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Recent progress, design characteristics and future directions of thermal energy storage technologies

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Abstract

Thermal energy storage (TES) technologies have gained significant traction across academic and industrial domains due to their capability to capture and subsequently release thermal energy with high throughput and efficiency. TES technologies are classified into sensible heat storage (SHS), latent heat storage (LHS), and thermochemical storage (TCEs). Despite their increasing uses in various applications such as district heating and cooling, and solar power, their efficiency depends on a variety of technical, economic and environmental factors. This review presents the recent development in TES technologies with emphasis on their technical, economic, and environmental implications. It also examines and compares these TES systems in terms of their designs, mechanisms, applications and suggests the optimal system for sustainable energy storage. More importantly, it addresses the recent challenges, opportunities and solutions to attain high performance TES devices with emphasis on material or medium selection, technical, economics, environmental and the uniform thermal characteristics. This critical review utilizes a structured design approach to collect the relevant data from Scopus database and analysed the TES technologies in terms of their designs, operation mechanisms, technical, economical and environmental implications. LHS and TCES have higher energy density and offer various benefits as discussed in this review, but the material selection and complex design, especially for TCES systems, hinder their transition from laboratory-based to industrial and scalable production. LHS based PCM nanomaterials (e.g. graphene, carbon, metallic and their hybrids) are anticipated to revolutionize the TES industry. This review is appealing to both researchers and engineers in the field as it provides the recent progress, mechanisms and future directions on TES technologies. Future studies should focus on developing integrated systems that integrate the high-density materials of LHS (e.g., PCMs) with the SHS and TCES systems to achieve reliable and robust TES system.

Keywords: Commercialization, Energy storage, Nanotechnology, Phase change materials (PCMs), Sustainable energy.

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1. Introduction

Recent demands to replace fossil fuel-based energy sources with renewable and sustainable ones have increased dramatically with several energy storage systems (TESs) are explored that show great promise for harnessing and subsequently releasing energy for use in various heating and cooling, automobile and industrial waste heat [1, 2]

. These technologies provide a safer alternative to the predominant greenhouse sources such as crude oil, coal, and gas, thereby integrating renewable energy into the sustainable and circular economy agenda [3]. This is a crucial transitional stage as the anticipation of future energies indicates that the fossil fuel reserves may become unsustainable in the coming century [4]. Among the renewable alternatives are wind, solar, geothermal, hydro, and hydrogen fuel cells, which present a great opportunity for reducing carbon footprints and providing sustainable energy reserves [5]. However, the inherent variabilities and intermittencies of these renewable sources require exploring other alternative technologies to provide a robust, sustainable, and robust supply. These demands have led to exploring mechanical, magnetic, chemical, and electrochemical-based energy storage and release technologies with the purpose of developing scalable, green, and affordable energy systems [6].

Recent advancements in material science, system integration, and energy policy have catalysed the evolution of TES technologies, positioning them at the forefront of next-generation sustainable infrastructure. They are grown as key technologies to transform energy use, storage, and release into reliable and sustainable ones thereby bridging the gap between the large-scale production, long storage periods, cost-effectiveness and low carbon [5, 6]. Therefore, the advanced definition of these TES can be described as a process to capture heat or energy and release it upon request with greater reliability in storage and release management. TES technologies can store energy (e.g., solar energy) during the day or during the summer and release it on demand (heating, electricity) or during winter. Thus, TES technologies including SHS, LHS, and TCEs provide solutions to harness energy with excellent reliability, affordable price and reduced environmental hazards. These systems offer distinctive advantages in terms of their capacity to store energy, the efficiency to charge and discharge energy, operational complexity and storage lifetime, technical, thermal losses, type of materials or medium used, environmental concerns and economic feasibility. For example, SHS works by raising the temperature of the medium material without the requirement for a material phase change which provides simple, feasible, and cost-effective solutions at moderate temperature ranges [7]. Meanwhile, LHS systems use phase transitions of the storage material; typically, from solid to liquid to store energy more densely, enabling compact design and stable operation. Finally, TCES technologies rely on reversible chemical or sorption reactions, allowing for high energy capacity, long-term storage capability, and minimal thermal losses. Based on the merits of their operating temperatures, the TES technologies can be further classified. For example, for temperatures of 200 °C and below, SHS technologies are used, which are widely found in residential homes low low-temperature applications for instance boiling water, heating, air-conditioning, and solar cooking etc. Meanwhile, above 200 °C is considered a high temperature which requires the use of high-temperature-based TES technology such as LHS and TCES [8]. In terms of materials usage, each TES technology utilizes various materials, for example, the SHS systems use natural rocks, molten salts, oils, and liquids. Meanwhile, the LHS and TCES systems use phase change materials and metal oxides and hydrates, respectively.

Despite substantial progress, each TES approach presents unique challenges in terms of material compatibility, thermal conductivity, reversibility, and system integration, as well as various environmental and economic implications that require further studies and exploration. This review aims to provide a structured and comparative review of SHS, LHS, and TCES technologies, highlighting their fundamental mechanisms, recent advancements and implications, and future outlooks. By synthesising current research and identifying critical gaps, this review seeks to support the selection and development of a reliable TES system to ensure sustained and decarbonised energy. Thus, this review brings about the recent advances in the mechanisms as well as the implications on various TES technologies such as achieving long-term material stability, economic scalability, and system-level optimization across these diverse operating conditions. To attempt to discuss these, this study conducted a structured literature study to gather relevant data from the Scopus databases by focusing on recent publications between 2020 and 2025. This review paper first classifies TES technologies and compares their operational metrics and mechanisms before diving into discussing their technological, economic, and environmental implications. Finally, this review paper provides future recommendations and concluding remarks and suggests a possible route technology to circumvent such implications. This review paper is a timely study as many researchers and engineers are exploring TES technologies to find cutting-edge alternative solutions to ensure a sustainable energy future, reduce carbon footprints, and achieve a circular economy. By unifying technical, economic, and environmental perspectives, our review aims to guide researchers, industry practitioners, and policymakers toward optimized TES solutions that can accelerate the decarbonization of global energy infrastructure.

2. Methodology

Research on TES platforms has grown rapidly as depicted by the increased number of publications per year Figure 1. In this study, the relevant and recent literature on TES and TES technologies, along with their technical, economic, and environmental implications were acquired from the Scopus database from 2020 to 2025 using the search keywords that ensure correct retrieval of sources. The search query formulation was conducted using the topic search that aims to capture keywords from titles, keywords and abstracts of relevant Scopus publications according to a Boolean query search strategy as follows: The general terms Thermal AND Energy AND storage were used to first screen the database and assess the publications per year and per source which indicates the publication number per year. Then the search was narrowed to specific TES technology such as “sensible heat storage”, “latent heat storage” and “thermochemical storage”. In addition, these technologies were also combined with terms reflecting technical, economic and environmental implications to narrow the search even further. Figure 2 shows the number of publications in TES and TES technologies from 2020 to 2025

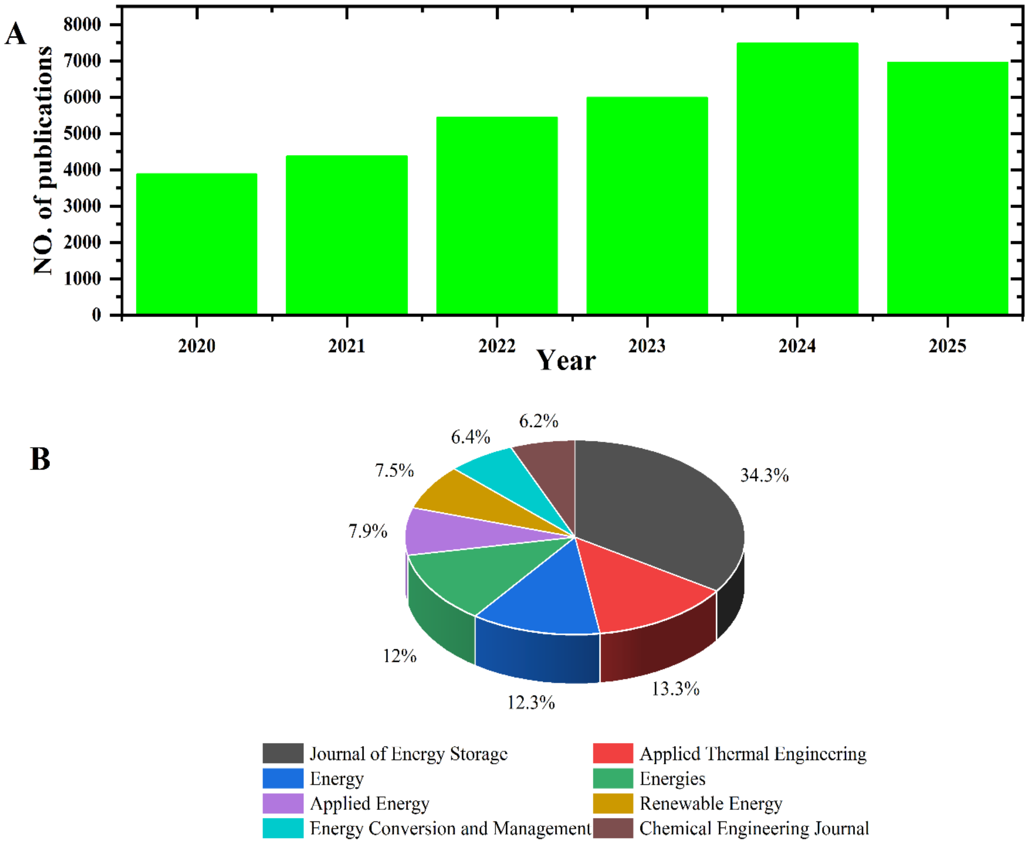

Figure 1.
Progress of publications on thermal energy storage from 2020 to July 2025 from the Scopus database. (A) number of publications per year, and (B) publications per year per source.

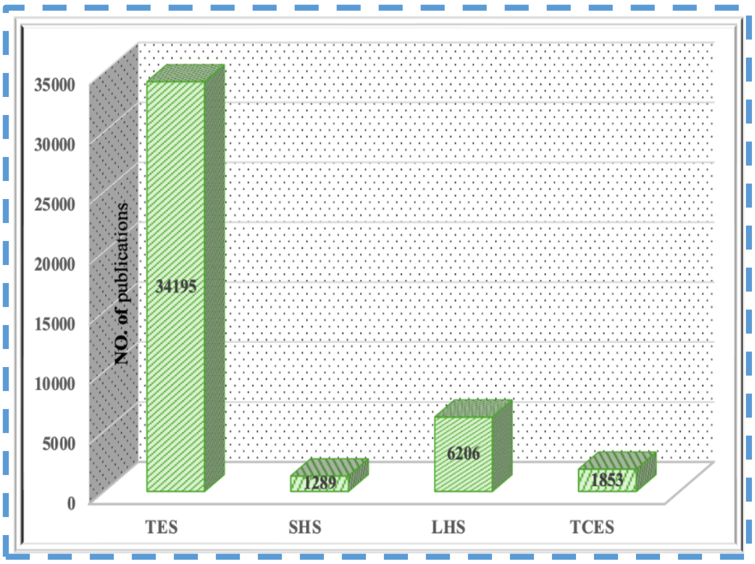

Figure 2.
Progress of the number of publications on TES and TES technologies from 2020 to 2025.

3. Designs and Mechanisms of TES Systems

This section aims to discuss the recent advances in the designs and mechanisms of different TES technologies, including the SHS, LHS, and TCES. Table 1 compares recent progress in TES systems in terms of their fundamentals, heat storage medium, total energy density, temperature storage, duration of storage, technology maturity and pros and cons.

Table 1.
General comparison between TES technologies.

Terms	SHS	LHS	TCES
Fundamental principles	1.Energy storage via temperature increase 2.Relies on rise in temperature change of the material	1.Energy storage occurs upon material’s phase change. 2.Relies on latent heat of materials	1.Store energy via endothermic and exothermic cycle 2.Relies on enthalpy reaction
Total heat storage	Q=m. Cp. ΔT	Q=m.L	Q=nA. ΔHr
Energy density(volumetric)	Low (50 kWh/m3)	moderate (100 kWh/m3)	Excellent (500 kWh/m3)
Energy density (Gravimetric)	Low (0.02 – 0.03 kWh/ kg)	Moderate (0.05 – 0.1 kWh/kg)	Excellent (0.5 – 1 kWh/kg)
Temperature storage	Charging step-based temperature	Charging step-based temperature	Ambient based temperatures
Duration of storage	Low (due to losses of energy)	Low (due to losses of energy)	Unlimited (theoretically)
Energy transport distances	Short	Short	Very long (theoretically)
Maturity	Industrial level	Pilot scale level	Laboratory and pilot scale level
Technology	Basic & versatile	Basic & versatile	Complex systems
Pors	Affordable Reliable Feasible	High density of storage compared to SHS Compact system	Very High storage density Longer term storage limited thermal losses
Cons	Low energy density storage with short storage duration and a lot of heat loss Requires higher thermal insulation to prevent losses	Some materials highly corrosive	Expensive Complex system
Economical implication	Cheap	Medium price	Expensive
Technical implication	Simple and feasible Low energy density	Some PCM materials are toxic	Complex design and system
Environmental implication	Safe	Medium safety	safe

Source: Aneke and Wang [8]; Lawag and Ali [9]; Cabeza, et al. [10] and Cabeza, et al. [11].

3.1. Sensible Heat Storage (SHS)

SHS is one of the most widely used TES technologies that depends on temperature increase of the medium or material (solid, liquid or salt molten) [12]. SHS is a mature technology; however, the amount of stored energy relies on the medium characteristics such as mass, heat capacity, energy density, and temperature difference [13]. Among the various materials used for SHS are rocks, water, metals, ceramics, concrete, and molten salts. Ideal materials for SHS should have high energy density, can withstand temperature changes, and have high specific heat in which the selection of certain materials depends on their thermal availability, stability, and cost-effectiveness [14]. For example, salts provide energy density of 100 to 200 kJ/kg, while rock or concrete provides up to 200 to 400 kJ/kg [15]. Even though SHS are able to operate across a wide temperature spectrum with various liquid or solid materials, they are only effective for short-term storage with over 95% efficiency for heat retention over 24-hour cycles prior to heat loss upon long-term storage duration. Mohamed, et al. [16] performed experimental studies to investigate the effects of adding porous black basalt to absorb solar energy and found it's a sensitive medium with promising performance for solar energy storage. Meanwhile, Kabeel, et al. [17]. investigated the ability of thick graphite to absorb and store energy and found that such material increased the distillate production from 74% to 80% due to the graphite's high thermal conductivity.

Despite the issue of cumulative energy losses especially for long-duration storage, SHS technologies possess remarkable features such as their versatility and simplicity, availability and cost effectiveness of their materials, compatibility with both residential and industrial thermal systems, wide operating temperature range and reliability [18]. Additionally, SHS technologies can be easily integrated with various systems such as solar thermal power plants, waste heat recovery systems, and district heating systems, which provide an advantage for decarbonization and energy efficiency. For example, in applications where operational scalability and flexibility are required, SHS is favoured due to its maturity and versatility for rapid deployment and use. In this context, SHS are always integrated with concentrated solar panels (CSP) via solid medium or two-tank molten salt medium which are able to store energy that is equivalent to many hours of electricity generation. SHS are also viable with non-electric solar uses such as domestic solar water heaters or industrial heating, however the temperature of the SHS's medium tends to decline over time and during discharge which may affect turbine's efficiency.

The state-of-the-art research in SHS focuses on improving the storage efficiency especially for longer periods and exploring conductive medium with enhanced heat capacity, thermal stability, and conductivity such as composite-based materials and nanofluids [19]. Additionally, materials such as graphite-based materials, porous ceramics, and geopolymers or their composites may improve the storage and use efficiency of SHS systems [2]. However, limited scalability and high cost of the nanomaterials and the complex integration with the SHS systems require further investigation as they influence the cost and versatility of these technologies. Besides that, integrating SHS systems with renewable energy-based systems and exploring artificial intelligence (AI) for real-time control and management of energy storage and dissipation is crucial to intelligent energy [20]. In addition, integrating SHS with other TES systems and energy intelligent management tools is essential to meet the global energy demands across multiple sectors with reduced cost and flexibility to renewable energy sources.

3.1.1. Mechanism of SHS Technologies

Thermodynamically, SHS systems can be attained by the increase of the medium or storage material's enthalpy without the requirement for material phase changes. The total of thermal heat storage of SHS systems can be obtained using Equation 1:

$$Q_{stored} = \int_{T_i}^{T_f} mc_p dt = mc_p (T_f - T_i) \tag{1}$$

Where Q_{stored} refers to the amount of stored energy in Joules, *m* is the mass of the medium storage, T_i and T_f refer to the initial and final temperatures in °C respectively, and c_p denotes the specific heat of the medium or storage material in J kg^{-1} K^{-1}. In the SHS systems, the medium or storage material can absorb solar energy using one of the following criteria: (1) conduction process, (2) convection process and or (3) radiation process which increases the Q_{stored} of storage material. In order to prevent energy losses or escape, the SHS systems are designed with a built-in insulation system. SHS technologies use a liquid or solid medium for storing energy. For liquid storage, the liquid medium can be circulated or moved around to release the heat, meanwhile solid storage materials require adding fluid to circulate the heat during charging and discharging processes. An example is the hematite ore made of iron, and silica to absorb and store sunlight using solar collectors and store it as heat energy inside a hematite reservoir. The system is shown in Figure 3 which was proposed by Santos, et al. [21]. In order to release this energy to light up homes and water tank heating, this energy is used to power the mechanical movements of the turbine which ultimately produce electric power. They also found that the aggregation of hematite materials affected their heat capacity due to the presence of air in the aggregated voids. Table 2 summarizes the SHS mediums or storing materials and their energy storage characteristics.

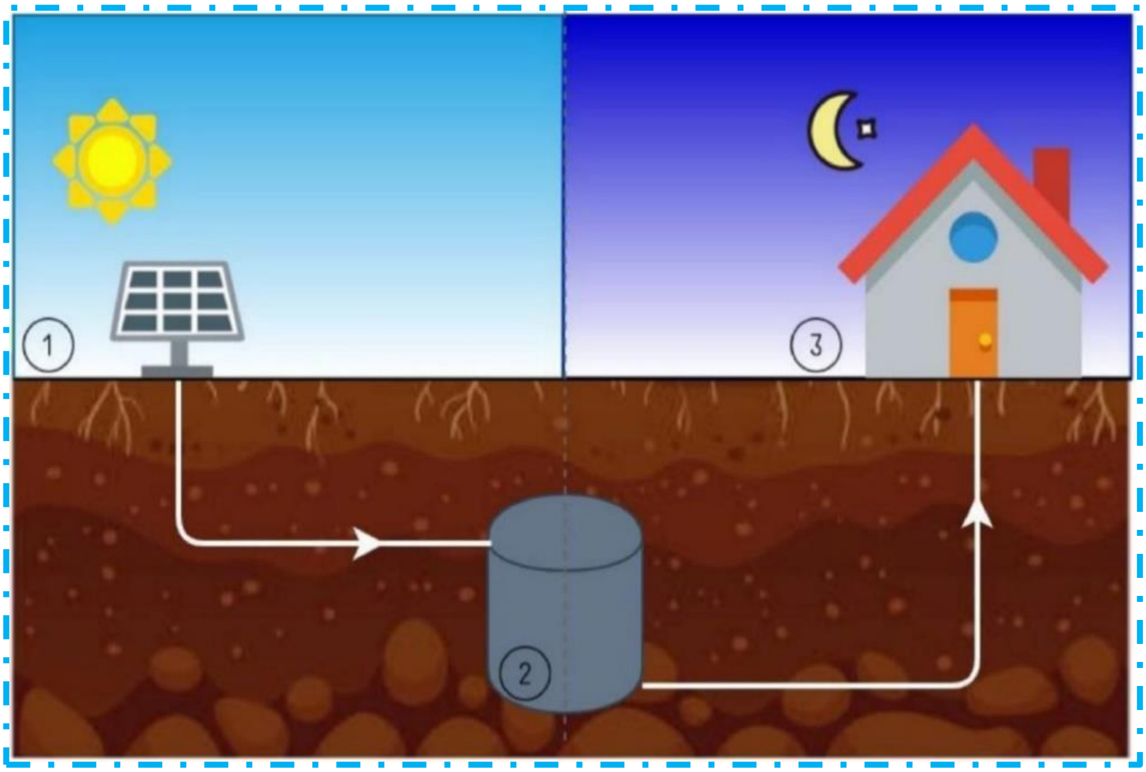

Figure 3.
The SHS solid material: 1) Solar panel that transfers energy to the reservoir during a hot sunny day, 2) reservoir hematite, and 3) heat release during nighttime
Source: Santos, et al. [21].

Table 2.
SHS medium materials and their thermophysical properties.

Storage medium	Thermal conductivities (W m^{-1} K^{-1})	Specific heat capacities (J kg^{-1} K^{-1})	Densities (kg m^{-3})	Refs.
Basalt glass	1.60	1270	2660	Liu, et al. [22]
Crushed rock	2.5	1060	1581	Zhou, et al. [23]
Cement	0.29	1550	1506	Abdulmunem, et al. [24]
Quartzite rock	0.29	860	2650	Nagaraj, et al. [25]
Graphite	88.578	1424	2250	Guan, et al. [26]
Concrete	2.37	920	2250	Özrahat and Ünalan [27]
Limestone	2.8	903	2600	Türkakar [28]
Cast iron	29.3	837	7900	Zanganeh, et al. [29]
Copper	0.56	837	2400	Zhang and Yan [30]
Ceramic foam	20.7	800	2327	

3.2. Latent Heat Storage (LHS)

LHS is another important type of TES that depends on the phase change of PCM materials, typically from liquid to solid or vice versa, to store and release heat at nearly constant temperatures. The total energy storage depends heavily on the latent heat of fusion or the latent heat of vaporization, depending on whether the phase change is between solid and liquid or liquid and vapor, respectively [31]. The latent phase change of the material depends on its enthalpy change per unit mass when the heat is applied for the phase change.

Unlike the SHS that depends on a temperature change, the LHS systems exploit the latent heat associated with phase transitions, allowing for higher energy storage density per unit mass or volume [32]. LHS technologies have higher energy densities than SHS and typically range from over 200 to more than 1000 kJ/kg, depending on the type of PCM used as a medium [31]. Among the most used PCMs are waxes, fatty acids, paraffins, metals and alloys, and various novel nano and micro materials which are selected according to the following criteria: (1) thermal stability, (2) phase change temperature, and (3) compatibility with LHS's operation and system conditions. These materials make LHS systems unique and dependent on the phase change or isothermal behaviour thereby enabling LHS systems to be suitable for various applications, especially those requiring higher energy density with thermal control [33]. Overall, LHS provides several benefits over the SHS, particularly the higher energy density as illustrated by the change in temperature versus energy curve in Figure 4 [34].

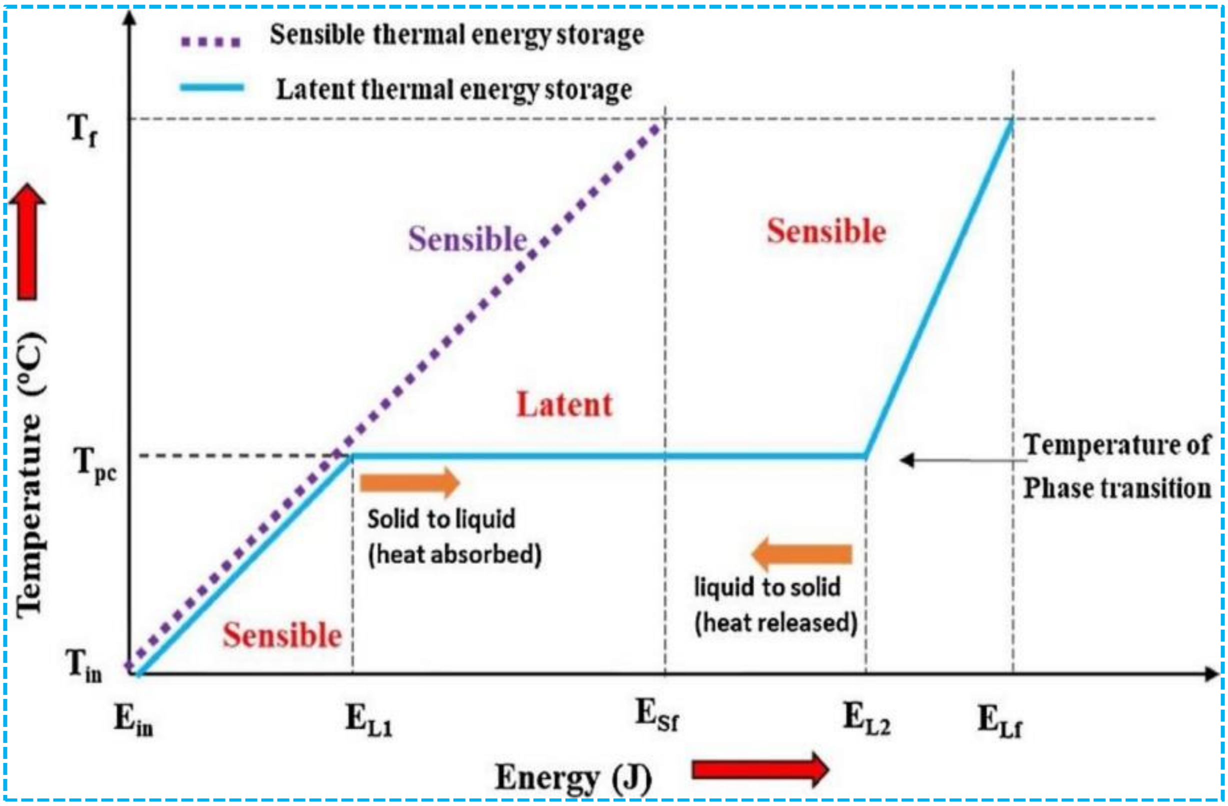

Figure 4.
Stored energy versus temperature comparing $Q_{S,stor}$ and $Q_{L,stor}$.
Source: Reddy, et al. [34].

In addition, LHS systems provide a stable output temperature, making them highly appealing for turbine-based applications such as solar thermal, waste heat recovery systems, ventilation, heating, and air conditioning devices, as well as regulating temperatures in electronics and buildings [6]. Moreover, the use of PCM materials allows LHS systems to have a wide temperature range, which makes their integration with high or low temperature systems feasible, as well as other scalable energy storage systems for instance passive heating or cooling platforms. However, there exist many challenges associated with PCM materials, such as their limited thermal stability and conductivity, which affect heat transfer during charge-discharge cycles and lead to incomplete solidification or melting, thus causing lower efficiency and reliability of LHS-based PCM systems [34]. Besides that, PCMs materials, especially the salt hydrates, suffer from phase segregation, volume changing, subcooling and stability over long-term charge and discharge cycles, leading to critical challenges in practical applications [35, 36]. Additionally, PCMs must be compatible with container materials to prevent corrosion during long-term energy storage. In this context, current research advances aim to incorporate nanomaterial-based PCM and nano-composites-based PCMs using encapsulating technologies, additives, and direct incorporation of conductive nanofillers such as MXenes, ceramics, graphene, carbon-based materials and metals to improve thermal stability, conductivity and thermal response rate of LHS systems [31]. Moreover, macro and micro-encapsulating techniques are being developed to prevent leakage, stabilize phase behaviour, and enhance handling and system integration. In addition, the thermochemical PCM hybrids and smart thermal storage systems using artificial intelligence (AI) for real-time thermal management are emerging as innovative directions [33]. Thus, the advancement in materials science, system integration, AI, and lifecycle performance analysis are critical factors that determine the future of LHS systems. LHS systems are expected to play a critical role, especially in the context of renewable energy utilization and decarbonization strategies. Recently, Zhang, et al. [31] presented a comprehensive approach of LHS for electronic cooling which fosters innovative PCM-based systems to improve the thermal properties in various scenarios Figure 5.

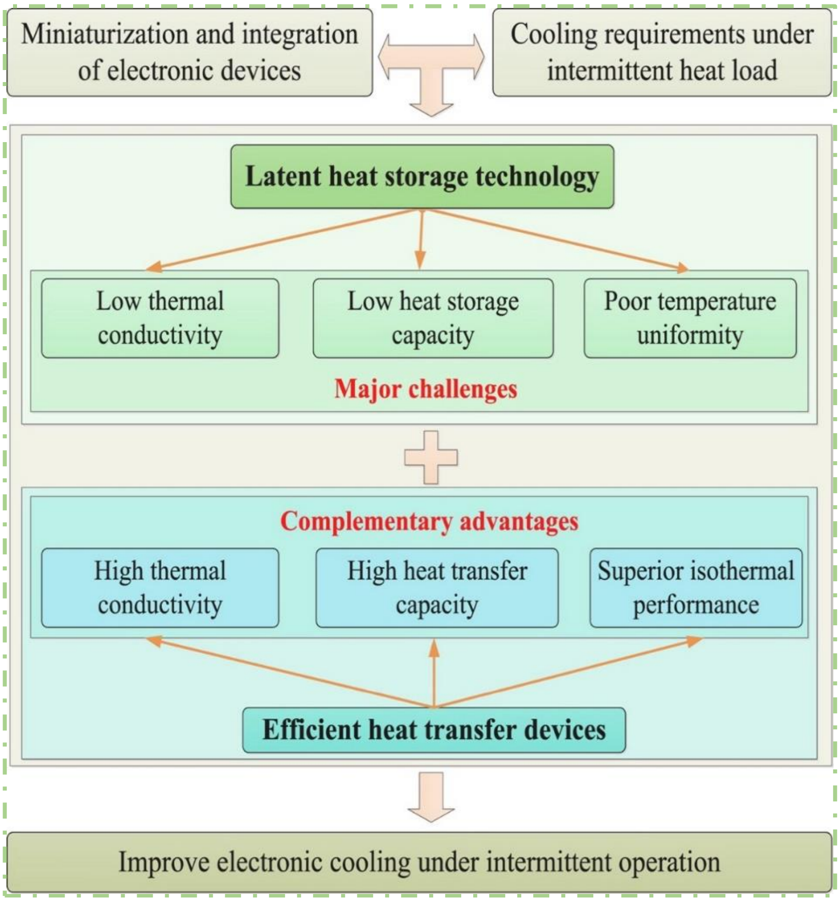

Figure 5.
Summary of the LHS development with innovative ideas for higher efficiency.

Source: Zhang, et al. [31].

3.2.1. Mechanism of LHS Systems

In LHS systems, energy is stored as thermal heat within the storage material particles and then released in the form of heat at a constant temperature during the phase change process. For example, liquid PCMs-based LHS technologies can store energy during their phase transition (melting temperature), where the chemical bonds within the materials dissipate, allowing for the storage or release of energy. Typically, the LHS's energy storage capacity can be determined using Equation 2:

$$Q_{LHS} = \int_{T_i}^{T_m} mc_p dT + ma_m \Delta h_m + \int_{T_i}^{T_m} mc_p dT \tag{2}$$

Where Q refers to the capacity of the material to store energy in kJ, m denotes the material's mass in kg, and cp refers to the material's specific heat in kJ kg^{-1} K^{-1}, a_m refers to material's melt fraction during heat storage, Δh_m denotes the material's specific fusion enthalpy in kJ kg^{-1}, and T is the temperature where $T_{i,}$ T_m and T_f refer to the initial, melting and final temperature respectively [21]. As shown in Equation 2, the first term describes the stored energy in the form of sensible or heat in the solid phase, followed by the latent heat of fusion of PCM shown in the second term of the equation, and the third term refers to the stored energy in the form of sensible heat in the liquid phase of the material.

In its basic form, the LSH system comprises a PCM material, a vessel or tank to contain the PCM material and a circulating fluid and all LSH systems operates in either active or passive storage types where the active ones uses natural convection to move heats between the PCM and circulating fluids, meanwhile the passive systems require compressors, pumps or fans to cause fluid flow circulation [6]. The LHS system uses the PCM materials to store energy during the phase change (e.g., solid to liquid or melt) such as heating the PCM material above the melting temperature using the circulating fluid [31]. Before the melting of the PCM material during heating, the system is called a sensible heating system in which the phase transition from solid to liquid which takes place at a constant temperature and takes some time to reach the melting point of the PCM material, at which the latent heat of fusion is stored within the PCM. The PCM materials continue their heating at constant temperature until it reaches equilibrium with the circulating fluid [9, 37, 38]. Similarly, in the solidification process of PCM material, the circulating fluid is applied to cool the PCM in a process called sensible cooling, where the sensible heat is continuously extracted from the PCM. When the PCM reaches the phase transition temperature that causes it to solidify, it emits latent heat of fusion in the circulating fluid in an isothermal process. After that, the cycle is complete once the PCM reaches equilibrium with the circulating fluid [31]. It's worth noting that the melting and solidification depend on the type of PCM materials and their thermal stability properties. Thus, the LHS systems are classified based on their PCM materials into inorganic, organic, and eutectic storage materials as illustrated in

Figure 6. The organic materials as mentioned before are the paraffins, fatty acids, glycols, esters, and alcohols. Meanwhile, the organic materials involve metals, salt hydrates, alloys, and so forth. The eutectic materials are a combination of organic and inorganic materials which do not basically separate during melting or freezing (phase change cycles) [39].

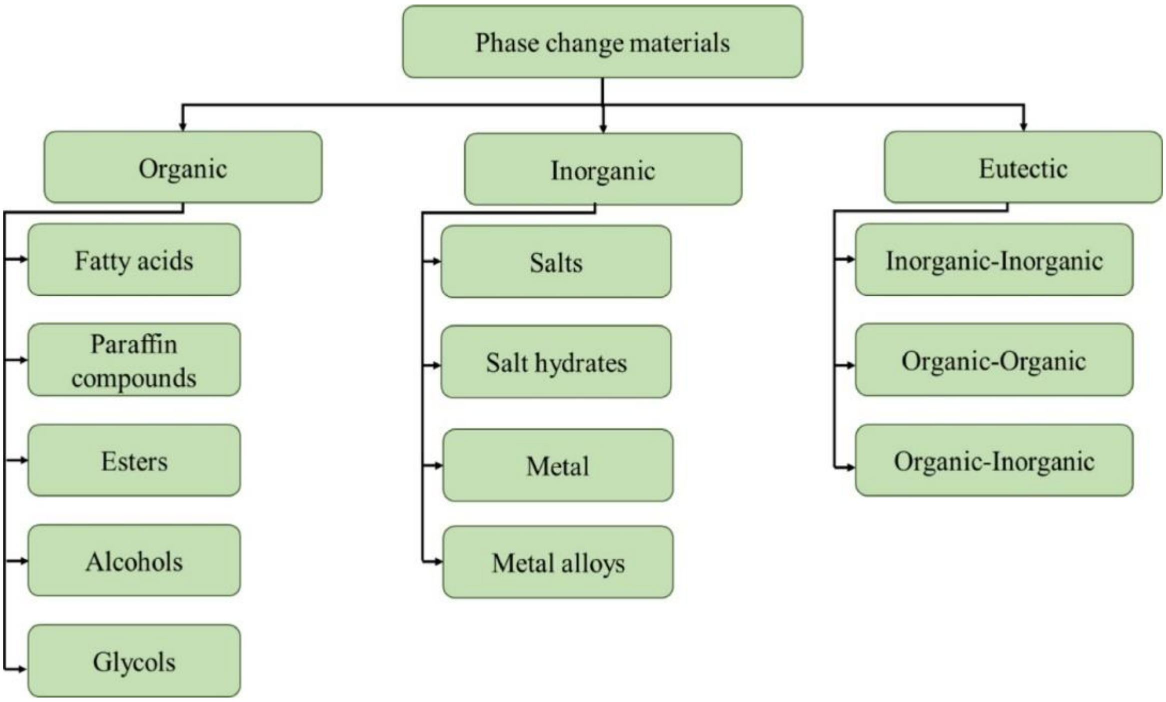

Figure 6.
Classification of PCM materials for LSH.

Two important characterization techniques enable precise measurements of the latent heat of fusion and melting point of PCMs, which are the Differential Scanning Calorimetry (DSC) and differential thermal analysis (DTA). In these techniques, the alumina is used as a reference material and the samples or PCMs are heated at a constant rate until the melting temperature. The differences in temperatures between the alumina and PCM are measured and plotted where the area under the curves denotes the latent heat of fusion, and the melting point is illustrated by the greatest slope in the curve. An example of the DSC curves for paraffin and paraffin/pals composites is shown in Figure 7.

Zhang, et al. [40] investigated the feasibility of single-walled carbon nanotube (SWCNTs) as an organic additive nanomaterial to improve the performance of various LHS PCM composites such as paraffin wax and pure paraffin. They found that, the addition of CNTs improved the thermal properties of the PCMs such as the thermal stability and thermal conductivity, but the heat capacity and melting point did remain unchanged. Chakraborty, et al. [41] proposed a paraffin-based PCM composite comprising a porous expanded graphite (EG) and paraffin. They found that the latent heat of pure paraffin wax was 200.8 J g-1, while that of samples containing 10, 14, 17, and 20 vol% EG were 155.9, 139.2, 133.7, and 131.3 J g−1, respectively. Table 3 summarizes various PCM composites used in LHS systems along with their thermal conductivities, latent heat and melting temperatures.

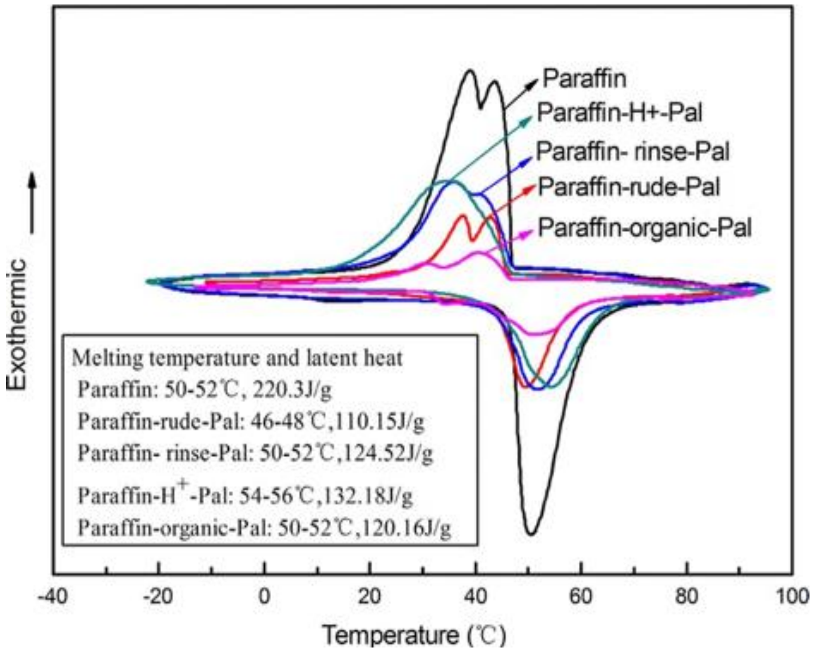

Figure 7.
DSC plots for paraffin and paraffin/Pals composite-based PCMs. Reproduced with permission from ref. Copyright Elsevier 2016.

Source: Yang, et al. [42]

Table 3.
Thermal properties of organic and inorganic PCMs used for LHS.

Organic based PCMs				
PCM	**Thermal conductivity (W m^{-1} K^{-1})**	**Latent heat of melting (J g^{-1})**	**Melting temperature (°C)**	**Ref.**
Paraffin/graphene	0.266	100.5	59.4	Leong, et al. [43]
Paraffin/polycarbonate	0.4	209	60	Yang, et al. [44]
Beeswax/MWCNT	0.46	115.5	60.2	Putra, et al. [45]
Tetradecylamine/graphene	0.34	293	39	Chen, et al. [46]
Paraffin wax/EG	3.57	220	28.02	Zhao, et al. [37]
Polyurethane/boron nitride	0.96	140	58.3	Ren, et al. [47]
Paraffin wax/ carbon foam	2.91	143	58	Mhiri, et al. [48]
Inorganic PCM materials				
Eutectic NaCl-KCL-MgCl2/Si3N4	16	94	471	Wang, et al. [38]
organo-metallic PCM/nano gallium	0.6	85.4	37.8	Raj, et al. [49]
Silicon microencapsulated n-ocadecane	0.1	103	35.5	Guo, et al. [50]
MgNO3 hexahydrate based PCM	0.8	151	92	Li, et al. [51]
Ceramic foam/molten salt composite	1.6	282	-	Zhang, et al. [52]
EG/modified n-alkanes	7.4	163	16.4	Zhang, et al. [53]
Eutectic NaCl – KCl – $MgCl_2$	0.9	251	471	Ran, et al. [54]
Sodium acetate trihydrate eutectic (SATE)	-	182	60.5	Liu, et al. [55]

3.3. Thermochemical Storage (TCS)

TCES is an advanced form of thermal energy storage that relies on reversible chemical reactions for storing and releasing energy [56]. Unlike sensible or latent heat storage which depend on temperature change or phase transition, TCES involves breaking and forming chemical bonds, thereby offering significantly higher energy densities (300 to over 6000 kJ/kg) and long-term storage potential without sustainable heat losses over time [57]. In a typical TCES storage technology, the absorption and release of energy are achieved during the charge phase (endothermic reaction) and discharge phase (exothermic reverse reaction), respectively. There are several advantages of TCES systems over SHS and LHS such as the high gravimetric and volumetric energy density, ability to operate at a wider temperature range, excellent ability for seasonal and long-term storage applications and ability to be integrated with renewable energy systems and industrial waste heat recovery technologies [58]. Among the remarkable materials that are used for TCES systems are metal oxides (e.g., Mn_2O_3/Mn_3O_4), salt hydrates (g., $Ca\ (OH)_2/CaO$), and hydroxides due to their outstanding kinetic and thermodynamic properties [56, 59]. Current research advances in TCES investigate other potential thermochemical materials (e.g., doped salts and nanomaterials, composites) with enhanced conductivity and reactivity that ensure sustainable energy storage and release [57, 58]. In addition, the use of machine learning and computational modelling may aid in predicting the combination of thermochemical materials, predicting their reaction and screening for potential and relevant candidates effectively and rapidly.

3.3.1. Mechanism of TCES

TCES systems are considered the most significant technologies that provide solutions for next-generation thermal storage applications with higher feasibility and applicability than their counterparts [60]. The basic principles of the TCES operation depend on the charge and discharge processes during the endothermic and exothermic reactions of the TCES's materials, respectively [61]. This allows for long, medium, or short-term heat storage with a wide range of temperatures that suit any application [61]. In a typical example where TCES systems are utilized to store heat from the sun, the storage of heat occurs during the day at various temperatures, where the solar thermal collectors are used. During cold weather, the heat is released to the air when the moist air passes through the sorption bed material (e.g., zeolite), which causes the release of heat combined with moisture to the air [59]. Table 4 summarizes the TCMs materials and their advantages, drawbacks and technology status.

Table 4.
Advantages and drawbacks of all low and medium-temperature TCES materials.

Material/Temperature	Advantage	Drawbacks	Technology status
NPK Fertilizers/low temperature	1.Available, cheap and can store up to 2.400kJ/kg 3.Require shorter time to charge &discharge 4.Has fast cooling rate <100 s	1.Requires further characterization studies 2. Suffers from aggregation and salt-crystallization, 3.Thermal stability concerns	laboratory prototypes
Metal Hydrides (low temperature heating application)	1.Excellent storage density 2. Excellent reversibility 3.large temperature range and cooling up to 2 C	1.Limited kinetic reactions 2.Limited thermal properties 3.Possible losses of energy 4.Limited storage density 5.High cost	Laboratory prototypes
Salt hydrates (for medium temperature applications)	1.High storage density (2.81 GJ/m3) 2. High Thermodynamic stability 3.Large operational range temperatures	1. Incongruent melting and Corrosion concerns 2.Has slow kinetic reactions	Laboratory prototypes
Magnesium oxide /water reaction system	1.Less toxicity 2. Large operational range temperatures 3.Excellent storage capacity (~1300 kJ/kg)	1.Limited thermal conduction property 2.cocnerns of MgO sintering	Laboratory prototypes
Methane Decomposition/ Synthesis	1.Avilable and cheap 2.Wide operational temperatures 3. Easy to storage and transfer	1.Toxic & corrosive 2.Low storage density	Pilot prototypes
Cyclohexane / Benzene	1. Excellent reaction enthalpy (141 kJ/mol) 2. Good exothermic reactions	1. possible interfering reactions 2.limited studies on endothermic reactions	Laboratory prototypes

Source: Salgado-Pizarro, et al. [56]**;** Prieto, et al. [59]**;** Desai, et al. [62] and Bellan, et al. [63]

TCEM systems can also be utilized to harness heat by the integration of high-energy-density and affordable mediums or materials with wide temperatures up to 1400, thereby offering a flexible selection of suitable materials for heat storage based on requirements [64]. This makes the TCS technologies one of the most promising thermal storage technology solutions with significant promise for commercialization [63]. In addition, TCES materials are remarkable due to their high and wide operational temperatures of over 1273 K. Despite their promise, the TCES systems are prone to oxidation and degradation at higher temperatures during the charge and discharge phases which might lead to energy losses [62, 65]. To circumvent these challenges, recent researchers have explored modifying the TCES materials with nanomaterials via doping, surface modification, and dip coating methods to reduce oxidation rate and reactivity of TCES materials. For example, Fe has been used as an efficient cationic dopant to improve the re-oxidation rate and reactivity of the Mn_2O_3/Mn_3O_4 system Desai, et al. [62]; Carrillo, et al. [64] and Li, et al. [65]. Mehos, et al. [66] proposed three technological routes which are the molten-salt, particle route and gas-phase route as heat storage routes for TCES technologies. Among these, the use of particles as heat materials is cost-effective and provides more heat stability even for high-temperature applications. The particle route is the most feasible and widely used in industries such as particle feeders, storage tanks, and hoppers. An example of the particle routes is shown in Figure 8 which is proposed for the concentrated solar power systems [65].

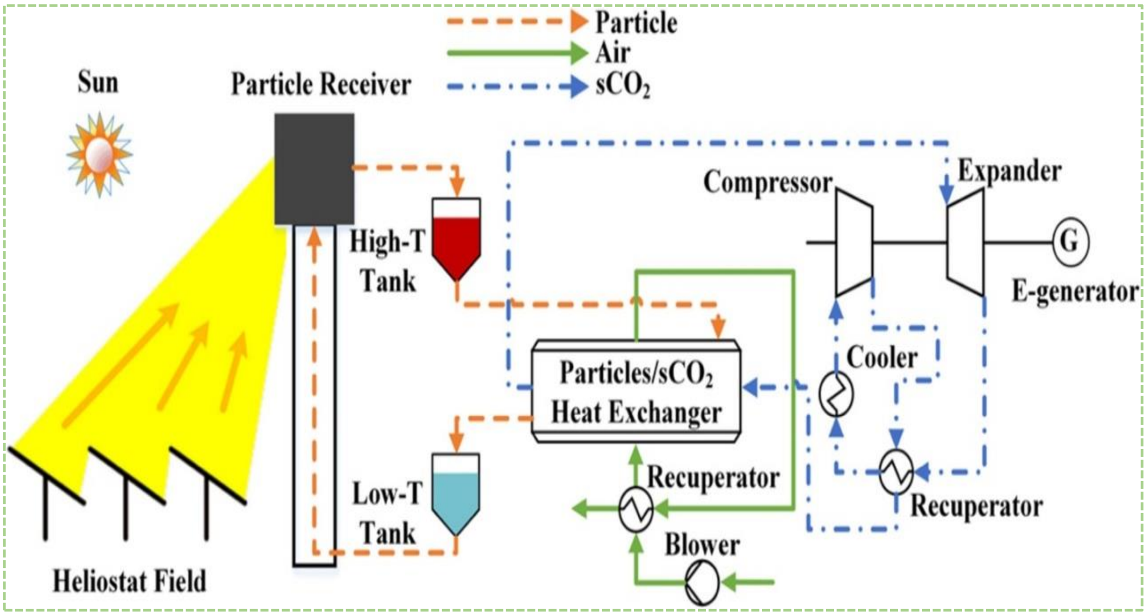

Figure 8.
Particle-based concentrated solar power system (CSP) with sCO2 Brayton cycle.
Source: Li, et al. [65].

4. Challenges and Implications of TES Systems

TESs, including STH, LSH, and TCES, have shown great potential to store thermal energy and resolve the environmental issues worldwide. Among these, LHS systems use the PCM materials that provide superior heat storage during the phase change or phase transition (from solid to liquid and vice versa) [33]. In the following subsections, the implications of SHS, LHS and TCES systems in terms of their technical, economic and environmental aspects are discussed and tabulated.

4.1. Technical implications of TES Technologies

The advancement of TES systems is central to enabling a more resilient and sustainable energy infrastructure. TES technologies provide a crucial solution for decoupling energy supplies from the demanded energy by storing extra energy for later use which reduces heat losses and allows efficient energy uses. As mentioned before, among the leading TES systems are SHS, LHS, and TCES; each of these technologies brings unique technical implications that influence their applicability, efficiency, integration potential, and scalability. This subject discusses the technical implications of TES technologies, including SHS, LHS, and TCES technologies.

4.1.1. Sensible Heat Storage (SHS)

The SHS technologies are the most widely used energy storage technologies as they rely mainly on the increase in materials' temperature to store and release thermal energy. Technically, the SHS technologies are relatively facile to develop and manage well with and existing operational technical behaviour. In addition, these systems are affordable and suitable for various temperature applications, particularly building heating and solar thermal power plants [67, 68].

Despite all that, SHS technology suffers from several technical limitations and implications such as the inherent low energy density that depends on materials' specific heat and their allowable temperature change, thermal properties and operational temperature range [1, 68, 69]. Besides, the retrieval and heat losses during storage, especially over long durations, hinder the technology's efficiency and long-term reliability. Moreover, these technologies require large storage volumes to store appreciable amounts of energy, which makes the design and management of large storage systems challenging and complex [70]. These technical implications affect the efficiency and lifespan and make the SHS technologies prone to degradation over repeated heating and cooling cycles.

4.1.2. Latent Heat Storage (LHS)

The LHS technologies were designed to address some of the limitations of the SHS via leveraging the PCMs to store and release energy at nearly constant temperatures with a wider working temperature range [49]. This led to a tremendous increase in the energy density, storage temperature range, and temperature control, temperature management and longer storage periods [67, 71]. PCM materials such as salt hydrates, paraffins, and eutectic materials are potentially vital for applications that require isothermal energy storage, such as cold storage, solar heating, and thermal management in electronic components [33]. PCM materials have a higher storage density than SHS 95 to 10 times higher) which makes them appealing for various practical uses such as air conditioning, solar thermal storage, lighting residential areas, heating, and etc. However, the selection of PCM materials is essentially dependent on their thermal properties such as thermal stability, melting point, and thermal degradation because the PCM material influences the phase transition and phase conversion enthalpies of the PCM system [6, 72].

Technically, the full realization of LHS systems is impacted by several challenges, mainly related to the system design and material performance [5]. In addition, several PCMs exhibit issues including the subcooling, low thermal conductivity, phase separation and material degradation over repetitive cycles [69]. Such factors could minimize the effectiveness and reliability of LHS technologies especially for real-world applications. Moreover, the LHS system designs, particularly for encapsulation strategies and heat exchangers are complex and require careful optimization to ensure long-term stability and efficient heat transfer [70, 73, 74]. LHS is thus promising for concentrated solar panel (CSP) integration, particularly where consistent thermal output is advantageous [75, 76]. Designs may incorporate cascaded PCMs to extend the effective temperature range. While widely used in building applications and tested in prototypes, commercial CSP adoption is still emerging [77, 78].

4.1.3. Thermochemical Energy Storage (TCES)

The TCES technologies are one of the most advanced and theoretically efficient TES systems as they store energy via the reversible chemical reaction phenomena, thus offering remarkably high energy density and limited heat losses during storage [79]. This ability to effectively store energy for long periods without losses makes the TCES systems highly appealing for seasonal and large-scale storage applications [60]. The TCES technologies can also be further tuned to operate over a wide range of temperatures making them suitable for diverse energy applications in industries or in solar power systems [60, 80].

Despite all that, TCES systems are in their early stage of technological readiness and have not been fully mass-produced on a large scale. Additionally, the selection of specific thermochemical materials such as hydroxides, metal oxides, and salt hydrates remains a vital barrier during the design of TECS systems [80, 81]. Moreover, various thermochemical materials suffer from issues such as incomplete reversibility, slow reaction kinetics, high reaction temperature and or poor cyclability [61]. In terms of reactor design to enable such reactions and heat exchange along with control systems, such a design requires sophisticated design and precise operational control, which limit their feasibility and hinder their rapid transition to real-world products. This means the mass production and scaling up of these technologies present huge economic and technical uncertainties and thus such systems remain exploratory in the laboratory scale [73-75]. Solar integration typically uses concentrated heat to drive endothermic reactions such as the calcium carbonate decomposition or metal oxide redox cycles, in which during the reverse reaction the heat release occurs. Some TCES systems can also produce fuels such as hydrogen or ammonia however, these systems require sophisticated reactor design and gas management capability [79].

To sum up, SHS technologies remain dominant and widely used due to their low cost, feasibility, despite their limitations in terms of energy losses at longer storage periods, and low energy density or properties of SHS's materials. The LHS provides better stability than SHS but suffers from issues such as the PCM materials selection and low conductivity. Meanwhile, the TCES technologies represent a class of emerging heat storage technologies that rely on chemical reactions to provide high density, integration flexibility, and long storage periods. To circumvent the limitations of each TES technology, developing a hybrid system that encompasses the strengths of each technology with novel PCM composite materials and improved reaction kinetics would lead to designing smart thermal management systems enabled by the advanced nanomaterials and artificial intelligence (AI) based control. Thus, there are various research and R&D projects and initiatives carried out worldwide to realize sustainable, facile, flexible and reliable energy infrastructures. The technical implications of SHS, LHS, and TCES heat storage technologies are described in Table 5.

Table 5.
Summary of technical implications of SHS, LHS, and TCES heat storage technologies.

Technology	**Mechanism**	**Energy density**	**Operational complexity**	**Efficiency range**	**Scalability**	**Technical challenges**
SHS	Sensible heat via temperature change	Low	Low	~70 – 90%	High	Heat losses. Require large volume storage
LHS	Latent heat via phase change	Moderate to high	Moderate	~73 – 93%	Moderate	PCM materials stability, low conductivity
TCES	Chemical reaction enthalpy	Very high	High	> 95%	High	Reactor design and materials selection

Source: Tawalbeh, et al. [6]; Prieto, et al. [59]; Thiel and Stark [71]; Shen, et al. [77] and Olympios, et al. [79].

4.2. Economic Implications of TES Technologies

The economic viability of TES systems plays a significant role in determining their scale-up production, usage, and integration with modern digitalized energy infrastructures particularly in the era of transition to renewable energy sources. Among the TES systems are the SHS, LHS and TCES which have emerged as critical enablers for reliable, resilient and efficient. However, the full deployment of these technologies is not only determined by their technical capabilities but also hinges on their economic aspects such as the cost of developing and maintenance (lifecycle cost), return on investments, and market readiness. Thus, in the following subsections, a dive into the critical economic implications of each TES technology will be discussed with a focus on the capital expenditure, operation expenditure, economic efficiency, and commercial scalability.

4.2.1. Sensible Heat Storage (SHS)

The SHS is one of the most economically viable and widely implemented TES technologies, due to its low materials and systems design and development costs. Among the widely available and cost-effective materials such as rocks, water, concretes, or molten salts as the main materials for the SHS technologies. This means that, the capital expenditure of SHS systems is relatively low especially for large-scale production such as the concentrated solar power plants where molten salts are used for bulk energy storage.

The operational costs of SHS technologies are low mainly on the thermal insulation design and preventative scheduled maintenance, however for applications that require high energy density the physical footprints and infrastructures of SHS systems may also increase, leading to economic burden especially for urban settings and mobile applications. Another challenge is the fact that the SHS technologies tend to lose energy over time which may require additional energy inputs to maintain a stable temperature and hence impact the overall cost.

Despite all that, SHS technologies have demonstrated robust cost reduction in various projects where space is not a limiting factor and where charging and discharging cycles are frequent and predictable. It thus remains a frontrunner in economic viability for district heating, solar power plants and industrial wase heat recovery.

4.2.2. Latent Heat Storage (LHS)

The LHS technologies also provide appealing economic value because they offer higher energy density than the SHSs and thus can be potential candidates for small-sized and limited space utilization applications. The only economic issue is the high prices of the PCM materials which can range from moderately priced paraffins to expensive salt hydrates or eutectic mixtures. In addition, the encapsulation methods, thermal conductivity enhancers and system integration are major factors for increasing the cost LHS materials and systems.

However, the lifecycle economics of LHS technologies in applications such as buildings, chain logistics, and buffering electronics is superior than the SHSs which justify the initial capital of SHS systems. In terms of operational economics, the LHS system’s cost of operation is relatively low as the PCMs are stable and the systems are well-maintained. However, the material degradation, the subcooling, and incomplete phase transitions may lead to long-term performance that may affect economic return.

In short, LHS technologies are better in terms of return on investment than SHSs but still face challenges in broader commercialization and scalability attributed to the costly materials and the limited ecosystems of suppliers.

4.2.3. Thermochemical Energy Storage (TCES)

The TCES technologies’ features such as the high energy density, limited heat loss over time, and the ability to operate in seasonal storage, make them of potential economic value as they offer unmatched cost savings in long-duration energy storage particularly for remote microgrids, renewable integrations and industrial process applications.

However, the current economic realities remain challenging because the capital expenditure and operational expenditure of TCES systems are high due to the high cost of materials (metal oxides, salt hydrates, and hydroxides), designing of the reactors, and system integration. Besides, several TCES materials require precise environmental control, advanced heat management, complex sensors and automation which add to both capital and operational costs of the final design.

At present, TCES remains at a lower technology and market readiness with limited commercialization and scalability. The market adoption of such systems is slow due to the high uncertainty in the long-term performance, scalability issues and lack of standardization. Yet, with their potential in seasonal storage and decarbonizing industry, the TCES systems are receiving greater attention and interment interests. This indicates that upon the maturity of these technologies, they will outperform both SHS and LHS economically in high-impact applications.

To sum up, SHS technologies are the most cost-effective and commercially mature TES systems, especially for bulk energy storage where low-cost materials and low maintenance can be achieved. The LHS systems provide a higher value proposition than SHS especially for controlled and compact environments where energy densities are prioritized over initial costs. The TCES technologies represent the future of economic sustainability in TES especially for seasonal storage, long-duration storage and high-capacity systems. However, market readiness and scalability of such technologies remain slow. Thus, the choice of the type of TES system must be aligned with the specific application needs, lifecycle cost, operational costs and long-term goals especially at this era where global energy technologies are evolving towards decarbonization. Table 6 summarizes the economic implications of TES technologies.

Table 6.
Economic implications of TES technologies (SHS, LHS, and TCES).

Technology	**Capital Cost**	**Operational Cost**	**Energy Density**	**Market Maturity**	**Return on investment**	**Economic Barriers**
SHS	Low	Low	Low	High	High (in bulk storage)	Space, thermal loss
LHS	Medium to high	Medium to high	Medium to high	Moderate	Medium (in targeted sectors)	PCM cost, degradation
TCES	High	Medium	Very high	Low to moderate	High (long-term)	Complexity design, Material cost

4.3. Environmental Implications of TES Technologies

The global demands for decarbonization and sustainable energy technologies have drastically elevated the role of TES systems to enable efficient usage of renewable energy sources. Each of the TES technologies, including SHS, LHS, and TCES exhibits unique environmental footprints depending on the materials employed, scalability, life-cycle impacts, and integration potential.

4.3.1. Sensible Heat Storage (SHS)

The SHS technologies are considered environmentally friendly as they use abundant and non-toxic media such as water, rocks, or salts. They are facile and chemically non-reactive which contributes to a low environmental risk profile, especially in closed-loop system [82]. However, for large storage, SHS systems require large material volumes due to their low energy density, which lead to higher materials demands and space use particularly for large-scale installations. In addition, SHS systems suffer from thermal loss, especially for longer storage durations which can reduce overall energy efficiency and increase operational energy input, thus indirectly impacting the carbon intensity. Recent advances on this filed such as using high-temperature particles, hybrid systems and improved tank designs are being exploited to overcome SHS limitations and provide better efficacy and cost reduction [83].

4.3.2. Latent Heat Storage (LHS)

The LHS technologies utilize the PCMs materials to store heat and release it at a constant temperature based on the phase change mechanism [31]. In terms of environmental benefits, LHS systems have advantages over SHS since they have lower thermal losses and higher energy density than of SHS [78]. However, organic PCM materials such as paraffin-based based that are derived from petroleum products raise concerns over fire safety and sustainability. In addition, the inorganic PCMs materials may induce corrosion risks and heavy metal content [33]. Another high environmental concern is the production and disposal of some PCMs materials [82]. Furthermore, the recycling and lifecycle recovery strategies remain underdeveloped, posing long-term ecological concerns. Thus, generally the LHS materials are safe but some may be corrosive or flammable and the operational issues of LHS include the supercooling, phase separation and thermal expansion [31, 77].

4.3.3. Thermochemical Energy Storage (TCES)

1. The TCES technologies represent the most potentially and advanced environmental systems than SHS and LHS by leveraging the reversible chemical reactions to enable high energy density and limited energy losses over long durations [20, 84]. This significantly reduces environmental losses and enables long-duration storage in compact systems. In addition, TCES technologies enable sector integration (such as industrial waste, CO2 free heating, heat recovery) thus enhancing the sustainability of the systems [61]. However, TCES materials may require energy-intensive synthesis or exhibit stability concerns over repeated cycles. Moreover, the reaction by-products and risks of leaching or degradation must be mitigated through advanced material design and encapsulation techniques [82].
2. Environmental and operational risks involve chemical handling and gas containment, in which the complexity of TCES systems demands advanced chemical engineering design and management. Despite that, the practical use of TCES technologies still faces many implications, including the material degradation over multiple cycles, low thermal conductivity of some reactants, slow reaction kinetics, and difficulties in maintaining chemical and mechanical stability during cyclic operation [60, 62, 63]. Moreover, the development of efficient reactor designs, scalable heat exchangers, and system integration models remains a key barrier to commercialization [61].
3. To sum up, from an environmental perspective, the TCES technologies hold the highest promise attributed to their superior energy density, storage capabilities for long periods, and limited heat loss. While SHS systems remain the most eco-friendly in terms of material abundance and simple designs, their limitations in the efficiency of storage and land use which reduce their environmental competitiveness. LHS systems are environmentally moderate but face challenges regarding their material toxicity and recyclability. The future of environmentally friendly TES technologies might focus on a hybrid design that combines the best aspects of each method, with TCES as the core energy for next-generation systems. Table 7 highlights the summary of the environmental implications of TES technologies.

Table 7.
Comparative summary of the environmental implications of TES systems.

Technology	Energy Density	Material safety	Emission (lifecycle)	Land use impact	Recycling/ End of life	Thermal losses	Environmental score (5 is the highest)
SHS	Low	High	Low	High	High (reuseable)	Medium	3
LHS	Medium to high	Medium to low	Medium	Medium	Low to medium	Low	4
TCES	High	medium	Very low	Low to moderate	Medium	Negligible	5

Source: Le Roux, et al. [20]; Reddy, et al. [34]; Raganati and Ammendola [57]; Bellan, et al. [63] and Aftab, et al. [78].

5. Discussion and Future Perspectives of TES Systems

TES technologies have indeed received significant traction across both academia and industrial domains due to their several advantages such as improving the integration of renewable energy, cost effectiveness, and feasibility [82]. However, several challenges still persist; the SHS systems must be developed and handled carefully to prevent leakages and corrosion exposures. Another challenge of the SHS systems is the non-uniformity of thermal characteristics of rocks and pebble materials and thus deep investigation of these materials to find suitable rocks with uniform thermal, mineral, and climatic conditions is essential [68]. LHS systems have higher energy densities and energy capacity than SHS and thus are suitable for wider and higher temperature-based applications [82]. The use of PCM materials in LHS systems enables the development of affordable, reliable, and environmentally safe energy storage technologies [43]. However, there are some limitations and challenges of using PCM materials such as their low thermal conductivity, cost efficiency, compatibility, safety and health properties, and disposal practices [34]. Thus, innovative modification of PCMs with conductive materials to improve conductivity and thermal properties is required, along with various extensive studies to improve their compatibility, disposal and safety concerns. TCES technologies are remarkable energy storage platforms that offer various distinct features such as low carbon emission, ability to be integrated for solar thermal power plants, and wide applications for district heating and industrial waste recovery systems [59]. However, extensive assessments of TCES technologies are required to scale their production from prototype and laboratory scale to industrial scale for mainstream adoption and usage which will indeed transform energy storage industry [60-62].

For future commercialisations, future research must be carried out to examine the ideal locations and sizes of the TES technologies in renewable energy technologies because both topology and geography are key features of a robust energy system. The integration of TES technologies with renewable energy sources requires deep analysis and experimental work to exhibit the feasibility of developing next-generation sustainable energy systems. For example, the storage systems via hydrogen-based technology provide a long-term energy storage solution but suffer from high cost which impacts their economic and commercial viability [49, 57, 60]. Moreover, future directions on TES technologies should also consider the PCMs based LHS technologies that combine many remarkable features including suitable phase changing temperature, high stability, non-toxicity, low cost, high heat capacity and minimal impact on environment. Among the promising mediums of PCMS are the salt hydrates, molten salts, eutectic mixtures, waste and recyclable materials and selected alloy/metals via sustainable synthesis. Future studies should also address other practical challenges of TES technologies beyond energy density such as the leakage, low thermal conduction, phase segregation, corrosion, supercooling, repeated thermal cycling and degradation under several practical testing. Integrating PCMS with adv advanced encapsulating materials to form stable, porous composites with synergized properties such as thermal enhancement, corrosion resistance, high energy density could revolutionize the field of TES technologies. However, PCMs selection is vital and must be guided with extensive screening in terms of thermophysical properties, life cycle assessment, techno-economic assessment to ensure the TES systems are safer, durable, scalable, and environmentally friendly for solar thermal systems, buildings, renewables and industrial waste hear recovery systems.

6. Conclusion

TES technologies such as SHS, LHS and TCES offer various benefits and opportunities for storing and releasing heat at different temperature ranges and with various mechanisms and implications. The TES systems are useful for residential heating/cooling systems, waste recovery, industrial applications, electronic heat management and etc. Each has distinct features, temperature range, heat storage capacity and density depending on the materials used and application. Despite having low energy density, SHS technologies are still the most viable and widely utilized type of energy storage systems. LHS and TCES have higher energy density and offer various benefits as discussed in this review, but the material selection and complex design, especially for TCES systems, hinder their transition from laboratory-based to industrial and scalable production. Future solutions to overcome technical, economic and environmental implications should focus on developing integrated systems that integrate the high-density materials of LHS (e.g., PCMs) with the SHS and TCES systems.

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