This method can also extend the application of PCMs in a wider range of TES systems and composite structures by providing them with a defined, durable, and manageable form.

Encapsulation provides many performance advantages:

- improve stability
- enhance thermal cycling durability
- allow PCMs to be incorporated into fluids, slurries, or building materials

Because of their fine scale particle size and even distribution, microencapsulated PCMs find a wide range of applications in building envelope materials, HVAC components, and in thermal textiles, storing and releasing heat effectively in lightweight construction materials [24]. This encapsulation shell also standardizes PCM geometry, improving heat-transfer behavior by making PCM integration more compatible with existing heat-transfer fluids and structural systems.

Despite these advantages, encapsulated PCMs have several well-noted challenges. The limitations of encapsulated PCMs include

- thermal contact resistance
- mechanical weaknesses during expansion/contraction
- higher manufacturing costs [7], [25]

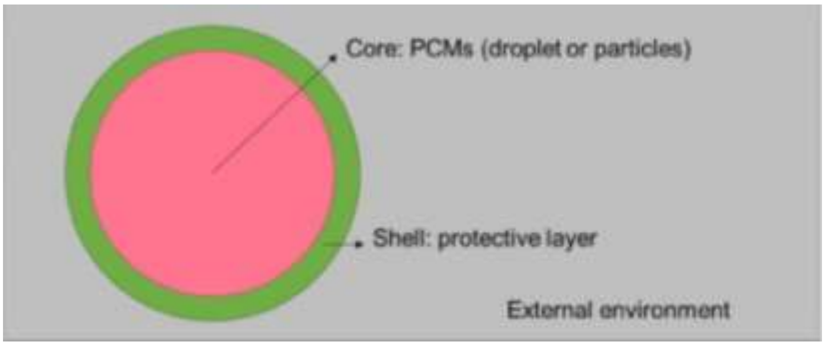

**Fig. 5.** Schematic structure of a PCM capsule. [25]

### 4.4.6 Gaps and Future Directions

Although considerable advancements have been made in materials development, heat-exchanger design, and reactor engineering for TES systems, the literature reveals a persistent and significant gap between laboratory-scale progress and real-world deploy ability.

Some gaps include:

- Materials Performance & Durability
- Scale-up & Manufacturing
- Standardization of Testing and Reporting

- Environmental, Health & End-of-life Impacts
- Techno-economic Evidence & Market Readiness
- Integration & Controls

## 4.4 Thermochemical Heat Storage (TCS)

It involves the storage of heat within reversible exothermic-endothermic chemical reactions that allow energy to be stored in a form of chemical potential rather than sensible or latent heat. TCS does not suffer from gradual heat losses over time, which occurs with SHS and LHS; hence it is capable of retaining energy stored for months or even years. In this regard, it is one of the most promising long-duration and seasonal heat storage technologies. With its high energy density, low standby losses, and material reversibility, TCS has managed to place itself as a strategic component for future renewable-energy systems, especially on applications that require long-term heat retention, district energy networks, and also concentrated solar power plants [10], [11], [26].

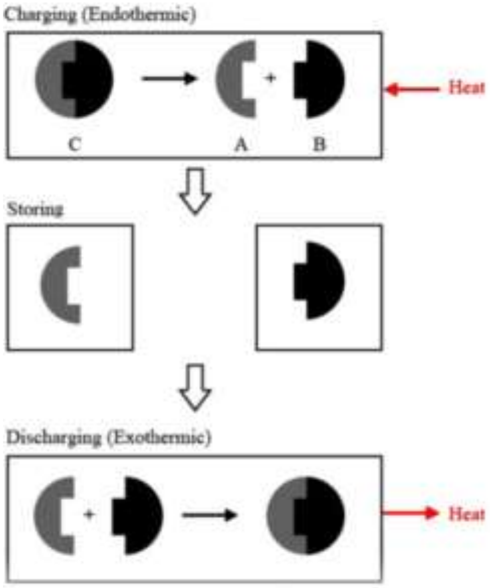

**Fig. 6.** Reversible process of a thermochemical reaction. [10]

### 4.4.1 Overview and Materials

Charging and discharging processes in TCS materials are coupled to chemical decomposition, hydration–dehydration, or sorption–desorption. Material choice will have a large impact on reaction kinetics, stability, energy density, and reactor design.

Common TCS materials include:

- Metal oxides: $CaO/Ca(OH)_2$, $MgO/Mg(OH)_2$, $Co_3O_4/CoO$
- Salts and salt hydrates $CaCl_2$, $MgSO_4$, LiBr
- Sorption-based materials: silica gel, zeolites, and activated alumina

Salt hydrates like $CaCl_2$, $MgSO_4$, and LiBr are some of the most studied owing to their good hydration–dehydration behavior, moderate operating temperatures, and relative material abundance [11]. In contrast, metal oxides offer very high energy density in many cases but often necessitate high operating temperatures (>400°C) that reduce their compatibility with low- temperature renewable heat sources.

Recent work also explores composite TCS materials where salts are integrated into porous matrices, such as expanded graphite or silica, improving reaction surface area and reducing structural degradation during cycling.

### 4.4.2 System Designs and Reactor Configurations

Recent improvements in TCS are not only related to materials, but also to reactor engineering optimizations. Well-designed reactors may strongly improve the heat and mass-transfer rates of the overall reaction.

Common reactor designs for TCS include:

- Packed-bed reactors - simple scalable reactors used for salt hydrates
- Fluidized-bed reactors: heat- and mass-transfer enhancement by particle mixing
- Open sorption systems - utilize ambient air moisture for hydration reactions
- Closed-loop reactors permit controlled vapor transport for better reversibility.

Key challenges to the design include ensuring a uniform reaction temperature, controlling the rates of gas flow or humidity, managing particle attrition, and minimizing thermal resistance. The coupling of heat-transfer engineering with chemical-reaction optimization remains one of the most important directions in TCS development.

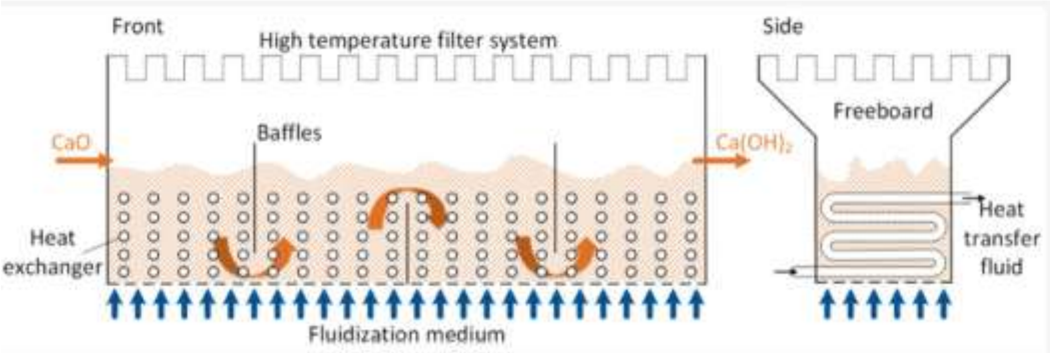

**Fig. 7.** Reactor design of a continuous TCS fluidized bed reactor. [10]

### 4.4.3 Gaps and Future Directions

Although progress has been significant, multiple gaps remain before TCS becomes ready for large- scale deployment. Key research needs include:

- Development of low-cost, fast-reacting materials with stable multi-cycle behavior
- Improved reactor designs with enhanced heat and mass-transfer characteristics
- Integration of LCA and techno-economic analysis into TCS evaluations
- Pilot-scale demonstrations to validate theoretical performance
- Coupling TCS with hybrid renewable energy systems for enhanced flexibility

Addressing these gaps will determine whether TCS can transition from laboratory-scale experimentation to industrially viable, long-duration thermal energy storage.

# 5. GAPS AND PROBLEM STATEMENT

## 5.1 Gaps

Identification of the research gaps for sensible, latent, and thermochemical TES systems is done through a systematic review of 31 peer-reviewed studies spanning material science studies, heat transfer design, encapsulation technology, and system engineering. The literature review was particularly focused on repeated patterns of limitations, contradictory results across studies, unverified claims, and areas where authors explicitly recommended further investigation.

| **TES Category** | **Key Technical Gaps** | **Examples / Evidence of Gap** | **Citations** |
|---|---|---|---|
| SHS | Low thermal conductivity; non-uniform heat transfer; Limited scale-up evidence | Metal-foam/fin enhancements show <20–30% improvement vs predicted 50–60% | [3] J. Shi, S. Wang, and G. Ma, "A review of metal foam for thermal energy storage applications," *International Journal of Heat and Mass Transfer*, vol. 195, 123145, 2022. |
| LHS (PCMs) | Low conductivity; Leakage; Poor cycling durability | Nanoparticles give only 5–15% real improvement vs theoretical 300% | [4] F. Mebarek-Oudina et al., "Nano-enhanced PCMs for improved thermal energy storage performance: A review," *Energies*, vol. 16, no. 3, pp. 1–22, 2023. |
| TCS | Slow kinetics; Poor reversibility; Structural degradation | Only 40–50% of theoretical capacity recovered; Pore collapse | [10] L. Xu et al., "Thermochemical energy storage: materials, systems and challenges," *Applied Energy*, vol. 277, 115605, 2020. |

## 5.2 Problem statement

TES is crucial to both renewable-energy stability and industrial heat management; however, practical deployment of the technology remains restricted due to various challenges in sensible, latent, and thermochemical systems. Sensible heat storage still faces the problems of low thermal conductivity and lack of uniform heat distribution, leading to a slow rate of charge and poor scalability. Latent heat storage, especially based on PCMs, has critical issues such as low conductivity, leakage, phase segregation, and rapid performance degradation. Thermochemical storage, despite high theoretical energy density, often shows slow reaction kinetics, irreversibility, and structural breakdown, while most of the systems realize less than half of their predicted storage capacity.

Although various studies predict enhancements with nanoparticles, composite matrices, encapsulation, and also new heat-exchanger designs, most of these approaches fail in practical applications because of nanoparticle agglomeration, capsule rupture, insufficient conductivity enhancement, or even unstable material cycling. Long-term durability data, standardized testing procedures, and also validated pilot-scale results are generally missing in the literature for all TES categories.

The key issue this review tries to overcome is the lack of a synthesized, critically analyzed knowledge of why existing SHS-LHS-TCS technologies are not able to meet operational specifications and what scientific and engineering barriers stand in the way of further progress. Synthesizing fragmented evidence on these matters, the review aims at an identification of specific research pathways toward increasing TES performance, durability, and commercial readiness.

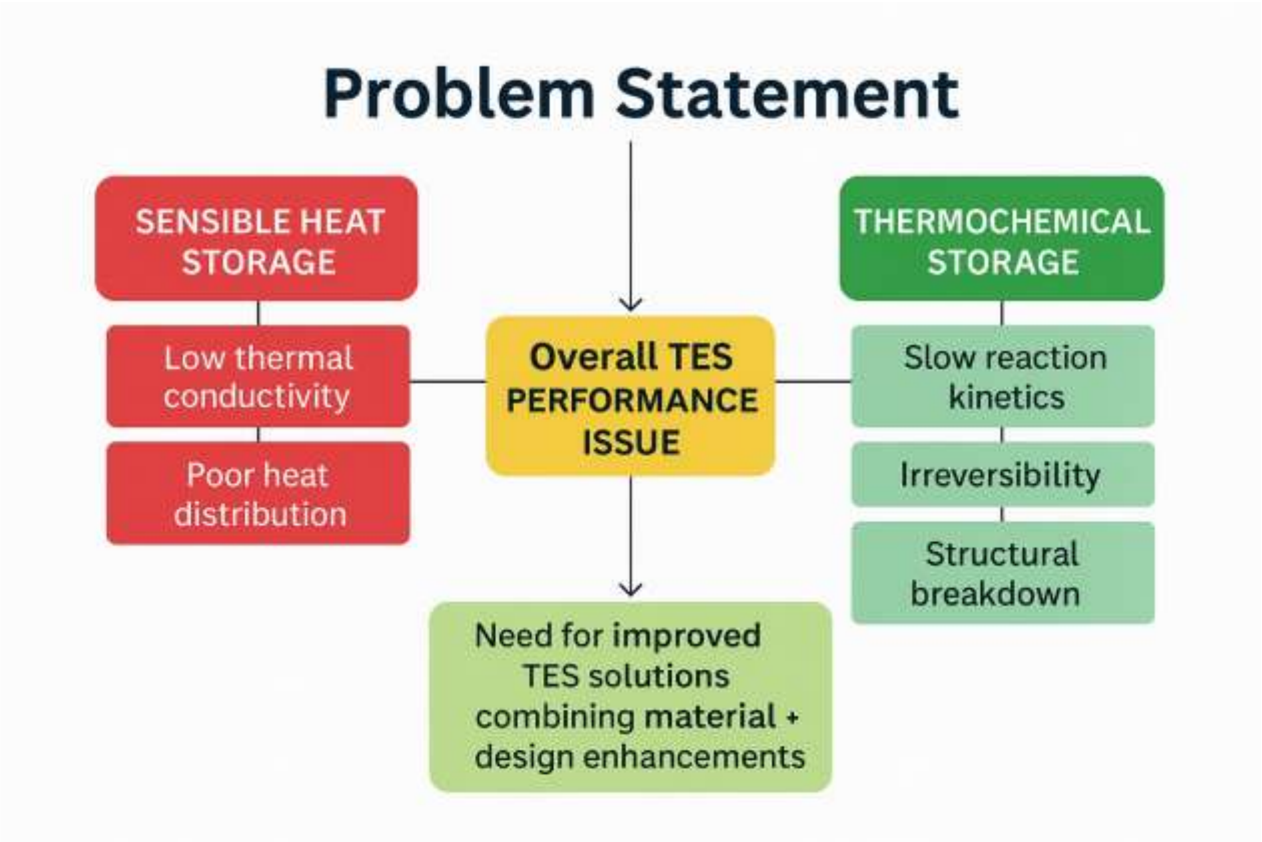

**Fig. 8.** Problem statement.

## 6. METHODOLOGY

This study encompasses a structured and systematic review methodology that is purposed to review, compare, and synthesize the advancement in sensible, latent, and thermochemical TES systems. The methodology includes six successive steps to ensure that the review study is transparent, reproducible, and academically sound:

1) selection of database and formulation of search expression
2) identification of studies
3) filtering through inclusion–exclusion criteria
4) classification and grouping of studies into themes
5) extraction of performance metric and comparative assessment
6) synthesis of research gap

### 6.1 Motivation

This calls for a need for a structured and rigorous review methodology, considering the rapid expansion and fragmentation of research related to TES. Many studies on sensible, latent, and thermochemical storage have used different experimental setups, enhancement techniques, performance indicators, and reporting formats, direct comparison of which is quite difficult, and drawing reliable conclusions is limited. A systematic approach is hence essential in filtering high- quality studies, creating a consistent evaluation framework, and synthesizing insights across diverse material and design modifications.

Moreover, most of the TES enhancement strategies, such as nano-additives, composite matrices, encapsulation, and advanced heat-exchanger geometries, although promising in laboratory results, are not validated for long-term or scalable applications. This gap justifies the need for a methodology that not only retrieves relevant literature but also critically assesses durability, scalability, and practical feasibility. It is ensured through the structured review process that the selected studies contribute meaningfully toward the understanding of the current limitations and give directions to future TES development.

## 6.2 Database Selection and Search Strategy

An extensive systematic search of the literature was performed in order to comprehensively survey the current status in TES studies regarding materials, design innovations, and performance enhancement methods. In this regard, major scientific databases, well-established for indexing high-impact journals in the fields of heat transfer, materials science, mechanical engineering, and renewable energy, were targeted. The databases utilized in this work include ScienceDirect (Elsevier), SpringerLink, IEEE Xplore, ASME Digital Library, MDPI, Taylor & Francis, and Google Scholar, all providing wide access to relevant experimental, numerical, and review publications.

A keyword-based Boolean search strategy was adopted to retrieve focused and meaningful research outputs. Keywords were organized around TES system types, enhancement mechanisms, and performance indicators. Typical representative search strings included:

- "Thermal energy storage" AND "design enhancement"
- "Phase change material" AND "nano-enhanced" AND "thermal conductivity"
- Thermochemical energy storage AND reaction kinetics AND cycling stability
- "Metal foam" AND "PCM" AND "heat transfer"
- "encapsulation" AND "PCM leakage"

These Boolean combinations were used to ensure that the search captured those studies addressing both material-level modifications and system-level design improvements. Searches were restricted to the period 2015–2025, allowing the review to encompass a decade of technological progress and emerging research trends in TES. This was followed by the identification of a total of 212 publications after the initial query.

## 6.3 Inclusion and Exclusion Criteria

The filtering of publications had to be done using a structured set of inclusion and exclusion criteria that ensured scientific validity, where only high-quality and data-rich studies were considered.

Inclusion Criteria

- Peer-reviewed journal articles or conference papers
- Focus on SHS, LHS, or TCS
- Quantitative performance indicator studies
- Papers on design innovations or material enhancement
- Durability, cycling stability, or degradation studies

Exclusion Criteria

- Patents, books without experiments, or non-peer-reviewed sources
- Those unrelated to TES or without thermal performance data
- Articles with incomplete methodology or missing metrics
- Various duplicate entries retrieved across databases

After applying these criteria, 31 papers were selected to be the core dataset.

### 6.4 Search Keywords and Database Summary

| Database | Keywords Used | Results Found | Shortlisted |
|---|---|---|---|
| ScienceDirect | TES, PCM, nano-enhanced, molten salts, cycling stability | 118 | 5 |
| SpringerLink | thermochemical storage, reaction reversibility, solid– gas TES | 42 | 3 |
| IEEE Xplore | heat exchangers, optimization, TES control systems | 19 | 4 |
| MDPI | encapsulation, bio-based PCMs | 21 | 6 |
| ASME | high-temp TES | 12 | 3 |
| Google Scholar | broad supplementary search | 60 | 10 |

### 6.5 Classification and Thematic Grouping

The 31 final studies were classified into three thematic groups:

1. Sensible Heat Storage (SHS):

The studies grouped under SHS focus on systems that store energy through temperature changes in either solid or liquid media. The research has mainly focused on the configuration of packed bed, molten-salt systems, and structures that enhance conduction, like fins and metal foams. These studies jointly emphasize improving thermal diffusivity, enhancing charge-discharge rates, and ensuring stability at large-scale operation.

2. Latent Heat Storage (LHS):

The range of LHS studies extends to organic, inorganic, and eutectic PCMs, and their modified forms such as nano-enhanced PCMs, composite PCMs, and encapsulated materials. Studies in this category focus on overcoming intrinsic low thermal conductivity of PCMs, enhancing melting/solidification kinetics, leakage prevention, and optimization of heat-exchanger geometries with faster and uniform thermal response.

3. Thermochemical Storage (TCS):

The TCS category includes works about reversible chemical and sorption reactions between materials like salt hydrates, metal oxides, and solid-gas reaction pairs. These studies basically develop reaction kinetics, reversibility, structural stability, and reactor design improvements for improved heat and mass transfer. These studies have emphasized the high theoretical energy density of TCS systems; however, most of them also proved that there are problems with a stable multi-cycle performance.

### 6.6 Gap Identification Method

Gaps are identified based on a structured three-stage evaluation process designed to align with key limitations observed across sensible, latent, and thermochemical TES technologies. In addition, this framework allows the synthesis of gaps-Section 4.5-to be based on measurable performance deviations, durability constraints, and cross-category deficiencies reported in the literature.

Stage 1 - Performance Discrepancy Analysis:

The first step compares the theoretical expectations against experimentally reported results. In latent heat storage, nanoparticles are theoretically expected to enhance the thermal conductivity of PCMs by up to 300%; however, most studies show only 10–15% enhancement because of agglomeration and viscosity effects [2], [4], [6]. Similarly, the metal-foam structures employed in SHS and LHS are expected to provide 50–60% heat transfer enhancement; however, empirical results regularly fall back in the 20–30% region, thus indicating interface and structural limitations [3], [17]. Materials like salt hydrates and oxides in thermochemical systems often recover only 40–50% of their theoretical enthalpy owing to incomplete reversibility and pore collapse [10], [11].

Stage 2 – Durability and Scalability Review:

The second stage dealt with long-term performance and scale-up feasibility. Most of the PCM studies report cycling stability for cycles less than 1000, thereby leaving long-term reliability unconfirmed [8], [19]. The common degradation mechanisms include leakage, phase segregation, and shell rupture in encapsulated PCMs [7], [25]. In the SHS systems, there are non-uniform temperature fields; thus, efficiency reduces at larger scales [16]. TCS materials have poor kinetics of reaction and structural breakdown over successive dehydration-rehydration cycles, which restricts system reversibility [10], [27]. For all classes, pilot-scale demonstrations are few, hence restricting real-world validation [14], [30].

Stage 3 - Cross-Category Comparison:

The final stage synthesized overlapping limitations across SHS, LHS, and TCS. One persistent issue involves non-standardized testing methodologies, with significant variability in heat-flux conditions, cycling protocols, and reporting metrics [28]. Similarly underdeveloped are techno- economic analyses and life-cycle assessments, which limit the scrutiny of scalability, cost, and environmental impact [22], [30]. TCS-related environmental concerns include nanoparticle toxicity, composite disposal, and reaction by-product management, all of which are insufficiently characterized [22], [23]. These cross-cutting gaps in state-of-the-art indicate that, despite promising laboratory advances, the realization of commercial viability in these TES technologies requires more integrated, long-term, and application-oriented research approaches.

# 7. CONCLUSION

This review reported modifications at both the design and material levels in sensible, latent, and thermochemical thermal energy storage systems, while emphasizing experimentally verified performance metrics and quantifiable disparities between theoretical predictions and practical realizations. In sensible heat storage, enhancements ranging from longitudinal fins and transversal perforations to open-cell metal foams exhibited only 20–30% heat transfer enhancement, despite best-case theoretical improvement predictions of 50–60% under ideal conduction pathways. Similarly, packed-bed and molten-salt systems continue to show temperature stratification and slow charge–discharge behavior, with large-scale units commonly yielding 10–15% lower thermal efficiencies than predicted due to axial conduction losses and thermal non-uniformity.

LHS systems demonstrate obvious advantages in volumetric energy density; however, they are practically limited by an intrinsic thermal conductivity as low as 0.2–0.4 W/m·K for most organic PCMs. Although nanoparticles may theoretically allow enhancements of more than 200–300%, experimental studies have consistently resulted in improvements within the 5–15% range due to nanoparticle agglomeration and sedimentation, increased viscosity, and weakened convection. Composite PCMs, based on graphite foams or expanded graphite matrices, reach higher levels of effective conductivity-often increased 20–60 times with respect to pure PCMs-but at the price of a reduction of 8–25% in latent heat content, due to the mass fraction of the supporting matrix. Encapsulation enhances shape stability and prevents leakage for more than 500–700 cycles; however, shell rupture, thermal contact resistance, and microcapsule fatigue limit the long-term reliability also beyond 1000 cycles.

TCS has the highest theoretical gravimetric energy density, mostly greater than 600–1200 kJ/kg. However, practical values recovered from the systems have been only 40–50% of the theoretical value. The reaction kinetics is still slow, and hydration/dehydration cycling shows incomplete conversion with pore collapse. Most TCS materials show structural degradation after 20–50 cycles, also not in accordance with the seasonal or industrial-scale storage requirements. Reactor-scale issues primarily related to poor heat and mass transport, non-uniform temperature fields, and resistive diffusion result in a 30–40% deficit with respect to the theoretical values for such systems.

A number of cross-cutting limitations have been identified in this review to be common across SHS, LHS, and TCS: a lack of uniform cycling protocols, long-duration stability tests, techno- economic and life-cycle assessments, and pilot-scale demonstrations able to validate improvements made at the laboratory scale. Overcoming such technical and methodological deficiencies requires the further development of thermal energy storage for commercially viable high-efficiency applications in renewable power systems, industrial waste heat recovery, and large-scale thermal management.

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