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Thermal energy storage in buildings: Opportunities and challenges

PRIYAM DEKA*
ANDRZEJ SZLĘK

Silesian University of Technology, Faculty of Energy and Environmental Engineering, Konarskiego 18, 44-100, Gliwice, Poland

Abstract The energy sector is a majorarea that is responsible for the country development. Almost 40% of the total energy requirement of an EU country is consumed by the building sector and 60% of which is only used for heating and cooling requirements. This is a prime concern as fossil fuel stocks are depleting and global warming is rising. This is where thermal energy storage can play a major role and reduce the dependence on the use of fossil fuels for energy requirements (heating and cooling) of the building sector. Thermal energy storage refers to the technology which is related to the transfer and storage of heat energy predominantly from solar radiation, alternatively to the transfer and storage of cold from the environment to maintain a comfortable temperature for the inhabitants in the buildings by providing cold in the summer and heat in the winter. This work is an extensive study on the use of thermal energy storage in buildings. It discusses different methods of implementing thermal energy storage into buildings, specifically the use of phase change materials, and also highlights the challenges and opportunities related to implementing this technology. Moreover, this work explains the principles of different types and methods involved in thermal energy storage.

Keywords: Thermal energy storage; Renewable energy; Phage change materials; Latent heat thermal energy storage; Sensible heat thermal energy storage

*Corresponding Author. Email: priyom.29@gmail.com

Nomenclature

C_p	–	specific heat capacity, $Jkg^{-1}K^{-1}$
f	–	melt fraction
I	–	exergy consumption
m	–	mass, kg
Q_s	–	heat energy, J
T	–	temperature, K
ΔT	–	temperature difference, K
ΔE	–	net energy
$\Delta \Xi$	–	net exergy
Δh	–	enthalpy change, J
Δq	–	latent heat of fusion, Jkg^{-1}

Greek symbols

α	–	thermal diffusivity
ε	–	exergy
η	–	energy efficiency
λ	–	thermal conductivity
ρ	–	density
Ψ	–	exergy efficiency

Abbreviations

CO_2	–	carbon dioxide
CSP	–	concentrating solar power
GIES	–	generator integrated energy storage
HVAC	–	heating, ventilation and air conditioning
LHSC	–	latent heat storage capacity
LHTES	–	latent heat thermal energy storage
PBSS	–	packed bed storage system
PCM	–	phase change material
PVS	–	photovoltaic system
SHSM	–	sensible heat storage materials
SHTES	–	sensible heat thermal energy storage
TCHS	–	thermochemical heat storage
TCM	–	thermochemical materials
TES	–	thermal energy storage

1 Introduction

Out of all the major energy consuming sectors, buildings are the highest energy consumers, consuming almost one-third of the total requirement [1]. In a recent study, it has been concluded that around 160 million buildings in the European Union consume around 40% of the total energy produced and have a similar share of CO_2 (carbon dioxide) emissions [1,2]. Moreover, it is expected to rise by 50% by 2050 [3]. Hence, developing technologies satisfying the energy demands through the use of renewable sources of energy is of utmost importance. Here, thermal energy storage (TES) technologies can play a very important role in meeting the energy demands in the building sector with regard to heating and cooling requirements. TES is a rather new and evolving technology in a few developed nations, which allows trapping the heat from solar radiation or cold from the environment by the use of specific thermal storage materials to provide a comfortable indoor temperature in the buildings. By the use of TES, the dependence on the conventional heating, ventilation and air conditioning (HVAC) systems run by electricity (which is majorly generated by burning fossil fuels in power plants) can be reduced to a certain extent. In Europe, it is estimated that around 1.4 million GWh per year can be conserved and almost 400 million tones of CO_2 emissions can be prevented by the use of heat and cold storage in the domestic and industrial building sectors [4]. Therefore, the adequate use of TES systems has a high potential in energy conservation and countering global warming. The TES technologies can be greatly enhanced and improved by conducting research and development in the areas like: (a) reduction in capital cost, (b) improvement in overall efficiency, (c) utilization and lifetime of TES and (d)development of TES standards and protocols [5].

On the basis of forced and natural convection, TES can be classified into active and passive systems, which is discussed in the later sections. Both these methods prove to be equally important for accomplishing energy redistribution related to heating and cooling requirements in buildings [6]. Considering various factors such as ambient conditions, location, cost of implementation, heating and cooling requirements, etc., active and passive systems are implemented. Applications related to them allow the utilization of waste energy, peak load shifting strategies and the use of thermal energy economically and conveniently.

Various materials are used to store heat or cold depending upon the requirement of the building and the budget for construction and maintenance of the TES systems. The most common classification of TES systems is as such: sensible heat thermal energy storage (SHTES), latent heat thermal energy storage (LHTES), and thermochemical storage. The use of SHTES systems is quite widespread because of their low construction investment, low maintenance cost, easy availability and convenience of use. The LHTES uses special materials known as phase change materials which are encapsulated into construction units such as walls, ceilings, floors, etc. A phase change material (PCM) is a material that uses chemical bonds to store and release heat. The transfer of heat energy from the PCM to the surrounding and from the surrounding to PCM occurs when its physical state changes from liquid to solid and *vice versa* [2,7]. However, the thermochemical heat storage (TCHS) systems are more complex than the other two counterparts, and hence limited use of this method can be seen around the world. TCHS uses reversible chemical or physical reactions to store and release heat [8].

This paper provides an extensive overview of the different types and methods of TES. It draws comparative discussion to provide better understandability and provides a solution-oriented approach. Also, it discusses the ongoing studies and the state-of-the-art scientific research of the past and the present on heat storage in buildings. Moreover, the economic aspects of the TES are taken into consideration. Furthermore, it reflects the challenges and opportunities of the present and the future related to the implementation of TES systems in the building and industrial sectors.

2 Thermal energy storage

The use of TES can be dated back to ancient times when natural sources of energy such as ambient air, ground, evaporation of water, building masses, rocks and water with human ingenuity were used to store heat energy or cold. Almost 400 years ago in Persia (present-day Iran), the importance of storing ice for space cooling and food storage can be found in the historical traces [9]. In modern times, the first TES system, which was a ground-sourced heat storage, was installed in Indianapolis, Indiana in the USA in the 1940s [9]. In the year 1975, Telkes used PCM materials in the latent heat thermal energy storage system for heating and cooling in buildings [10]. The studies and research have come a long way from the past. The development of TES systems other than the simple LHTES systems such as PCM encapsulated constructions in buildings and the use of thermochemical materials (TCM) can be found in the scientific literature, as TES has become and will continue to be a necessity in the approaching future.

A large portion of the total energy consumption by buildings is used for space heating [10,11]. The dependence on fossil fuels for energy requirements of the residential and industrial building sectors must be reduced due to the rapid depletion of fossil fuels and other major environmental concerns such as global warming. TES systems can be used as a tool to counter these problems by sharing a part of energy consumption through the use of renewable resources such as solar and wind energy. TES is defined as the storage of heat energy and cold by means of specific materials to transfer heat or cold when needed for space heating or cooling. If heat during the day and cold during the night can be stored and released as per requirement to the indoor of the buildings, a part of all peak loads can be shifted to off-peak periods [2, 12, 13]. In a more specific scenario, if the heat from the solar radiations can be trapped in the day during summer, and released during a few hours of the day and the entire night, energy consumption by the conventional HVAC systems can be reduced and hence peak load periods can be avoided, resulting in effective energy management and economic benefits [2, 13]. There are other benefits as well as a few drawbacks of TES systems which are discussed in Table 1.

Table 1: Advantages and drawbacks of TES systems.

Advantages	Drawbacks
Reduces peak demands and level demands by storing heat energy when there is low demand and releasing it when demand rises [11]	Greatly depends upon climatic conditions of the particular place and season of the year [14]
Stores renewable energy and reduces CO_2 emissions [1]	Storing energy greatly depends on the energy storage densities of the material. Materials with lower energy storage densities do not serve the purpose well [13]
Cost effective with regard to energy consumption [1]	Costs of materials with high energy storage densities are high [13]
Optimizes overall efficiency of the energy systems [3]	Individual efficiency of the TES systems is low and cannot entirely provide heat energy of space heating [15]

As TES systems are implemented primarily to serve the purpose of space heating/cooling, the factors related to energy consumption are quite necessary to address. These factors are mainly the design heat losses, efficiency of the TES systems, duration of occupied period by the inhabitants of the building, and thermal inertia of the building. Furthermore, the factors related to the implementation of TES systems into buildings are installation and operation cost of the systems; method of TES used; seasonal and climatic conditions of the locality; and the design and integration of the system. Figure 1 shows the schematic diagram of a TES system.

Moreover, depending on factors like the location of the building, effective storage and transfer of heat or cold, climatic conditions, size of the building, size of the storage and requirement of indoor comfort, TES can

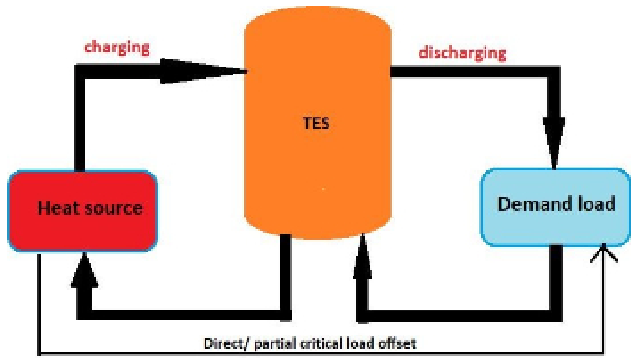

Figure 1: Schematic diagram of a thermal energy storage system [2].

be integrated into a building in different locations such as the building core, external solar facade, suspended ceilings, ventilation systems, photovoltaic (PV) systems and water tanks (Fig. 2).

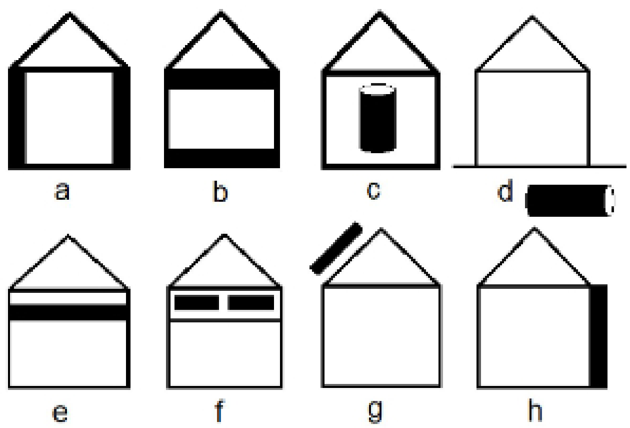

Figure 2: Thermal energy storage implemented in (a) walls, (b) floor and ceiling, (c) tank inside the building, (d) underground tank, (e) suspended ceiling, (f) ventilation, (g) PV system, (h) external facade [1].

TES systems are classified considering various aspects which are depicted in Fig. 3. On the basis of the heat convection mode, it is divided into active and passive TES. On the basis of materials used, it is classified into sensible heat thermal energy storage (SHTES), latent heat thermal energy storage (LHTES) and thermochemical heat storage (TCHS). Moreover, TES can also be classified into small-scale units and large-scale units. Furthermore, it can again be classified according to the motive of TES or the purpose served by it, *viz.*, TES for space heating and TES for space cooling. These systems are comprehensively discussed in the later sections of the paper. Hedegaard *et al.* [16] developed a model combining heat pump with different heat storage options: (a) passive heat storage in the building structure *via* radiator heating, (b) active heat storage in concrete floors *via* floor heating, and (c) use of thermal storage tanks for space heating and hot water. The results showed that the model could represent the working of actual TES systems and promise better performance.

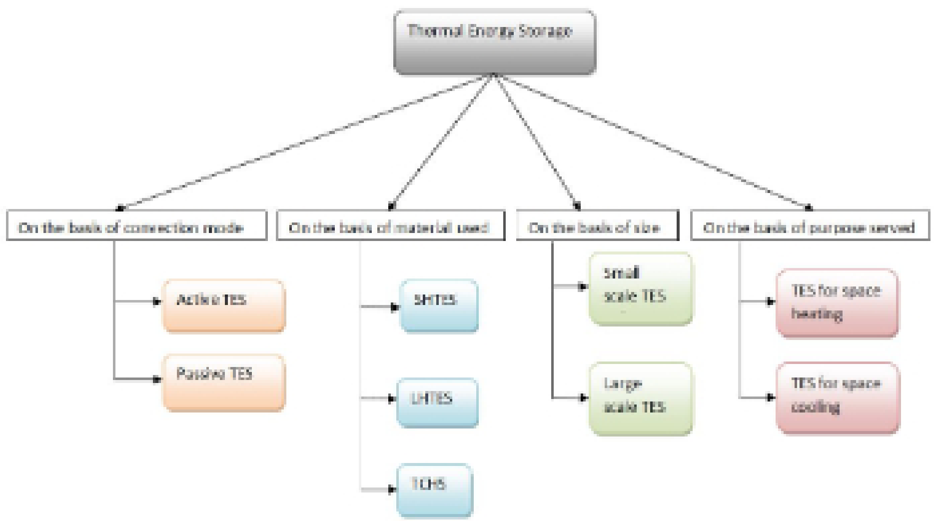

Figure 3: Classification of thermal energy storage systems.

For the TES systems to be more performance oriented, a few properties must be considered. High density of energy storage and high capacity of power for charging and discharging are a few of these desirable properties [1]. The TES material used while designing a unit also plays a vital role in the overall functioning and efficiency of the system. Ostry and Charvat [17] have pointed out a few factors affecting the amount of energy stored in the TES:

- the mass of the building structures,
- specific heat capacity of the TES materials,
- the gap between the initial and the final temperature of the material during the storage process.

Sarbu *et al.* [4] state that the use of a TES system can be justified by the following parameters:

- thermal storage capacity of the medium,
- size of the storage medium,
- power of the TES unit,
- efficiency of the TES unit,
- storage period (duration of the heat storage),
- charging and discharging time,
- cost effectiveness of the system.

2.1 Energy and exergy analyses

Conventional TES systems use energy efficiency as a parameter to compare their performances. This is generally based on the first law of thermodynamics, i.e. the law of conservation of energy. The energy efficiency is basically an accounting of the energy entering and energy exiting the system. However, the energy efficiency does not depict the actual performance of the TES systems as factors like thermodynamic losses are not accounted for, which results in deviation from the actual performance of the system. This is where exergy analysis comes in handy and counters the ineffectiveness of the energy analysis, as it is based on the second law of thermodynamics and helps to identify the causes, locations and magnitudes of the process inefficiencies [18]. Exergy analysis is based on the acknowledgement that energy cannot be created or destroyed but can get degraded in terms of quality, so it cannot be utilized for performing tasks. The term exergy actually represents the available energy or it is defined as that part of a quantity of thermal energy which can be converted to work in an ideal reversible system within a reference environment [19, 20].

The general balance for the TES can be written as [20]:

$$\text{Input} + \text{Generation-Output-Consumptuion} = \text{Accumulation}\,. \tag{1}$$

This general equation can be written for mass, energy, entropy as:

$$\text{Mass input} - \text{Mass output} = \text{Mass accumulation}\,, \tag{2}$$

$$\text{Energy input} - \text{Energy output} = \text{Energy accumulation}\,, \tag{3}$$

$$\begin{aligned}&\text{Entropy input} + \text{Entropy generation}\\ &\qquad - \text{Entropy output} = \text{Entropy accumulation}\,. \end{aligned} \tag{4}$$

Hence, by combing the law of conservation of energy and non-conservation law of entropy, the exergy balance can be written as [18]:

$$\begin{aligned}&\text{Exergy input} - \text{Exergy output}\\ &\qquad - \text{Exergy consumption} = \text{Exergy accumulation}\,. \end{aligned} \tag{5}$$

In mathematical terms, energy and exergy equations are written as:

$$\Delta E = Q_c - (Q_d + Q_l)\,, \tag{6}$$

$$\Delta \Xi = \varepsilon_c - (\varepsilon_d + \varepsilon_l) - I\,, \tag{7}$$

where Q_c and ε_c are the input energy and input exergy, Q_d and ε_d are output energy and output exergy, Q_l and ε_l are energy losses and exergy losses, ΔE and $\Delta \Xi$ are the net energy and net exergy respectively. Moreover, I is the exergy consumption.

Equations (6) and (7), in terms of the subprocess values can be written as:

$$Q_l = \sum_{j=1}^{3} Q_{lj}\,, \tag{8}$$

$$I = \sum_{j=1}^{3} I_j\,, \tag{9}$$

$$\varepsilon_1 = \sum_{j=1}^{3} \varepsilon_{lj}\,, \tag{10}$$

$$\Delta E = \sum_{j=i}^{3} \Delta E_j\,, \tag{11}$$

$$\Delta \Xi = \sum_{j=1}^{3} \Delta \Xi_j\,, \tag{12}$$

where $j = 1$, 2, and 3 for charging, storing and discharging periods.

From Eqs. (1) and (2), individual energy and exergy balances can be obtained for the charging period as:

$$Q_c - Q_{l.1} = \Delta E_1 \,, \tag{13}$$

$$\varepsilon_c - \varepsilon_{i1} - I_1 = \Delta \Xi_1 \,; \tag{14}$$

for the storing period as:

$$-Q_{l2} = \Delta E_2 \,, \tag{15}$$

$$-\varepsilon_{l2} - I_2 = \Delta \Xi_{l2} \,, \tag{16}$$

and for the discharging period as:

$$-\left(Q_d + Q_{l3}\right) = \Delta E_3 \,, \tag{17}$$

$$-\left(\varepsilon_d + \varepsilon_{l3}\right) - I_3 = \Delta \Xi_3 \,. \tag{18}$$

The energy efficiency (η) and the exergy efficiency (Ψ) can be expressed as:

$$\eta = \frac{Q_d}{Q_c} = 1 - \frac{Q_l + \Delta E}{Q_c} = \frac{Q_d + \Delta E}{Q_c} = 1 - \frac{Q_l}{Q_c} \,, \tag{19}$$

$$\psi = \frac{\varepsilon_d}{\varepsilon_c} = 1 - \frac{\varepsilon_l + \Delta \Xi}{\varepsilon_c} = \frac{\varepsilon_d + \Delta \Xi}{\varepsilon_c} = 1 - \frac{\varepsilon_l}{\varepsilon_c} \,. \tag{20}$$

2.2 Economic aspect of thermal energy storage

Thermal energy storage systems are economically justifiable if the initial capital investment and the annual operation costs are less than those of the conventional systems providing the same service. Apart from using TES to harness renewable energy, it is also implemented to have a low initial and operating cost of other plant components. Dincer and Rosen [21] statethat the initial equipment cost can be lowered when large durations are obtained between energy demands. Economic feasibility is a major aspect as studies and researches in the field of TES are increasing. In a study conducted in the United Kingdom, it has been found that the amount of solar energy received by a typical house is more than the total energy consumed by the building on a particular day [22]. In California, assuming a 20% stake in the TES systems, the energy supplier has a reduced operating cost of 30–50% in serving air conditioning loads, and household buildings can also have a lower energy cost (over 1.5 billion US dollars) [21]. However, the technology required to harness this solar energy and stored it as heat energy for later use demands economic feasibility. Moreover, the high cost of PCMs makes it difficult for the TES systems to compete with the conventional space heating/cooling systems. Gautam *et al.* [22] in their study have found that economic feasibility of TES can be attained to a certain extent by combining concentrating solar power (CSP) plants (for electricity) with TES. The author also proposed to provide subsidies for TES systems by the government. Despite the high cost of installation, TES from solar energy can act as a principal source of space heating in the future [22].

Bai *et al.* [23] conducted numerical analyses of a shell and tube LHTES for its performance and overall cost. Two different PCMs were tested in the same model of the TES system. One with 35% lithium carbonate and 65% potassium carbonate and the other PCM with 60% aluminium, 34% magnesium and 6% tin. From this study, it is concluded that the shell and tube LHTES systems can reduce the TES cost as compared to the conventional TES system.

Zhao *et al.* [24] conducted a study to assess the optimum charging temperature for three different configurations (SHTES, LHTES and hybrid) of a packed bed storage system (PBSS). It has been found that the cut-off temperature for cost optimization is 500°C compared to conservative cut-off temperatures. Moreover, the results concluded a cost reduction of 19.8%, 2.2% and 2.3% for a 1-stage SHTES, 2-stage LHTES and a 3-stage hybrid system.

Nithyanandam *et al.* [25] conducted studies on an encapsulated phase change material TES system and an LHTES with embedded heat pipes, both integrated with CSP plants for their performance and cost effectiveness. The authors conclude that a smaller capsule radius of the PCM has lower storage capital cost without compromising the performance. Also, the levelised cost of electricity can be reduced to 0.06 USD/kWh.

Habeebullah *et al.* [26] investigated the integration of an ice storage system in the Grand Holy Mosque of Saudi Arabia. The author concluded that the partial load storage with the current electricity tariff in Saudi Arabia is insignificant; whereas an off-peak period with full load storage showed a certain amount of savings with regard to economics.

Wagner *et al.* [27] through their analyses conclude that using a 2-tank molten salt TES integrated with a CSP plant increases the total plant cost but reduces the overall operating and maintenance costs of the plant.

Yang *et al.* [28] have conducted an investigation to review the techno-economic aspects of seasonal TES systems. It is observed from the study that borehole and aquifer SHTES systems showed better economic performance and the LHTES and TCS systems showed better technical performances. A combination of the SHTES and its other two counterparts can result in better techno-economic performance of the seasonal TES systems.

Lai *et al.* [29] have investigated the economic aspects of a generation integrated energy storage (GIES) and a non-GIES system coupled with wind generation in the United Kingdom. For GIES, the most prominent factor is the generator capital cost, and for non-GIES, the key factor is the energy storage capital cost. The Monte Carlo model of investigation shows that the levelised cost of electricity for GIES and non-GIES are 0.05–0.12 GBP/kWh and 0.07–0.11 GBP/kWh, respectively, for a 100 MW wind power generator and 100 MWh energy storage.

3 Active thermal energy storage

Active TES systems are characterized by forced heat or mass convection to transfer heat or cold from the storage to the indoor space of the buildings with the assistance of a few mechanical components [2,3]. Predominantly, these techniques are implemented for off-peak storage of thermal energy in buildings. Hence, the peak load can be decreased and shifted to night when the electricity is cheaper [2]. It contributes to a high degree of control of the indoor ambience and enhances the way of storing heat energy [1]. The use of active TES integrated into conventional HVAC systems proves to be very significant when it comes to maintaining indoor comfort temperatures. The use of heat pumps is very prominent and widespread in this technique. It finds its use mostly with the LHTES methods although there are exceptions where it is used with SHTES materials. The heat captured during the day or the cold stored during the night (dominantly by the PCM or TCM) can be more efficiently transferred to the indoor with assistance from components like heat pumps and fans [2]. Although the use of mechanical components run by electricity from conventional ways has an impact on the overall operation cost of the system, it provides better and more effective space heating or cooling when compared to the primitive SHTES methods. Therefore, one of the ways to implement active TES (to compensate for the cost of running the mechanical components) is by integrating it with efficient CSP plants.

Farid *et al.* [30] conducted a numerical analysis (one dimensional) of an active TES floor heating system using PCM where the stored heat is transferred to the indoor of the building with the assistance of an electric heater. The sketch of the system is presented in Fig. 4.The PCM material used was paraffin wax (melting point of 40°C and layer thickness of 3 mm)and was placed between the floor tiles on the top and the electric heater at the bottom. From the analyses, it had been found that the heat output from the floor could be significantly increased from 30 to 75 W/m^2 with the use of the PCM layer.

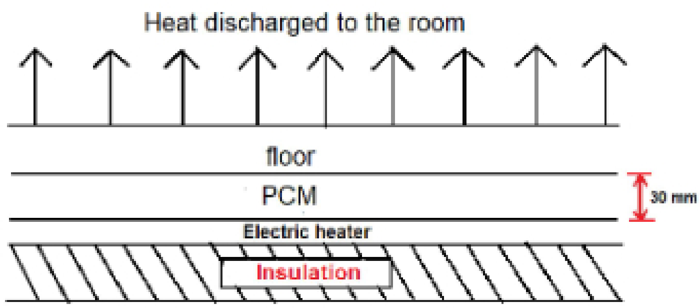

Figure 4: Sketch of the active TES analyzed by Farid *et al.* [30].

Lin *et al.* [31] conducted experimental analyses of an under-floor TES unit with shape stabilized PCM plates. The LHTES material comprised 75 wt% paraffin (PCM) and 25 wt% polyethylene as supporting material. The melting point and the heat of fusion of the PCM were 52°C and 200 kJ/kg. The results were satisfactory as the indoor room temperature got increased without the need of increasing the temperature difference and above half of the total electric heat energy got shifted from the peak period to the off-peak period, which eventually provided better economics.

Kenneth *et al.* [32] analyzed a solar space heating unit integrated with a PCM for domestic buildings in the United Kingdom, in the research facility of the University of Brighton. The TES unit included an array of solar flat plate collectors whose purpose is to provide heat to the water tank and panels of PCM of calcium chloride (melting point of 29°C). The solar panels were made of aluminum sheets, which were covered by two concentrated copper tube coils. Through the inner tube, hot water was circulated and the PCM was stored in the outer tube. The whole unit was located under the floor of the building (test facility). Fans were deployed to carry the heat from the tubes to the room. The results concluded that the unit could reduce energy consumption by 18% to 32%.

4 Passive thermal energy storage

The TES systems which use natural convection to transfer heat or cold to the required space are termed passive TES systems. In other words, these systems do require the assistance from the HVAC units to transfer heat [1]. The driving factor responsible for charging and discharging of the storage is the temperature difference between the TES and the surrounding [17]. Therefore, it is necessary for the indoor temperature to vary in order to store heat or cold. Due to this concern, among all other factors, the boundary conditions related to the indoor of the building are of vital importance, when passive systems are designed this condition can be attained by the use of materials (rammed earth, alveolar bricks, concrete, stones, etc.) with high thermal mass in the building construction. This technique is mostly implemented in the building walls, floors, ceilings and dominantly in water tank storages. The weight of the building structures also plays an important role in passive systems. Heier *et al.* [33] in their study of passive systems found that the temperature swings in a heavier building are significantly less than that of a lighter building, thus better comfort can be attained in the heavier building (Fig.5). Passive TES applications generally can be of two types, *viz.*: LHTES with PCMs and SHTES with materials of high thermal mass [33]. As the use of the HVAC systems is nullified, the TES systems conserve electrical energy from the conventional sources. The use of the PCMs is also possible when integrated into wallboards, which eventually create a layer over the main walls of the building. Moreover, PCMs can also be mixed with conventional concrete to increase their thermal capacity [2].

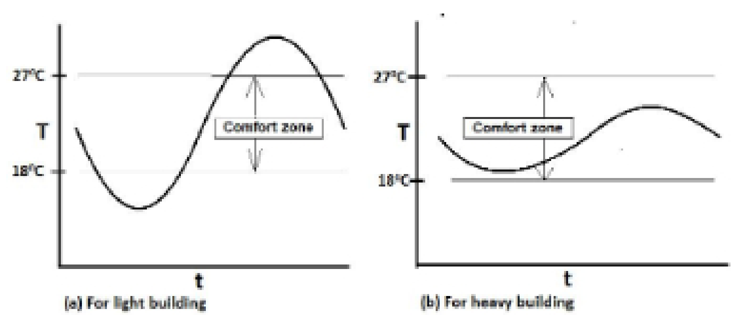

Figure 5: Sinusoidal temperature fluctuations inside buildings [33].

Noren *et al.* [34] studied the effect of thermal mass on a 6-apartment Swedish building. The simulations were conducted with three different numerical codes for better results. Three different setups were created: (a) light construction with wood and gypsum, (b) medium-weight construction with a thick wooden layer, and (c) heavy construction with concrete. The indoor temperature was maintained between 21°C to 24°C by the use of radiators (used for heating) and windows were used for cooling. Results from all three numerical codes showed that the building with heavier construction demanded lower heating requirements and better comfort was attained with lesser temperature swings.

Ståhl *et al.* [35] in his doctoral thesis studied the effect of thermal mass on heating and cooling requirements of buildings in the Nordic climate by using numerical codes. Four different types of buildings were considered: (a) a terrace house, (b) a block of apartments, (c) a school building and (d) an office building. Moreover, a heavy construction of concrete floors, ceilings and outer walls and light construction of timber frames and plaster boards were studied for every building type. The analyses resulted in 1% or 2% lower heating and cooling needs in the smaller buildings and about 4% reduction of the same in the office building.

Yahay and Ahmed [36] studied gypsum ceiling panels integrated with PCM in Malaysia with the motive to regulate the indoor temperature of the building. It is observed from the results that in order to keep the indoor temperature at 250°C during the day, the building required lesser energy due to the presence of the TES unit. A reduction of 12% in energy requirement is claimed through the study.

Pieppo *et al.* [37] has numerically studied a 120 m^2 low-energy house integrated with PCM walls only in the south-facing wall of the building in two different climatic conditions (Helsinki, Finland and Wisconsin, USA). Two different control strategies were adopted: the minimum energy approach and the maximum comfort approach. In the first strategy, the indoor temperature varied from 18–26°C and in the second strategy, the indoor temperature was maintained within a more narrow range of 19–21°C. For the minimum energy approach, the total heating requirement of the building with PCM wallboards was 6% and 15% lower than a similar conventional building without PCM wallboards in Helsinki and Wisconsin, respectively. Moreover, in the maximum comfort approach, the total heating requirement in buildings with PCM wallboards was 7% and 20% lower than a similar conventional building.

Scalat *et al.* [38] conducted a full-scale experiment on a building room equipped with gypsum wallboards impregnated with 25% PCM and another identical room with conventional wallboards. The rooms were heated up to 26°C from 12°C (ambient temperature) and then allowed to cool down and the results were compared. The author concluded that the room equipped with the TES unit cools down much slower than the room without a TES unit. Moreover, while heating up the room, a similar pattern could be observed.

5 Sensible heat thermal energy storage

Sensible heat thermal energy storage (SHTES) is a type of TES where the TES material stores heat below its melting point (if solid) or vaporization point (if liquid) and uses this sensible heat to provide comfort and maintain the required indoor temperature. Here the TES materials have higher melting and vaporization points and hence never go through a phase change. The amount of heat storage greatly depends on the thermal capacity of the material, the temperature difference between the medium and the ambience, and the size or volume of the storage medium used [17]. A few of the most common SHTES materials are stone, reinforced concretes, brick masonry and water [1]. Velraj *et al.* [39] and Kalaiselvam *et al.* [40] have classified the SHTES systems, which is illustrated in Fig. 6.

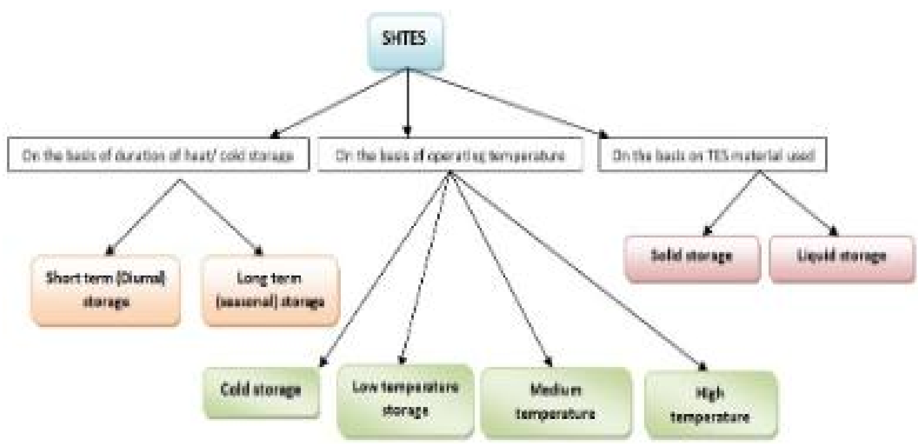

Figure 6: Classifications of SHTES [39, 40, 46].

In the diurnal storage systems, the heat energy is stored for a short term (a few hours daily) to counter the fluctuation between energy availability and demand during the day. It may be the heat energy stored during the day and using it during the night or cold stored during the day and using it during the day [39]. Whereas, in the seasonal storage systems, the heat energy or cold stored in one season is utilized in the other season. Among the seasonal storage systems are rock-bed systems, underground systems with boreholes, soil (earth-to-air thermal storage system), caverns, aquifers, and solar ponds [20, 39]. Also based on the operating temperature, the SHTES systems are divided into cold storage (only for space cooling), low-temperature ($< 100°$C) storage, medium-temperature (100–250°C) storage and high-temperature ($> 250°$C) storage.

In SHTES, the amount of heat stored depends upon [19]:

- the mass of the material,
- specific heat capacity of the material,
- the temperature difference between the material and the ambience.

Mathematically, the heat energy stored by the TES and the above mentioned variables can be correlated by the following equation [17, 19]:

$$Q_s = mC_p\Delta T\,, \tag{21}$$

where Q_s is the amount of sensible heat energy stored, m is the mass of the material used in the TES, C_p is the specific heat capacity of the material and ΔT is the temperature difference.

The storage materials used in the SHTES systems must have some characteristic properties. Kalaiselvam and Parameshwaran [40] have enumerated a few of these properties in their book chapter, which are as follows:

- large thermal storage density of the material;
- high thermal conductivity within the operating temperature range;
- excellent charging and discharging capabilities;
- thermal stability and reliability;
- chemically stability without decomposition;
- energy efficient;
- cost effective;
- non-volatile, non-toxic, non-reactive and low corrosive to the substance holding it;
- of low thermal expansion coefficient;

- of high compressive strength and high fracture toughness (for solid materials);
- of lower carbon footprint.

The authors also concluded that the implementation of SHTES into buildings can improve the energy efficiency and thermal efficiency by 30–35% and 40–60%, respectively. Moreover, with an efficiently designed storage tank with better stratification, the useful heat energy can be enhanced from 20–60%.

Dincer *et al.* [20] conducted an informative study on the aspects of SHTES. The conclusions made by the author are as follows:

- the selection of the SHTES system mainly depends on the operation conditions, economic feasibility and the required duration of storage;
- through a well-stratified water storage tank, almost 90% storage efficiency can be attained;
- presently, SHTES is considered the most economical TES technique among all other techniques.

Karlsson *et al.* [41] through their study on the influence of thermal inertia in building structures proved that an increase in the thermal capacity of the internal thin walls can significantly improve thermal comfort and reduce energy consumption.

Rempel *et al.* [42] investigated different passive SHTES systems such as Trombe walls, exposed mass walls and direct gain floors for their heat storage and release. It is found that although the SHTES systems cannot supply instant heating or cooling due to the lack of mechanical components, adjustments can be made in the design with regards to the materials, configurations and wall thickness to reduce the energy consumption as per the occupants' requirements of space heating or cooling.

Al-Sanea *et al.* [43] through their study concluded that with an increase in the thermal capacity of a building, peak transmission loads get reduced in both summer and winter, and heating or cooling energy consumption gets reduced during the moderate temperature months in between summer and winter.

Zhu *et al.* [44] conducted a study on energy conservation of thermal mass walls in zero-energy buildings. The climatic condition was that of a desert. Two identical buildings were considered for this study, a baseline building with light thermal mass walls and a zero energy building with thermal mass walls. The results showed a reduction in the requirement of purchasing heat, however, the cooling need in the heavy building was higher. The author explains that the heat stored in the heavy building could not escape the building at a higher rate at night and thus the cooling requirement during the next day increases.

5.1 Characteristic parameters related to SHTES

Mathematically, the heat energy stored by TES and the above mentioned variables can be correlated by the following equation [17, 19]:

$$Q = mC_p (T_f - T_i), \tag{22}$$

where Q is the stored heat energy, m is the mass of the storage medium, C_p is the specific heat of the material, T_f is the final temperature of the medium, T_i is the initial temperature of the medium.

The physical properties of some of the most commonly used SHTES materials are listed in Table 2.

Table 2: Properties of SHTES materials [17].

Materials	Density (kgm^{-3})	Specific heat ($\text{Jkg}^{-1}\text{K}^{-1}$)	Thermal capacity (106 $\text{Jm}^{-3}\text{K}^{-1}$)
Water	998	4182	4.17
Steel	7850	440	3.45
Reinforced concrete	2500	1020	2.55
Granite	2500	950	2.38
Plain concrete	2100	1020	2.14
Solid brick	1800	900	1.62
Wood	400	2510	1.00
Gypsum board	750	1060	0.80

The stratification ability of a TES is influ encedby the thermal diffusivity of the material used. Higher thermal stratification allows for easy release of heat. The thermal diffusivity (α) of a material depends on the thermal conductivity (λ), density (ρ) and the specific heat (C_p) of the material [45]:

$$\alpha = \frac{\lambda}{\rho C_p}. \tag{23}$$

The thermal effusivity is another parameter which mainly influences the thermal inertia of the building. The thermal effusivity is defined as the rate at which a material can absorb heat [45]. In other words, an increase in thermal effusivity increases the heat absorption by material and thus decreases the energy consumption by the building:

$$\text{Thermal effusivity} = \sqrt{\lambda \rho C_p}\,. \tag{24}$$

6 Latent heat thermal energy storage

In LHTES systems, heat storage is done by materials undergoing a change in their physical state or phase change. When the materials undergo a phase change, they store the heat for the source as latent heat and release it when required by again going back to their previous physical state. LHTES systems used in buildings can be integrated into the walls, roofs, ceilings and floors [2]. These LHTES materials are known as phase change materials, which are discussed in the later sections. This process also makes use of some sensible heat initially in the heat storage process and further when the operating temperatures are higher. Figure 7 explains the phase change of materials in LHTES systems.

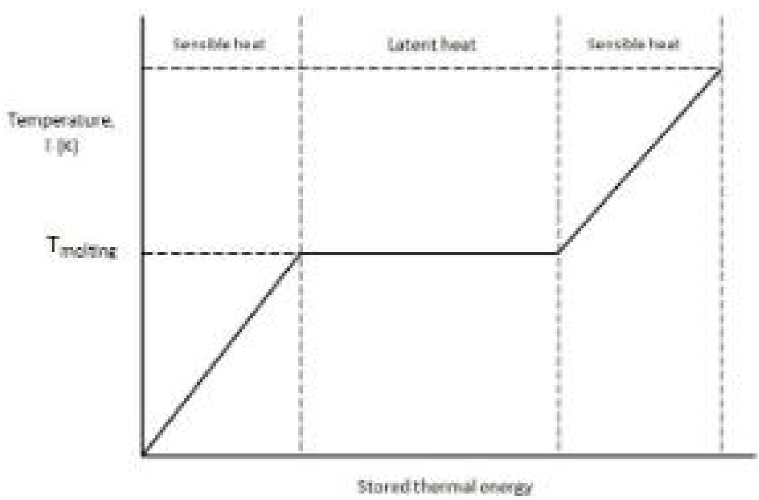

Figure 7: Phase change in the temperature-enthalpy diagram [46].

The following factors influence the storage capacity of LHTES systems:

- mass of the heat storage medium,
- specific heat of the solid and liquid phases of the materials,

- difference between the melting/vaporization point of the material and the initial temperature,
- difference between the final temperature and the melting/vaporization point,
- specific heat of fusion.

The storage capacity of LHTES systems can be represented by the following equation:

$$Q_l = m\left[C_{p_s}\left(T_m - T_i\right) + f\Delta q + C_{p_l}\left(T_f - T_m\right)\right], \tag{25}$$

where Q_l is the heat energy stored in the LHTES, m is the mass of the material, T_m is the melting point of the material, T_i is the initial temperature of the material, T_f is the final temperature of the material, C_{ps} is the specific heat of solid phase, C_{pl} is the specific heat in the liquid phase, f is the melt fraction, Δq is the latent heat of fusion.

LHTES has the advantage over SHTES of using materials possessing higher energy storage densities and hence, the size of the systems gets reduced [1]. Moreover, LHTES if used in a passive application, i.e. implementing PCMs in walls, floors and ceilings of the building can greatly reduce indoor temperature fluctuations [3]. It acts as a reservoir of heat and can be utilized for instant use, unlike the SHTES passive systems. However, LHTES systems are not the most widespread technology as they are more complex than the simple SHTES units, and due to high prices of PCMs. Furthermore, while conventional SHTES materials can serve a dual purpose of storing heat and providing structural strength, PCMs can store heat better but do not provide any structural benefits to the building construction [17].

7 Phase change materials

LHTES materials are often known as phase change materials. These materials store heat in the form of their latent heat of melting (if PCM is solid) or vaporization (if PCM is liquid) while changing their physical state [2, 9, 13, 17, 47–49]. Latent heat is defined as the amount of heat energy required to change the physical state of a matter (from solid to liquid/gas or from liquid to gas) at a constant temperature. Figure 7 illustrates a phase change of a material with respect to a temperature-enthalpy diagram. For the optimum result of heat storage, the PCM must have a higher latent heat of phase change, so that a higher amount of heat energy can be stored at a constant temperature [13, 50]. Moreover, the melting temperature or the temperature at which the PCM changes its phase should be in the comfortable temperature range.

Qureshi *et al.* [7] through their study concluded that the use of PCM is very advantageous when it comes to space heating and peak load shifting and reduction in electricity consumption bills through real-time pricing tariff. Furthermore, it has also been identified that the application of PCM in building materials has the potential of saving electrical energy for air conditioning during summer.

Guarino *et al.* [48] investigated the use of passive TES integrating PCM in the walls of solaria or rooms with high solar gains, for the purpose of energy conservation and reduction of indoor temperature fluctuations. Unlike many PCM applications used to shield the interior from the exterior temperature, this study was conducted to increase the effective use of solar gains by absorbing them in the storage system for later use. The results showed a decrease in indoor temperature swings by up to 10°C and heat peak loads were reduced down to 40% during high irradiation days in winter. Moreover, the authors conclude that a concentrated PCM TES is able to reduce heating requirements by 17% a year. However, ventilation is required as without it the PCM would not undergo a complete charge/discharge cycle.

The Pieppo *et al.* [37] study on a PCM integrated wall in a passive application concludes that optimal diurnal storage of heat happens when the melting point of the PCM is in the range of 1–3°C above the ambient room temperature. Moreover, Zhang *et al.* [13] state that the melting temperature of most of the PCMs falls in the temperature range of 18–20°C.

Benlekkam *et al.* [49] conducted a numerical analysis on thermal performance of the hybrid nano-PCM used for the LHTESS. A is developed to solve the Navier-Stocks and energy equations. The numerical model based on the enthalpy-porosity technique conducted computation for the melting and solidification processes of the hybrid nano-PCM in a shell and tube latent heat storage. The study concluded with improved the effective thermal conductivity and density of the LHTES due to the use of hybrid nano-PCM. Moreover, when the mass fraction of a hybrid nano-PCM is increased by 0.25%, 0.5%, 0.75% and 1, the average charging time got improved by 12.04 %, 19.9 %, 23.55%, and 27.33 %, respectively.

PCMs are both used in passive and active TES applications. In passive applications, the use of gypsum boards integrated with PCM is quite popular. A few of the common PCMs along with their melting points and heats of fusion are listed in Table 3. Due to a relatively small volume change of the PCMs, the amount of stored heat is equal to the enthalpy change in the material, which is given by [17]:

$$\Delta Q = m\Delta h\,, \tag{26}$$

where ΔQ is the heat stored, m is the mass of the PCM, Δh is the enthalpy change.

Table 3: List of PCMs with their melting points and heat of fusion.

PCM	Melting point (°C)	Heat of fusion (kJ/kg)
$CaCl_2.6H_2O$	24–29	192
$Na_2S_2O_3$	40	210
Hexadecane	18	236
Heptadecane	22	214
Octadecane	28	244
Black paraffin	25–30	150
Butyl stearate	19	140
Capric-lauric 45/55	21	143
Capric-lauric 82/18	19.1–20.4	146
Capric-mystric 73.5/26.5	21.4	152
Capric-palmitate 75.2/24.8	22.1	153
peg 1000 + peg 600	23–26	150.5
Propyl palmitate	19	186
RT25	25	147

The desirable properties of PCMs can be divided into thermophysical properties, kinetic properties and chemical properties. Tyagi *et al.* [2] and Sarbu *et al.* [4] describe these properties, which are as follows:

Thermophysical properties:

- high latent heat of fusion,
- melting point in the range of comfort for the occupants,
- high specific heat to further store heat energy before and after the phase change,

- high thermal conductivity both before and after phase change,
- optimum charging and discharging capacities,
- lower volume change after the phase change,
- congruent melting of the medium (PCM).

Kinetic properties:

- higher nucleation rate to prevent supercooling of the liquid phase,
- higher rate of crystal growth.

Chemical properties:

- complete reversible cycle of phase change,
- non-reactive with the material holding the PCM to avoid corrosion and other unwanted reactions which may cause its degradation,
- non-toxic, non-volatile and non-explosive.

Ostry *et al.* [17] outline the disadvantages related to using PCMs in buildings which are:

- PCMs may react with the construction material of the building and change its properties,
- risk of leakage from the building structure,
- majority of applied PCMs have poor thermal conductivity in the solid phase.

7.1 Classification of PCMs

PCMs are mainly classified into three types, namely, organic PCMs, inorganic PCMs and eutectics [4, 51]. These types are further classified, which is shown in Fig. 8.

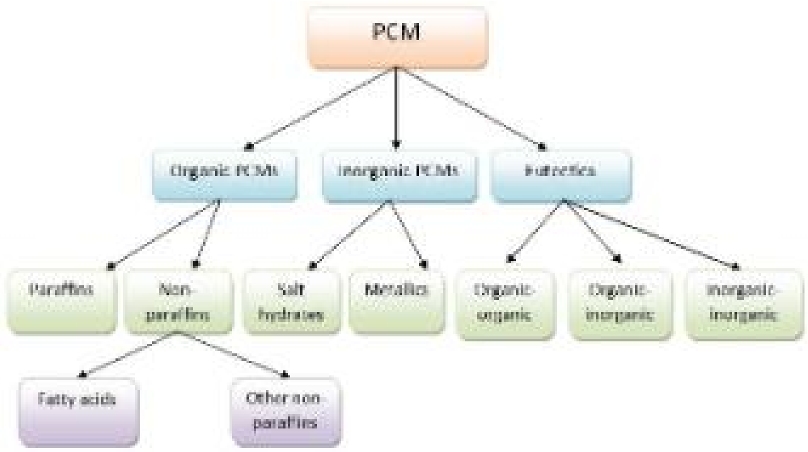

Figure 8: Classifications of PCMs.

7.1.1 Organic PCM

Organic PCMs include mainly paraffins and non-paraffins [51]. They melt and solidify several times without the issue of phase segregation. Their latent melting heats degrade and hence crystallize with almost no super-cooling.

Paraffins mainly include straight chain n-alkanes. A large amount of heat is released with the crystallization of the (CH_3)–chain. The melting points of these PCMs are dependent on the number of carbon atoms and hence they are applied in various TES applications [47]. With the increase in the chain length, the melting point and the latent heat of fusion increase. Paraffins possess qualities such as reliability, predictability, non-corrosiveness and cost effectiveness, which make them suitable for applications in a wide range of LHTES and SHTES systems. n-Hexadecane ($T_{\text{melting}} = 291-293$ K), n-Nonacozane ($T_{\text{melting}} = 336.4$ K) and n-Triacontane ($T_{\text{melting}} = 338.4$ K) [32] are some examples of paraffins.

Non-paraffins include esters, fatty acids, alcohol and glycols which are suitable for energy storage [52]. Unlike paraffins, non-paraffins differ in their individual properties. They have a wide range of materials and find their use in many TES applications [52]. Fatty acids are the most commonly used non-paraffin organic PCMs. The use of fatty acids offers a temperature range of 40–50°C [46].

Some of the desirable features of the organic PCMs are: high latent heat of fusion, congruent melting, self-nucleation and non-corrosiveness. However, there are a few undesirable qualities as well, which are: low thermal conductivity, flammability, low flash point, toxicity and instability at higher temperatures [52]. Sharma *et al.* [53] state that the issue of low thermal conductivity can be solved by using metallic fins and supercooling can be reduced by adding a nucleating agent to the PCM.

7.1.2 Inorganic PCM

Inorganic PCMs are used in high temperature thermal storage as their melting points can be as much as 1000°C [48]. They can be classified into metallic/salt hydrates and metallics. The desirable features of these materials are: high latent heat per unit mass and volume, more cost effective than organic PCMs, non-volatile/non-flammable, do not supercool and show no degradation of heat of fusion with time [53]. However, their maintenance can be very challenging.

Salt hydrate is defined as the mixture of inorganic salts including water of crystallization forming a typical crystalline solid. Its general formula is $AB.nH_2O$. The phase change of these materials, i.e. from solid to liquid is actually due to the dehydration of the salts, despite resembling the thermodynamic phase change. Sharma *et al.* [53] define that the metallic hydrates melt to either completely anhydrous salts:

$$\mathrm{AB.nH_2O} \rightarrow \mathrm{AB} + \mathrm{n.H_2O}\,, \tag{27}$$

or to salt hydrates with fewer moles of water:

$$\mathrm{AB.nH_2O} \rightarrow \mathrm{AB.mH_2O} + (\mathrm{n}-\mathrm{m})\mathrm{H_2O}\,. \tag{28}$$

Melting of salt hydrates is divided into three types: congruent melting, incongruent melting and semi-congruent melting. In congruent melting, the anhydrous salt gets completely dissolved in the water of crystallization present, whereas in incongruent melting the water of crystallization is not sufficient to dissolve the entire amount of salt. However, in semi-congruent melting, the solid and the liquid phases remain in equilibrium during the phase change process at different melting compositions [54].

Salt hydrates experience an issue of incongruent melting because the water of crystallization present in the material is insufficient to melt the entire solid phase. As there occurs a density difference between the solid and the liquid phase, the solid particles settle down at the bottom of the container. Another disadvantage of salt hydrates is that they have poor nucleating properties, which results in supercooling before crystallization.

Metallic PCMs consist of metal alloys and metals having low melting points. They possess high thermal conductivities and high melting enthalpies per unit volume. However, they are quite scarcely applied due to their low melting enthalpies per unit weight [4]. Moreover, they have another undesirable property, which is low specific heat [53].

7.1.3 Eutectic PCMs

Eutectics are materials formed as a result of combination of two or more PCMs. To be more precise, these are mixtures of different materials in the proportion which provides the lowest possible melting point [55]. These constituent PCMs melt and freeze congruently which forms a mixture of crystals of the components during the process of crystallization. They can be divided into organic-organic eutectics, organic-inorganic eutectics and inorganic-inorganic eutectics [13, 51].

7.2 Methods of integrating PCM into buildings

There exist various methods of integrating PCM into buildings, the most common of which are: micro-encapsulation, shape stabilization, macro-encapsulation and impregnation.

7.2.1 Micro-encapsulation

Micro-encapsulation is one of the effective ways of integrating PCM into construction materials. Apart from preventing leakage of PCM during the liquid phase, it also improves the thermal conductivity of the PCM with better melting and freezing cycles [56]. This method is further divided into three methods, which are the physical method, physical-chemical method and chemical method [55,57]. Some of the common commercial PCM micro-capsules are Micronal DS 5008, Micronal DS 5001, Micronal DS5040X, Microtek MPCM 24, and Inertek. These PCM micro-capsules are mostly integrated into cementitious composites such as concrete, mortar, and plaster.

Cabez *et al.* [58] studied the effect of microencapsulated PCM into concrete walls on the thermal storage of the wall by comparing with a conventional concrete wall. The study resulted in concluding that the wall with microencapsulated PCM showed higher thermal inertia and reduced indoor temperature when compared to the conventional concrete wall.

Castellon *et al.* [59] evaluated the influence of micro-encapsulated PCM in a sandwiched panel. Three different methods of implementing the technique were studied: (case 1) mixing micro-encapsulated PCM with polyurethane and applying the mixture to the metal sheets, (case 2) adding micro-encapsulated PCM before adding polyurethane to the metal sheets and (case 3) adding polyurethane before the adding micro-encapsulated PCM to the metal sheets. The third case showed some positive results with the increase in the thermal inertia of the system.

7.2.2 Shape stabilization

Due to the occurrence of leakage of PCM from its holding construction material, the shape stabilization technique is implemented. It is done by using supporting materials. Apart from preventing leakage, it also improves the thermal conductivity and thermal behaviour of the PCM during melting and freezing cycles. A few of the commonly used supporting materials are xGnP, expanded graphite, silica fume, diatomite and bentonite [56]. There are three methods of fabrication of shape stabilized PCMs: direct absorption, impregnation and sol-gel methods.

7.2.3 Porous inclusion

Porous inclusion is the simplest method of PCM incorporation into construction materials. Here, the PCM is induced or impregnated into the pores of a porous building material [17]. There are two ways of the porous inclusion technique: direct impregnation and vacuum impregnation [56]. There are various factors which influence the performance of the PCM when impregnated into construction materials, which are: the selection of supporting materials, method of impregnation and absorption capacity of the host material.

7.2.4 Macro-encapsulation

Micro-encapsulation is a method where the PCM is not mixed directly with the host material, which offers the advantage of preserving the actual properties of the host materials [17]. Mostly PCMs are macro-encapsulated in the building roof, walls and ceilings in aluminum panels, aluminum containers, plastic panels, plastic containers, plastic tubes, plastic pouches and plastic balls [56]. PCM encapsulated in aluminum enhances the thermal conductivity but there is a risk of corrosion, whereas plastics are the most compatible host materials for many inorganic PCMs [17].

Ramakrishnan *et al.* [60] investigated the performance of an old building refurbished with macro-encapsulated PCM. The results conclude that the refurbished building with PCM macro-encapsulated PCM has the potential to reduce discomfort inside the building by 65% (above 28°C) during the daytime. However, night ventilation is required to release the absorbed heat (during the day). Moreover, the thickness of the PCM macro-encapsulated layer influences the performance of the TES system.

Lizana *et al.* [3] from their study claims that the temperature inside a building can be reduced by at least 1°C by implementing PCM, during the summer days. However, Gracie *et al.* [61] and Castell *et al.* [62] conclude that although incorporating PCM into building through micro-encapsulation can reduce the energy consumption, which is not significant enough to cause a global impact on energy savings.

7.3 Integrating PCM in buildings

The use of PCM in buildings is seen in various sectors such as the automotive sector, power sector, residential buildings, etc. Precisely, in passive applications PCM can be integrated into building envelopes, walls, floors and ceilings.

7.3.1 Integration of PCM into building materials

Li *et al.* [63] developed a PCM composite of paraffin by vacuum absorption into expanded graphite. The thermal charging and discharging of the composite were studied with multi-channel temperature recorder. The results showed that the phase change temperature and latent heat of the paraffin-expanded graphite composite were 28.55°C and 183.0 kJ/kg, respectively, and these values are higher than that of normal paraffin. Moreover, the heat storage coefficient of the PCM composite-mortar combination was 1.72 times that of the conventional cement mortar, i.e. the former is more efficient than the latter.

Ramakrishnan *et al.* [64] developed a PCM composite of paraffin and hydrophobic expanded perlite and integrated it into conventional cement mortar, with the aim to partially replace fine aggregate with the composite PCM. Proportion ratios of 20%, 40% and 80% were studied. It was found that with an increase in the amount of PCM composites, the thermal storage capacity increased but the thermal conductivity decreased. It was concluded that the PCM composite integrated mortar has higher insulation performance than that of the conventional cement mortar.

Liu*et al.* [65] integrated eutectic hydrate salt/expanded graphite oxide and eutectic hydrate salt/poly (acrylamide-co-acrylic acid) integrated into cement mortar by the method of mechanical blending. The author concludes that the flexural and compressive strength of the combination decreases with the increase in the percentage of the PCMs. However, the attained compressive strength is capable enough to be used in the building envelope. Moreover, the thermal storage capacity increased with the increase in the PCM content, and the thermal conductivity was decreased.

Hawes *et al.* [66,67] conducted studies on the performance of PCM integrated into concrete and have found that it can increase the thermal energy storage of the building by 300%.

7.3.2 Integration of PCM into wallboards

A lot of studies on the integration of PCM into wallboards have been conducted by various researchers. Alicia Oliver [68] had conducted an experiment to study the performance of Micronal DS5001X mixed with gypsum and reinforcing additives such as fibers and plasticizer. The results have shown that a gypsum board of 1.5 cm with the PCM can store about five times the thermal energy which is stored by the laminated gypsum board and a 12 cm thick brick wall.

Hawes *et al.* [67] integrated PCM by impregnating it (20–30% by weight) in gypsum wallboard. The author concludes that the thermal storage capacity of the wallboard increased with PCM integration. Also, fire resistance, compatibility with paint, material stability and flexural strength has increased. However, the weight of the wallboard increased by 22%.

Athienitis *et al.* [69] conducted both numerical and experimental studies on gypsum wallboards impregnated with PCM for passive solar TES application. The results of the numerical and experimental analyses were compared. It has been found that using PCM in the gypsum wallboard can reduce the maximum ambient temperature by around 4°C during the day, and reduce the maximum cooling load during the night. Thus, the application of PCM enhances the heat storage capacity and provides thermal comfort.

Shilei *et al.* [70] evaluated the performance of gypsum wallboard impregnated by PCM (26% by weight). The study concluded that the temperature fluctuations and the thermal flow got reduced in the room with the PCM-gypsum wallboard. The author states that the PCM impregnated gypsum wallboards are quite effective in space cooling applications.

Three different types of wallboards were studied by Ahmad *et al.* [71]: (a) a polycarbonate panel filled with paraffin granulates, (b) a polycarbonate panel filled with polyethylene glycol 600, (c) a PVC panel filled with PEG 600 and coupled to a vacuum insulation panel. The results concluded that both polycarbonate panels filled with granules or with PEG 600 were not convenient. However, the PVC panels filled with PEG 600 documented compatible properties. After reliability tests, all three models showed better thermal performances.

7.3.3 Integration of PCM into building roofs

Pashupathy *et al.* [72] investigated an inorganic eutectic PCM both numerically and experimentally. Two test rooms were considered: one without PCM attachment and the other with PCM panels sandwiched between brick and mortar slabs on the top and a concrete slab at the bottom. Numerical simulations were conducted for determining the performance for ambient conditions, the heat transfer coefficient, PCM panel thickness and the effect of water circulation through the PCM panel. The roof with PCM panels showed reduced temperature fluctuations, whereas the roof without PCM experienced high temperature fluctuations.

A three dimensional numerical analysis of the roof of a building was conducted for the climatic conditions of Chennai, India for the month of January by Bhamare *et al.* [73]. The results have shown that unlike the roof without PCM, the roof with PCM kept the ceiling temperature in the range of 25.5–27.5°C and also reduced the maximum temperature load during the day. The experiment concluded that the PCM integrated roofs can be applied for space cooling applications, as there can be seen a reduction in energy consumption together with attaining a comfortable temperature inside the building.

Safari *et al.* [74] studied three models of a building integrated with different HVAC schedules and PCMs of different thicknesses and melting points (23°C, 25°C and 27°C). The experiment proved that the integration of PCM increases the heating and cooling performance of the HVAC systems both during summer and winter. Moreover, the PCM with 27°C melting point has shown the highest annual energy savings.

Elarga *et al.* [75] investigated the use of PCM with different melting temperatures on the roof of a building in Italy. One week of experimental results was compared with a conventional building roof without PCM integration. The peak heat load was reduced by 13% to 59% depending on the topology of the PCM. Moreover, the outdoor temperature was between 16–32°C and the indoor temperature was found between 20–33°C. The results conclude that PCM integrated roofs of buildings prove higher thermal efficiency during the summer season.

7.3.4 Integration of PCM in building floors

Karim *et al.* [76] investigated the use of PCM integration in floors to improve the thermal comfort inside buildings. The PCM integrated floor absorbs the heat energy during the day, thus cooling the space, and releases the heat during the night. The process is effective and saves energy with regard to the cooling requirements of the building.

Vik *et al.* [77] studied a test room inside a laboratory, separated by a roof in Oslo, Norway. PCM was integrated into the floor of the test room. The author concluded that using a 15 m^2 PCM integrated floor achieved significant passive space cooling. The cooling effect increased when the PCM was directly exposed to the occupied area. This experiment proved to be cost effective and resulted in significant energy savings.

Mehdaoui *et al.* [78] investigated a test facility equipped with PCM floors in Tunisia during February and March (a total of 14 days). The test cell with the PCM floor had a temperature of 28°C and when the PCM floor was removed, the indoor temperature fluctuated from 29°C to 40°C. The author concluded that the thermal comfort was enhanced by the use of the PCM equipped floor due to lower temperature fluctuations.

Royon *et al.* [79] studied the effect of floor integrated with five different configurations of PCMs by numerical analyses in COMSOL Multiphysics software. The results of the numerical analyses were then compared with experimental results. The study found that the surface temperature variation was reduced to about 2°C with enhancement in the peak load shifting. Moreover, the floor panels with 50–100% PCM integration showed minimum temperature fluctuations.

8 Thermochemical heat storage

In thermochemical heat storage (TCHS), heat is stored by a reversible thermochemical process. A heat source is used for exciting the reversible reaction by means of sorption or chemical reaction [3]. The materials utilized in this method are called thermochemical materials (TCMs) [1]. Firstly, the heat is stored in the material by the endothermic reaction and discharged when required, by the exothermic reaction. Sometimes catalysts are required for this reversible process to take place. For instance, when heat is applied (endothermic process) to a TCM A, it splits into components B and C. When heat is required for the space heating applications, B and C combines (exothermic process) to form A with the release of the stored heat [80]. High energy density and lack of heat losses in this process make it a preferable option for TES.

There are three types of TCMs used for TES: (a) adsorption materials, (b) salt hydrates and (c) composite materials [17]. Adsorption materials are those which have high porosity and large inner surfaces. Generally, these materials are used in granule forms such as spheres and cylinders with diameters ranging between 1–5 mm. These granules consist of pores inside them and these pores are classified as macropores (pore size more than 50 nm), mesopores (pore size more than 2 nm and less than 50 nm) and micropores (pore size less than 2 nm). The adsorption process basically occurs in the micropores and the diffusion of the gas-phase molecules occurs mainly in the macropores and the mesopores. The most common examples of adsorption materials are silica gel, zeolite and active carbon.

Salt hydrates as discussed earlier can also be used as TCMs. A few of the common salt hydrates are sulphates like magnesium sulphate, chlorides like calcium chloride and magnesium chloride and bromides such as strontium bromide.

A composite TCM is developed by combining a highly dispersed metal salt into a carrier matrix by passive or active means. In the active process, the carrier matrix takes part in the absorption process, whereas in the passive process any porous material can be used as the carrier. These materials show better performances than salt hydrates [8]. In most cases, zeolite is used as the carrier material. Here, the salt solution is impregnated into zeolite to develop such TCMs. The use of composites shows a better pace of reaction, material stability and thermal capacity in TES applications [8].

8.1 Desirable features of the thermochemical materials

A TCM with high performance is characterized by the following qualities [8]:

- high adsorption capacity,
- high heat of adsorption (for high energy storage density),

- fast endothermic and exothermic processes for effective storage and release of heat,
- an appropriate level of desorption temperature.

8.2 Types of thermochemical heat storage

TCHSs are classified into open and closed storage systems. In the open storage system, the storage medium is in direct contact with the indoor environment (for example floors equipped with TES materials), whereas in the closed storage system the storage medium is not in direct contact with the indoor of the building (for example water tank) [3]. In open storage systems, the heat cannot be stored or released for longer durations and it is directly transferred to the space. However, in the closed systems, the heat can be stored for a longer duration due to the size of the medium and can be transferred through mechanical components such as radiators, coils, fans, etc.

9 Conclusions

Implementing scientific research based approaches in harnessing renewable sources of energy and ways of implementing them is of utmost importance, as fossil fuel stocks are depleting at a greater rate. To reduce carbon emissions, the dependency on fossil fuels has to be decreased gradually and eliminated finally. The building sector is the largest consumer of the produced electricity, which is majorly generated from burning fossil fuels in the power plants. Shifting to renewable sources of energy is also beneficial from the economic point of view, as the capital saved annually can be utilized by the governments to address other global issues like poverty and hunger.

Thermal energy storage (TES) is one of the many ways to counter the above mentioned issues. It can be implemented into the building sector for heating and cooling requirements or provide assistance to the conventional HVAC systems used today. TES basically stores the heat energy from solar radiation and releases it as per requirement of the buildings. In fact, the use of TES systems in ancient times is evident from the literature. The present study on the TES systems draws the following conclusions:

- Thermal energy storage systems provide assistance to the conventional HVAC systems as well as reduce energy consumption and CO_2 emissions.

- The factors influencing the performance of a TES system are: the design of the TES system, climatic conditions of the location of the building, heating and cooling needs, installation and operation cost of TES and the method of TES used.

- TES can be implemented into different parts of the building such as roof, ceilings, walls and floors. Moreover, it can also be implemented in the exterior of the building by the use of storage tanks.

- The exergy analysis of a TES system is better than the energy analysis as it provides information about the useful energy which can be converted into work.

- The SHTES systems are the most cost efficient TES systems. They have lower installation and operating costs than those of the LHTES and TCHS systems. The cost of PCM encapsulated materials and TCMs is higher than that of the SHTES materials, which has a negative impact on the installation of LHTES and TCS systems. Efficient ways and methods to develop these expensive materials can create a huge opportunity to grow the industry of TES systems. Integration of TES applications with CSP plants can result in the cost effectiveness of TES systems. Moreover, government subsidies can play a part in promoting the use of these materials in buildings.

- In SHTES systems, the mass of the material has a great influence on the TES as it does not undergo a phase change due to its high melting and vaporization points, and TES completely depends on its sensible heat. The higher the mass of the material, the better TES can be achieved.

- In LHTES systems, PCMs go through phase change due to their lower melting and vaporization points. Hence, TES depends on both the sensible and latent heats of the materials. PCMs have higher thermal storage densities and therefore construction materials of the buildings can have lower masses. Due to higher thermal capacities of PCMs, the LHTES systems show better performance than the SHTES systems.

- Apart from the mass of the TES medium, the temperature difference between the surroundings and the medium also greatly influences the storage capacities.

- Apart from space heating and cooling, the use of TES can greatly reduce the temperature fluctuations inside the building, thus providing better comfort to the inhabitants. Moreover, the temperature swings in the heavier buildings are less than those of the lighter buildings.
- PCMs are classified into organic, inorganic and eutectics. Organic PCMs have several benefits over inorganic PCMs. Nonetheless, inorganic PCMs are more affordable, abundant and have high thermal storage densities.
- Thermochemical heat storage (TCHS) is a comparatively newer idea for TES systems. It shows better performances, but TCMs are expensive and their implementation is a bit more difficult than that of their other two counterparts.

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References

[1] De Gracia A., Cabeza L.F.: *Phase change materials and thermal energy storage for buildings.* Energ. Buildings **103**(2015), 414–419.

[2] Osterman E., Butala V., Stritih U.: *PCM thermal storage system for "free" heating and cooling of buildings.* Energ. Buildings **106**(2015), 125–133.

[3] Lizana J., Chacartegui R., Barrios-Padura A., Ortiz C.: *Advanced low-carbon energy measures based on thermal energy storage in buildings: A review.* Renew. Sust. Energ. Rev. **82**(2018), 3705–3749.

[4] Sarbu I., Sebarchievici C.: *A comprehensive review of thermal energy storage.* Sustainability **10**(2018), 1, 191.

[5] Hedegaard K., Balyk O.: *Energy system investment model incorporating heat pumps with thermal storage in buildings and buffer tanks.* Energy **63**(2013), 356–365.

[6] Kalaiselvam S., Parameshwaran R.: *Applications of thermal energy storage systems.* In: Thermal Energy Storage Technologies for Sustainability. Academic Press, 2014, 359–366.

[7] Qureshi W.A., Nair N.K.C., Farid M.M.: *Impact of energy storage in buildings on electricity demand side management.* Energ. Convers. Manage. **52**(2011), 5, 2110–2120.

[8] Kerskes H.: *Thermochemical Energy Storage. Storing Energy.* Univ. of Stuttgart, Stuttgart 2016.

[9] Morofsky E.L.: *History of thermal energy storage.* In: Thermal Energy Storage for Sustainable Energy Consumption (H.Ö Paksoy, Ed.), NATO Science Series, vol. 234. Springer, Dordrecht 2007.

[10] Stritih U.: *Heat transfer enhancement in latent heat thermal storage system for buildings*. Energ. Buildings **35**(2003), 11, 1097–1104.

[11] www.danfoss.com/en/about-danfoss/insights-for-tomorrow/integrated-energy-systems/thermal-energy-storage/ (accessed 12 March 2022).

[12] Ma Y., Kelman A., Dally A., Borrelli F.: *Predictive control for energy efficient buildings with thermal storage: modeling, stimulation, and experiments*. IEEE Cont. Syst. **3**2(2012), 1, 44–64.

[13] Zhang Y., Zhou G., Lin K., Zhang Q., Di H.: *Application of latent heat thermal energy storage in buildings: State-of-the-art and outlook*. Build. Environ. **42**(2007), 6, 2197–2209.

[14] www.meeedesignservices.com (accessed 7 Feb. 2022).

[15] Reynders G., Amaral Lopes R., Marszal-Pomianowska A., Aelenei D., Martins J., Saelens D.: *Energy flexible buildings: An evaluation of definitions and quantification methodologies applied to thermal storage*. Energ. Buildings **166**(2018), 372–390.

[16] Odukomaiya A., Woods J., James N., Kaur S., Gluesenkamp K.R., Kumar N., Mumme S., Jackson R., Prasher R.: *Addressing energy storage needs at lower cost via on-site thermal energy storage in buildings*. Energ. Environ. Sci. **14**(2021), 5315-5329.

[17] Ostry M., Charvat P.: *Materials for advanced heat storage in buildings*. Procedia Engineer. **57**(2013), 837–843.

[18] Dinçer I., Rosen M.A.: *Energy and exergy analyses of thermal energy storage systems*. In: Thermal Energy Storage: Systems and Applications. Wiley, 2010, 233–334.

[19] Kalaiselvam S., Parameshwaran R.: *Thermal energy storage technologies*. In: Thermal Energy Storage Technologies for Sustainability. Academic Press, 2014, 57–64.

[20] Dincer I., Dost S., Li X.: *Performance analyses of sensible heat storage systems for thermal energy storage*. Int. J. Energ. Res. **21**(1997), 1157–1171.

[21] Dincer I., Rosen M.A.: *Energetic, environmental and economic aspects of thermal energy storage systems for cooling capacity*. Appl. Therm. Eng. **21**(2001, 11, 1105–1117.

[22] Gautam A., Saini R.P.: *A review on technical, applications and economic aspect of packed bed solar thermal energy storage system*. J. Energ. Stor. **27**(2020), 101046.

[23] Bai F., Wang Y., Wang Z., Sun Y., Beath A.: *Economic evaluation of shell-and-tube latent heat thermal energy storage for concentrating solar power applications*. Energy Proced. **69**(2015), 737–747.

[24] Zhao B., Cheng M., Liu C., Dai Z.: *System-level performance optimization of molten-salt packed-bed thermal energy storage for concentrating solar power*. Appl. Energ. **226**(2018), 225–239.

[25] Nithyanandam K., Pitchumani R.: *Cost and performance analysis of concentrating solar power systems with integrated latent thermal energy storage*. Energy **64**(2014), 793–810.

[26] Habeebullah B.A.: *Economic feasibility of thermal energy storage systems.* Energ. Buildings **39**(2007) 3, 355–363.

[27] Wagner S.J., Rubin E.: *Economic implications of thermal energy storage for concentrated solar thermal power.* Renew. Energ. **61**(2014), 81–95.

[28] Yang, T., Liu W., Kramer G., Sun Q.: *Seasonal thermal energy storage: A techno-economic literature review.* Renew. Sust. Energ. Rev. **139**(2021), 110732.

[29] Lai C.S., Locatelli G.: *Economic and financial appraisal of novel large-scale energy storage technologies.* Energy **214**(2020), 118954.

[30] Farid M.M., Chen X.D.: *Domestic electrical space heating with heat storage.* Proc. Inst. Mech. Eng. A.-J. Power Energ. **213**(1999), 2, 83–92.

[31] Lin K., Zhang Y., Xu X., Di H., Yang R., Qin P.: *Experimental study of under floor electric heating system with shape-stabilized PCM plates.* Energy Build. **37**(2005) 3, 215–220.

[32] Kenneth I.P., Gates J.: *Solar thermal storage using phase change material for space heating of residential buildings.* In: Proc. RICS Foundation Construction and Building Research Conf. Univ. of Brighton, 2001.

[33] Heier J., Bales C., Martin V.: *Combining thermal energy storage with buildings – a review.* Renew. Sust. Energ. Rev. **42**(2015), 1305–1325.

[34] Norén A, Akander J., Isfält E., Söderström O.: *The effect of thermal inertia on energy requirement in a Swedish building-results obtained with three calculation models.* Int. J. Low Energ. Sust. Buildings **1**(1999), 1–16.

[35] Ståhl F.: *Influence of thermal mass on the heating and cooling demands of a building unit.* Chalmerstekniskahögskola, Gothenburg 2009.

[36] Yahay N.A., Ahmad H.: *Numerical investigation of indoor air temperature with the application of PCM gypsum board as ceiling panels in buildings.* Procedia Engineer. **20**(2011), 238–248.

[37] Peippo K., Kauranen P., Lund P.D.: *A multicomponent PCM wall optimized for passive solar heating.* Energ. Buildings **17**(1991), 4, 259–270.

[38] Scalat S., Banu D., Hawes D., Parish J., Haghighata F., Feldman D.: *Full scale thermal testing of latent heat storage in wallboard.* Sol. Energ. Mat. Sol. Cell. **44**(1996), 1, 49–61.

[39] Velraj R.: *Sensible heat storage for solar heating and cooling systems.* In: Advances in Solar Heating and Cooling (R.Z. Wang, T.S. Ge, Eds.). Woodhead, 2016, 399–428.

[40] Kalaiselvam S., Parameshwaran R.: *Sensible Thermal Energy Storage.* In: Thermal Energy Storage Technologies for Sustainability. Academic Press, 2014, 65–81.

[41] Karlsson J., Wadsö L., Öberg M.: *A conceptual model that simulates the influence of thermal inertia in building structures.* Energ. Buildings **60**(2013), 146–151.

[42] Rempel A., Rempel A.: *Rocks, clays, water, and salts: Highly durable, infinitely rechargeable, eminently controllable thermal batteries for buildings.* Geosciences **3**(2013) 1, 63–101.

[43] Al-Sanea S.A., Zedan M.F., Al-Hussain S.N.: *Effect of thermal mass on performance of insulated building walls and the concept of energy savings potential.* Appl. Energ. **89**(2012), 1, 430–442.

[44] Zhu L., Hurt R., Correia D., Boehm R.: *Detailed energy saving performance analyses on thermal mass walls demonstrated in a zero energy house*. Energ. Buildings **41**(2009), 3, 303–310.

[45] Lizana J., Chacartegui R., Padura A.B., Valverde J.M.: *Advances in thermal energy storage materials and their applications towards zero energy buildings: A critical review*. Appl. Energ. **203**(2017), 219–239.

[46] Ben Romdhane S., Amamo A., Ben Khalifa R., Saïd N.M., Younsi Z., Jemni A.: *A review on thermal energy storage using phase change materials in passive building applications*. J. Build. Eng. **32**(2020), 101563.

[47] Koo J., So H., Hong S. W., Hong H.: *Effects of wallboard design parameters on the thermal storage in buildings*. Energ. Buildings **43**(2011), 8, 1947–1951.

[48] Guarino F., Athienitis A., Cellura M., Bastien D.: *PCM thermal storage design in buildings: Experimental studies and applications to solaria in cold climates*. Appl. Energ. **185**(2017), 95–106.

[49] Benlekkam M.L., Nehari D.: *Hybrid nano improved phase change material for latent thermal energy storage system: Numerical study*. Arch. Mech. Eng. **69**(2022), 1, 77–98.

[50] Noël J.A., Kahwaji S., Desgrosseilliers L., Groulx D., White M.A.: *Phase change materials*. In: Storing Energy (T.M. Letcher, Ed.). Elsevier, 2016, 249–272.

[51] Tyagi V.V., Buddhi D.: *PCM thermal storage in buildings: A state of art*. Renew. Sust. Energ. Rev. **11**(2007), 6, 1146–1166.

[52] Yuan Y., Zhang N., Tao W., Cao X., He Y.: *Fatty acids as phase change materials: A review*. Renew. Sust. Energ. Rev. **29**(2014), 482–498.

[53] Sharma A., Tyagi V.V., Chen C.R., Buddhi D.: *Review on thermal energy storage with phase change materials and applications*. Renew. Sust. Energ. Rev. **13**(2009), 2, 318–345.

[54] Casini M.: *Phase-change materials*. In: Smart Buildings. Woodhead, 2016, 179–218.

[55] Abuelnuor A.A.A., Omara A.A.M., Saqr K.M., Elhag I.H.I.: *Improving indoor thermal comfort by using phase change materials: A review*. Int. J. Energ. Res. **42**(2018), 6, 2084–2103.

[56] Marani A., Nehdi M.L.: *Integrating phase change materials in construction materials: Critical review*. Const. Build. Mater. **217**(2019), 36–49.

[57] Jamekhorshid A., Sadrameli S.M., Farid M.: *A review of microencapsulation methods of phase change materials (PCMs) as a thermal energy storage (TES) medium*. Renew. Sust. Energ. Rev. **31**(2014), 531–542.

[58] Cabeza L.F., Castellon C., Nogues M., Medrano M, Leppers R., Zubillaga O.: *Use of microencapsulated PCM in concrete walls for energy savings*. Energ. Buildings **39**(2007), 2, 113–119.

[59] Castellón C., Medrano M., Roca J., Cabeza L.F., Navarro M.E., Fernández A.I.: *Effect of microencapsulated phase change material in sandwich panels*. Renew. Energ. **35**(2010), 2370–2374.

[60] Ramakrishnan S., Wang X., Sanjayan J., Wilson J.: *Thermal performance of buildings integrated with phase change materials to reduce heat stress risks during extreme heat wave events*. Appl. Energ. **194**(2017), 410–421

[61] De Gracia A., Rincón L., Castell A., Jiménez M., Boer D., Medrano M.: *Life cycle assessment of the inclusion of phase change materials (PCM) in experimental buildings*. Energ. Buildings **42**(2010), 1517–1523.

[62] Castell A., Menoufi K., de Gracia A., Rincón L., Boer D., Cabeza L.F.: *Life cycle assessment of alveolar brick construction system incorporating phase change materials (PCMs)*. Appl. Energ. **101**(2013), 600–608.

[63] Li M., Wu Z., Tan J.: *Heat storage properties of the cement mortar incorporated with composite phase change material*. Appl. Energ. **103**(2013), 393–399.

[64] Ramakrishnan S., Wang X., Sanjayan J., Wilson J.: *Thermal energy storage enhancement of lightweight cement mortars with the application of phase change materials*. Procedia Engineer. **180**(2017), 1170–1177.

[65] Liu Y., Xie M., Gao X., Yang Y., Sang Y.: *Experimental exploration of incorporating form-stable hydrate salt phase change materials into cement mortar for thermal energy storage*. Appl. Therm. Eng. **140**(2018), 112–119.

[66] Hawes D.W., Banu D., Feldman D.: *Latent heat storage in concrete II, Sol.* Energ. Mater. **21**(1990), 61–80.

[67] Hawes D.W., Feldman D., Banu D.: *Latent heat storage in building materials*. Energ. Buildings **20**(1993), 77–86.

[68] Oliver A.: *Thermal characterization of gypsum boards with PCM included: Thermal energy storage in buildings through latent heat*. Energ. Buildings **48**(2012), 1–7.

[69] Athienitis A.K., Liu C., Hawes D., Banu D., Feldman D.: *Investigation of the thermal performance of a passive solar test-room with wall latent heat storage*. Build. Environ. **32**(1997), 405–410.

[70] Shilei L., Neng Z., Guohui F.: *Impact of phase change wall room on indoor thermal environment in winter*. Energ. Buildings **38**(2006), 18–24.

[71] Ahmad M., Bontemps A., Sallée H., Quenard D.: *Experimental investigation and computer simulation of thermal behavior of wallboards containing a phase change material*. Energ. Buildings **38**(2006), 357–366.

[72] Pasupathy A., Athanasius L., Velraj R., Seeniraj R.V.: *Experimental investigation and numerical simulation analysis on the thermal performance of a building roof incorporating phase change material (PCM) for thermal management*. Appl. Therm. Eng. **28**(2008), 556–565.

[73] Bhamare D.K., Rathod M.K., Banerjee J.: *Numerical model for evaluating thermal performance of residential building roof integrated with inclined phase change material (PCM) layer*. J. Build. Eng. **28**(2020), 101018.

[74] Saffari M., de Gracia A., Ushak S., Cabeza L.F.: *Economic impact of integrating PCM as passive system in buildings using Fanger comfort model*. Energ. Buildings **112**(2016), 159–172.

[75] Elarga H., Fantucci S., Serra V., Zecchin R., Benini E.: *Experimental and numerical analyses on thermal performance of different typologies of PCMs integrated in the roof space*. Energ. Buildings **150**(2017), 546–557.

[76] Karim L., Barbeon F., Gegout P., Bontemps A., Royon L.: *New phase-change material components for thermal management of the light weight envelope of buildings.* Energ. Buildings **68**(2014), 703–706.

[77] Vik T.A., Madessa H.B., Aslaksrud P., Folkedal E., Øvrevik O.S.: *Thermal performance of an office cubicle integrated with a bio-based PCM: experimental analyses.* Energy Proced. **111**(2017), 609–618.

[78] Mehdaoui F., Hazami M., Taghouti H., Noro M., Lazzarin R., Guizani A.: *An experimental and a numerical analysis of the dynamic behavior of PCM-27 includes inside a vertical enclosure: application in space heating purposes.* Int. J. Therm. Sci. **133**(2018), 252–265.

[79] Royon L., Karim L., Bontemps A.: *Optimization of PCM embedded in a floor panel developed for thermal management of the lightweight envelope of buildings.* Energ. Buildings **82**(2014), 385–390.

[80] Linder M.: *Using thermochemical reactions in thermal energy storage systems.* In: Advances in Thermal Energy Storage Systems (L.F. Cabeza, Ed.). Woodhead, 2015, 357–374.