Advancement in Thermal Energy Storage Application: A Comprehensive Overview

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Advancement in Thermal Energy Storage Application: A Comprehensive Overview

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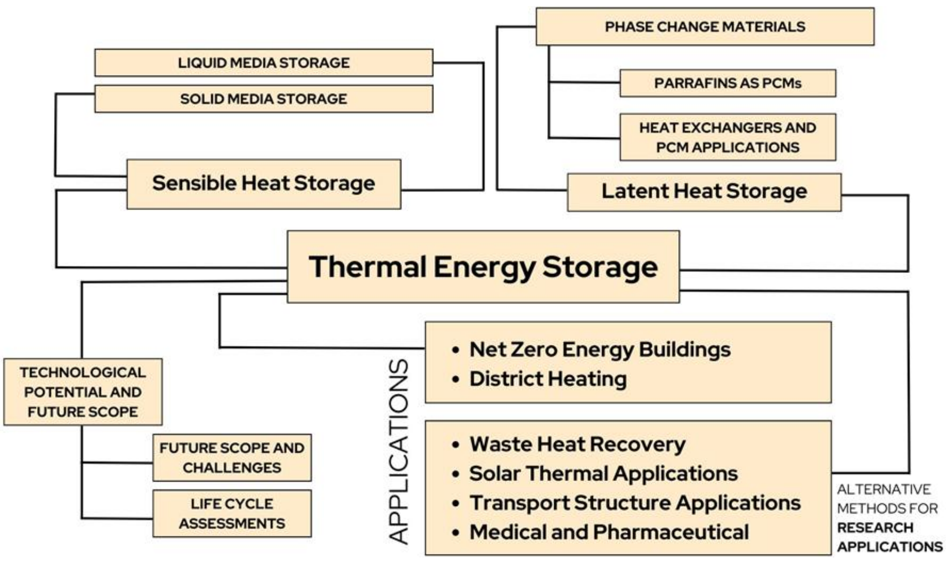
Abstract: Recent advancements in Thermal Energy Storage (TES) have garnered significant attention across various fields due to their promising applications and potential. TES delineates two distinct methods for storing thermal energy: heat transfer retention and energy storage. Recent breakthroughs in sensible heat storage have been achieved using rocks and fluids, while Phase Change Materials (PCMs), heat exchangers, and Latent Heat Storage (LHS) devices have garnered significant attention due to their superior energy density and efficiency. The outcomes underscore the transformative potential of TES systems through integrating nanomaterials, control algorithms, and renewables, promising a revolution in energy storage paradigms. The study also highlights the peak district heating capacity reduction achieved through PCM integration, demonstrating the efficiency of both Sensible Heat Storage (SHS) and LHS in enhancing waste heat recovery, and solar heat storage, and contributing to significant emissions reductions. This synthesis of outcomes positions the review as a pivotal resource, offering nuanced insights into Thermal Energy Storage's advancements and multifaceted applications.

Graphical abstracts:



Keywords: Thermal Energy Storage; Waste Heat Recovery; Solar Applications; Net Zero-Energy Building; District-Heating

1. Introduction

Early civilizations had a long history of monopolizing thermal energy storage (TES). This is a result of human ingenuity and renewable, clean energy sources. Alternative means of energy are derived from the immediate environment, the sky, the ground, and water evaporation through the thermal storage of concrete slabs, rocks, water, soil, and phase transition materials[1]. Heat is transported by evaporation, convection, and radiation, among other methods. Examining these historical issues may aid the current effort to reduce energy demand by maximizing renewable energy sources[2].

The energy was first stored in the form of ice and snow in rivers, streams, and mountains. Straw huts served as cold storage for regional food. Midway through the 19th century, ice was used to cool and remove air that had been forced through fans. HVAC systems with energy storage take load demand into account. Deal with the issues of peak energy usage and data storage. New Dutch endeavours without the customary backing[3].

TES is critical to engineering fields and essential for making human life sustainable in the future. Photovoltaic systems require an efficient technique for conserving and preserving surplus heat gathered during times of strong sunlight and freed for use at night or during other times. Similarly, heating systems with variable landfill gas supply and use intervals benefit from warm storage. This paper reviews various types of TES and conducts a qualitative comparative analysis of their feasibility for future energy sustainability. It also examines sensible heat storage (SHS), latent heat storage (LHS) systems, and thermochemical heat storage (TCHS), and deliberates the requirement for life cycle assessment (LCA) of systems to determine the practicality of new advances[4].

Energy storage is crucial for later use, offering advantages like power quality, stability, and reliability. Recent years have seen increased research into storage technologies due to the energy crisis[5]. Methods include electrical, thermal, chemical, hydraulic, and electrochemical. This study focuses on specific systems like latent heat, power, pumped hydroelectric, and thermal storage. Advancements in storage technology are gaining traction, with a 15–25% increase in wealthier countries[6]. This could positively impact the electrical industry's value chain. Pumped hydroelectric storage is advanced, while compressed air storage may be a viable alternative despite geographic limitations[7,8].

Thermal energy storage (TES) systems balance energy supply and demand and improve system efficiency by reducing peak demand, energy use, emissions, and prices[9]. They also enable a higher proportion of renewable energy by storing and utilizing solar heat even in the absence of sunshine when combined with concentrated solar power (CSP)[10]. Policymakers are presented with various renewable energy options, including TES, which can rapidly respond to load spikes and provide high-temperature storage[11]. Additionally, TES systems can utilize turbine heat for heating homes. Customized design and installation based on application site specifications maximize TES feasibility[12]. TES systems effectively meet energy demands by utilizing phase change materials (PCM) for storing and releasing thermal energy. The combination of TES and renewable energy enhances efficiency and grid flexibility, driving market expansion for large-scale heating, cooling, and power generation in green buildings[13].

To address environmental concerns and ensure long-term feasibility, sustainable approaches must be adopted for TES systems[14,15]. Effective energy management and conservation strategies are crucial for reducing energy use, costs, and carbon dioxide emissions, and improving energy efficiency while maintaining comfort standards. Fig. 1 depicts the breakdown of energy consumption and losses in commercial buildings[16,17].

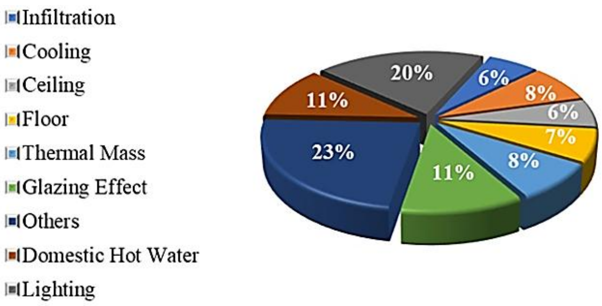


Fig. 1: The typical breakdown of construction end-energy consumption and losses.

Thermo-Syphon Technologies (TST) have gained popularity in the architectural and engineering industries due to their energy-efficient schemes. Initiatives to increase fuel efficiency and improve thermal storage components are being pursued to address global energy demand[18]. TST systems offer environmentally friendly solutions and potential Leadership in Environmental and Energy Design (LEED) certification for carbon-neutral buildings. The urgency to reduce greenhouse gas emissions, address environmental change, and mitigate the consequences of global warming has grown since the energy scarcity of the late 1970s and early 1980s[10].

Energy consumption by end users plays a vital role in improving the economy through energy production, distribution, and conservation. The expansion of the world economy has led to widespread energy utilization in various sectors like building, development, commercial, industrial, transportation, and residential. This review discusses futuristic technologies such as net zero energy buildings (nZEBs) that incorporate thermal energy storage (TES) and solar energy collection. TES has the potential for a technological revolution, and research is focused on optimizing its sustainable use. The development of sustainable cities has been advanced by implementing nZEB with thermal storage applications and waste management systems[19]. These systems utilize various thermal processes, specific heat of materials, and TES with different timespans. Advancements have been made in heat storage, including custom phase change materials (PCMs), while monitoring the energy transfer rate. Other thermal storage methods are also being developed to align with specific applications[20]. TES is a significant technology for energy storage, utilizing sensible heat storage (SHS), latent heat storage (LHS), and high-temperature TES, which is still in its early theoretical stage. Despite the challenges associated with thermal energy storage, its exploration is valuable due to its high energy storage density[21–23].

Researchers are exploring ways to enhance temperature distribution and performance in thermal mass materials through internal alterations and external applications like electric, sonic, magnetic, and pneumatic vibrations[24]. However, several challenges and research gaps remain in advancing TES technology. It is crucial to identify effective determinants for optimal sizing of thermal storage systems and investigate how heat flow can be mutually enhanced under different conditions. Addressing these aspects of research is essential for the successful utilization of energy[25–29].

The objective of this review article is to present an overview of TES and its wide application, including the fundamentals of TES, different types of TES, technological potential, applications in net-zero energy buildings and district heating, research, and development key initiatives, LCA, challenges, and prospects. The paper will conclude by demonstrating how TES is a viable energy storage technology with numerous potential applications.

2. Thermal Energy Storage

TES is increasingly adopted as a cost-effective energy storage technology with long-term storage capabilities. It plays a vital role in renewable systems and finds applications in industrial operations such as peak shaving, grid balancing, load shifting, and energy efficiency[30–33]. The three main types of TES are sensible heat storage (SHS), latent heat storage (LHS), and thermochemical heat storage (TCHS). SHS stores energy as sensible heat associated with temperature change[34]. The LHS materials store energy as latent heat, which is the energy linked to a phase change. TCHS involves storing energy in the form of chemical bonds. Fig. **2** shows a bifurcation of the types of TES based on different sub-segments[10]. Extensive research has been conducted on SHS components and systems, but they have limitations in heat storage capacity and temperature control during storage and release[35–38]. On the other hand, LHS systems have higher energy density and can maintain a steady temperature corresponding to the phase transformation temperature of the storage material. Both LHS and SHS systems have been studied theoretically and empirically, often using synthetic heat sources[10].

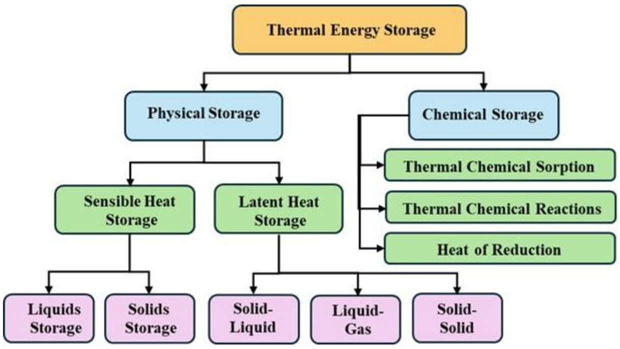


Fig. 2: Classification of TES

2.1 Sensible Heat Storage (SHS)

SHS materials do not change phase and may store thermal energy in either a solid or liquid state. Concrete and ceramics are cost-effective solid materials with strong thermal conductivities[39]. Several fluids, notably water, air, oil, and sodium, have been studied to carry heat until molten salts were chosen as the best[40]. With the finest balance of cost, heat storage capacity, density, and environmental effect, water continues to be the most often utilised medium in SHS systems. Like any SHS technique, it is inherently best used in situations where a material's temperature is first lowered to collect charging energy and then raised later using the stored energy[41].

2.1.1 Liquid Media Sensible Heat Storage

Water, oils, hard liquor, inorganic molten salts, and other perceptible liquid-storage substances are all commonly used. Water is the best option for many applications with low temperature needs up to 100°C[42,43]. Waxes are typically employed for applications requiring middle temperatures between 100°C to 250°C. Table 1 displays the thermal heat capacities for various liquid SHS media. The primary potential concern, however, is the oxidation of those oils over time. For high-temperature storage applications (>300°C), few molten electrolytes have been taken into consideration. High thermal stability, comparatively cheap material prices, heat capacity, high density, nonflammability, and heat of vaporization are all benefits of molten salts[44,45].

Table 1. Specific and volumetric thermal heat capacities for liquid SHS media/ materials[46–48].

Materials	Temperature-Range (°C)	Fluid	Density (kg/m^3)	Specific-thermal-capacity (kJ/(kg K)	Vol.-thermal capacity (kJ/m^3 K)
Thermal - oil	0.0-400.0	Oils	850.0-900.0	1.60-2.10	1360.0-1620.0
Calorie HT-43	12.0-260.0	Oils	850.0-880.0	2.20	1870.0-1936.0
Engine-oil	≤160.0	Oils	885.0	1.88	1669.0
Propane	<96.0	Organic-liquid	800.0	2.5.0	2000.0
Ethanol	<76.0	Organic-liquid	785.0	2.50	1962.0
Butane	<115.0	Organic-liquid	805.0	2.40	1932.0

Octane	<125.0	Organic-liquid	705.0	2.40	1692.0

The cost of the TES may be determined primarily by the liquid storage medium. In these circumstances, inexpensive solid filler elements can enhance differentiation by replacing expensive liquid storage materials[49,50].

2.1.1.1 Storage in water

Water, which has a higher specific heat than other materials, is a cheap and simple way to store heat at low temperatures. In aggressive environments, its high vapour pressure necessitates costly wrapping and pressure-resistant confinement. Water can be utilized in temperatures ranging from 25.0°C to 90.0°C and can store 250.0 kJ/kg or 2.5105 kJ/m^3 for a 60.0°C temperature shift[51]. It is also widely used in radiators for solar thermal applications and everyday activities such as washing and bathing. For instance, in solar power systems, water can be employed as a medium for energy production and delivery[52]. Water is an extensively used storage medium for solar heating and space heating systems. Thermal stratification or a thermocline can form in a solar hot water storage tank because of buoyancy forces, which ensure the lowest temperatures at the bottom and the highest at the top of the tank. Stratification helps avoid mixing during storage, resulting in improved energy collection and fuel efficiency. Materials used to make water storage tanks include steel, aluminium, reinforced concrete, fiberglass, and more[53,54] are shown in Fig. 3[55,56].

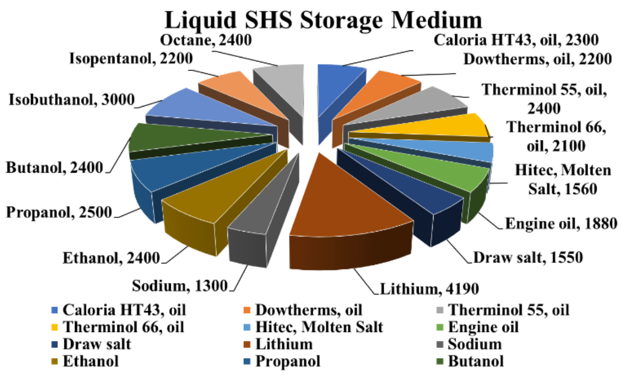


Fig. 3: Different types of Liquid Storage medium and their heat capacities.

2.1.1.2 Storage in Brine

Substantial quantities of solar energy may be captured and stored as low-heat thermal energy (50°C to 95°C) utilizing solar ponds, which are an easy and affordable method for doing so. They have the potential to use it for power generation, process industry heat supply, and combined winter heating. The four major classifications of solar lagoons are Partitioned (multi-layered) or non-partitioned, gelled, or non-gelled, convicting, or non-convicting, and distinct collector and retention or in-pond storage[57,58]. Yet, the non-convicting saline slope solar pond is where most current research efforts are focused. Salt-containing water (or sea water), whose concentration rises with shallow depth, is often used to form a gradient in this kind of solar pond. Sodium chloride (NaCl) and Magnesium chloride ($MgCl_2$) are the two most common salts utilized in this kind of reservoir. Sun rays are absorbed by the black or shady bottom of a salt-slope pond, elevating the lake's temperature to up to 95°C as a result. It is simple to retrieve the TES in the pond's bottom levels without disrupting the higher layers. The 3355 m^2 solar farm in Mexico, which began operation in 1986, is the largest solar pond in the United States. A 70-kW steam Rankine turbine generator, as well as a 18927.06 liters per day desalination plant, are indeed powered more by ponds, which provide space heating to a nearby food processing business[59]. The pond produced more than 302832.94 liters of drinkable water in 24 hours, more than 100.0 kW at peak power output, and attained or sustained temperatures above 90 °C in its heating zone[10].

2.1.1.3 Storage in other fluids

Oils derived from petroleum and liquefied minerals have become popular alternatives to water as thermal fluids. They have a lower heat capacity as compared to water but can function at temperatures above 300 °C. These oils are usually restricted to temperatures below 350 °C, as they are more stable than other alternatives. Overall, these thermal fluids are reliable and efficient options for many applications[60–62].

2.1.2 Solid Media Storage

Thermal energy may be stored in solid materials such as rocks, metal, asphalt, sand, bricks, etc. at both low and high temperatures. The energy may be stored in this arrangement at either high or low temperatures, as these substances won't boil or freeze. By preserving more heat, analogous to sensible heat in solids, it is possible to avoid difficulties induced by excessive water pressure in vapour and the limitations of other liquids. Additionally, solids don't leak from their containers. Materials like cast iron have a higher density than other SHS materials[63]. Cast iron is more costly than rock or brickwork, so its return on investment is marginally higher. Pebble beds or gravel heaps are inexpensive ventures for storing materials[64,65].

Table 2 presents the specific and volumetric thermal heat capacities of various solid SHS materials, offering insight into their performance characteristics. Figure 4 further illustrates the relationship between the density and specific heat capacities of these materials, highlighting their potential for practical thermal energy storage applications.

Table 2. Specific and volumetric thermal heat capacities of solid SHS materials[65,66].

Material	Specific thermal capacity kJ/(kg K)	Volumetric thermal capacity kJ/(m³)	Temperature Range	Density (kg/m³)	Reference
Wood	2.39	1673	20	700	Gugulothu et al.[67]
Steel	0.48	3800	20	7850	Balaji et al.[65]
Sodium	1.3	750-925	100-800	975-1203	Jamil et al.[68]
Sand	0.8	1244	20	1555	Panchal et al.[69]
Rock pebbles	0.88	1410	20	510	Dumka et al.
Magnetite	0.752	3893	20	5177	Elashmawy et al.[70]
Iron	0.452	3571	20	7900	Balaji et al.[65]
Gravelly earth	1.84	3772	20	2050	Bhalavi et al.[71]
Glass	0.837	2268	20	2710	M.El et al.
Concrete	0.88	1760	20	2000	Dumka et al.
Brick	0.84	1176-1596	0-1000	1400-1900	Ravichandran et al.[72]
Aluminium	0.896	2428	20	2710	Mugisidhi et al.[73]
Adobe	1	1700	20	1700	Bhalavi et al.[71]

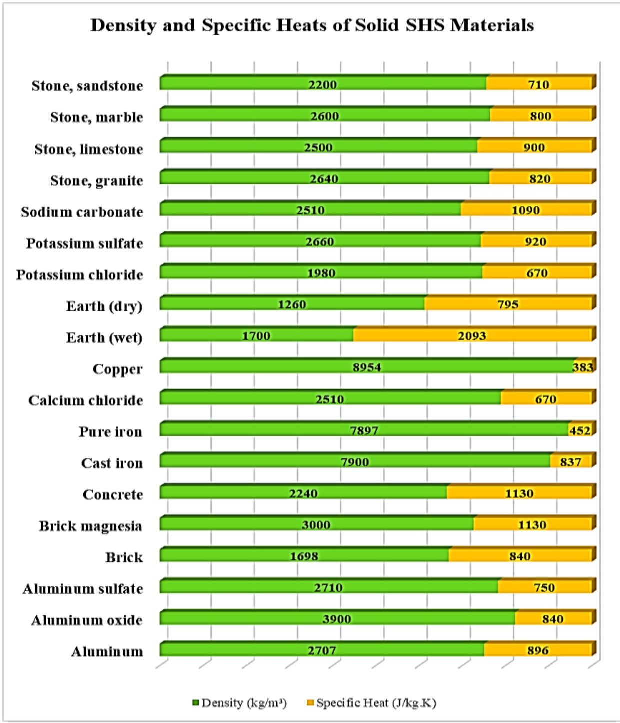


Fig. 4: Density and specific heats of solid SHS materials.

2.1.2.1 Storage in rocks

The size, shape, and packing density of the rocks, the temperature transfer fluid, and the kind of storage system are a few factors that affect the heat transmission fluid's performance in a pebble bed or stone pile storage system[74]. This makes it a practical and viable solution for the storage of solar energy. Furthermore, solar air heaters may be used to raise the temperature of the storage system to 100 °C, making it an effective and reliable system for storing energy.

For space heating applications, a basic rule of thumb is to use 300-500 kg of rock per square metre of solar collector surface. During a 50 °C temperature change, stones and asphalt may store around 36 kJ/kg, or approximately 105 kJ/m3[75]. It is also possible to use rock or pebble substrates for storage at considerably higher temperatures, up to 1000°C. Fluidized beds are more efficient than rock beds in terms of energy transmission between the heat-carrying fluid and the disc drive and may be used for low, moderate, and high-temperature photovoltaic collectors. Continuous-flow thermal storage can also be employed to recover waste heat[22].

2.1.2.2 Storage in building fabric

Heat storage is a technology that can be used in both new and existing buildings. Common materials used for heat storage are ceramic bricks made from olivine, magnesite, microthermal, or zeolite. Passive or active storage solutions may also be implemented using structural cement. Manufacturers are continually improving packaging and dielectric materials, and the most popular application of heat storage is the utilization of building mass to increase floor temperatures[76]. This is achieved by incorporating concrete, which acts as a heat storage medium, and connecting it to direct electric impedance wiring, air ducts, or a heat-transfer fluid such as water.

In construction, inertia and unreinforced mass storage are two distinct methods of storing mass. Systems can be designed to reduce heating costs by utilizing the structure's weight without the need for additional air conditioning units but with specialized controls. Sweden was the first to develop hollow-core ventilation systems that distribute supply air through floor slabs and connect it to the structure's bulk. This method is now widely used for research and development on nZEBs, and heat storage for thermal comfort applications is essential and must be closely monitored[77] .

2.1.2.3 Storage in metals

Inorganic salts and metals are usually suggested materials for high-temperature (120°C to 1400 °C) energy storage. Examples of such metals include aluminium, magnesium, and zinc, which are considered suitable in terms of heat conductivity and cost[78]. Additionally, various manufacturing pollutants such as copper chips, iron slag, wrought iron slag, aluminium slag, and copper slag could be exploited for energy storage[79,80].

2.2 Latent Heat Storage (LHS)

The use of LHS materials, including PCMs for TES, is enticing because of their large energy storage density. LHS materials exhibit a high heat capacity during the solid-liquid phase transition, which is beneficial for storing thermal energy[81]. However, the power density and total storage efficiency of LHS materials are limited by their relatively poor thermal conductivity[82]. To enhance the performance of PCM, the long-term goals include constructing advanced cooling storage systems, optimizing physical interfaces, and integrating LHS materials with other technologies. To achieve these goals, there is a need for improved knowledge of multi-physics phase change processes, better engineering of LHS materials, and an enhanced understanding of LHS material properties[83–85]. Fig. **5** demonstrates a graphical representation of the points of existence of a sensible heat zone and a latent heat zone for THS material.

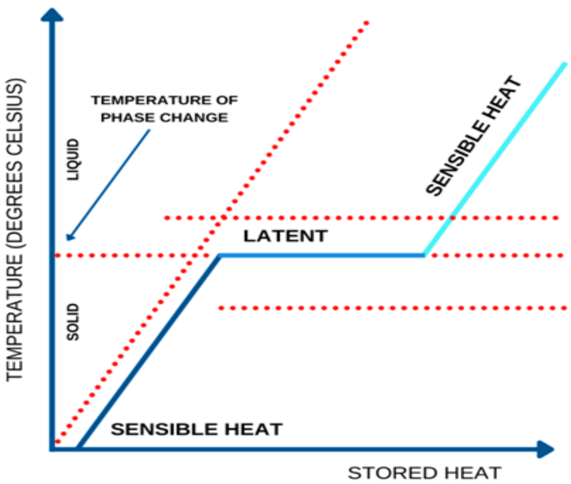


Fig. 5: A graphical representation of the points of the existence of sensible heat and latent heat.

2.2.1 Phase Change Materials (PCMs)

To create a latent high-temperature thermal energy system, three components are needed: a heating substance that undergoes a solid-to-liquid diffusion process within the temperature range necessary, and most of the added heat is stored as heat flux; a receptacle for carrying the storage component; and a thermal sending and receiving outer layer for transporting heat from a hot source. Furthermore, understanding heat storage materials and heat exchangers is vital for developing a LHS system[86,87].

PCMs have been extensively researched for several years because of their significant latent heat and relatively small temperature or volume changes. Recent developments and challenges associated with electrification, high-power-density electronics, fuel cells, and building air conditioning have reignited interest in PCM heat transfer. PCMs offer several advantages, such as waste heat recovery, harmonizing the supply and need for clean energy, buffering transient heating, regulating electrical utility storage, and achieving carbon neutrality. Furthermore, their cost-effectiveness compared to other energy storage methods makes them an attractive option for integrating with solar power and other easily available sources of energy[88]. Fig. **6** shows the transition temperatures and heat of fusion for different PCMs[89,90], while Fig. 7 shows a detailed bifurcation of PCMs[91] based on their transition temperatures within specified ranges and relative heat of fusion, and Fig. 8 shows PCM material properties.

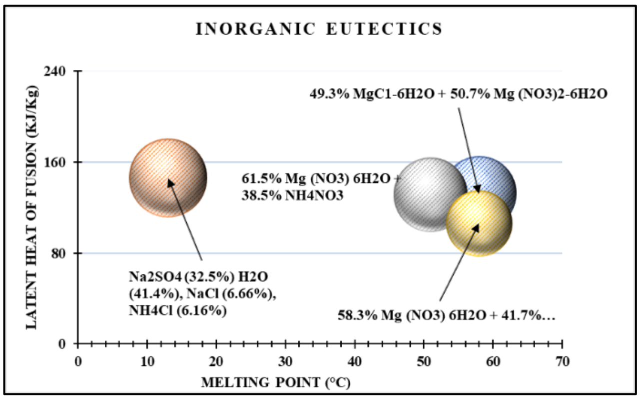


Fig. 6: Transition temperatures and heat of fusion for different PCMs.

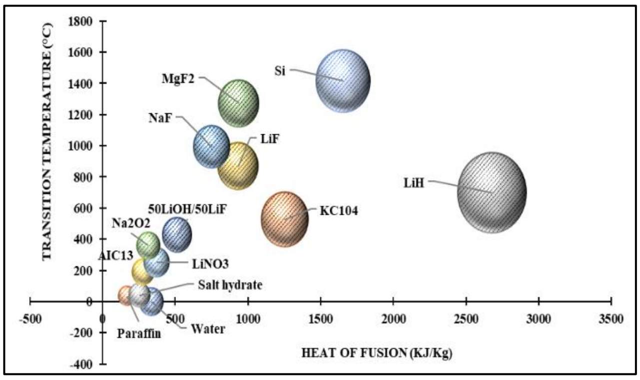


Fig. 7: A detailed bifurcation of PCMs based on their transition temperatures within specified ranges and the relative heat of fusion.

PCM solar thermal is based on the long-studied processes of melting and solidification[92]. It absorbs a substantial amount of thermal energy at the melting point Tm due to the hydrogen-bond channel's toggle[15,93–100].

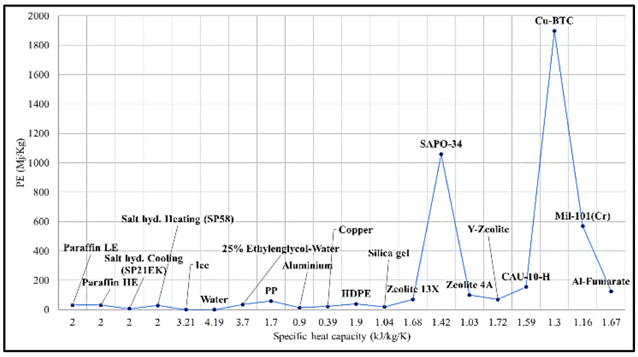


Fig. 8: PCM material properties

2.2.1.1 Paraffin as PCMs

Paraffins have advantageous properties, such as high heat of fusion, minimal super-cooling, heat of vaporization in the molten metal, chemical inertness and stability, self-nucleating, and commercial viability, making them suitable for energy storage applications. Nevertheless, they have restricted thermal conductivity and a change in volume throughout the phase of transition[101,102]. To improve these features, aluminium fillers, metal matrix architectures, beaked tubes, and copper shavings are used, as plastic containers and various container geometries[103]. Technical-grade paraffins are studied for LHS applications due to their melting temperature range and affordability, along with commercial waxes such as n-eicosanoid and n-octadecane[104]. Reductive-temperature operations make use of natural matter, salt hydrates, and low melting-point tool steels, while paraffin waxes, lipids, and hydrates are developed for temperatures of 400-500 K[105,106]. Figure 9 and Figure 10 show the inorganic and organic PCMs (paraffin wax-based) comparative analysis for their melting point temperatures and latent heat of fusion.

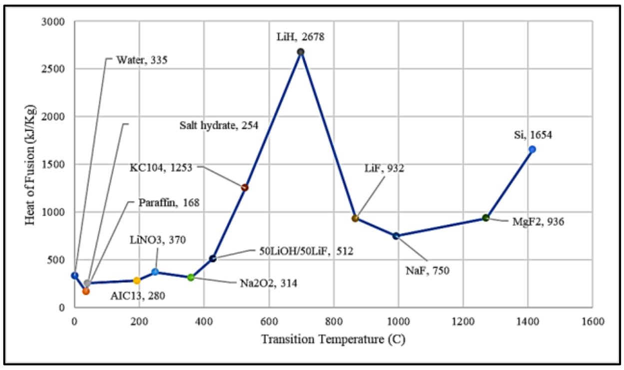


Fig. 9: Inorganic PCMs (Paraffin wax based) shown in a comparative analysis between melting point temperatures and latent heat of fusion.

For applications requiring higher temperatures (>500 K), PCMs are essentially made entirely of molten salts and alloys. The container material selection should be made carefully due to the strong corrosive properties of the same[107,108].

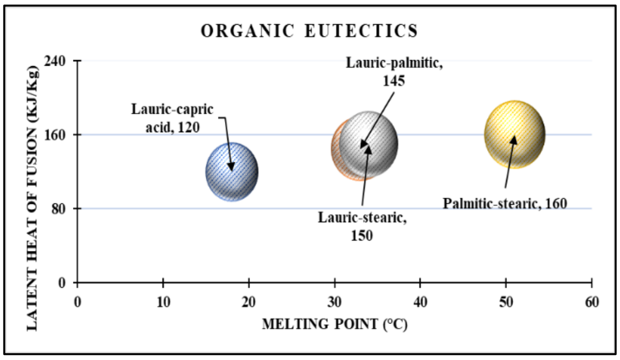


Fig. 10: Organic PCMs (Paraffin wax based) shown in a comparative analysis between melting point temperatures and latent heat of fusion.

2.2.1.2 Heat Exchangers

A heat exchanger is required in a latent heat TES (LHTES) system to move energy from the heat generator toward the TES system and from that material to the heating element Fig. 11. In designing an LHTES system, the kind of heat-exchanging surface is crucial since it has a big impact on the temperature gradients that happen during the charging and discharging processes of the store. Quantitative data on the PCM's temperature distribution and phase innovation process is necessary for proper LHTES system design[109,110]. The majority of PCMs (particularly those in the solid phase) have insulating properties, which makes the heat-retrieving operation difficult. The use of metallic expanded surfaces with exposed heat-conducting tubes or heating elements can solve this issue[111]. The researchers investigated heat transfer data for technical grade PCM, which was contained in a storage container. They used aluminium honeycomb discs and square fins made of aluminium and copper to expand the surfaces. These fins were oriented towards the container's sidewalls. The heat transfer analysis involved paraffin wax of technical quality melting and freezing around cylindrical heat-carrying tubes that were either finned or un-finned and oriented horizontally or vertically. They discovered via experimentation that the addition of square copper fins improved heat transmission, resulting in a decrease of the solidification periods of commercial-grade paraffin by up to 11 times[52,112].

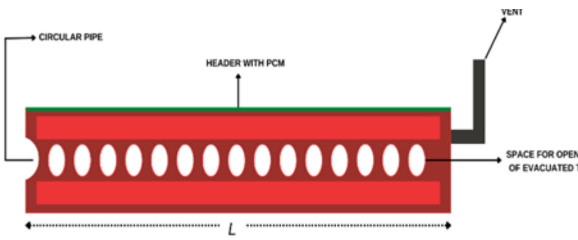


Fig. 11: A schematic diagram of a heat exchanger with a PCM unit.

2.3 Technological Potential and Future Scope

Phase change materials (PCMs) come in various forms, from inorganic salts to liquid metals, and may be used in a variety of settings, from home hot water tanks to spacecraft construction. All PCMs, however, share a key characteristic: they transition from liquid to solid during use. This transition allows latent heat to be utilized, providing an alternative to sensible heating as a method of energy storage or temperature control. To maximize efficiency, certain PCM characteristics must be optimized[113,114].

Further research is needed to optimize the phase transformation characteristics of PCMs for use in energy storage devices. This research should focus on the development of novel eutectic blends, improved conductivities and heat properties, cost-efficiency, and resistance to the effects of aging. Such research could lead to more effective and innovative PCMs with greater societal impact that can be successfully implemented in concentrated solar technologies[115].

3. Applications of TES

3.1 Net Zero Energy Buildings

Technology has brought about significant increases in pollution levels worldwide, posing a hazard to human health and the environment in various ways. The oil and gas industry is a major contributor[116]. As individuals, we all rely heavily on energy consumption in our daily lives. In turn, this has increased the number of carbon emissions released into the atmosphere, with increased energy uses for cooling, heating, and many other essential services such as electricity production[117,118].

A net-zero energy building (nZEB) is a grid-tied building with exceptional energy effectiveness. It ensures that the total primary energy delivered to the building via power systems is equal to the total primary energy consumed, thus achieving a balance between energy production and consumption[119]. Figure 12 gives a detailed illustration of the different components of an nZEB.

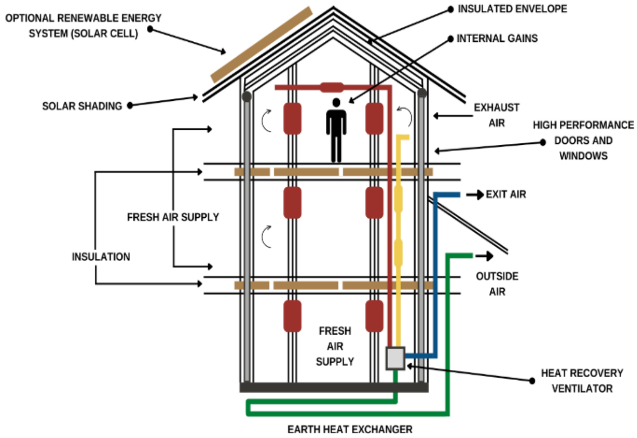


Fig. 12: A schematic diagram of the setup of a nZEB

As a result, an nZEB will only create power whenever the variables are ideal but will depend on external renewable resources when needed. If great performance in buildings is going to be reached through the utilization of measures that have been generally understood and completely defined, a major decrease in CO_2 emission emissions must be enforced towards nZEBs[120–123]. This in no way prevents the possibility of adjusting the objective and cut-off thresholds of those signals to the specifics of the natural ecosystem[107,124,125]. Table 3 shows the studies conducted on nZEB optimization using PCM integration.

Table 3. Research done on nZEB optimization using PCM integration.

Author	Objective	Result
Stritih et al. 2018[126]	Utilization of passive PCMs for TES in nZEBs	PCMs store daytime heat and release it at night. TRNSYS was used to design and analyze a composite wall consisting of several PCMs for passive, near-zero building applications. PCMs in walls reduce energy requirements every day and help meet future nZEB standards.
Kalbasi et al. 2022 and 2023[17,127]	Using PCMs to meet energy efficiency for nZEBs	Installing the PCM on the top layer saved energy. A PCM phase change is not necessarily good. PCM without phase transition lowered energy consumption more, whereas PCM with phase transition reduced energy consumption less. PCM reduced CO2 with and without phase change.
Fiorentini et al. 2015 and 2017[128]	Optimization of HVAC systems with integrated PCM TES for nZEBs	PVT collectors heat or cool ambient fresh air to heat or cool PCM storage units and interiors. PCM heat can condition the air entering the air handling unit.
Lin et al. 2020[129]	Design optimization of TES using PCM for nZEB	The inner PCM tube diameter, distance-to-diameter ratio, PCM type, number of tubes, and intake water temperature all affected the TES unit's charging performance. The best design improved TES density from 13.58 to 26.47 kWh/m^3.
Solomon et al. 2015[130]	Encapsulated PCM for TES	The EPCM capsule's empty centre casing melts fastest. The slowest EPCM capsule melts void topped. Heat transmission is needed to accommodate the PCM's thermal expansion upon melting in an EPCM capsule's vacuum area.
Mazzeo et al. 2017[131]	Building envelope PCM layer energy behaviour assessment	In an air-conditioned setting, a PCM with a melting temperature between the winter and summer set points maximizes cumulative stored energy.

Thermally activated building systems (TABS) use pipes installed in the core of the ceiling frame to sustain a comparatively consistent temperature of 20°C to 24°C throughout the year[132)]. Such capabilities help to cool as well as provide large heat luminous cooling if the building's width is adequate (25–30 cm), a high heat volume material is used in construction projects (like concrete), and floorboards on both edges are not encapsulated by a building's thermoelectric insulating product to ensure adequate accessible accrual thermal mass[133–135)]. TABS are more efficient and economically feasible for the cooling as well as heating of buildings through the integration of the building structure for energy storage (Table 4). TABS are being utilized more frequently, yet control is still frequently a problem that must be fixed136)

Table 4. Research conducted on nZEB development using TES integration.

Author	Objective	Result
Hai T et al. 2023[137)]	Environmentally optimized nZEBs with green hydrogen production design and transient modelling	Building air conditioning offers year-round comfort. 55°C DHW. The roof can become a ZEB to reduce Kuwait's greenhouse gas (GHG) emissions. The gadget reduces fossil fuel CO_2 emissions by 33%.
Degefu D et al. 2023[138)]	Geopolymer concrete for nZEBs	The samples with different starting water contents had equal vapour permeability and moisture effectivity. The samples with different beginning water contents exhibited equal moisture effectivity and vapour permeability.
Li Y et al. 2022[139)]	Energy savings based on thermal adaptability	Summer thermal comfort for senior rural home dwellers was poor, with a predicted mean vote model adaptation coefficient of 0.065, substantially lower than the Chinese average of 0.21. Lowering the room temperature improved "a bit dreadful" living conditions. Design and structural improvements might save 52.15% of energy, providing net-zero rural dwellings.
Shaik S. et al. 2022[140)]	PCM's burnt clay brick design decreases air cooling expenditures and CO2 exclusion.	According to the analysis, the duplex home that incorporates PCM layer brick on the exterior side and OM-29 PCM provides the most significant yearly reduction in electricity costs, which amounts to $2079.0 in hot climates and $2095.0 in integrated climate zones. Moreover, this setup delivers the most effective countermeasures against GHG emissions, reducing them by $87.80 per tonne of CO_2 on an annual basis and $0.88 in composite climates. The accounting rate of return is also reasonable, taking 11.20 years in inclement climates and 11.28 years in hot, arid climates.
Sami S. et al. 2022[141)]	Performance assistance of a desalination station with heating, cooling, and power units integrated with nZEB	The system's springtime optimum exergy efficiency was 81.2% and the lowest overall price rate was 21.15 $/h. The best spring PVT space (165m^2) has 75.3% energy efficiency and a 20.92 $/h total price.
Luo Y. et al. 2022[142)]	Reversed heat flow building envelope for nZEB HVAC systems	Each of the five systems with the lowest yearly power use has a typical ideal thermal load setting.
Bondareva N. et al. 2022[143)]	PCM-concrete block heat transfer for thermal comfort	At peak temperatures, tilt angles change the internal surface by 4.5°. PCM walls conduct more heat than roofs under the same external thermal conditions.

3.2 District Heating

District heating systems rely on TES to store and deliver energy at various times during the day. The stored energy is used to provide energy when needed and can be used to reduce the need for peak-time power generation. The main TES used in district heating systems are seasonal heat storage (SHS) and long-term heat storage (LHS)[144–146)].

SHS is used to store energy over a year and may be utilised for both heating and cooling. It is frequently utilised in conjunction with nonconventional energy sources such as geothermal, solar thermal, and biomass. The stored energy may be used during peak times to decrease the need for peak-time power generation. LHS is used to store energy over longer periods, such as weeks or months. It can be used to provide heat in the evening and early morning when demand is highest[147)].

Recent developments in district heating and TES have focused on enhancing the efficiency of the systems and integrating them with non-conventional energy sources. Researchers are also exploring the use of smart control systems to regulate the use of stored energy and optimize the need for peak-time power generation. Researchers are also looking into ways of using TES to reduce energy costs, improve energy security, and reduce carbon emissions. This involves examining how TES may be used to store energy from nonconventional sources like solar and wind and then use it to provide heating and cooling as needed[148)].

Researchers are looking into how TES can be implemented to reduce dependence on conventional sources, such as natural gas and coal. This includes exploring how TES may be used to provide firm capacity to district heating systems and reduce the need for backup power generation[149,150].

3.3 Alternative Focus Segments for Research and Development

3.3.1 Waste Heat Recovery

To improve system efficiency, sustainable thermal energy storage (SHS and LHS) can be integrated with waste heat recovery systems (WHRS). SHS and LHS systems can store heat from processes such as industrial and manufacturing processes as well as from solar energy collected by solar thermal collectors. This stored heat can then be used to heat buildings and generate electricity. Waste heat consumes 70% of the thermal portion of energy produced in thermoelectric and nuclear power plants. The surplus heat has a lower temperature than the boiling point of water. Researchers describe a protracted thermal-storage material capable of absorbing heat energy from 38°C to 67°C[151]. SHS and LHS systems can also be used to decrease the maximum demand for electricity in a building by moving the peak demand to off-peak periods[152]. This reduces the overall cost of electricity as well as the strain on the power grid. SHS and LHS systems can also be used to reduce emissions from the burning of fossil fuels. The requirement to burn fossil fuels to fulfil peak energy demand is decreased by storing heat while energy demand is relatively low and then releasing the stored energy when energy demand is high. his can help minimise CO_2 and other GHG emissions[153–156].

There has been a significant focus on optimizing TES through research and development, aiming to improve storage efficiency and reduce system costs. One promising avenue for achieving this goal is using thermoelectric devices, which are semiconductor mechanisms able to convert electricity into thermal energy for heating or cooling, as well as recover waste thermal energy and convert it into electricity. These devices have the potential to significantly contribute to reducing CO_2 and GHG emissions while providing a relatively clean source of energy[157]. For SHS systems, this involved research on the usage of novel resources, such as PCMs, for heat storage. Researchers have also been looking into the use of waste thermal energy from various industrial processes or nonconventional energy sources as heat sources for SHS systems[158]. For LHS systems, research has emphasised on finding novel materials and systems that can have a high energy storage density. This includes exploring the use of nanomaterials and other advanced materials for heat storage[159]. Additionally, research has focused on optimising of the LHS system for maximum efficiency and reducing costs. Research and development in sustainable TES for waste heat recovery is continuing to grow and is providing promising solutions for reducing energy consumption and increasing energy efficiency[160].

3.3.2 Solar Thermal Applications

Solar thermal technologies are becoming increasingly popular for their ability to produce clean energy with minimal environmental impact. TES systems may be used to elevate the efficiency of solar thermal technologies by storing excess energy produced during the day for use during peak demand or later in the day when demand is higher. This can reduce the need for other sources of energy, such as natural gas or coal, which can have a negative environmental impact[161].

Low-temperature solar thermal (LTS) systems typically involve the use of flat plate collectors, which use the sun’s radiation to heat a fluid like water. This heated fluid is then used to heat a building or other space. TES systems can be used with these low-temperature systems for the storage of the thermal energy produced during the day and the release of it during periods of peak demand or when needed at night[162].

Medium-temperature solar thermal (MTS) systems involve the use of concentrated solar collectors, which use mirrors or lenses to concentrate the sun’s radiation onto a receiver. This heated receiver heated a working fluid, which is used for heating a building or other space. TES systems can be used with these medium temperature systems to store the thermal energy produced during the day and release it during peak demand periods or when needed at night[46,163,164].

High-temperature solar thermal (HTS) systems involve the use of concentrated solar power (CSP) systems, which employ huge mirrors to concentrate the sun’s radiation onto a receiver. This receiver is then used for heating a working fluid, which is in turn used to drive a turbine and generate electricity. The TES systems can be used with these high-temperature systems for the storage of thermal energy produced during the day and the release of it during periods of peak demand or when needed at night[165].

Recent research and development into TES systems has focused on enhancing the efficiency of these systems and reducing the cost of installation and maintenance. Research has been conducted into the use of PCMs to store thermal energy, as well as the usage of advanced thermal storage systems like sensible heat storage (SHS) and latent heat storage (LHS) systems. Research into these systems has focused on enhancing the efficiency of energy storage and reducing the cost of installation and maintenance[166–168].

3.3.3 Transport structures (Roads, pavements, and bridges)

SHS and LHS systems can be used in transport structures in a variety of ways, just as THS can be used to reduce peak demand by storing energy during off-peak hours and releasing it during periods of peak use[169,170]. This can help reduce the need for additional infrastructure and improve efficiency. Heating and cooling for the transport structure and its occupants can be provided by using the stored energy. This can improve the comfort level of passengers and reduce the need for additional HVAC systems[171)].

TES is also useful in various built-environment components, such as car parks, platforms, roadways, and bridges, in addition to buildings and energy systems. Introducing TES might aid in integrating the deterioration of such infrastructures brought on by seasonal temperature variations, which can result in compressive stresses, distortion, and cracking[172)]. Underground energy storage and the straight inclusion of LHS into fine aggregates have been investigated in this context, especially for use in de-icing roads and viaduct decks[173–176)].

Recent research and development efforts have emphasized the efficiency and cost-effectiveness of TES systems. Researchers have been exploring the use of PCMs to store larger amounts of energy in smaller volumes. PCMs are materials that can store energy as they change physical states, allowing them to store more energy than conventional SHS systems. Other research efforts have focused on improving the efficiency of TES systems that already exist and developing new methods for controlling the release of energy. Overall, TES systems offer a promising solution for enhancing the efficiency and comfort of transport structures. With continued research and development, these systems can help reduce energy consumption, improve the passenger experience, and strengthen and stabilize the structure[177)].

3.3.4 Medical Applications

TES has a very useful set of applications in the medical and pharmaceutical sectors. The sectors see wide TES integration for material preservation and testing. The TES is increasingly being used in the medical sector to improve efficiency, reduce costs, and ensure a reliable energy supply. It has been used to store energy for medical processes such as sterilization and cooling of sensitive medical equipment and as a source of energy for medical equipment[178)]. Recent research and development in TES in the medical sector include the development of passive cooling systems for medical facilities, the use of PCM for TES, and the usage of TES systems in combination with renewable energy sources[179)].

Passive cooling systems are being developed to provide reliable cooling for medical facilities. This type of cooling system uses TES to reduce energy consumption, reduce peak electricity demand, and ensure reliable cooling. TES in the medical sector can also employ PCMs[180)]. PCMs are materials that absorb and release heat when they transit between liquid and solid phases. This makes them ideal for storing heat generated from medical processes such as sterilization. TES systems can be used in combination with renewable energy sources to provide a reliable energy supply. These systems can store renewable source-based energy, such as solar and wind, and then release it when needed[181,182)]. This can reduce the need for additional energy sources and lower energy costs. Recently, because of their unique heat-absorbing and heat-rejecting characteristics, PCMs have also been utilized in a variety of biomedical applications. Thermotherapy is the treatment of Buruli ulcers, arthritis, and other transmissions of microorganisms, so everyone can benefit from PCMs' temperature since it enables them to store or radiate heat for prolonged periods. PCMs have also been utilized in hot and cold therapies for medical operations and utilization. Examples of hot and cold therapy using PCM include heat cushions for rheumatism or physiotherapy, blankets to prevent hypothermia, and chilling packs used through operations, accidents, or stressful sports activities[180)]. However, a longer treatment time at a more stable temperature is possible thanks to the PCM, which takes on the role of standard SHS methods. Another PCM enables temperature adjustment for cooling when cold water or ice is frequently used[183)].

4. Future scope and challenges

The evolution, expansion, and development of advanced material components for TES hold great potential to revolutionize energy storage. Nanomaterials, such as graphene and carbon nanotubes, have already shown promising results for TES, and their use is likely to expand in the future. The application of advanced control algorithms to TES systems can enhance their efficiency and reliability. With the development of more efficient TES systems, the cost of energy storage will decrease, making it more accessible to more people. TES systems can be used in conjunction with renewable energy sources, such as solar and wind, to help balance energy supply and demand[184)]. With the development of more efficient TES systems, the cost of energy storage will decrease, making it more accessible to more people. TES systems can be used in conjunction with renewable energy sources, such as solar and wind, to help balance energy supply and demand[165)]. With the development of more efficient TES systems, it will become possible to store energy in a more distributed manner, which can reduce the need for large, centralized power plants. With the development of new materials, TES can be used to store energy in more compact forms, such as in the form of PCMs. One of the major challenges associated with TES is the difficulty of storing large amounts of energy for long periods. Another issue is the significant cost of TES systems. The cost of materials and technology used in such systems is high, which limits their widespread adoption. The efficiency of TES systems is also a challenge. High temperatures are required for efficient energy storage, and achieving these temperatures can be difficult. TES systems can also be difficult to control as they are sensitive to changes in temperature. Lastly, TES systems require a large amount of space, which can be difficult to provide in some applications[185)].

The life cycle assessment (LCA) is another approach that can be utilized as a TES assessment technique for the impact evaluation of SHS and LHS materials in various aspects, including resources, energy consumption in a generation, operations, and environmental impact from cradle to grave[186]. Throughout a TES's lifespan, LCA contributes to the manufacture, use, and landfill processes as well as all resource and energetic inputs and results[187–189].

5. Conclusions

This review has included an extensive study of the types and trends relevant to this segment of TES. The two main methods for storing thermal energy that are being investigated for various uses, including space heating and the generation of hot water, are heat transfer retention and storage of energy. The development of sensible heat storage, which absorbs heat in rocks or fluids, is at an advanced stage. Conversely, heat, an emerging technology, has garnered significant attention due to its numerous practical benefits. Researchers are conducting studies on PCMs and heat exchangers about the design of LHS devices. We still need to resolve a variety of problems before we can widely access technically and financially advantageous latent heat TES systems. The major findings include:

1. Nanomaterials, advanced control algorithms, and renewables can revolutionize energy storage through TES systems, making it more efficient and accessible.
2. The studies summarized in Table 4 demonstrate that PCM integration can optimize nZEBs, and achieving great performance in buildings requires a significant decrease in CO2 emission emissions.
3. District heating systems use seasonal heat storage (SHS) and long-term heat storage (LHS) for energy storage and delivery at various times of the day, which can reduce the need for peak-time power generation. Research to improve the efficiency and integration of district heating systems and thermal energy storage (TES) with renewable energy sources is being conducted, as well as the usage of smart control systems and TES to reduce energy costs, improve energy security, and decrease reliance on fossil fuels.
4. SHS and LHS systems can be used to elevate the efficiency of waste heat recovery systems, store heat from solar and industrial processes, reduce emissions from the burning of fossil fuels, and reduce the amount of waste heat generated in thermoelectric and nuclear energy stations.

Although PCMs have been subjected to numerous studies, there is a paucity of data in the literature regarding their thermophysical characteristics, particularly those of technical grade PCMs, such as density, specific heat, and thermal conductivity within the liquid and solid stages. Regardless of the observed thermophysical parameters of technical grade PCM and the literature, a disagreement was detected. Therefore, to assist in the efficient and suitable layout of thermal storage facilities, experimental-based analyses regarding these specific thermophysical characteristics in both liquid and solid phases of PCMs are essential.

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Nomenclature

Abbreviation

CAES:	Compressed Air Energy Storage
CFC:	Cloro Fluoro Carbons
CHP:	Combined Heat and Power
CO_2:	Carbon Dioxide
CSP:	Concentrated Solar Power
DHW:	Domestic Hot Water
EU:	European Union
GHG:	Green House Gases
HVAC:	Heating Ventilation and Air Conditioning
LCA:	Life Cycle Assessment
LEED:	Leadership in Environmental and Energy Design
LHS:	Latent Heat Storage
LHTES:	Latent Heat Thermal Energy Storage
nZEB:	net Zero Energy Buildings
PCM:	Phase Change Materials
TABS:	Thermally Activated Building Systems
TES:	Thermal Energy Storage
SHS:	Sensible Heat Storage
UTES:	Underground Thermal Energy Storage

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