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The Strategy of Using PCMs in Building Sector Applications

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ABSTRACT

With the recent large increase in the building sector's energy use to provide thermal comfort to consumers, the restrictions of climate change, and the scarcity of energy supplies, there has been a need to develop ways to reduce energy consumption. The use of phase change materials (PCMs) as a thermal energy storage (TES) system has attracted a lot of attention as a technique to improve thermal performance, conserve energy, and improve occupant comfort. When storing energy via phase change, the key advantage in terms of building materials is the higher energy density, which indicates that more energy can be stored in a constant volume. This study focuses on the vital role of PCMs in building applications by presenting the different classifications of PCMs as well as their integration techniques, systems, and benefits for building applications. Different case studies for full scale buildings are presented. A design strategy is concluded for integrating PCMs in buildings.

Keywords: Phase change material (PCM), Thermal energy storage, Building application, PCM systems, Design strategy.

Abbreviations	
PCM	Phase Change Material
TES	Thermal Energy Storage
UHI	Urban Heat Island
PCHCM	Phase Change Humidity Control Material
PV	Photovoltaic
AC	Air Conditioning

1.INTRODUCTION

Energy and environment are two of the most important issues that humanity is facing today. Industrial improvements and population expansion have resulted in a tremendous increase in energy consumption over several centuries [1]. Concerns about climate change have prompted further research into energy-efficient alternatives [2]. The energy consumption of the building sector is increasing as the economy grows and the demand for interior thermal comfort rises [3-5]. Accordingly, architects and engineers should explore strategies to minimize the amount of fossil fuels used in building design for heating and cooling [6]. Many solutions for improving thermal comfort have already been implemented, including shading, courtyards, green roofs, natural ventilation, mass creation, and thermal energy storage (TES) [7-14].

TES has received considerable attention in recent decades [2] because TES systems have the potential to store spare energy and release it when there is a shortage, thereby bridging the gap between energy supply and demand [2, 15]. The systems are classified into three categories as shown in **Figure 1**.

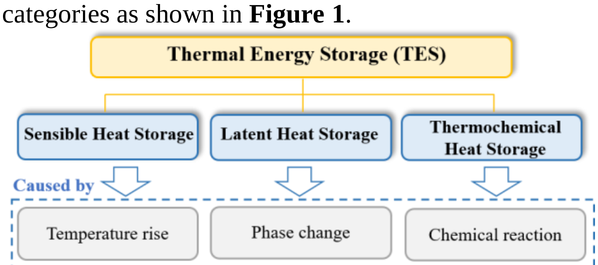

Figure 1. Classification of Thermal Energy Storage Systems. Source: Authors based on [16].

One of the most efficient ways to store thermal energy is by latent heat storage via phase change materials (PCMs). When compared with sensible heat storage, PCM has a larger heat storage capacity and more isothermal behavior during charging and discharging [17]. Moreover, in thermochemical process at ambient temperature, the two components are kept separate. As a result, this method of TES is more suited to long-term storage, such as seasonal storage.

The utilization of PCMs is based on a basic idea. The material turns from solid to liquid as the temperature rises. The PCM absorbs heat since the process is endothermic. Similarly, when the temperature drops, the material transitions from a liquid to a solid state. The PCM desorbs heat since the process is exothermic [18].

This study addresses the idea of using PCMs in building applications, their classifications, properties, integration techniques, benefits, systems, and full-scale case studies. Finally, summarizing a design strategy for integrating PCMs in building applications.

2. PCM CLASSIFICATIONS AND PROPERTIES

Based on the chemical composition, three primary classifications of PCMs can be incorporated into building materials [1, 19]. Incorporating organic, inorganic, and eutectics types of PCMs involves four techniques like direct, immersion, encapsulation, and shape stabilization [20]. Some properties of PCMs like thermodynamic, chemical, kinetic, and economic are desired to be employed in the applications in buildings [21]. Moreover, various physical phenomena of PCMs like melting temperature, supercooling effect, etc. are recommended to be evaluated when considering the effectiveness of applications in buildings (see

Table 1).

Table 1. PCM classifications, properties, and integration techniques. Source: Authors based on [1, 19-24].

	PCMs	Notes
Classification	**Organic**	Paraffin, Non-Paraffin
	Inorganic	Salt Hydrate, Metallics
	Eutectics	Organic-Organic, Organic-Inorganic, Inorganic-Organic
Physical Phenomena	Melting Temperature	The temperature of phase transformation
	Supercooling Effect	The phenomenon which the liquid doesn't solidify or crystallize, even its temperature is lower than the freezing point
	Thermal Life Cycle	Number of repeated cycles (solidification/melting) before the decrease in PCM thermal properties occur
	Long-Term Stability	Depends on two factors: poor material stability owing to thermal cycling and PCM corrosion with the container.
	Segregation Effect	Process irreversible, making their storage density decreases with cycling and causing a decrease in their thermal properties
	Flammability	Fire retardant additives can be added.
	Compatibility with Other Materials	Compatibility tests are carried out under typical circumstances for the planned application. Appropriate material combinations are selected from their outcomes
Desired Properties for Building Applications	Thermodynamic Properties	-High latent heat of fusion, thermal conductivity, and high specific heat. -Small change in volume -Congruent melting
	Chemical Properties	Chemical stability, full reversible cycle, No degradation Non-corrosiveness, Non-toxic, Non-flammable
	Kinetic Properties	-High rate of nucleation, crystal growth.
	Economic Properties	effective cost and availability
Integration Techniques	Direct	directly add liquid or powdered PCMs to construction materials
	Immersion	construction materials are immersed in melted PCMs and then absorbed into their inner pores
	Encapsulation (micro-macro)	PCM is packed before integration
	Shape Stabilization	A mixture of a liquid PCM and a supporting material

3. BENEFITS OF USING PCMS IN BUILDING APPLICATIONS

The usage of PCMs in buildings provides improved indoor thermal comfort for residents by minimizing interior temperature swings and decreasing total energy consumption due to load reduction. TES systems provide the advantage of controlling energy through storage as well as lowering the consumption of fossil fuels, which are the primary source of CO_2. Furthermore, the construction sector relates to the urban heat island (UHI) phenomenon, which causes higher surface and air temperatures in metropolitan areas. The purpose of installing PCMs in a building is to lower and manage the power demand for heating and cooling by practically reducing the maximum thermal load on the building [25, 26].

3.1. Enhancing Thermal Comfort

PCMs have the potential for being employed in current construction materials to help regulate interior temperature fluctuations and improve thermal comfort [25]. For instance, temperature variations are minimized when PCMs are installed. The emphasis should be on choosing a PCM that melts/freezes at the correct temperature so that temperatures remain constant around the comfort temperature. This improves the interior environment in two ways. First, the temperature is more stable throughout the day, thereby decreasing sensations of thermal discomfort caused by temperature fluctuations. Second, the maximum temperature is lowered, and it will not reach a level that causes greater thermal discomfort. Another advantage of PCMs is that they may result in a more consistent temperature between surfaces and air temperatures, decreasing thermal discomfort caused by radiative heat [27] (see **Figure 2**).

Moreover, temperature stability and control for temporary constructions can be provided by PCMs, which is an excellent approach in crisis situations such as the Covid-19 pandemic [28].

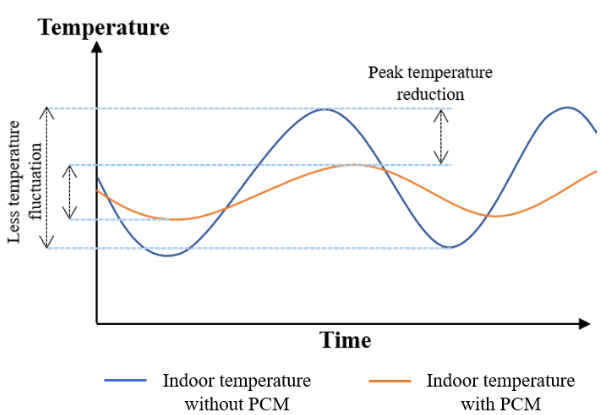

Figure 2. Effect of PCM integration on thermal comfort. Source: Authors based on [29].

Inside-building air quality has a significant impact on human comfort, and this is a major post-pandemic concern [30]. The humidity level is known to impact indoor air quality, specifically virus survival and dissemination, as well as other important qualities for residents, such as sleep quality and probable eye and airway discomfort [31, 32].

Phase change humidity control material (PCHCM) is a novel type of composite that combines high-performance PCM microcapsules with hygroscopic materials to manage humidity [33]. By absorbing and releasing heat and moisture, the PCHCM composite can control the hygrothermal environment indoors [34]. Hygroscopic materials can absorb and desorb moisture and behave as sponges. When the interior air humidity rises, these porous materials may absorb water vapor from the air, slowing the rate of increase in the indoor humidity. When the interior air humidity drops, it releases the water vapor to maintain the indoor humidity [35].

3.2. Energy Saving

The rapid expansion of the construction sector is estimated to contribute to an increase in energy consumption. Heating and cooling accounts for over a quarter of all energy consumed in buildings worldwide. Therefore, one of the most difficult contemporary issues in sustainable development is energy conservation. The heat transmission of the building envelope results in significant heat loss, and in response, researchers are focusing on energy saving enclosure structure technologies [36, 37]. By using PCMs, excess heat and cold can be stored in buildings by enhancing their thermal inertia, the immediate cooling and heating loads encountered in these structures can be reduced, and, as a result, the energy consumption of mechanical heating and cooling systems can be lowered [38]. According to studies, PCMs may store 5–14 times more heat per unit volume than sensible heat storage materials [39].

Active TES techniques have a large initial investment. Because of this, in order to maximize the energy savings during operation, an appropriate control strategy must be used. By using such automation, it is possible to cut operational expenses and energy consumption while also contributing to climate and environmental preservation without losing comfort [39, 40].

3.3. Peak Load Shifting

The demand for electricity changes through the day and night, depending on industrial, commercial, and residential activity. This change results in a varied pricing scheme between peak and off-peak periods, which are typically from midnight to early hours of the morning [41]. The highest demand over a billing cycle is known as peak demand or peak load, and it varies depending on the building type. Peak loads during the day strain the electrical grid and necessitate the sizing of heating, ventilation, and air conditioning systems to accommodate higher heating or cooling loads. This requires constructing additional power generation facilities. The peak load can be distributed during the day, minimizing the highest peaks, by moving the peak load away from peak hours of electrical demand using PCMs [27].

Figure 3 explains how using PCMs can minimize and shift the peak due to temperature reduction. This shift in power demand from peak to off-peak hours will result in considerable financial savings. The development of an energy storage system might be one solution to the problem of power supply and demand: surplus energy will be stored in energy storage devices until needed. [41].

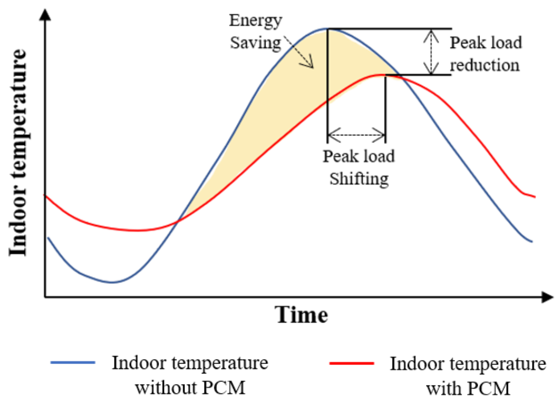

Figure 3. The effect of indoor temperature differences with and without PCM on energy savings [42].

3.4. Mitigating the UHI Effect

Owing to heat storage and release in buildings, increased concrete coverings, population growth, and heat sources created in urban areas, UHI phenomena occurs, resulting in a greater temperature in core sections of cities than in suburban regions. Traditional methods to minimizing UHI include increasing the reflectivity of buildings and roadways, as well as adding additional green areas, wind paths, and water space. [43].

Building roofs can be enclosed with PCM, which could help with thermal balancing. These materials receive solar and infrared light and release some of the accumulated thermal energy into the atmosphere via convective and radiative processes. This is accomplished through PCM impacting the surface temperature rather than the roof's thermal resistance [44] (see **Figure 4**).

Moreover, the UHI effect and thermal distresses in concrete pavements are caused by higher pavement temperatures. One of the potential solutions to lower this temperature is to use PCM [45].

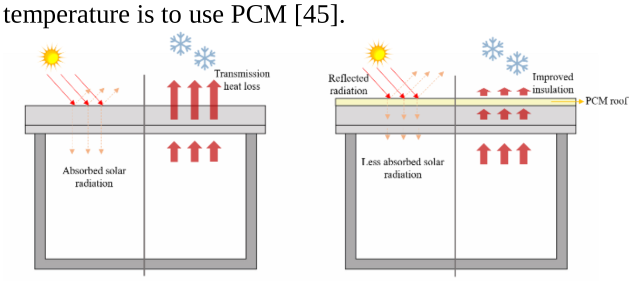

Figure 4. Mitigating the UHI effect by PCM-roof :(left) without PCM and (right) with PCM. Source: Authors based on [46].

4.PCM SYSTEMS

PCMs can be integrated with different systems in a passive or active way. **Figure 5** shows different PCM systems.

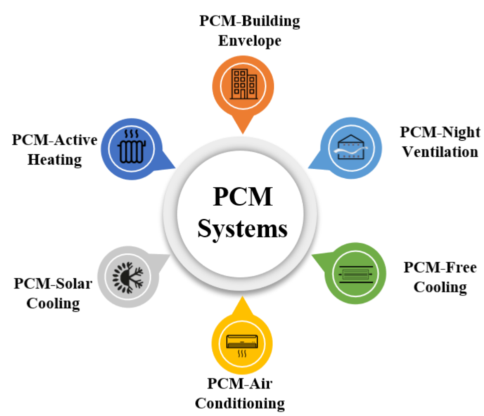

Figure 5. Different PCM Systems.

4.1. PCM-Building Envelope

Generally, the building envelope consists of materials such as bricks, cement, and concrete that store thermal energy in a sensible form. To absorb, store, and release heat energy in the structures, all these materials employ sensible heat storage strategies [47].

The PCM is generally installed in a passive or active design in the building envelope. Heat transmission during melting and solidification occurs spontaneously in passive applications; however, the active approach requires active methods, such as fans and pumps, to improve the heat transfer rate during phase transition or generate additional heat, such as solar collectors. The passive pattern has been tested in various climates and has been shown to significantly reduce building energy use during the day [48-50].

Because of their reasonable efficiency, affordability, and ease of use, PCM-building envelopes remain of interest among available PCM systems [51]. **Figure 6** shows different building components for envelope system.

4.2. PCM-Night Ventilation

To fully utilize PCM's capacity, it must be fully charged and discharged at each cycle. This means that the PCM should solidify overnight in order to absorb heat the next day. PCM is usually installed on the inner surface of the building envelope to regulate the temperature of the indoor environment. As a result, it may not fully solidify at night, and then there will be no significant energy savings. For this, night ventilation is a useful technique that can be used in conjunction with PCM-enhanced structures to charge the PCM at night (see **Figure 7**) [67].

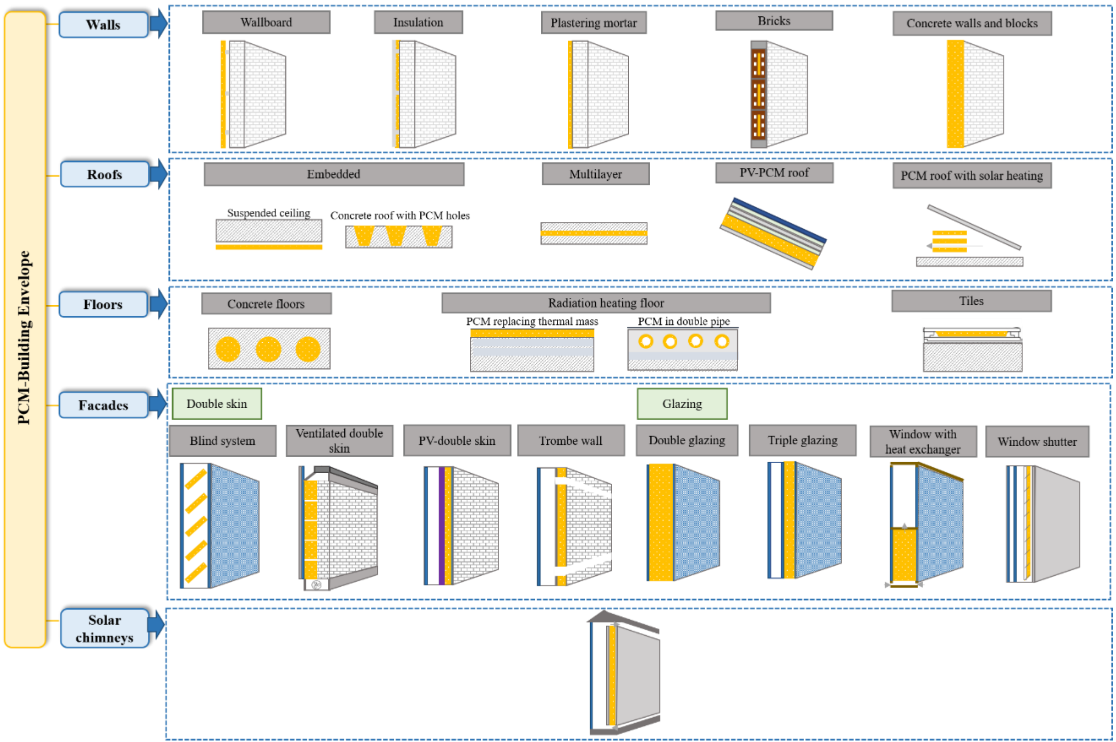

Figure 6. PCM envelope system components source: The authors adopted from [19, 52-66].

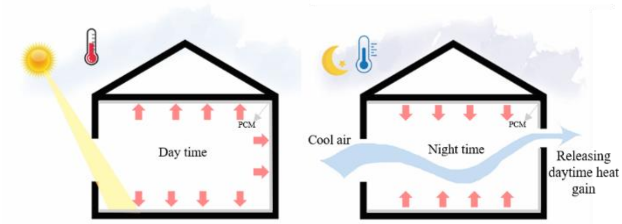

Figure 7. PCM-Night ventilation system.

4.3. PCM-Free Cooling

Free cooling technology requires a storage unit that stores the thermal energy either by varying the storage medium's internal energy (sensible heat storage), varying the storage material phase (latent heat storage), or both [68]. The main advantages are cooling with greenhouse gas reduction and the excellent maintenance of indoor air quality inside the building. Since the difference in temperature between day indoors and night outdoors is small, the best storage option is PCM [69] (see **Figure 8**).

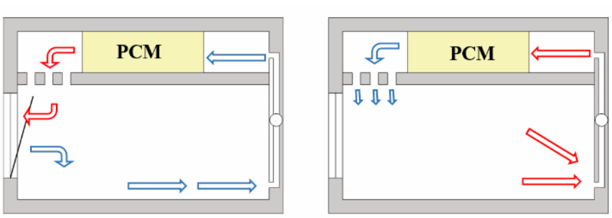

Figure 8. (left) Cooling of PCM at night and (right) Cooling of building during the day. Source: Authors based on [70, 71].

4.4. PCM-Air Conditioning

PCM in an air conditioning (AC) system might considerably reduce cooling load, allowing for the use of AC with reduced power sizes [72]. PCMs are usually integrated with AC as flat plates, double tube storage, or spherical capsule units [73] (see **Figure 9**). Latent heat TES might be employed in a chilled water circuit, ventilation system, or the thermal power generation of desiccant cooling and absorption systems in an air conditioning system [74].

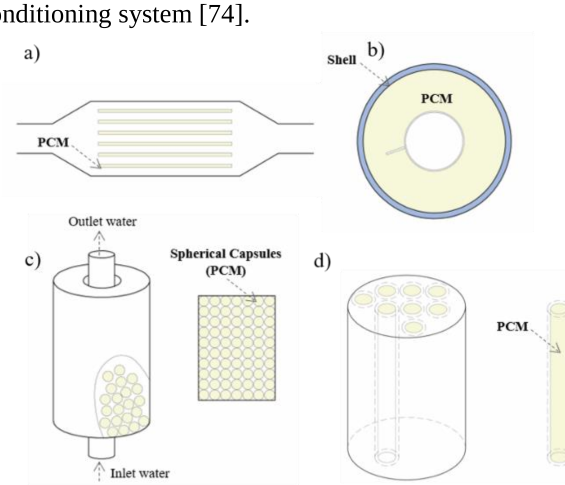

Figure 9. Configurations of integrating PCM in an AC system: a) flat plate, b) double tube, c) spherical capsule, and d) shell and tube. Source: Authors based on [73].

4.5. PCM-Solar Cooling

The main drawback of solar energy is the mismatch between energy demand and supply since it is time dependent. As a result, when energy is accessible but not allocated to any operation, TES may become an important issue [75, 76]. PCMs are commonly utilized to store thermal energy in renewable energy technologies, particularly solar systems, until it is needed. For example, Sudhakar, et al. [77] evaluated the performance of solar photovoltaic panel with PCM integrated natural water circulation cooling method. Results showed an improvement in the power output performance (see **Figure 10**).

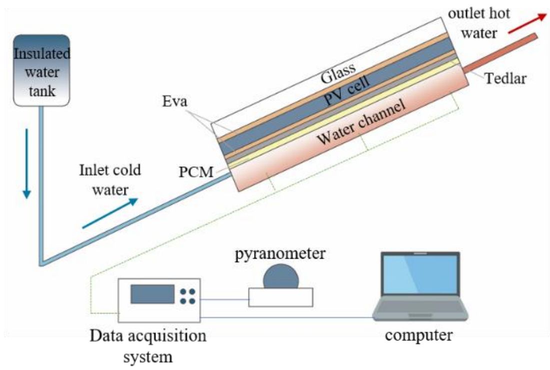

Figure 10. Solar PV-PCM with water cooling. Source: Authors based on [77].

4.6. PCM-Active Heating

Renewable energies, such as solar, ambient air, and geothermal energy, have the drawback of fluctuating outputs, which means they may not be able to meet energy demands while buildings are in use. One major technique for addressing this problem is to employ TES devices (e.g., PCM), which can store renewable energy when it is abundant and release it when it is in short supply to meet building energy demands [78, 79] (see **Figure 11**).

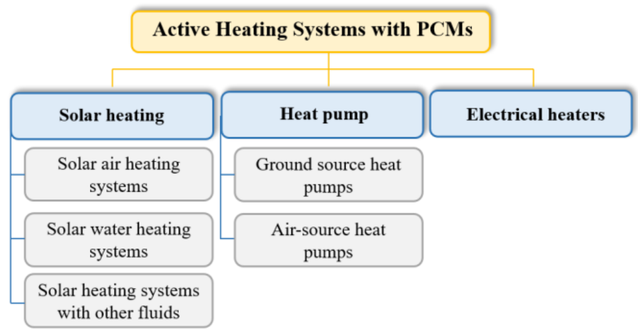

Figure 11. Building systems with PCMs for active heating purposes [53].

Table 2. Full scale building case studies with PCMs.

Case Study	Building Type	Location/ Climate	PCM Type/ Temperature/ Integration	PCM Component	PCM Effect	Outcomes	Ref.
E3 House	Residential	Italy, Humid Subtropical Temperate	Paraffin, 23°C, Micro-encapsulation	Wall	Heating, Cooling	E3 house is below the value of energy needed for heating for similar buildings by more than 10 times.	[80]
Oak Ridge House	Residential	U.S., Humid Subtropical	Non-paraffin 27.5°C Micro-encapsulation	Insulation	Cooling	Reduction in cooling load by about 5%	[81]
BASF House	Residential	England, Temperate Oceanic	Paraffin 23°C Micro-encapsulation	Ceiling	Heating	By combining PCM with other passive methods, the actual measured energy consumption is 12.5 kWh/m2/year	[82]
Kingspan Lighthouse	Residential	U.K., Temperate Oceanic	Paraffin 23°C Micro-encapsulation	Ceiling	Cooling	The Lighthouse's energy efficiency is considerably higher than that suggested by the conventional evaluation protocol.	[83]

Case Study	Building Type	Location/ Climate	PCM Type/ Temperature/ Integration	PCM Component	PCM Effect	Outcomes	Ref.
Academic Office Charles Sturt University	Office	Australia Humid Subtropical	Paraffin 23°C Micro-encapsulation	Wall-Floor	Cooling, Heating	The production of carbon dioxide and energy consumption reduced by 65% in comparison with equivalent traditional office buildings.	[84]
New Hampshire Middle School	Educational	U.S., Warm Summer continental	Salt hydrate 21.6°C Macro-encapsulation	Ceiling	Cooling, Heating	There was a 56% reduction in fan use for heating (run time of HVAC) and a 58% reduction in cooling runtime.	[85]
Bank Rolling Hills	Administrative	U.S., Hot summer Mediterranean	Non-paraffin --- Macro-encapsulation	Ceiling	Cooling, Heating	A significant decrease of about 26% (30,000 kWh/yr) was observed in raw HVAC current consumption.	[86]
Senior Citizen's Apartment	Residential	Switzerland, Hot summer humid continental	Salt hydrate 26°C–28°C Macro-encapsulation	Glazing system	Heating	In winter, PCMs operate as a suitable solar wall, storing heat from incident solar radiation and releasing it at night, ensuring great environmental comfort. With a minimum temperature of 24°C. In summer, the maximum temperature is 27°C	[87, 88]
University of Washington	Educational	U.S., Mediterranean	Non-paraffin 21°C–25°C Macro-encapsulation	Walls-Floors	Cooling, Heating	The results allowed for uninstalling the air conditioning. Energy savings were estimated at $70,000 per year.	[86]
TrekHaus	Residential	U.S., Humid subtropical	Non-paraffin 25°C Macro-encapsulation	Walls-Ceiling	Cooling, Heating	There was a 50% reduction in HVAC consumption in the unit with PCM.	[89]

5.FULL SCALE PCM-BUILDING CASE STUDIES

The majority of studies on integrating PCMs into buildings are numerical with the use of different simulation tools like EnergyPlus, TRNSYS, ANSYS Fluent, and COMSOL Multiphysics, or by creating experimental prototypes. However, some case studies for full scale buildings with PCMs are shown in **Table 2** to prove the influence of PCMs. It's worth noting that all cases include a PCM-building envelope system with different components.

6. DISCUSSION

The case studies' outcomes indicate that using PCMs in buildings have a positive impact on energy usage for cooling and heating while also enhancing interior temperatures.

Among organic, inorganic, and eutectic PCMs, organic PCMs are the most commonly used (both paraffin and non-paraffin), according to case studies of building field testing. Taking into account climate circumstances, PCM melting temperature ranges from 21°C to 28°C. The encapsulation method, which includes both micro and macro encapsulation, is the most frequently used of the integration techniques. The outcomes indicate that PCMs can increase thermal comfort while lowering energy consumption.

Based on the analyses of various cases, a design strategy for integrating PCMs in building applications is summarized in **Figure 12** There are five main parts to this strategy:

- First, begin with the PCM type, which falls into one of the following three categories: organic, inorganic, and eutectics, with organic PCM being the most common.
- Second, select the melting temperature of PCM, which is primarily determined by two factors: climate and the building system selected.
- Third, implement integration techniques, which are mainly divided into four categories, with encapsulation techniques being preferred to overcome leakage issues and prevent reactions to the outside environment.
- Fourth, choose a building system, which includes a range of alternatives, with the building envelope system being most prevalent.
- Finally, conduct a verification with experimental prototypes or simulation tools such as EnergyPlus, ANSYS Fluent, TRNSYS, and COMSOL Multiphysics. This step is crucial to ensure the correct choice of PCM properties, melting temperature, and thicknesses because each case study has its own unique set of conditions.

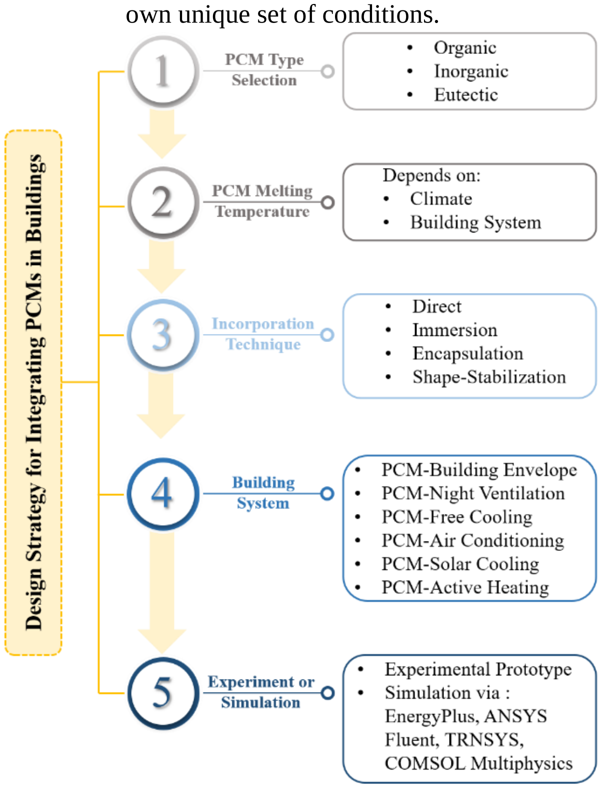

Figure 12. Design strategy for integrating PCMs.

7. CONCLUSION

This study presents the vital role of PCMs in building applications to improve thermal comfort, energy saving, and other benefits. The following points can be concluded:

- It is possible to integrate PCMs into passive and active systems in buildings, giving preference to the building envelope system.
- PCM use in different applications showed great potential in terms of improving thermal comfort either in cooling or heating, energy savings, peak load shifting, and mitigating the UHI effect with various integration techniques and building systems, making it an effective and innovative material to be used in buildings.
- PCMs can be integrated within different building components such as walls, floors, roofs, facades, and solar chimneys.
- Some PCM-building components can be used in building retrofitting.
- It is possible to use two or more PCM-building components together.
- Encapsulation techniques are the most appropriate and safe for building applications.
- Organic PCMs are the most frequently used in building applications.
- It is important to select the appropriate PCM melting temperature.
- Climate conditions of each region affect the choice of PCM melting temperature.
- PCMs with a melting temperature of 21°C–28°C are the most frequently used in building applications.
- For developing countries, it would be more efficient to use components that can be added to the building, not components that affect the structure, due to workers' lack of experience and the price of complicated systems.
- It is important to verify the effectiveness of simulation tools and experimental prototypes.
- Studying the integration of PCMs in various places in Egypt with varying temperatures between day and night is required to determine the extent of their influence
- Examine the effect of mixing PCM layers with different melting temperature on thermal comfort.
- Some critical issues should be thoroughly investigated in order to ensure long-term performance:
  - Extensive study on the potential harmful effects on environment during the different

phases of PCMs starting from their manufacture, production, development, usage and disposal.

- More research into the toxicity of PCM products and long-term health hazards and consequent limitations.
- More research is needed to improve different incorporation techniques in order to avoid any possible leakage.
- Further investigation of cases of demolition and maintenance of buildings containing PCMs in order to ensure optimal handling and to overcome the possibility of leakage or other risks.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this study.

Declaration of Funding

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