

Review

Advances in Thermal Energy Storage Systems for Renewable Energy: A Review of Recent Developments

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Abstract: This review highlights the latest advancements in thermal energy storage systems for renewable energy, examining key technological breakthroughs in phase change materials (PCMs), sensible thermal storage, and hybrid storage systems. Practical applications in managing solar and wind energy in residential and industrial settings are analyzed. Current challenges and research opportunities are discussed, providing an overview of the field's current and future state. Following the PRISMA 2020 guidelines, 1040 articles were initially screened, resulting in 49 high-quality studies included in the final synthesis. These studies were grouped into innovations in TES systems, advancements in PCMs, thermal management and efficiency, and renewable energy integration with TES. The review underscores significant progress and identifies future research directions to enhance TES's efficiency, reliability, and sustainability in renewable energy applications.

Keywords: thermal energy storage; phase change materials; renewable energy integration; hybrid storage systems; literature review



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1. Introduction

Thermal energy storage (TES) systems are necessary for enhancing renewable energy efficiency and reliability, storing surplus energy from sources like solar and wind to bolster grid stability and energy security. Recent TES advancements, particularly in phase change materials (PCMs), sensible thermal storage, and hybrid systems, promise improved energy density, cost reduction, and overall system efficiency [1–4]. PCMs are substances that absorb and release large amounts of thermal energy during their phase transition, typically from solid to liquid and vice versa. During this process, PCMs store heat when melting and release it upon solidifying, making them ideal components for thermal energy storage applications [1]. Various types of PCMs are used in TES, including organic, inorganic, and eutectic PCMs. Organic PCMs, such as paraffin, are known for their chemical stability and wide range of operating temperatures [3]. Inorganic PCMs, such as hydrated salts, offer a higher energy storage density and are frequently used in applications requiring high storage capacities [5]. Eutectic PCMs combine characteristics of both organic and inorganic materials, providing a tailored mix for specific applications that require a consistent melting point [6]. PCMs have several advantages, such as high energy storage capacity and the ability to operate at nearly constant temperatures during the phase change process [7]. However, they also face challenges, including low thermal conductivity, which can limit the heat transfer rate, and the need for encapsulation techniques to prevent material leakage and degradation over time [8]. In thermal energy storage systems, PCMs are essential for storing energy during high renewable energy generation periods, such as solar and wind. This energy storage capability allows for more efficient supply and demand management, enhancing grid stability and supporting the integration of renewable energy sources [9].

Thermal energy storage is crucial for the transition to renewable energy systems because it stores excess energy generated by intermittent sources such as solar and wind [1–3]. This article reviews recent advances in TES technologies, highlighting their importance in improving the stability and efficiency of renewable energy grids and reducing dependence on fossil fuels [4,10–12]. Additionally, this review provides a roadmap for future research, identifying key areas such as developing new phase change materials, hybrid thermal storage technologies, and integration strategies with renewable energy sources [5,13,14]. By addressing both the relevance of TES in the energy transition and the directions for future research, this article offers a comprehensive view of the current state and future potential of thermal energy storage technologies [15,16]. Techno-economic analyses emphasize optimizing TES for higher energy storage densities and thermal conductivities crucial for maximizing performance [10]. Studies on microencapsulated PCMs highlight their mechanical and thermal properties, suggesting superior performance over conventional systems [11]. Despite challenges in deployment and scalability, integrating PCMs in buildings shows potential for curbing fossil fuel use [3]. However, gaps remain. While various PCM compositions and configurations are explored, standardized testing protocols and real-world performance assessments are lacking. Addressing technical, economic, and regulatory barriers is essential for scaling TES integration into existing infrastructure [4,10,11]. This review surveys recent TES advancements, synthesizing the literature to identify research gaps and propose pathways for enhancing TES system efficiency, reliability, and cost-effectiveness in renewable energy applications.

The current literature extensively covers TES systems, focusing on enhancing efficiency and sustainability. Techno-economic analyses highlight the need for technological innovations to increase energy density, reduce investments, and enhance overall efficiency [1]. PCMs, such as microencapsulated sodium nitrate, are promising for improving thermal storage capacity compared to conventional systems [2]. In building applications, PCM-based TES reduces fossil fuel dependency despite challenges in implementation and costs [3]. Comparative studies emphasize efficient storage using eutectic mixtures like paraffin and palmitic acid for solar thermal applications [4]. Stable PCM emulsions are reviewed for their role in thermal management and energy storage [10]. Advances in TES categorize sensible, latent, and thermochemical technologies, guiding future research [11]. Natural stones enhance heat transfer in hybrid thermal storage systems [12], while optimization in porous media improves overall thermal performance [13].

High-temperature thermal storage systems employing salts and PCMs offer economic efficiency [14]. Sodium acetate trihydrate is a long-term PCM for diverse applications [5]. Integration with coal-fired plants optimizes sensible and latent storage, supporting thermal economic strategies [15]. Additives and encapsulation techniques continue to enhance PCM thermal properties [16]. Non-spherical PCM modules demonstrate effective industrial and domestic use [6], while lithium-based PCMs show promise in enhancing Stirling engines [17]. PCMs integrated into hydronic systems improve efficiency [6], and nano-emulsions stabilize energy systems [18]. Integrating net-zero greenhouses boosts overall efficiency [19], and reversible endothermic reactions of salts provide effective cooling solutions [20]. Concrete enhanced with PCMs improves efficiency in solar power plants [21], while combined renewable and thermal storage systems aim to replace fossil fuels [22]. Bio-based polymers integrated with PCMs enhance sustainability in industrial applications [23], and atomic layer deposition improves nanoparticle thermal storage [24]. Hybrid systems optimize charge/discharge cycles [25], while solar energy efficiency benefits from artificial photosynthesis and heat systems [26]. Geothermal heat pumps incorporating PCMs reduce environmental impact [27], and bio-based PCM matrices find applications in industrial settings [28]. Thermal conductive storage systems compete with sensible and latent heat systems [29], and decentralized agro-industrial PCM solutions reduce production costs [30]. Latent heat storage systems meet demands in solar energy applications [31], and PCM heat exchange systems integrate effectively with solar applications [32].

Plate-based PCM systems optimize energy storage and thermal efficiency [33], while Al-Si-Fe alloys promise high-temperature energy storage solutions [34]. Lifecycle assessments highlight CO₂ reduction and resource efficiency in PCM systems [35], and energetic analyses optimize thermal efficiency [36]. Composite materials improve PCM stability [37], and computational fluid dynamics (CFD) models refine PCM system designs [38]. Overall, PCM-based thermal storage systems are advancing energy efficiency and sustainability. High-performance PCMs enhance storage capacity and stability [36], and PCM integration with conductive materials improves overall efficiency [7]. Economic viability is driving widespread adoption of PCM systems [39], with microencapsulated PCMs reducing implementation costs [40] and numerical models refining system designs [41]. Industrial integration strategies further reduce costs [41], while bio-based PCMs enhance sustainability [42]. Inorganic PCMs support high-temperature applications [43], and PCM dispersion is advancing renewable energy integration [44]. System optimization across disciplines is critical [45], as PCM selection continues to focus on emissions reduction [46]. PCM systems are advancing air conditioning efficiency [47], and nanotechnology is enhancing PCM efficiency [48]. Integrated concentrated solar solutions are further improving overall system efficiency [49].

During the course of this review, several substantial gaps have emerged in the current literature on TES systems. Despite recent advances in technologies such as PCMs, sensible thermal storage, and hybrid systems, significant deficiencies remain. One notable gap is the lack of standardized testing protocols and comprehensive real-world performance assessments across various PCM systems, which limits accurate cross-study comparisons and practical deployment in industrial and residential contexts. Moreover, the seamless integration of TES systems into existing infrastructure confronts significant technical, economic, and regulatory hurdles that hinder widespread adoption and scalability. To address these issues, this review provides a roadmap for researching TES technologies. By synthesizing existing literature and highlighting critical areas that require further investigation, this study seeks to guide future research efforts toward optimizing TES systems. This roadmap is essential for overcoming the barriers to TES adoption and ultimately enhancing energy efficiency, supply reliability, and grid stability in transitioning toward more sustainable, low-carbon energy systems.

2. Methodology for the Literature Review

2.1. Introduction to PRISMA Methodology

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) is a widely accepted methodology to ensure clarity, transparency, and reproducibility in systematic reviews. The PRISMA Statement provides a detailed checklist and flow diagram that guide researchers through identifying, screening, and including studies in a systematic review [50]. PRISMA is well-suited for reviews in engineering and energy due to its structured approach, enabling thorough and unbiased synthesis of diverse studies. Unlike other methodologies, such as the Cochrane Handbook for Systematic Reviews of Interventions, MOOSE (Meta-analysis of Observational Studies in Epidemiology), GRADE (Grading of Recommendations Assessment, Development, and Evaluation), CONSORT (Consolidated Standards of Reporting Trials), and CHEERS (Consolidated Health Economic Evaluation Reporting Standards), which are specific to fields like healthcare and epidemiology, PRISMA offers a flexible framework applicable across various scientific domains, including materials science and energy management.

In the context of this review, the PRISMA methodology will be meticulously followed to ensure a robust and transparent literature synthesis. This review highlights the latest advancements in thermal energy storage systems, focusing on crucial technological breakthroughs, practical applications, and future research opportunities. By adhering to PRISMA 2020, this review will provide a comprehensive and reliable overview of the current state and future potential of thermal energy storage technology for renewable energy, facilitating informed decision-making and further advancements in the field.

Figure 1 illustrates the three main phases of the PRISMA methodology employed in this literature review. The Identification Phase involves developing a comprehensive search strategy, defining inclusion and exclusion criteria, and removing duplicates from the initial list of studies. The Screening Phase focuses on reviewing the titles and abstracts of the identified studies to ensure they meet the inclusion criteria, using a Boolean evaluation approach. The Included Phase entails a detailed review of the full-text articles that passed the screening phase, assessing their relevance, methodological rigor, and contribution to the field, and scoring them to select the highest-quality studies for the final synthesis.

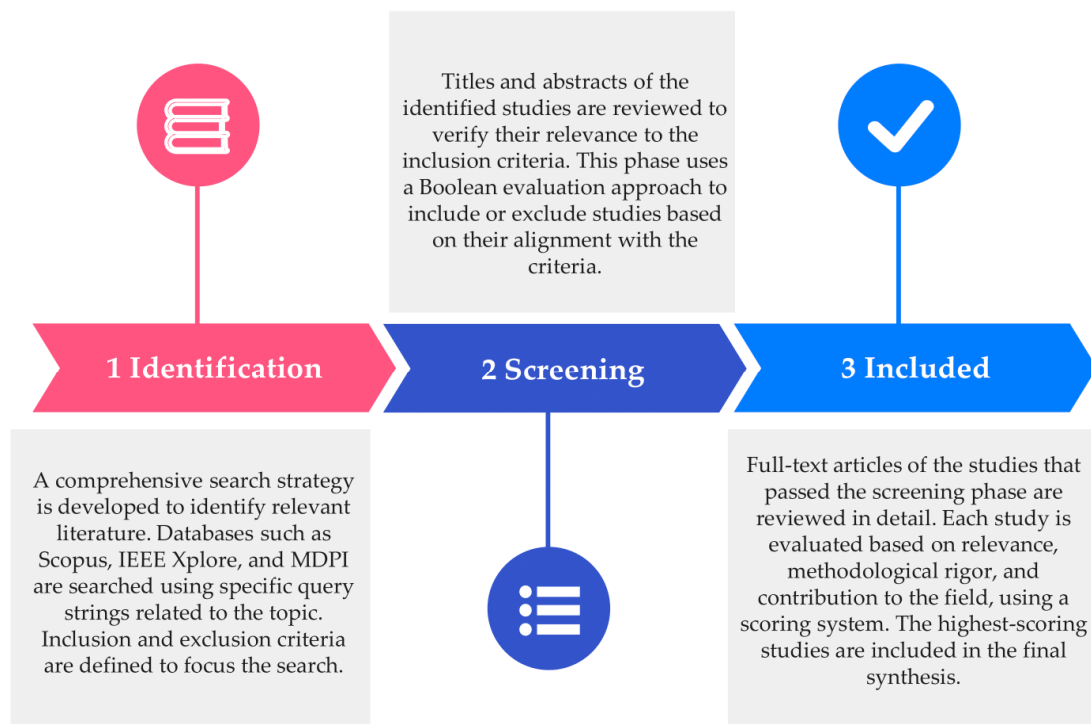


Figure 1. Simplified Process Diagram for PRISMA Methodology.

2.2. Identification Phase

The Identification Phase is the initial step in the PRISMA methodology, aiming to ensure a comprehensive and systematic approach to locating relevant studies for a systematic review. This phase involves developing a detailed search strategy, defining inclusion and exclusion criteria, and utilizing specific databases to gather literature. The primary objective is to compile a robust and unbiased collection of studies that address the advancements in TES systems for renewable energy.

2.2.1. Inclusion and Exclusion Criteria

We established specific inclusion and exclusion criteria to ensure a rigorous and comprehensive review of advancements in TES systems for renewable energy. The inclusion criteria focus on studies published within the last five years (2019–2024) to capture the most recent advancements, ensuring the relevance and timeliness of our review. We included only peer-reviewed journal articles to maintain a high standard of quality and reliability, as these works typically undergo thorough evaluation by experts in the field. Articles must be published in English to ensure consistency in language and facilitate comprehensive analysis. We specifically sought studies addressing TES advancements within the context of renewable energy applications, ensuring that the selected research directly contributes to our understanding of this specific area. In contrast, we excluded outdated research that primarily references data before 2019 and non-peer-reviewed sources and publication types such as conference papers, editorials, review articles, commentaries, book chapters, theses,

dissertations, white papers, and reports. Table 1 summarizes the inclusion and exclusion criteria established for selecting relevant studies.

Table 1. Inclusion and Exclusion Criteria for the Literature Review.

Inclusion	Criteria	Exclusion
Studies published within the last 5 years (2019–2024) to capture the most recent and relevant advancements in the field.	Publication Period	Studies that primarily reference data or advancements from before 2019, without contributing new findings or perspectives.
Only peer-reviewed journal articles will be considered to ensure the quality and reliability of the findings.	Type of Publications	The following types of publications will be excluded from the review: conference paper, editorials, review articles, commentaries, book chapters, theses and dissertations, white papers, reports.
Articles must be published in English to maintain consistency in language and facilitate comprehension. Studies must specifically address advancements in thermal energy storage systems within the context of renewable energy applications. Articles should present original research data or significant advancements in TES technologies, including phase change materials, sensible thermal storage, or hybrid systems.	Language	Articles published in languages other than English will be excluded.
	Focus on TES and Relevance	Articles that do not focus on TES in the context of renewable energy, or those that only peripherally mention TES without significant contribution to the field.

2.2.2. Databases

The bibliographic resources for this literature review were sourced from three prestigious databases: Scopus, IEEE Xplore, and MDPI. These databases were selected due to their extensive coverage of high-quality research articles, ensuring a comprehensive, transparent, and objective review.

- **Scopus:** Known for its stringent content selection standards and extensive coverage across multiple disciplines, Scopus provides access to high-quality, peer-reviewed materials. The platform’s advanced analytical tools and bibliometric indicators add credibility and depth to our review.
- **IEEE Xplore:** A leading resource for electrical engineering and related fields, IEEE Xplore grants access to influential and frequently cited publications, ensuring that the most current and relevant studies are included.
- **MDPI (Multidisciplinary Digital Publishing Institute):** As a fully open-access platform, MDPI makes peer-reviewed research accessible to a broad audience, promoting inclusivity and widespread dissemination of knowledge.

These databases offer a robust and diverse collection of relevant literature, capturing a broad spectrum of high-quality studies. By focusing on these well-regarded sources, we ensure that our review provides a comprehensive and reliable overview of the field, aligned with the highest standards of academic research.

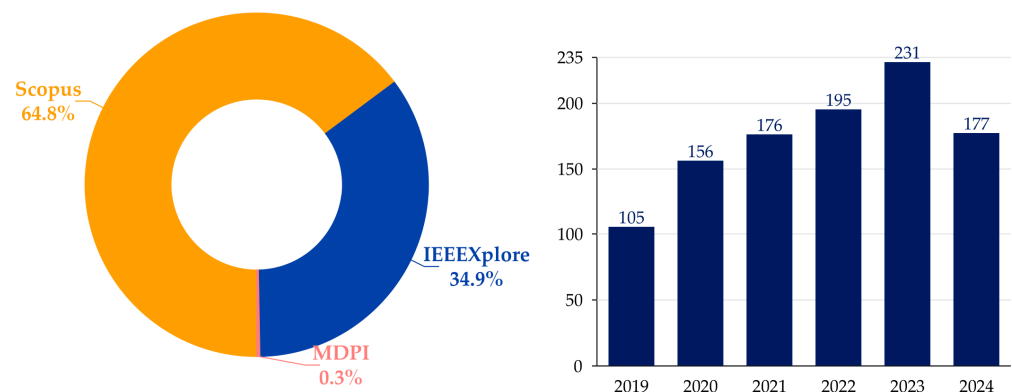
2.2.3. Search Terms

To execute a thorough literature search in the selected databases, the following search terms were defined based on the title and content of the introduction of this review article: “Thermal Energy Storage”, “Phase Change Materials and Technologies”, and “TES for Renewable Energy Integration”, as shown in Table 2.

Table 2. Query String Used in the Preferred Databases for Literature Prospection.

Database	Query String
Scopus	ALL ("Thermal Energy Storage") AND (TITLE-ABS ("Renewable energy")) AND (TITLE-ABS ("Phase Change Materials")) AND (LIMIT-TO (PUBYEAR, 2024) OR LIMIT-TO (PUBYEAR, 2023) OR LIMIT-TO (PUBYEAR, 2022) OR LIMIT-TO (PUBYEAR, 2021) OR LIMIT-TO (PUBYEAR, 2020) OR LIMIT-TO (PUBYEAR, 2019)) AND (LIMIT-TO (LANGUAGE, "English"))
IEEE Xplore	("All Metadata":Thermal Energy Storage) AND (("Abstract":Renewable energy) OR ("Abstract":Phase Change Materials))
MDPI	Filters applied: Journals, Year range: 2019–2024. Search text: Thermal Energy Storage; Search Type: All fields; AND; Search text: Renewable Energy; Search Type: Abstract; AND; Search text: Phase Change Materials; Search Type: Abstract; Years: between 2019 and 2024; Article Type: Article.

The application of search terms across each database yielded 1119 items. After the initial search, all identified articles were imported into reference management software (Zotero 7) to eliminate duplicates. This process allowed for the identification and removal of 79 duplicates, resulting in a final count of 1040 items for this first phase of the systematic review. Upon reviewing the metadata of the items, the statistics shown in Figure 2 were constructed.

**Figure 2.** Distribution of Items by Database and Year for the Identification Phase of the Literature Review.

Regarding items per database, Scopus generated the most significant results, with 674 items. This was expected due to Scopus's extensive coverage, which includes works from both IEEE Xplore and MDPI. Following Scopus, IEEE Xplore contributed a significant number of items, 363 in total, reflecting its specialization in the field of electrical engineering and related disciplines. MDPI, while providing considerably fewer items (3), still plays a crucial role in this review. However, it is important to note that the apparent low count of MDPI and IEEE Xplore items in the initial statistics results from our bibliographic management tool's duplicate elimination process. When the tool identifies duplicate entries across Scopus, IEEE Xplore, and MDPI, it retains the Scopus entry due to its broader indexing capabilities and removes the corresponding IEEE Xplore (IEEE-XXX) and MDPI (MDPI-XXX) entries. Consequently, although the numerical representation of MDPI and IEEE Xplore items appears reduced, their studies are not excluded from the review; rather, they are embedded within the Scopus dataset (S-XXX). This process ensures that all relevant research from these databases is included in our analysis, without redundancy. This approach allows us to present a comprehensive and high-quality review, effectively reflecting the contributions of IEEE Xplore and MDPI to the field. The limited number of items explicitly attributed to MDPI in Figure 2 should not be interpreted as a lack of consideration of MDPI works but as a technical consequence of our duplicate management strategy. In any case, the limited number of items from MDPI underscores the need for

comprehensive reviews that synthesize and highlight advancements in thermal energy storage systems for renewable energy, thereby contributing to the visibility and impact of high-quality research in this domain.

The statistics indicate a clear trend regarding item distribution by year. The number of items increases steadily from 105 in 2019 to a peak of 231 in 2023. Despite the year 2024 still being in progress, the current count of 177 items is promising and suggests that the trend of increasing research output in this field is continuing. This upward trajectory highlights the growing interest and advancements in thermal energy storage systems for renewable energy.

The resulting works will now be evaluated in the Screening Phase, where their titles and abstracts will be reviewed to verify their relevance and adherence to the inclusion criteria. Appendix A.1 provides the bibliographic information for all the resulting articles. Each item has been assigned an ID based on the database from which it was extracted, with prefixes corresponding to the initials of these databases. This system facilitates the management of information and the development of bibliometric analyses by the researchers.

2.3. Screening Phase

The Screening Phase is a critical component of the systematic review process, designed to ensure that only the most relevant and high-quality studies are included for further analysis. During this phase, the titles and abstracts of the identified studies are meticulously reviewed to verify their relevance to the predefined inclusion criteria. This evaluation is conducted using a Boolean approach, where each study is either included or excluded based on its alignment with the established criteria. To enhance the objectivity and reliability of this process, two independent researchers carry out the screening independently. Each researcher reviews and assesses all articles against the inclusion and exclusion criteria, thereby minimizing bias and subjective influence. This dual-screening method is crucial for increasing the reliability of the screening process and ensuring a thorough evaluation of each study.

A binary scoring system is employed during this phase, where a score of 1 indicates that an article fully meets the inclusion criteria and should be included, while a score of 0 signifies that the article does not meet at least one exclusion criterion and should be excluded. This clear and straightforward scoring system helps streamline the evaluation process and ensures consistency in the assessment of each study. In cases where there are discrepancies in the scoring between the two screeners, discussions are held to resolve these differences and reach a consensus. This collaborative approach further enhances the reliability and accuracy of the screening process, ensuring that the final selection of studies is comprehensive and precise.

The meticulous nature of the Screening Phase is essential for maintaining the integrity of the systematic review. The review can provide a robust and unbiased synthesis of the available literature by ensuring that only studies meeting all inclusion criteria are selected. The involvement of two independent screeners also ensures that diverse perspectives are considered, reducing the likelihood of overlooking relevant studies or including inappropriate ones.

Figure 3 contains an infographic that summarizes the Screening process of the review. A total of 346 articles (33% of the total sample) fully met the inclusion and exclusion criteria imposed in the review. The screeners filled out a verification matrix during this phase, providing a clear overview of the criteria and the screening process outcomes. This matrix is a valuable tool for documenting decision-making and ensuring transparency in how studies were selected or excluded. By adhering to these rigorous screening procedures, the review aims to deliver reliable and high-quality insights into the advancements in thermal energy storage systems for renewable energy.

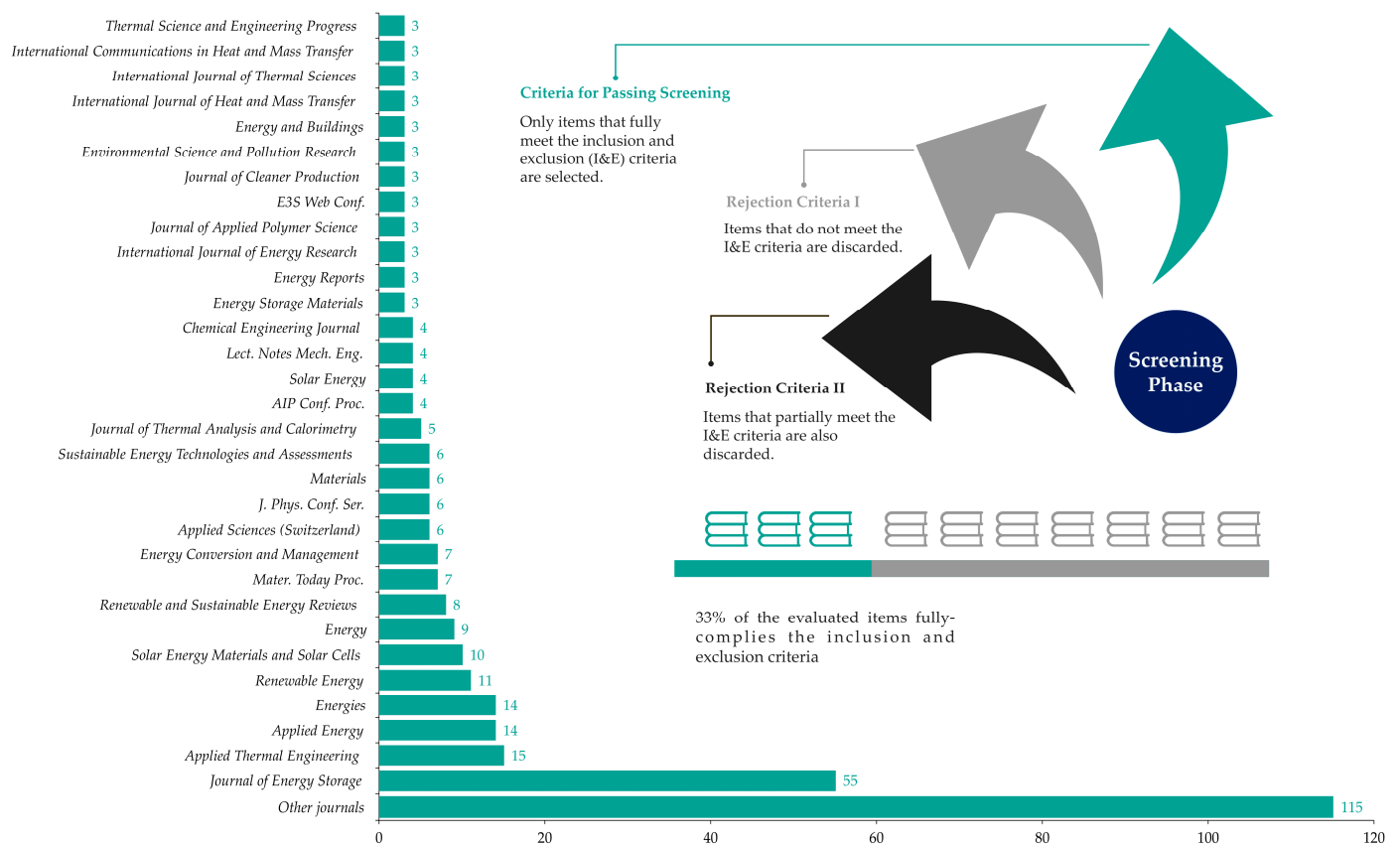


Figure 3. Infographic Summarizing the Screening Process and Verification Matrix.

2.4. Included Phase

The Included Phase involves a thorough Eligibility Assessment, where the 346 articles that passed the initial screening are subjected to a full-text review to evaluate their suitability for the final synthesis. This stage is crucial for ensuring that the selected studies are highly relevant and substantially contribute to the field. To achieve this, a series of criteria have been established, each evaluated on a scale of 1 to 3, to rigorously assess each article's eligibility. The criteria and metrics for full-text evaluation are outlined in Table 3.

Each study will be scored across these ten criteria, with higher scores indicating relevance, quality, and potential impact. The criteria are designed to provide a comprehensive assessment, covering aspects such as the study's relevance to TES and materials, methodological rigor, experimental validation, and the novelty and contribution of the findings. Clarity and completeness, technical depth, reproducibility, data quality and integrity, practical applicability, and overall impact on the field are also considered.

This detailed evaluation process ensures that only the most pertinent and high-quality studies are included in the final synthesis, thereby enhancing the robustness and reliability of the systematic review. Using a structured scoring system helps maintain consistency and objectivity in the evaluation, while the dual-screening process further minimizes bias and increases the credibility of the findings. By rigorously applying these criteria, the review aims to provide valuable insights and contribute significantly to advancing thermal energy storage systems and materials for renewable energy applications.

Table 3. Criteria and Metrics for Full-Text Evaluation.

Criterion	Description and Evaluation Metrics
Relevance to TES and Materials	How well the study addresses advancements in thermal energy storage systems and materials in the context of renewable energy applications. (1: Somewhat Relevant, 2: Relevant, 3: Highly Relevant)
Methodological Rigor	The robustness and appropriateness of the research methodology employed in the study. (1: Basic, 2: Adequate, 3: Excellent)
Experimental Validation	The extent to which the study includes experimental results, simulations, case studies, or real-world implementations. (1: Limited, 2: Moderate, 3: Extensive)
Novelty and Contribution	The originality and significance of the study’s contributions to the field. (1: Conventional, 2: Noteworthy, 3: Innovative)
Clarity and Completeness	The clarity of writing and the completeness of the information provided in the study. (1: Clear, 2: Very Clear, 3: Exceptionally Clear)
Technical Depth	The level of technical detail and depth in the study. (1: Introductory, 2: Detailed, 3: Highly Detailed)
Reproducibility	The extent to which the study provides enough detail to allow replication of the results. (1: Somewhat Reproducible, 2: Reproducible, 3: Highly Reproducible)
Data Quality and Integrity	The quality and integrity of the data presented in the study. (1: Acceptable, 2: Good, 3: Excellent)
Practical Applicability	The potential for practical application of the study’s findings in real-world scenarios. (1: Possible, 2: Likely, 3: Very Likely)
Impact on Field	The potential impact of the study’s findings on the field of thermal energy storage and materials for renewable energy. (1: Moderate, 2: Significant, 3: Groundbreaking)

Figure 4 illustrates the results of this comprehensive evaluation process. To determine the number of items to include in the final synthesis, a threshold of 75% of the maximum possible score (30 points) was established for the eligibility of items in this review. This criterion, equivalent to 22 points out of 30, ensures that only studies of high quality and relevance in the field of thermal energy storage systems and materials in renewable energy applications are selected. The included works are guaranteed to maintain high methodological rigor, clarity, technical depth, and potential impact in the field by setting such a high standard. This threshold promotes the inclusion of studies that contribute innovative and significant findings, are validated through experimental results, and present data of high quality and integrity. It helps filter out studies that, while interesting, do not meet the levels of excellence necessary to make substantial contributions to research and practical applications in thermal energy storage.

As evidenced in Figure 4, only 49 items met the minimum threshold of 22 points and were included in the final review. Figure 5 displays the statistics of the literature to be included. Figure 5a illustrates the annual evolution of publications, highlighting a marked interest in the topic in the current year (2024), underscoring this research’s relevance. The number of items has progressively increased from 6 in 2019 and 2021 to 14 in 2024, indicating growing scholarly attention and advancements in thermal energy storage systems and materials for renewable energy applications. Figure 5b shows the distribution of items by journal. The *Journal of Energy Storage* leads with 13 items, demonstrating its pivotal role in disseminating thermal energy storage research. This is followed by *Energies* with three items and both *Applied Sciences* (Switzerland) and *Applied Energy* with two items each. Other journals, such as *ASME International Mechanical Engineering Congress and Exposition Proceedings*, *Solar Energy Materials and Solar Cells*, and *Polymer Composites*, each contribute 1 item, reflecting a broad and diverse interest across various publications. This distribution highlights the interdisciplinary nature of research in this area, with contributions spanning multiple high-impact journals. The significant number of items from the *Journal of Energy Storage* and other key journals validate the quality and relevance of the selected studies, ensuring that the final review encompasses high-caliber research that can significantly advance the field of thermal energy storage.

ID	Relevance to TES and Materials	Methodological Rigor	Experimental Validation	Novelty and Contribution	Clarity and Completeness	Technical Depth	Reproducibility	Data Quality and Integrity	Practical Applicability	Impact on Field	Total
S-426	3	3	2	3	3	1	1	3	3	25	
S-446	3	3	2	3	3	1	1	3	3	25	
S-709	3	3	3	3	1	1	2	3	3	25	
S-222	3	3	2	3	2	1	1	3	3	24	
S-260	3	2	3	3	1	3	1	3	3	24	
S-478	3	3	2	3	1	1	1	3	3	23	
S-104	3	2	2	3	3	1	1	3	3	23	
S-174	3	3	2	3	3	1	2	3	1	23	
S-219	3	3	1	2	3	3	1	1	3	23	
S-280	3	2	2	3	3	1	2	3	2	23	
S-286	3	3	2	3	1	1	1	3	3	23	
S-287	3	3	1	2	3	3	1	1	3	23	
S-318	3	3	1	3	3	1	2	3	1	23	
S-362	3	3	3	2	3	1	1	1	3	23	
S-382	3	2	3	3	1	1	1	3	3	23	
S-402	3	3	2	3	1	1	1	3	3	23	
S-442	3	3	3	3	1	1	2	1	3	23	
S-460	3	2	3	2	3	1	2	1	3	23	
S-487	3	2	3	3	1	1	2	3	3	23	
S-495	3	2	2	3	3	1	1	2	3	23	
S-577	3	3	2	3	1	1	1	3	3	23	
S-669	3	3	1	2	3	3	1	1	3	23	
S-403	3	3	1	2	3	1	1	1	3	22	
S-604	3	2	2	3	3	1	1	3	1	22	
S-016	3	2	3	3	1	1	1	3	2	22	
S-022	3	3	2	3	1	1	2	3	1	22	
S-069	3	2	3	2	3	1	1	1	3	22	
S-110	3	3	2	3	1	1	1	2	3	22	
S-150	3	3	2	2	3	1	1	1	3	22	
S-189	3	3	2	2	3	1	1	1	3	22	
S-203	3	2	3	2	3	1	1	1	3	22	
S-235	3	3	1	2	3	1	1	2	3	22	
S-242	3	3	1	3	3	1	1	1	3	22	
S-243	3	3	3	2	3	2	1	1	3	22	
S-302	3	2	2	3	3	1	2	1	3	22	
S-307	3	3	2	2	3	1	1	1	3	22	
S-373	3	2	3	2	3	1	1	1	3	22	
S-428	3	2	3	2	3	1	1	1	3	22	
S-444	3	3	1	3	3	1	1	1	3	22	
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S-206	3	2	3	2	3	1	1	2	3	21	
S-231	3	2	1	2	3	1	1	2	3	21	
S-244	3	3	1	2	3	1	1	1	3	21	
S-241	3	2	3	2	3	3	2	1	1	21	
S-247	3	3	3	2	3	1	1	1	3	21	
S-259	3	3	1	2	3	3	1	1	3	21	
S-275	3	3	2	3	3	1	2	2	1	21	
S-291	3	3	1	2	3	3	1	1	3	21	
S-301	3	2	3	3	1	1	1	3	1	21	
S-317	3	2	3	3	3	1	1	1	3	21	
S-322	3	2	2	3	3	1	1	2	3	21	
S-325	3	3	1	2	3	1	1	1	3	21	
S-326	3	2	2	3	1	1	1	3	3	21	
S-327	3	3	1	2	3	3	1	1	3	21	
S-333	3	2	3	2	3	1	1	2	3	21	
S-358	3	2	2	3	1	1	1	3	3	21	
S-363	3	3	2	3	3	1	1	1	3	21	
S-371	3	3	3	2	3	1	1	1	3	21	
S-398	3	2	2	3	3	1	1	3	1	21	
S-405	3	1	3	2	3	1	1	1	3	21	
S-421	3	3	2	3	3	1	1	1	3	21	
S-422	3	2	2	3	3	1	1	2	3	21	
S-434	3	2	3	2	3	1	1	2	3	21	
S-443	3	3	3	2	3	1	1	2	2	21	
S-451	3	1	3	2	3	1	1	1	3	21	
S-464	3	2	2	3	3	1	1	1	3	21	
S-507	3	2	3	2	3	1	1	2	3	21	
S-566	3	3	1	2	3	1	1	1	3	21	
S-572	3	3	1	2	3	3	1	1	3	21	
S-578	3	3	1	2	3	1	1	1	3	21	
S-589	3	2	3	3	3	1	1	1	3	21	
S-590	3	3	1	2	3	3	1	1	3	21	
S-592	3	1	1	3	3	1	1	2	3	21	
S-607	3	2	3	3	3	1	1	1	3	21	
S-617	3	3	1	2	3	3	1	1	3	21	
S-627	3	3	2	2	3	1	1	2	2	21	
S-636	3	2	2	2	3	1	1	2	3	20	
S-647	3	2	3	3	3	1	1	1	2	20	
S-652	3	2	3	3	3	1	1	2	1	20	
S-656	3	1	3	2	3	1	1	1	3	20	
S-659	3	1	1	3	3	1	1	1	3	20	
S-668	3	2	2	3	3	1	1	1	3	20	
S-679	3	3	3	2	3	1	1	1	2	20	
S-681	3	2	2	3	3	1	1	1	3	20	
S-697	3	1	2	2	3	1	1	1	3	20	
S-101	3	2	2	2	3	2	1	1	3	20	
S-105	3	2	3	2	3	1	1	1	3	20	
S-109	3	3	3	2	3	1	1	2	1	20	
S-127	3	3	1	3	3	1	1	1	3	20	
S-128	3	3	1	3	3	1	1	1	3	20	
S-137	3	2	3	2	3	1	1	1	3	20	
S-143	3	3	1	3	3	1	1	1	3	20	
S-146	3	1	1	2	3	3	1	1	2	20	
S-158	3	3	1	3	3	1	1	1	3	20	
S-162	3	2	3	2	3	1	1	1	3	20	
S-165	3	2	3	2	3	1	1	1	3	20	
S-168	3	2	3	2	3	1	1	1	3	20	
S-176	3	1	3	3	3	1	1	1	3	20	
S-179	3	3	3	2	3	1	1	2	1	20	
S-184	3	3	2	2	3	1	1	1	3	20	
S-196	3	3	2	2	3	1	1	1	3	20	
S-221	3	1	1	3	3	1	1	1	3	20	
S-223	3	1	1	3	3	1	1	1	3	20	
S-236	3	3	1	2	3	1	1	1	2	20	
S-237	3	3	2	3	3	1	1	2	1	20	
S-246	3	3	2	3	3	1	1	1	3	20	
S-250	3	1	1	3	3	1	1	1	3	20	
S-254	3	2	1	2	3	1	1	1	3	20	
S-264	3	2	2	2	3	1	1	1	2	20	
S-267	3	1	3	3	3	1	1	1	3	20	
S-269	3	2	1	2	3	1	1	1	3	20	
S-293	3	1	1	2	3	2	1	1	3	20	
S-297	3	3	1	3	3	1	1	1	3	20	
S-304	3	1	1	3	3	1	1	1	3	20	
S-310	3	2	2	2	3	1	1	3	2	20	
S-321	3	2	3	2	3	1	1	1	3	20	
S-345	3	2	1	2	3	1	1	1	3	20	
S-354	3	3	3	2	3	1	1	2	1	20	
S-368	3	2	3	2	3	1	1	1	3	20	
S-383	3	2	1	2	3	1	1	1	3	20	
S-412	3	3	3	2	3	2	1	1	1	20	
S-436	3	3	1	2	3	1	1	2	3	20	
S-449	3	2	3	2	3	1	1	1	3	20	
S-473	3	2	3	2	3	1	1	1	3	20	
S-480	3	1	3	3	3	1	1	1	3	20	
S-488	3	1	3	3	3	1	1	1	3	20	
S-489	3	2	3	2	3	1	1	1	3	20	
S-514	3	2	3	2	3	1	1	1	3	20	
S-535	3	2	1	2	3	1	1	1	3	20	
S-581	3	2	2	3	3	1	1	1	3	20	
S-584	3	2	3	2	3	1	1	1	3	20	
S-585	3	3	2	3	3	1	1	2	1	20	
S-588	3	2	3	2	3	1	1	1	3	20	
S-623	3	3	2	2	3	1	1	1	3	20	
S-641	3	2	3	2	3	1	1	1	3	20	
S-648	3	2	3	2	3	1	1	1	2	20	
S-674	3	2	3	2	3	1	1	1	3	20	
S-605	1	1	3	2	3	1	1	1	3	19	
S-006	1	3	3	2	3	1	1	1	3	19	
S-007	3	1	1	2	3	3	1	1	3	19	
S-011	1	3	3	2	3	1	1	1	3	19	
S-018	3	2	3	2	3	1	1	1	2	19	
S-035	3	3	1	2	3	1	1	1	3	19	
S-048	3										

Finally, Figure 6 displays the complete flowchart of the PRISMA methodology followed in this systematic review. This flowchart outlines each phase of the process, from the initial identification and screening of studies to the final inclusion of high-quality, relevant articles [50].

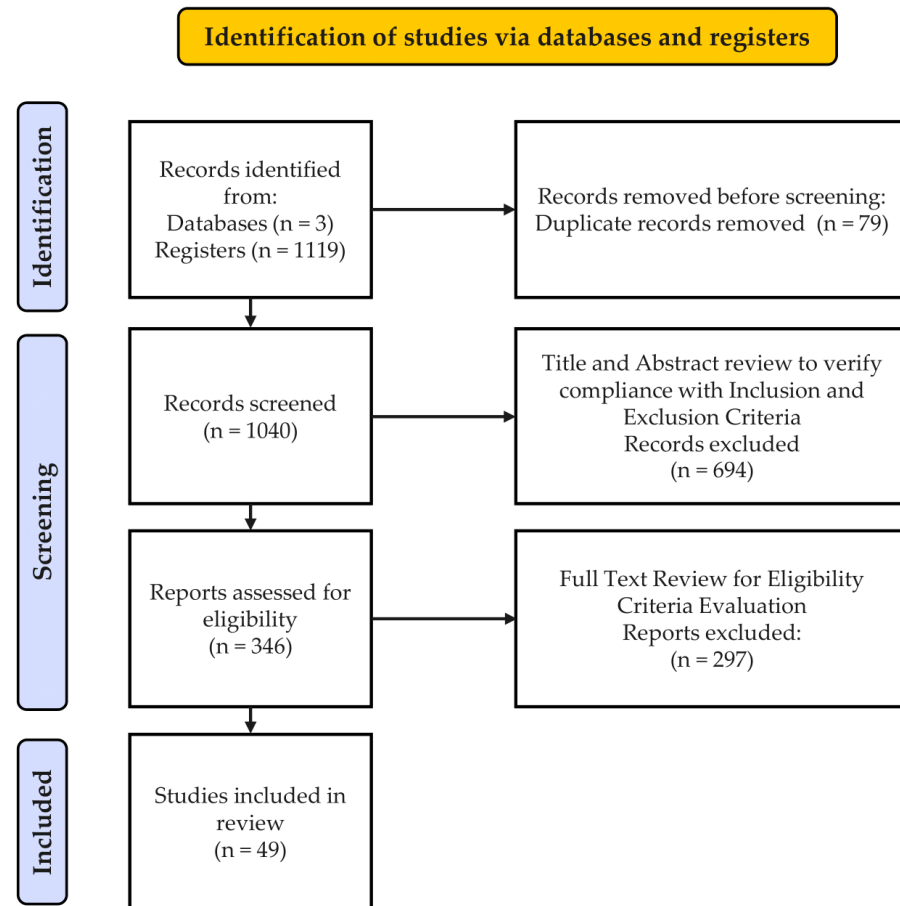


Figure 6. Flowchart of the Overall Literature Review Methodology.

3. Synthesis of the Articles Included in the Literature Review

This section synthesizes the articles included in the literature review, focusing on recent advancements and innovations in thermal energy storage systems. The synthesis is organized into key thematic areas, highlighting significant developments in material innovation, hybrid storage technologies, and advanced encapsulation methods. Each subsection provides a detailed overview of the state-of-the-art technologies, addresses existing challenges, and outlines potential directions for future research.

3.1. Innovations in TES Systems

3.1.1. New Latent Heat Storage Materials

The development of phase change materials (PCM) has been crucial for enhancing the capacity and efficiency of thermal storage. Recent advancements have focused on creating materials with high storage capacity and improved thermal stability [9]. For instance, research on direct steam generation (DSG) in solar collectors has shown promising results for high-temperature solar applications using advanced materials that enhance thermal stability and storage capacity [51]. Additionally, research on laminar forced convection in channels with PCM has demonstrated significant improvements in heat transfer and system efficiency, which is vital for industrial and residential applications [52]. A notable aspect of modern PCMs is their ability to store higher energy density. This is achieved through the use of novel compounds and advanced manufacturing techniques. A recent study

presented PCM materials with improved thermal conductivity and storage capacity due to the incorporation of additives and optimization of the material's molecular structure [53]. These advancements are essential for applications where efficiency and stability are critical, such as solar and wind power generation [54–56].

3.1.2. Hybrid Thermal Storage Technologies

Hybrid systems that combine sensible and latent heat storage represent a significant innovation in thermal energy storage [57]. These systems leverage the advantages of both types of storage to optimize capacity and energy efficiency. For example, a hybrid technology that integrates sensible and latent thermal storage has been developed, enhancing energy efficiency and system stability in industrial applications [58]. This combination allows for more flexible thermal energy management, which is crucial for applications requiring a quick and efficient response to fluctuations in energy demand [7,59,60]. A recent experimental study evaluated the effectiveness of a hybrid system in solar applications, demonstrating that integrating PCM into sensible storage systems can significantly improve storage efficiency and thermal energy management capacity [61]. This hybrid approach maximizes the amount of stored energy and improves the system's operational efficiency, reducing energy losses and increasing sustainability [62–64].

3.1.3. Microencapsulation and Nanoencapsulation of PCM

The encapsulation of phase change materials is a technique that has shown promising results in improving the thermal and mechanical properties of PCMs [65]. Microencapsulation protects the active material and enhances its integration into various applications, while nanoencapsulation offers a larger surface area and better distribution of the encapsulated material [66]. A recent study presented an analysis and experimentation on PCM encapsulation for solar applications, highlighting how this technique can improve the system's efficiency and thermal stability [67–69]. Encapsulation protects PCMs from degradation and leakage and improves heat transfer by increasing the contact surface between the PCM and the surrounding medium [8]. Research has shown that the nanoencapsulation of PCMs can significantly increase the material's thermal conductivity, enabling faster and more efficient heat transfer [70]. This is particularly beneficial in applications where rapid response and high efficiency are essential, such as in renewable energy systems and heating and cooling applications [6,71,72].

Additionally, advanced encapsulation methods, such as composite materials and layer deposition techniques, have allowed the development of PCMs with superior thermal and mechanical properties [73,74]. These methods improve the stability and storage capacity of PCMs and facilitate their integration into a wide range of applications, from renewable energy generation to energy management in buildings [7,34,40]. Thus, advancements in TES systems are driving significant improvements in energy storage capacity, efficiency, and sustainability, which is crucial for effectively integrating renewable energy into the power grid. These developments enhance the operational efficiency of storage systems and reduce reliance on fossil fuels, promoting a more sustainable and resilient energy future [75–78].

3.2. *Advances in PCM*

3.2.1. Development of Biomaterial-Based PCMs

Phase change materials derived from biomaterials have shown great potential for improving sustainability in industrial and residential applications. Based on renewable sources, these materials reduce environmental impact and offer competitive thermal properties. A recent study demonstrated the effectiveness of biomaterial-based PCMs in building thermal regulation, significantly reducing reliance on traditional heating and cooling systems [51,66]. Additionally, integrating these materials into industrial applications has enabled more efficient energy management, leveraging the inherent properties of biomaterials to improve thermal stability and storage capacity [52,67]. A notable example is

the use of PCMs derived from vegetable oils and animal fats, which have shown high heat storage capacity and robust thermal stability. These materials are biodegradable and can be produced at low cost, making them a viable option for a wide range of applications [68,73]. Experimental studies have confirmed that these PCMs can be effectively encapsulated to enhance their performance and durability, which is essential for long-term applications [56,71].

3.2.2. High-Temperature Inorganic PCMs

Inorganic PCMs operating at high temperatures have gained attention for their ability to withstand extreme conditions, making them ideal for high-demand energy applications such as concentrated solar power. These materials, such as molten salts, can store large amounts of thermal energy and release it in a controlled manner, improving the efficiency of power generation systems [54,61]. Research has shown that inorganic PCMs, such as calcium chloride and sodium nitrate, possess superior thermal properties and high storage capacity, making them suitable for integration into concentrated solar power systems [53,60]. Furthermore, using these materials in industrial applications has allowed for better waste heat management, optimizing energy use, and reducing greenhouse gas emissions [6,79]. A recent study evaluated the integration of inorganic PCMs in thermal storage systems at concentrated solar power plants, demonstrating significant improvements in system efficiency and stability [80]. These materials have also been investigated for their ability to be reused in multiple thermal cycles without significant degradation, which is crucial for sustainable industrial applications [70,77].

3.2.3. Innovations in Composite and Nanoscale Materials

Advances in composite materials and nanomaterials have opened new possibilities for enhancing the thermal properties and stability of PCMs [81]. Incorporating nanomaterials, such as metal nanoparticles and carbon nanotubes, into PCMs has been shown to improve these materials' thermal conductivity and storage capacity [8,75]. These innovations allow for more efficient heat transfer and quicker thermal response, essential for dynamic and high-demand energy applications. An example of these innovations is the creation of composite PCMs with nanomaterials, which enhance thermal storage capacity and increase mechanical strength and material stability [76,82]. Studies have shown that incorporating carbon nanotubes into PCMs can increase thermal conductivity by up to 50%, significantly improving system efficiency [59,63].

Moreover, nanoscale composite materials allow a more uniform distribution of the encapsulated material, improving thermal stability and PCM durability [62,83]. These innovations are crucial for applications requiring precise and efficient thermal management, such as high-power electronics and renewable energy systems [55,84,85]. Therefore, advances in phase change materials are transforming the efficiency and sustainability of thermal energy storage. Biomaterial-based PCMs offer an eco-friendly and efficient alternative for industrial and residential applications, while high-temperature inorganic PCMs provide robust solutions for high-demand energy applications. Innovations in composite and nanomaterials are significantly enhancing the thermal properties and stability of PCMs, enabling more efficient thermal energy management across a wide range of applications [78,86–90].

3.3. Thermal Management and Efficiency

3.3.1. Improvement in Thermal Conductivity

Improving the thermal conductivity of PCMs is essential for optimizing heat transfer and the overall efficiency of TES systems [91]. A promising approach to increasing thermal conductivity is the incorporation of nanomaterials, such as metal nanoparticles and carbon nanotubes, into PCMs. These additives significantly enhance the PCM's ability to transfer heat, resulting in greater energy efficiency [51,67]. Recent studies have shown that adding aluminum and copper nanoparticles to PCMs can increase thermal conductivity by up

to 30%, markedly improving system performance [53,73]. Using composite materials that combine PCMs with conductive matrices has also developed advanced solutions for high thermal demand applications [52,59]. Another effective method to improve thermal conductivity is the structural design of PCMs. Creating porous structures and including metal fins in PCMs have positively enhanced heat transfer [61,86]. These strategies increase thermal conductivity and improve thermal stability and material durability, which is crucial for long-term applications [8,62].

3.3.2. PCM-Based Heat Exchanger Systems

Heat exchanger systems using PCMs represent a significant innovation for improving energy efficiency in residential and industrial applications [92]. These systems leverage the PCM's ability to store and release large amounts of thermal energy during phase transitions, allowing for more efficient and sustainable thermal management [54,58]. The design and implementation of these systems focus on maximizing the contact surface between the PCM and the surrounding medium, facilitating faster and more efficient heat transfer [75]. A recent study evaluated the effectiveness of PCM-based heat exchangers in residential heating and cooling systems, demonstrating a significant reduction in energy consumption and an improvement in thermal comfort [70,79]. In industrial applications, PCM-based heat exchangers are highly effective for waste heat recovery, optimizing energy use, and reducing greenhouse gas emissions [56,82]. These systems allow for more flexible and efficient integration of thermal storage technologies, enhancing sustainability and cost-effectiveness in industrial operations [60,93].

3.3.3. Computational Modeling and Simulation

Modeling and simulation tools, such as computational fluid dynamics (CFD), are crucial in designing more efficient and reliable TES systems. These tools enable researchers and designers to analyze and optimize the thermal behavior of PCMs and thermal energy storage systems under various operating conditions [55,66]. The use of CFD has facilitated the understanding of heat transfer processes and the mechanisms of melting and solidification in PCMs, providing valuable insights for improving the design and efficiency of TES systems [6,68]. A notable example is the modeling of PCM-based heat exchangers, where simulations have helped identify optimal configurations that maximize heat transfer and minimize energy losses [63,87]. Additionally, computational simulations allow for evaluating TES systems' performance in real-world scenarios, essential for developing practical and scalable solutions [63,76]. These tools have also been fundamental in designing composite materials and advanced structures that enhance the thermal properties and stability of PCMs [88,94]. Hence, improving thermal conductivity, innovative heat exchanger system design, and using modeling and simulation tools drive significant advances in thermal management and efficiency of thermal energy storage systems. These developments improve operational efficiency, contribute to sustainability, and reduce reliance on fossil fuels [64,71,74,80,83,84,89].

3.4. Renewable Energy Integration with TES

3.4.1. Applications in Solar and Wind Energy

Integrating TES systems with solar and wind energy technologies has improved grid stability and reliability. These systems allow for storing excess energy generated during high-production periods and releasing it during low-generation periods, thus balancing energy supply and demand [51,61]. A recent study evaluated the effectiveness of TES in solar plants, showing how thermal storage capacity significantly improves operational efficiency and production stability [2,8]. Similarly, in wind energy, integrating TES has allowed for better management of fluctuations in energy generation, ensuring a more consistent and reliable supply [52,82]. These applications optimize the use of renewable energies and contribute to reducing greenhouse gas emissions [58,73].

3.4.2. Reducing Dependence on Fossil Fuels

Integrating TES systems has proven to be an effective strategy for reducing fossil fuel dependence in various sectors. Industry and power generation case studies have shown how TES can store thermal energy during low-demand periods and release it when needed, thus minimizing the need for fossil fuel-based energy sources [8,66]. A notable example is the use of TES in cogeneration plants, where thermal storage allows for maximizing the energy generated and reducing fossil fuel consumption [79,93]. In the industrial sector, implementing TES has enabled more efficient waste heat management, using this stored energy for production processes and significantly reducing the need for additional energy [59,75]. These case studies underscore the potential of TES to promote a transition to more sustainable and less fossil fuel-dependent energy systems [55,86].

3.4.3. Autonomous and Off-Grid Systems

TES systems in autonomous and off-grid applications have been crucial for providing sustainable energy solutions in remote areas without access to the electrical grid. These systems allow for storing energy generated by renewable sources, such as solar and wind, and using it when needed, ensuring a reliable and continuous energy supply [54,70]. In isolated regions, TES has enabled the implementation of autonomous energy systems that do not depend on fossil fuels, improving the quality of life and promoting sustainable development [6,56]. A recent study highlighted the effectiveness of TES in rural communities, where stored energy is used for lighting, heating, and other essential services, reducing the need for diesel generators and decreasing carbon emissions [60,76].

Furthermore, off-grid TES systems are essential for critical applications, such as health centers and telecommunications, where reliable energy supply is vital [62,68]. These systems provide sustainable energy and offer greater resilience against natural disasters and other supply interruptions [87,94]. Therefore, integrating thermal energy storage systems with renewable energy technologies transforms how we manage and use energy. These solutions improve grid efficiency and stability, reduce fossil fuel dependence, and provide sustainable energy solutions for remote and autonomous communities [63,64,69,80,88].

3.4.4. Grid-Connected Systems

Grid-connected systems, or on-grid systems, are energy configurations that are directly integrated with the main electrical grid. Unlike off-grid systems, which operate independently and require comprehensive local energy storage solutions, on-grid systems can interact dynamically with the grid. This integration allows for both the export of excess generated energy back to the grid and the import of energy when additional supply is needed, providing flexibility and reliability in energy management [18]. One of the main advantages of grid-connected systems is their ability to use the grid as a backup power source, reducing the need for extensive local energy storage solutions. This capability minimizes the costs associated with energy storage, such as the need for large-scale battery systems, and allows users to sell excess energy back to the grid, potentially generating additional revenue [25]. For instance, during high renewable energy generation periods, such as midday solar peaks, excess energy can be fed back into the grid, enhancing overall grid stability and reducing reliance on fossil fuel-based power generation [32].

Grid-connected systems are commonly employed in urban and industrial environments where access to the electrical grid is readily available. In these settings, TES can be optimized to store excess renewable energy generated during periods of low demand and release it during peak times, thus enhancing the overall efficiency and stability of the energy supply [36]. This approach is handy for managing energy loads in large buildings and industrial facilities, where energy consumption patterns can vary significantly throughout the day. Compared to off-grid systems, which must be entirely self-sufficient, grid-connected systems benefit from the support of the main electrical grid, which reduces the reliance on large-scale storage and provides greater flexibility in energy management. This ensures a more consistent power supply and allows for better integration of variable

renewable energy sources, such as solar and wind, into the energy mix [40]. The integration of TES in grid-connected systems also plays a significant role in demand-side management and grid stability. By storing excess energy during periods of low demand and releasing it during peak demand, TES helps balance supply and demand, reducing strain on the grid and supporting the integration of renewable energy sources [43]. This capability is critical for modern energy systems that aim to increase the share of renewables while maintaining reliability and efficiency.

Table 5 highlights the primary innovations and corresponding challenges identified in the study of TES systems. This comprehensive overview underscores the novel advancements in various areas, such as new latent heat storage materials, hybrid thermal storage technologies, and improvements in thermal conductivity. Additionally, the table addresses the integration of TES with renewable energy sources, demonstrating significant progress in reducing fossil fuel dependence and enhancing the sustainability of autonomous and off-grid systems. These insights emphasize the potential of TES technologies and outline the critical hurdles that need to be addressed to pave the way for future original research and practical applications in this evolving field.

Table 5. Innovations and Challenges in Thermal Energy Storage Systems Study.

Area of Innovation	Innovations Found	Challenges Arising from Innovations
New Latent Heat Storage Materials	-Direct steam generation in solar collectors with advanced materials [1]. -Enhanced heat transfer through forced laminar convection in channels with PCM [3]. -PCM materials with improved thermal conductivity and storage capacity through additives and molecular optimization [2].	-Improve thermal stability and long-term storage capacity. -Scalability and industrial application of these techniques. -Stability and efficiency under different operational conditions.
Hybrid Thermal Storage Technologies	-Systems combining sensible and latent storage, enhancing energy efficiency and stability [4]. -Integration of PCM in hybrid solar systems, optimizing storage and efficiency [5].	-Effective integration into existing systems and management of rapid response to demand fluctuations. -Minimize energy losses and increase system sustainability.
Microencapsulation and Nanoencapsulation of PCM	-Advanced microencapsulation techniques to improve efficiency and thermal stability [13]. -Nanoencapsulation enhancing thermal conductivity and heat transfer [70].	-Develop cost-effective and durable encapsulation methods for long-term applications. -Evaluate the feasibility of large-scale production and impact on overall system efficiency.
Biomaterial-Based PCM	-PCM derived from vegetable oils and animal fats with high heat storage capacity and thermal stability [51,73]. -Effective integration in industrial and residential applications [52,67].	-Ensure sustainability and minimize production costs.
High-Temperature Inorganic PCM	-Use of molten salts and other inorganic PCM in high energy demand applications [54,61]. -Integration in concentrated solar power systems, enhancing efficiency and stability [80].	-Solve encapsulation and durability issues in different environments. -Ensure thermal stability and storage capacity over multiple thermal cycles. -Evaluate material reuse and durability under industrial conditions.
Composite and Nanoscale Materials Innovations	-Incorporation of metal nanoparticles and carbon nanotubes in PCM to enhance thermal conductivity [8,75]. -Development of composite PCM with nanomaterials improving mechanical strength and thermal efficiency [76,82].	-Optimize the distribution and stability of encapsulated materials. -Balance production costs with improvements in efficiency and durability.

Table 5. Cont.

Area of Innovation	Innovations Found	Challenges Arising from Innovations
Improving Thermal Conductivity	-Use of nanomaterials and advanced composites to increase the thermal conductivity of PCM [51,67]. -Structural design of PCM with porous structures and metal fins [61,86].	-Maintain long-term stability and efficiency. -Implement these improvements in real applications and evaluate long-term performance.
Heat Exchanger Systems Based on PCM	-Design of systems maximizing contact surface and enhancing heat transfer [54,58]. -Effectiveness in residual heat recovery and energy use optimization [70,79].	-Ensure flexible and efficient integration in various industrial and residential applications. -Minimize greenhouse gas emissions and improve sustainability.
Computational Modeling and Simulation	-Use of computational fluid dynamics (CFD) to optimize TES systems design and efficiency [55,66]. -Identification of optimal configurations to maximize heat transfer and minimize energy losses [63,87].	-Improve the accuracy of simulations and their application in real scenarios. -Develop models that are easily adjustable to various operational conditions and system types.
Applications in Solar and Wind Energy	-Integration of TES in solar plants and wind systems to improve operational stability and efficiency [51,61]. -Significant reduction in greenhouse gas emissions [58,73].	-Ensure consistent and reliable energy supply under various climatic conditions. -Expand the adoption of these technologies in various regions and scales.
Reducing Fossil Fuel Dependence	-Use of TES in cogeneration plants and industrial processes to minimize fossil fuel consumption [8,66]. -Efficient management of residual heat and use of stored energy for production processes [59,75].	-Develop strategies for broader and more effective TES integration in high fossil fuel dependency sectors. -Balance implementation costs with benefits in emissions reduction and energy efficiency.
Autonomous and Off-Grid Systems	-Implementation of TES in remote areas and off-grid systems to provide sustainable energy solutions [54,70]. -Reduction in diesel generator dependence and carbon emissions [60,76].	-Ensure the reliability and sustainability of energy supply in the absence of the electrical grid. -Develop solutions that are economically viable and technically robust for various autonomous applications.

4. Discussion

The literature review of thermal energy storage (TES) systems advancements for renewable energy has revealed significant trends and technological breakthroughs. Developing novel phase change materials (PCMs) with higher energy density and improved thermal stability has enhanced TES capacity and efficiency, making them suitable for industrial and residential applications. Combining sensible and latent heat storage, hybrid thermal storage technologies optimize capacity and energy efficiency, particularly in solar applications. Encapsulation techniques, including microencapsulation and nanoencapsulation, have improved the thermal and mechanical properties of PCMs, facilitating their integration into various applications. Biomaterial-based PCMs offer an eco-friendly and cost-effective alternative for TES, while high-temperature inorganic PCMs are ideal for applications like concentrated solar power. Innovations in composite and nanoscale materials have significantly improved the thermal conductivity and storage capacity of PCMs. Enhancing thermal conductivity through nanomaterials and structural design innovations has optimized TES system efficiency. PCM-based heat exchangers improve energy efficiency in residential and industrial settings by leveraging PCMs' ability to store and release thermal energy efficiently. Computational tools like computational fluid dynamics are crucial for designing and optimizing TES systems. Integrating TES systems with solar and wind energy technologies enhances grid stability and reduces greenhouse gas emissions. TES systems also reduce fossil fuel dependence and provide sustainable energy solutions for remote and off-grid areas. Despite these advancements, challenges remain, including the

need for standardized testing protocols and integration barriers. Addressing these gaps is essential for optimizing TES systems and ensuring their effective deployment in renewable energy applications. This review provides a roadmap for future research to enhance the efficiency, reliability, and sustainability of TES technologies, contributing to a more resilient energy future.

5. Conclusions

This comprehensive review has synthesized the latest advancements in TES systems applied to renewable energy, highlighting key technological breakthroughs in PCMs, sensible thermal storage, and hybrid storage systems. This article highlights the critical importance of TES in the transition to renewable energy systems and lays out a clear roadmap for future research in TES technologies. We have identified key areas for development, such as improving PCMs with higher energy density and thermal stability, advancing hybrid storage technologies that combine sensible and latent thermal storage, and creating more effective strategies for integrating TES with renewable energy sources. These research areas are essential for overcoming current barriers and maximizing the potential of TES to contribute to a more sustainable energy future. The review has systematically evaluated the practical applications of these technologies in managing solar and wind energy and their roles in residential and industrial settings.

A remarkable aspect of this study was using the PRISMA methodology to ensure a rigorous and systematic selection of high-quality and relevant studies. Out of the initial 1119 records identified, 49 studies were ultimately included in the final synthesis after thorough screening and full-text eligibility assessments. This stringent selection process ensured that only the most pertinent studies with significant contributions to the field were reviewed. The findings reveal substantial advancements in TES technologies, particularly in developing new PCMs with higher energy density and improved thermal stability. Hybrid storage systems combining sensible and latent heat storage have shown significant potential in enhancing energy efficiency and system stability. Innovations in encapsulation techniques, including microencapsulation and nanoencapsulation, have further improved the thermal and mechanical properties of PCMs, facilitating their integration into various applications.

The thematic analysis also identified emerging trends and future research directions. For instance, developing biomaterial-based PCMs and high-temperature inorganic PCMs presents promising avenues for sustainable and efficient thermal energy storage solutions. Additionally, advancements in composite and nanoscale materials enhance TES systems' thermal conductivity and overall performance.

Despite these advancements, several challenges remain, including the need for standardized testing protocols, comprehensive real-world performance assessments, and addressing technical, economic, and regulatory barriers to widespread TES integration. Addressing these gaps will further enhance TES systems' efficiency, reliability, and cost-effectiveness and ensure their effective integration into renewable energy infrastructures.

Overall, this review underscores the critical role of TES technologies in supporting the transition to sustainable energy systems. The ongoing research and innovations in this field are pivotal for enhancing energy security, reducing greenhouse gas emissions, and promoting the broader adoption of renewable energy sources. Future research should continue to focus on overcoming existing challenges and exploring new materials and technologies further to advance the capabilities and applications of TES systems.

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Appendix A

Appendix A.1. Information of Identified Studies for the Literature Review

The complete bibliographic information for the 1040 articles identified in this literature review (with duplications removed) is available for download at the following GitHub URL: <https://t.ly/NaOl9> (accessed on 13 August 2024).

Appendix A.2. Bibliographic Information of the Articles That Passed the Included Phase of the Literature Review

Table A1. Bibliographic information of the articles used for the literature review synthesis.

N°	ID	Ref.	Title	Author	Year	Innovations in TES Systems	Advancements in PCM	Thermal Management and Efficiency	Renewable Energy Integration with TES
1	S-426	[51]	Optimal design of phase change material storage for steam production using annual simulation	Sharan, P.; et al.	2019	✓	✓	✓	✓
2	S-446	[53]	Evaluation of wavy wall configurations for accelerated heat recovery in triplex-tube energy storage units for building heating applications	Said, M.A.; et al.	2024	✓	✓	✓	✓

Table A1. Cont.

N°	ID	Ref.	Title	Author	Year	Innovations in TES Systems	Advancements in PCM	Thermal Management and Efficiency	Renewable Energy Integration with TES
3	S-709	[52]	Investigation of forced convection of a novel hybrid nanofluid containing NEPCM in a square microchannel: Application of single-phase and EulerianEulerian two-phase models	Bazdidi-Tehrani, F.; et al.	2024	✓	✓	✓	✓
4	S-222	[58]	Investigation on Thermophysical Properties of Multi-Walled Carbon Nanotubes Enhanced Salt Hydrate Phase Change Material	Rajamony, R.K.; et al.	2023	✓	✓	✓	✓
5	S-260	[61]	Residential Micro-CHP system with integrated phase change material thermal energy storage	Khader, M.A.; et al.	2024	✓	✓		✓
6	S-078	[8]	Optimal forecasting of thermal conductivity and storage in parabolic trough collector using phase change materials	Muruganantham, P.; et al.	2021	✓	✓	✓	✓
7	S-104	[79]	Nano-enhanced phase change materials for thermal energy storage: A comprehensive review of recent advancements, applications, and future challenges	Wong, W.P.; et al.	2023	✓	✓	✓	✓
8	S-174	[67]	Phase diagrams of fatty acids as biosourced phase change materials for thermal energy storage	Mailhé, C.; et al.	2019	✓	✓		
9	S-219	[75]	Nano-enhanced phase change materials: Fundamentals and applications	Said, Z.; et al.	2024	✓	✓	✓	✓
10	S-280	[86]	A review on thermophysical properties and thermal stability of sugar alcohols as phase change materials	Tomassetti, S.; et al.	2022	✓	✓	✓	✓
11	S-286	[54]	The local non-equilibrium heat transfer in phase change materials embedded in porous skeleton for thermal energy storage	Han, P.; et al.	2024	✓	✓	✓	✓
12	S-287	[82]	Shape-stable MXene/sodium alginate/carbon nanotubes hybrid phase change material composites for efficient solar energy conversion and storage	Ye, X.; et al.	2022	✓	✓	✓	✓

Table A1. Cont.

N°	ID	Ref.	Title	Author	Year	Innovations in TES Systems	Advancements in PCM	Thermal Management and Efficiency	Renewable Energy Integration with TES
13	S-318	[66]	Phase change materials for building construction: An overview of nano-/micro-encapsulation	Sivanathan, A.; et al.	2020	✓	✓	✓	✓
14	S-362	[73]	Nano-enhanced thermal energy storage coupled to a hybrid renewable system for a high-rise zero emission building	Daneshazarian, R.; et al.	2023	✓	✓		✓
15	S-382	[6]	Numerical modelling and experimental testing of a thermal storage system with non-spherical macro-encapsulated phase change material modules	Heinz, A.; et al.	2023		✓		✓
16	S-402	[93]	Evaluation of PCM thermophysical properties on a compressed air energy storage system integrated with packed-bed latent thermal energy storage	Yu, X.; et al.	2024	✓	✓	✓	
17	S-442	[59]	Effect of bypassing the heat transfer fluid on charging in a latent thermal energy storage unit	Baghaei Oskoueï, S.; et al.	2023	✓	✓	✓	✓
18	S-460	[70]	Experimental study on the thermal response of a metal foam dual phase change unit thermal storage tank	Bai, Y.; et al.	2024	✓	✓	✓	✓
19	S-487	[55]	Experimental investigation on the energy storage/discharge performance of xylitol in a compact spiral coil heat exchanger	Anish, R.; et al.	2021	✓	✓	✓	✓
20	S-495	[56]	Technical assessment of phase change material thermal expansion for passive solar tracking in residential thermal energy storage applications	Mendecka, B.; et al.	2022	✓	✓		✓
21	S-577	[62]	An improved effectiveness-NTU method for streamlining the design and optimization of packed bed latent thermal energy storage	Tang, Y.; et al.	2024	✓	✓		✓
22	S-669	[60]	MXene based advanced materials for thermal energy storage: A recent review	Jamil, F.; et al.	2021	✓	✓	✓	✓
23	S-003	[87]	A novel composite phase change material of high-density polyethylene/D-mannitol/expanded graphite for medium-temperature thermal energy storage: Characterization and thermal properties	Wang, H.; et al.	2023	✓	✓	✓	✓

Table A1. Cont.

N°	ID	Ref.	Title	Author	Year	Innovations in TES Systems	Advancements in PCM	Thermal Management and Efficiency	Renewable Energy Integration with TES
24	S-004	[68]	Novel strategies and supporting materials applied to shape-stabilize organic phase change materials for thermal energy storage—A review	Umair, M.M.; et al.	2019	✓	✓	✓	✓
25	S-016	[76]	Design and fabrication of solar thermal energy storage system using potash alum as a pcm	Malik, M.S.; et al.	2020	✓	✓	✓	✓
26	S-022	[94]	Consistent DSC and TGA methodology as basis for the measurement and comparison of thermo-physical properties of phase change materials	Müller, L.; et al.	2020	✓	✓		✓
27	S-069	[63]	Laboratory Testing of Small Scale Solar Facade Module with Phase Change Material and Adjustable Insulation Layer	Vanaga, R.; et al.	2022	✓	✓		✓
28	S-110	[88]	Simulation of solidification process of phase change materials in a heat exchanger using branch-shaped fins	Asgari, M.; et al.	2021		✓	✓	✓
29	S-150	[72]	A new composite phase change material for thermal energy storage	Su, C.-F.; et al.	2019	✓	✓	✓	✓
30	S-189	[80]	Guidelines for phase change material selection based on a holistic system model	Rea, J.E.; et al.	2020	✓	✓		✓
31	S-203	[69]	Building energy efficiency and load flexibility optimization using phase change materials under futuristic grid scenario	Wijesuriya, S.; et al.	2022	✓	✓	✓	✓
32	S-235	[64]	Performance evaluation of cement-based composites containing phase change materials from energy management and construction standpoints	Junaid, M.F.; et al.	2024	✓	✓	✓	✓
33	S-242	[83]	Suppression of supercooling and phase change hysteresis of Al-25mass%Si Micro-Encapsulated Phase Change Material (MEPCM) synthesized via novel dry synthesis method	Mba, J.C.; et al.	2024	✓	✓	✓	✓
34	S-243	[84]	Phase Change Materials Energy Storage Enhancement Schemes and Implementing the Lattice Boltzmann Method for Simulations: A Review	Shirbani, M.; et al.	2023	✓	✓	✓	✓

Table A1. Cont.

N°	ID	Ref.	Title	Author	Year	Innovations in TES Systems	Advancements in PCM	Thermal Management and Efficiency	Renewable Energy Integration with TES
35	S-302	[74]	Life cycle inventory and performance analysis of phase change materials for thermal energy storages	Madeswaran, N.; et al.	2021	✓	✓	✓	✓
36	S-307	[71]	Latent heat storage bio-composites from egg-shell/PE/PEG as feasible eco-friendly building materials	Trigui, A.; et al.	2024	✓	✓	✓	✓
37	S-373	[89]	The Use of Phase Change Materials for Cooling Applications in the Hot Climate of the UAE	Haggag, M.; et al.	2024	✓	✓		✓
38	S-428	[85]	Experimental and numerical study of latent heat thermal energy storage with high porosity metal matrix under intermittent heat loads	Kumar, A.; et al.	2020	✓	✓	✓	✓
39	S-444	[57]	Clay composites for thermal energy storage: A review	Voronin, D.V.; et al.	2020	✓	✓		✓
40	S-523	[65]	Isopropyl palmitate integrated with plasterboard for low temperature latent heat thermal energy storage	Alkhazaleh, A.H.	2021	✓	✓	✓	✓
41	S-543	[7]	Experimental study on charging and discharging behavior of PCM encapsulations for thermal energy storage of concentrating solar power system	Issa, O.O.; et al.	2024	✓	✓	✓	✓
42	S-551	[77]	Numerical investigation into selecting the most suitable shell-to-tube diameter ratio for horizontal latent heat thermal energy storage	Modi, N.; et al.	2023	✓	✓		✓
43	S-582	[90]	Cycling stability of poly (ethylene glycol) of six molecular weights: Influence of thermal conditions for energy applications	Johansson, P.; et al.	2020	✓	✓		✓
44	S-593	[13]	A State of the Art Review on Sensible and Latent Heat Thermal Energy Storage Processes in Porous Media: Mesoscopic Simulation	Mabrouk, R.; et al.	2022	✓	✓	✓	
45	S-600	[9]	Charging process of a partially heated trapezoidal thermal energy storage filled by nano-enhanced PCM using controllable uniform magnetic field	Izadi, M.; et al.	2022	✓	✓	✓	✓

Table A1. Cont.

N°	ID	Ref.	Title	Author	Year	Innovations in TES Systems	Advancements in PCM	Thermal Management and Efficiency	Renewable Energy Integration with TES
46	S-653	[78]	A detailed analysis of a novel auto-controlled solar drying system combined with thermal energy storage concentrated solar air heater (CSAC) and concentrated photovoltaic/thermal (CPV/T)	Benlioğlu, M.M.; et al.	2023	✓	✓		✓
47	S-679	[81]	Development in efficiency, cost, optimization, simulation and environmental impact of energy systems	Teixeira, J.C.F.; et al.	2019	✓	✓		✓
48	S-684	[91]	Enhancing solar still thermal performance: The role of surface coating and thermal energy storage in repurposed soda cans	Sathyamurthy, R.; et al.	2024	✓	✓	✓	✓
49	IEEE-002	[92]	A Novel Thermal Energy Storage System in Smart Building Based on Phase Change Material	F. Wei; et al.	2019	✓	✓		

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