

# Thermal energy storage (TES) technology for active and passive cooling in buildings: A Review

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**Abstract.** Thermal energy storage (TES) system is one of the outstanding technologies available contributes for achieving sustainable energy demand. The energy storage system has been proven capable of narrowing down the energy mismatch between energy supply and demand. The thermal energy storage (TES) - buildings integration is expected to minimize the energy demand shortage and also offers for better energy management in building sector. This paper presents a state of art of the active and passive TES technologies integrated in the building sector. The integration method, advantages and disadvantages of both techniques were discussed. The TES for low energy building is inevitably needed. This study prescribes that the integration of TES system for both active and passive cooling techniques are proven to be beneficial towards a better energy management in buildings.

## 1 Introduction

The global concern towards the energy crisis has become a major flashpoint in recent years. The worldwide energy demands have increase precipitously in past decades and presumed to be continually rising [1]. The foreseen significance growth of the energy demand is induced by climatic change and economy development is further amplified by the expected increase of the local population [2]. Although the current energy source has proved to meet the demand by far, this fossil-based energy source is anticipated to be depleted.

In order to counterbalance the impact of climatic change, population growth, economy development, and the rising of global energy demand, the efficient thermal management is vital. In fact, this scenario indicates the urgencies for an alternative source yet reducing the overdependence on fossil fuels. Amongst all the demands, buildings account for 40% of the total energy consumptions [3]. A part of that, heating, ventilating and air conditioning (HVAC) systems are recorded to consume 60% of the energy in buildings. [3, 4]. For the last forty years, the demand of the building sector is seen to comply an increasing trend of 1.8% annually [4]. It is forecasted to exceed 180 exajoules (EJ) by the middle of this century, in case of the situation is uncontrollable. [5].

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Remarkable efforts have been made by years, aiming to alleviate the energy efficiency and to minimize the energy consumption. The concept of energy efficiency in building sectors is related to the energy supply that benefit the end users [5]. The best alternative to reduce energy cost in buildings is with the incorporated of suitable heating and cooling design [6]. Cooling strategies in building can be categorized into three; active, passive and hybrid cooling. Active cooling strategy encompass all conventional HVACs, whereas the passive strategy is attributed to the utilization of natural energy resources, available from the environment despite consumes the conventional energy means [7].

The introduction of mechanical refrigeration systems in building sector has increase the likelihood of achieving a better thermal comfort for a longer period. The flexibility of this system has provide good assistance and led to the change of the life styles and work habits. Nonetheless, due to the current energy crisis, passive cooling technique has been recommended as one of the suitable techniques since it is environmentally-harmless [8].

Thermal energy storage (TES) is acknowledged as the viable solution to achieve the efficient thermal management in buildings [9]. Sustainable cooling system with TES in buildings can be accomplished through passive systems and active systems [10]. This paper briefly discusses the active and passive TES technology integrated with the building sector, as well as the suitable integration method for desired application.

## 2 Thermal Energy Storage (TES)

Thermal energy storage (TES) system has received extensive attention from researchers for its ability in eliminating environmental problems. The capability of TES in bridging the gap between the supply and demands of energy [11] can increase the efficiency of energy consumption. TES is defined as the temporary holder of thermal energy in the form of hot or cold substances for later utilization [12]. Moreover, TES system also leads to a better economic feasibility, reducing the investment and running cost, respectively. Furthermore, it is believed to release less CO<sub>2</sub> emission, thereby reducing the level of environmental pollution [10]. In recent years, TES system has been proven as a promising method that is utilized in various applications such as space and water heating, cooling and air-conditioning [13].

Thermal energy can be stored by three methods; sensible heat, latent heat and thermochemical energy storage. Sensible heat storage (SHS) is the most common way of energy storage which storage process can be sensed by the change in temperature of the medium [14]. The energy storage density in SHS is determined by the value of its specific heat capacity and also the temperature changes based on designed application [10]. Meanwhile, the latent heat storage (LHS) is referred to the heat stored during a phase change process, is then calculated from the enthalpy difference  $\Delta H$  between the solid and liquid phase [16].

Latent heat storage using PCMs is reported to be more efficient compared to the sensible energy storage because it provides higher heat storage capacity and more isothermal behavior during charging and discharging [17]. PCMs can be defined as a substance that is capable of storing thermal energy in the form of latent heat [18]. PCMs release and absorb an amount of energy in the form of latent heat at a relatively constant temperature during the solidifying and melting process respectively. The investigation on PCMs to store solar heat for space heating is recorded as the earliest investigation on TES systems for heating and cooling in building which is conducted in early 1930s. Nevertheless, the earliest system is not economical [19]. Further on, the research and development (R&D) on this technology continuously improved by years. Another TES system is thermo chemical energy storage. The storage densities of this method is proclaimed to be similar to PCMs. Nonetheless, this method is reported to be more complex than SHS and LHS [20].

### 3 TES technology for buildings

The integration method of TES system can be classified as active or passive system [21]. There are also some applications that adopting the hybrid of active and passive cooling system. Theoretically, with respect to the heat transfer fluid (HTF) being actively or not, thermal storage also can be classified into 'active' or 'passive' storage types [10]. Referring to Mehling and Cabeza [10], an 'active' storage system is mainly characterized by forced convection heat transfer, and mass transfer in some cases. Meanwhile, in the case of free or no convection occurred in TES, the storage system is denoted as 'passive' [10]. Implicitly, passive cooling with TES can be described as a technique to cool a system without external energy resource. Whereas, active cooling strategy covers all the thermal storage being integrated to the conventional HVAC systems [22]. Table 1 presents the storage type of TES.

**Table 1.** Storage types [10].

<i>Notation with respect to the method of heat transfer</i>	<i>Notation with respect to the HTF being (actively moved or not)</i>
<b>Storage with heat transfer on the storage surface</b>	
Insulated environment	passive/active
No insulation and good thermal contact between storage and demand	passive/active
<b>Storage with heat transfer on internal heat transfer surfaces</b>	
Heat exchanger type	active
Direct contact type	active
Module type	active
<b>Storages with heat transfer by exchanging the heat storage medium</b>	
Slurry type	active
Sensible liquid type	active

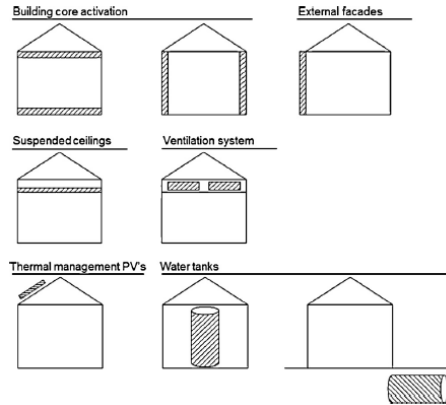
#### 3.1 Active Cooling

An active cooling system is mainly characterized by forced convection heat transfer [10]. In general, the purpose of active TES integration in buildings is to cater for free cooling. Besides, for several applications such as HVAC systems and domestic hot water application, TES system is been utilized for peak shaving purpose [23,24,25]. Some of the suitable TES integration in the building is illustrated in Figure 1. It involves the integration to the core of the building, suspended ceilings, external solar facades, Photovoltaic (PV) system, ventilation system, and water tank as thermal storage [26].

Similar to the passive cooling, building thermal inertia is commonly incorporated to improve the thermal performance of the construction systems such as floors, ceiling and walls. As stated above, the difference is; for active storage, HTF is actively moved through the system and the forced convection occurred.

Yamaha and Misaki [27] studied the air distribution system integrated with a PCM thermal storage for peak shaving purpose. PCMs mixtures of paraffin waxes with the heat of fusion around 90 KJ/kg was chosen as thermal storage medium. During the charging period of 5 am to 8 am, the heat transfer fluid (air) is blown from the air conditioner (AC), then it will pass through PCM thermal storage and return back to the AC, creating a closed loop as shown in Figure 2. The charging operation then took over 4 hours (9 am to 1 pm) with the ordinary air conditioning

process occurred. The operation then followed by discharging process from 1 pm to 4 pm where air is blown via the PCM storage tank to the room. The result reveals that the incorporated of 400kg PCMs is applicable to sustain a constant room temperature in 73.8m<sup>2</sup> room surface of an ordinary office building, without any cool source. This study concedes that the utilization of PCM could improve overall energy management in buildings.



**Fig. 1.** Active cooling TES integration in building [26].

On the other hand, Kondo and Ibamoto [28] studies the feasibility of the utilization of PCM ceiling boards with the aim to minimize energy consumption during the peak time. The thermal capacity of PCM ceiling board was measured by using a small chamber, approximately 16m<sup>2</sup> surface area. The PCM ceiling boards was developed by adding the microencapsulated PCM to the commonly used rock wool ceiling board. The mixture of n-paraffins with a melting point of 25°C was used in this study.

During overnight, the cool air from air handling unit (AHU) will flow into the ceiling chamber space and cools the PCM ceiling board, storing the cool thermal energy. During the peak shaving period, the air from the room returns to the AHU through the ceiling chamber space. The warm air returning from the room is cooled down when passing through the cool PCM ceiling board, before entering the AHU unit. As a result, the maximum thermal load is recorded to decrease by 14.8%. Besides, the utilization of PCM ceiling boards is reported to lower the electricity cost for 91.6% compared to the use of conventional rock wool ceiling board. This study concludes that the utilization of PCM ceiling system is effective for peak shaving control [28].

Zhou et al. [29] proposed the commonly used of variable air volume air-conditioning (VAV-AC) to be enhanced by attaching the shape stabilized phase change material (SSPCM) plates to the inner surfaces of all external walls. The proposed SSPCM is a high-density polyethylene (HDPE) and paraffin. The melting temperature and heat of fusion of proposed PCMs is 23°C and 160 kJ/kg respectively. The result shows that the building peak load and electricity cost could be reduced for over 20% and 11% respectively.

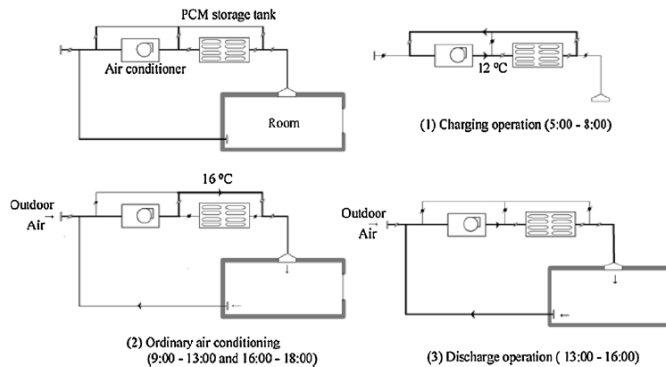
### 3.2 Passive Cooling

The principle aim of passive cooling is to maximize the comfort and health of building tenants and minimizing the energy demand, simultaneously. Passive TES has been proven to effectively improve the comfort conditions while minimizing the needs of mechanically heating or cooling systems [30]. This strategy removes heat from the building and prevents any heat gain from the surroundings [31].

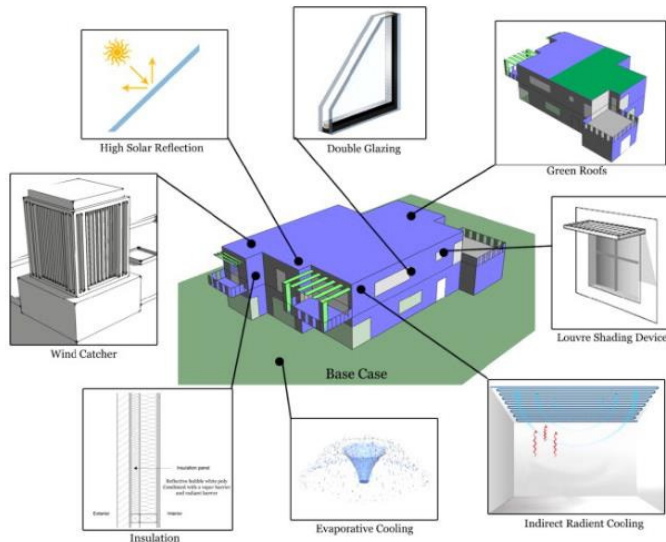
In general, the flow of energy in passive design is based on natural means, radiation, conduction, convection without the use of mechanical devices to dissipate heat. It utilizes on-

site energy, accessible from natural environment, together with the architectural design of building components [32]. Passive cooling requires a good natural resources as a heat sinks. For instance, onsite heat sinks are soil, night sky (environment) or wind. The example of recent passive systems includes thermal mass [33], solar heating and night ventilation technique [33], shading effect using blinds [34], use of ventilation facades and coated glazing elements [35].

In Dubai, United Arab Emirates (UAE), passive cooling strategies were investigated. An energy simulation software, Integrated Environmental Solutions (IES) was used to simulate the cooling performance of the buildings. This study proposed eight passive cooling strategies (Figure 3). For instance, the utilization of double glazing and good shading devices are proposed to minimize the heat gain. These strategies has been proven that it could attain the reduction of energy consumption. Green roofing method was also verified as an effective roof insulation. The passive cooling strategy shows a remarkable finding of 23.6% total annual energy consumptions [30].



**Fig. 2.** Set up for PCM storage tank integrated with air conditioning system [26].



**Fig. 3.** Passive cooling strategies [30].

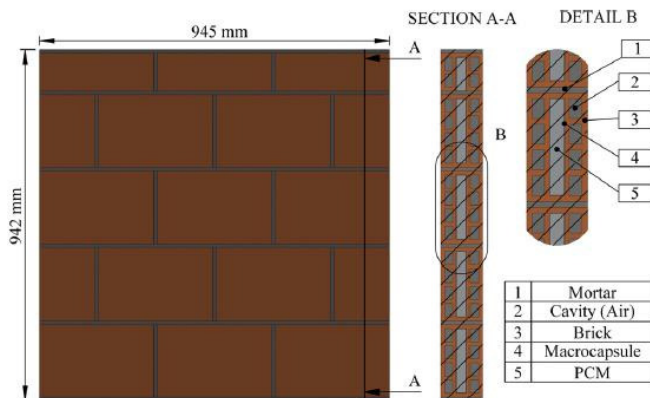
### 3.2.1 Material candidates for passive cooling storage

Typical heat sinks alternative used in buildings are high thermal mass materials such as stone, concrete, or alveolar bricks [36]. Standard solar walls and solar water walls are the example

of sensible storage that are being applied to save energy in buildings [37, 38]. PCMs thermal storage is also a good candidate for passive cooling in buildings. For instance, PCM is recorded to be able to store eighteen times more energy compared to the brick material [39]. PCMs thermal storage can be incorporated into building components such as ceiling, floor, windows, enclosure and partition walls.

The main purpose of integrating PCM into lightweight construction materials is to increase the thermal mass. Numerous studies has been conducted on the integration method of PCM into buildings. It involves PCM encapsulation, micro-encapsulation, direct incorporation immersion, and shape stabilization [40]. The incorporation of PCM macro encapsulated into a typical Portuguese clay brick masonry enclosure wall was investigated [39]. Both testing and numerical simulation were carried out in the project. The steel macro capsules with the size of 300mm x 170mm x 28mm and 0.75mm mean thickness were filled with PCM and been implanted into the middle brick as shown in Figure 4.

Experimental result shows that the incorporation of macro encapsulated PCM into the wall could reduce the thermal amplitude of 10°C to 5°C. Besides, it is also can prolonged the time delay of about 3 hours. In short, this result indicates that PCM is a viable option to store the thermal energy, which yields the reduction of the temperature fluctuation. The maximum energy savings recorded is 1888 kJ or 0.52 kWh. Considering the PCM works for 146days a year with the PCM cycle occurs once a day at maximum performance, the PCM wall is capable to store 76 kWh. For a mean compartment size of 100 m<sup>2</sup>, the presented solution could decrease over 760 kWh of energy demands from the HVAC system per year [41].

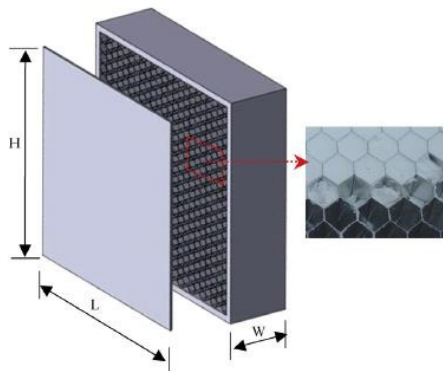


**Fig. 4.** System configurations of passive cooling with incorporated PCM into typical Portuguese clay brick masonry enclosure wall [41].

Other than that, PCM-wallboards are developed with the incorporated of expanded graphite nanosheets in order to enhance the thermal conductivity with the purpose to improve overall energy distribution [42]. Besides, the addition of an aluminum honeycomb with microencapsulated PCM-wallboard (Figure 5) also investigated towards the same objectives [43]. Good insulation is also highlighted as a promising approach to incorporate PCM in building. This concept has been studied by Yang et al. [44]. It shows that the integration of PCM thermal storage with insulation performance of polyurethane foam make a good team for energy savings purpose in buildings.

Besides, the mixture of PCM with concrete or mortar is listed as one of the suitable approaches of passive cooling system [45, 46]. One of the objective of this integration is to sustain the mechanical properties of the concrete, in the time increasing its specific heat capacity. Entrop et. al., [47] studied the performance of PCM integrated concrete floor. Full scale experimental investigation on four identical chambers were conducted. The only heat source in this experiments are from the solar irradiation through the windows. Experimental

test rig was constructed with two chambers use the conventional floor while another two chambers are incorporated with PCM concrete floor. Result shows that this technique is capable to reduce the temperature fluctuations in the PCM- concrete chambers. Nonetheless, the concrete floor is commonly will be covered by any kind of covering such as tiles, polyvinyl or wood. This will shelter the PCM concrete floor from direct solar radiation. Hence, it was found that there are difficulties in implementing this technique in a broader scale practice [47].



**Fig. 5.** PCM-honeycomb wallboard [43].

Form the observation, the most remarkable advantage of passive cooling technique is the ability to improve the thermal comfort with the use of nil or minimum power consumption. Passive cooling technique is agreed to be eco-friendly compared to the active cooling technique. Even so, passive cooling is a climate-influenced technique. Hence, different approaches are needed for a different climate zone. This circumstance prescribed that their performance may fluctuate with time of day and seasons. As many drawbacks of passive cooling technique are found, further studies are found crucial. Researchers should focus on the initiative to reduce the overdependence of this technique onto several factors such as climate, and site designs.

On the contrary, if a building cannot be cooled using passive means, the active cooling technique need consideration. Active cooling technique is accounted to be more flexible and can be implemented in various ways. Previous studies show that the integration of TES system is very useful to reduce the energy consumption during peak time. In a nutshell, one may conclude that the integration of TES system in building application has been extensively studied. Despite of some limitations, the integration of TES system for both active and passive techniques has been proven to be beneficial towards energy sustainability. Excellent energy management is foreseen to be able to counterbalance the soaring energy demand.

## 4 Conclusion

The integration of the thermal energy storage for active and passive cooling in building is discussed. Several examples of both cooling design has been presented in this paper. The utilization of passive cooling with TES system is limited due to the overdependence on climatic factor, storage materials properties, and the architecture of the building itself. In contrast, active cooling technique is more versatile and could be integrated in many ways. Nonetheless, the integration of these system may result additional issues to the building physics such as humidity issue, air tightness and thermal bridge. Therefore, further study on this subject matters are required to achieve the optimum cooling design in order to attain the reduction of overall energy consumption.



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