Chapter 9
Phase Change Materials in Buildings:
Fundamentals, Applications, and Future Perspectives

Salim Barbhuiya
https://orcid.org/0000-0002-4325-281X
University of East London, UK

Bibhuti Das
NITK Surathkal, India

Dibyendu Adak
https://orcid.org/0000-0003-1494-3010
NIT Meghalaya, India

ABSTRACT

This chapter thoroughly explores Phase Change Materials (PCMs) and their applications in buildings. It begins by introducing the background, context, and objectives before delving into PCM fundamentals, covering types, phase change mechanisms, and key properties. Beyond theory, the chapter explores practical applications in thermal regulation, energy efficiency, HVAC systems, thermal energy storage, passive building design, heat recovery, and PCM integration. Discussion includes various PCM types—organic, inorganic, eutectic mixtures, and bio-based—alongside selection criteria for building applications. Methods to enhance PCM performance, such as nano-enhancements, microencapsulation, and hybrid solutions, are explored. The chapter addresses integration and design considerations and concludes with insights into future directions, trends, and implications for sustainable building practices.

DOI: 10.4018/979-8-3693-3398-3.ch009

1. INTRODUCTION

Phase Change Materials (PCMs) are at the forefront of transformative change within the construction industry, heralding a paradigm shift towards enhanced energy efficiency and elevated thermal comfort standards in buildings. Their remarkable capacity to absorb and release substantial quantities of thermal energy during phase transitions, such as the conversion from solid to liquid or liquid to gas, while maintaining a consistent temperature, has ignited widespread interest and exploration. This intrinsic characteristic endows PCMs with the capability to actively regulate indoor temperatures, effectively mitigating temperature fluctuations and lessening dependence on conventional heating and cooling systems.

Amidst an escalating global demand for sustainable building practices, PCMs have emerged as a cornerstone technology in the battle against climate change and the pursuit of minimised energy consumption in the built environment. Therefore, fostering a comprehensive understanding of PCM applications, benefits, and challenges within building design and construction has become an imperative for advancing sustainability objectives and realizing the vision of energy-efficient buildings. By embracing PCM technology, stakeholders stand poised to catalyse the transition towards a greener and more resilient built environment (Chandel & Agarwal, 2017; Wang et al. 2022a; Kapasalis et al. 2024). Through strategic integration and utilisation of PCMs, they can actively contribute to meeting the evolving needs of occupants and society at large, while simultaneously aligning with progressive sustainability goals on both local and global scales.

The motivation behind this chapter on Phase Change Materials (PCMs) lies in addressing pressing challenges in sustainable building design. With a growing emphasis on energy efficiency and environmental conservation, PCM technology offers a promising solution. By elucidating PCM properties, applications, and benefits, this chapter aims to equip practitioners, policymakers, and researchers with the knowledge needed to effectively integrate PCMs into building design and construction. Furthermore, by highlighting challenges, opportunities, and best practices, the chapter seeks to foster innovation and facilitate informed decision-making in pursuit of more sustainable and resilient built environments.

Despite its comprehensive coverage, this chapter on Phase Change Materials (PCMs) in buildings has some limitations. Due to the vast scope of PCM applications, certain niche areas may not receive detailed examination. Additionally, the chapter may not delve deeply into specific technical aspects or emerging research trends within PCM technology. Furthermore, while practical applications are explored, the chapter may not provide exhaustive case studies or real-world examples. Finally, given the dynamic nature of sustainable building practices, some discussions on future directions and trends may lack complete foresight. Overall, while informative, readers should supplement this chapter with additional sources for a comprehensive understanding of PCM integration in buildings.

2. PHASE CHANGE MATERIALS: FUNDAMENTALS AND CHARACTERISTICS

2.1 Definition and Basic Concepts

Phase Change Materials (PCMs) are substances capable of storing and releasing large amounts of thermal energy during the process of changing phase, typically from solid to liquid or liquid to gas, and vice versa. This property is known as latent heat storage. PCMs undergo these phase transitions at specific temperatures, known as melting (solid to liquid) and freezing (liquid to solid) points. During these transitions, the temperature remains constant until all the material has completed the phase change. PCMs exhibit high energy storage densities compared to conventional materials, making them efficient for thermal energy storage applications. They find use in various industries, including building construction, electronics cooling, food preservation, and thermal energy storage systems. Basic concepts of PCMs include their types (organic, inorganic, eutectic mixes, and bio-based), selection criteria based on operating temperatures and application requirements, methods of enhancing PCM performance (such as encapsulation or incorporation of nanoparticles), and considerations for integration into building materials and systems for improved energy efficiency and thermal comfort.

2.2 Types of Phase Change Materials

Phase Change Materials (PCMs) encompass diverse types tailored to various applications. Organic PCMs, derived from carbon-based compounds like paraffins and fatty acids, are prominent for their high latent heat storage capacities. Inorganic PCMs, including salt hydrates and metals, offer stability and thermal conductivity. Eutectic mixes, such as calcium chloride and calcium nitrate blends, present sharp melting points ideal for specific temperature requirements. Bio-based PCMs, sourced from renewable biomass, introduce eco-friendly alternatives. Each type of PCM possesses distinct characteristics, catering to specific needs across industries ranging from building construction to thermal energy storage systems. Table 1 provides a concise overview of the main types of PCMs, their descriptions, examples, and common applications.

Table 1. Phase Change Material Types and Applications

Type	Description	Examples	Applications	Reference
Organic PCMs	Derived from carbon-based compounds	Paraffins, fatty acids, PEGs	Building construction, thermal energy storage systems	Karaipkli & Sari, 2016; Jeong et al. 2019; Rathore & Shukla, 2021
Inorganic PCMs	Consist of salts, metals, and hydrated salts	Salt hydrates, metals	Thermal energy storage, electronics cooling	Sun et al. 2020; Bao et al. 2020 ; Junaid et al. 2021
Eutectic Mixes	Blends with sharp melting points	Calcium chloride and calcium nitrate eutectic mix	Low-temperature applications, thermal energy storage	Shilei et al. 2016; Karthick et al. 2020 ; Srinivasaraonaik et al. 2020
Bio-Based PCMs	Derived from renewable biomass sources	Fatty acids from vegetable oils, carbohydrates, proteins	Eco-friendly applications, thermal energy storage	Boussaba et al. 2018; Mehrizi et al. 2023 ; Baylis & Cruickshank, 2023

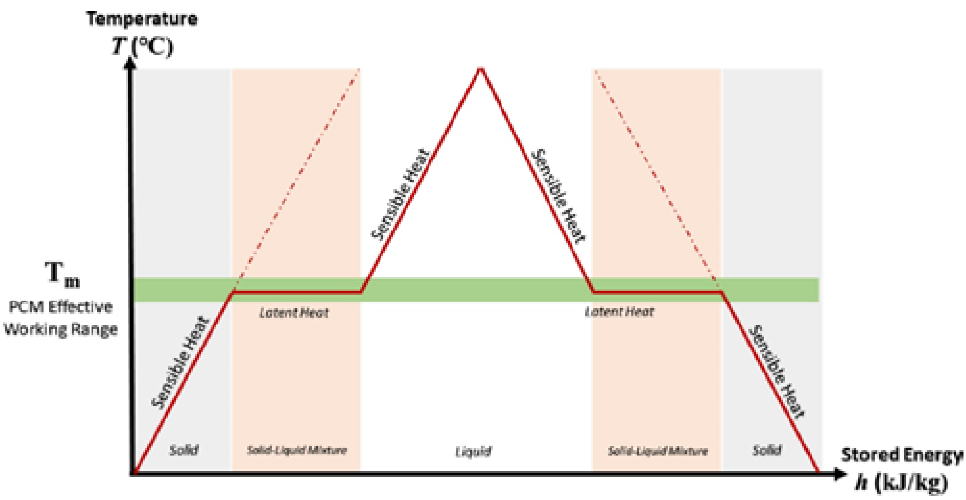
2.3 Phase Change Mechanisms

Phase Change Materials (PCMs) undergo a change in their physical state, such as from solid to liquid or vice versa, during a phase change process. The mechanisms involved in these phase changes are primarily governed by the transfer of heat energy. There are three main phase change mechanisms in PCMs:

1. Latent Heat Absorption/Release: PCMs absorb or release latent heat energy during the phase change process without experiencing a significant change in temperature. For example, when a solid PCM absorbs heat, it undergoes a phase change into a liquid state, storing the absorbed heat energy. Conversely, when the PCM cools down, it releases the stored heat energy as it solidifies.
2. Melting and Solidification: The phase change process involves the melting of a solid PCM into a liquid state as it absorbs heat and solidification of the liquid PCM into a solid state as it releases heat. During melting, the PCM molecules overcome the forces holding them in a solid structure, transitioning into a less organized liquid phase. Solidification involves the reverse process, where the molecules arrange themselves into a more ordered structure to form a solid.
3. Nucleation and Growth: Nucleation refers to the initial formation of small regions of the new phase within the PCM material. These small regions, called nuclei, act as sites for further phase change growth. As heat is applied or removed from the PCM, these nuclei either grow or shrink, leading to the overall phase change process.

Phase change materials (PCMs) serve as latent heat storage mediums, undergoing a phase transition between liquid and solid states, typically occurring isothermally during melting (heat storage) or solidifying (crystallization recovery). As PCMs shift from solid to liquid, they absorb thermal energy through an endothermal process that breaks the chemical bonds within the material, storing it as latent heat. Upon cooling, PCMs release this stored energy exothermally as they revert to their solid state. This behaviour allows PCMs to function effectively as thermal storage mediums. The phase transition process of PCMs is visually depicted in Fig. 1.

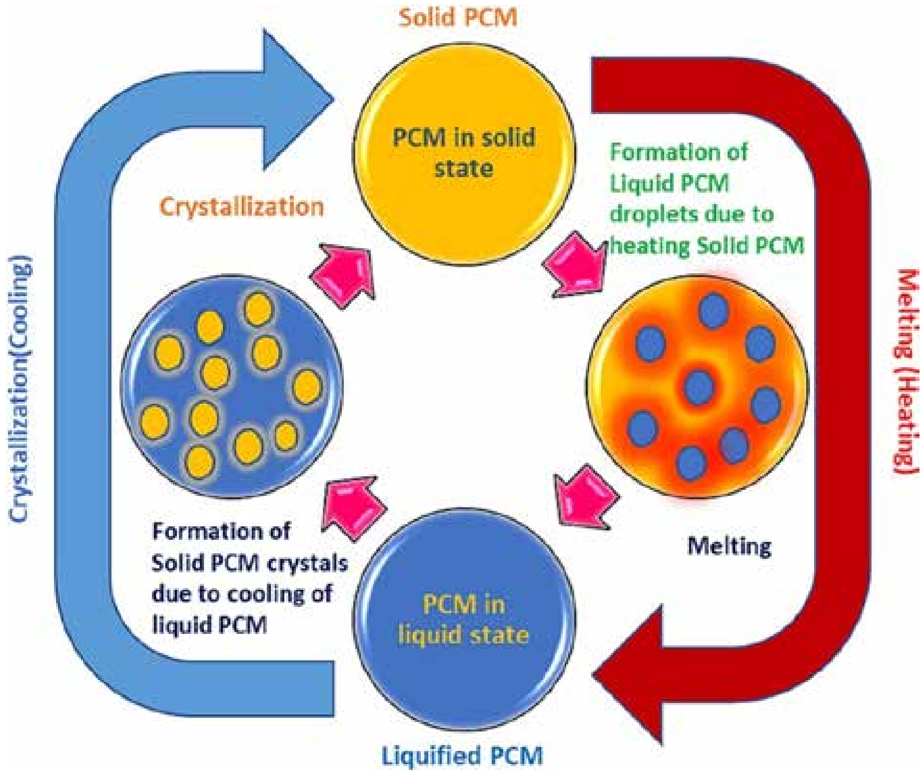
Figure 1. PCM phase change transition



(Faraj et al. 2021)

Solid-Liquid-PCMs utilise latent heat of fusion, transitioning from solid to liquid as temperatures surpass their melting point, absorbing heat. Conversely, when temperatures dip below the melting point, they release stored energy, reverting to a solid state. This reversible process maintains thermal equilibrium, effectively regulating indoor temperatures. The schematic in Fig. 2 illustrates this phase transition. By harnessing SL-PCMs' thermal properties, buildings can achieve efficient temperature control, reducing reliance on conventional heating and cooling methods. This not only enhances energy efficiency but also contributes to sustainable building practices, promoting environmental stewardship.

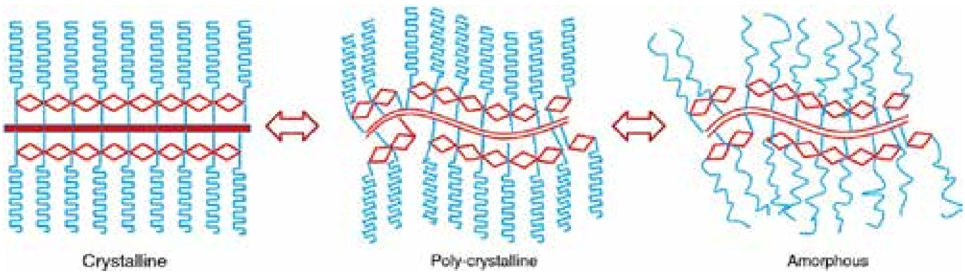
Figure 2. The schematic representation of phase change process in solid-liquid PCMs (SL-PCMs)



(Reddy et al. 2024)

In the realm of phase transitions, solid-liquid transformations entail a higher enthalpy of phase change compared to solid-solid transitions. This signifies that more energy is absorbed or released during the shift from solid to liquid state than between different solid phases. Notably, these transitions are reversible in nature, contingent upon ambient temperature fluctuations. Whether it's the transition between solid phases or the conversion from solid to liquid, the process hinges on the prevailing environmental conditions. Figure 3provides a visual depiction of this phenomenon, illustrating the transition from one solid phase to another.

Figure 3. The schematic representation of solid-solid phase change transitions crystalline-poly crystalline-amorphous transitions in polymeric solid-solid phase change materials



(Raj et al. 2020)

2.4 Key Properties of PCMs

Key properties of Phase Change Materials (PCMs) are essential for determining their suitability in various applications. These properties include latent heat storage capacity, indicating the amount of energy absorbed or released during phase transitions. Melting and freezing points determine the operational temperature range, while thermal conductivity influences heat transfer rates. Density affects system volume and mass requirements, while stability and compatibility ensure long-term performance and reliability. Cost considerations and environmental impacts, such as toxicity and sustainability, also play crucial roles in PCM selection. Understanding these properties is vital for optimising PCM performance in thermal energy storage systems, building construction, and other applications. Table 2 provides a concise overview of the key properties of PCMs, their descriptions, and their importance or considerations for practical applications.

Table 2. Properties of Phase Change Materials (PCMs) and Their Importance

Property	Description	Importance/Considerations	Example
Latent Heat Storage Capacity	Amount of energy absorbed or released during phase transitions	Higher values indicate greater energy storage capability	Paraffin wax (200 J/g)
Melting and Freezing Points	Temperature range at which phase transitions occur	Matching operational temperatures enhances efficiency	28°C - 32°C
Thermal Conductivity	Ability to conduct heat	Higher conductivity facilitates faster heat transfer	0.5 - 2 W/mK

continued on following page

Table 2. Continued

Property	Description	Importance/Considerations	Example
Density	Mass per unit volume	Influences system volume and mass requirements	800 - 1000 kg/m^3
Stability and Durability	Resistance to degradation and thermal cycling stability	Essential for long-term performance and reliability	No degradation after 1000 cycles
Compatibility	Suitability with other system components	Prevents leakage and material degradation	Compatible with polymer coatings
Cost	Economic feasibility	Balancing cost with performance and longevity	$2 - $5 per kg
Environmental Impact	Toxicity, biodegradability, sustainability	Consideration for environmentally conscious applications	Biodegradable and non-toxic

3. APPLICATIONS OF PHASE CHANGE MATERIALS IN BUILDINGS

Phase Change Materials (PCMs) find diverse applications in buildings, notably in enhancing thermal comfort and energy efficiency. They are incorporated in building envelopes, such as walls and roofs, to regulate indoor temperatures by absorbing and releasing heat during phase transitions. PCMs can reduce peak loads on heating and cooling systems, leading to lower energy consumption and operational costs. In warmer climates, they help maintain cooler indoor temperatures during the day by storing heat and releasing it at night. Conversely, in colder climates, they retain heat accumulated during the day and release it when temperatures drop, improving overall thermal performance and occupant comfort.

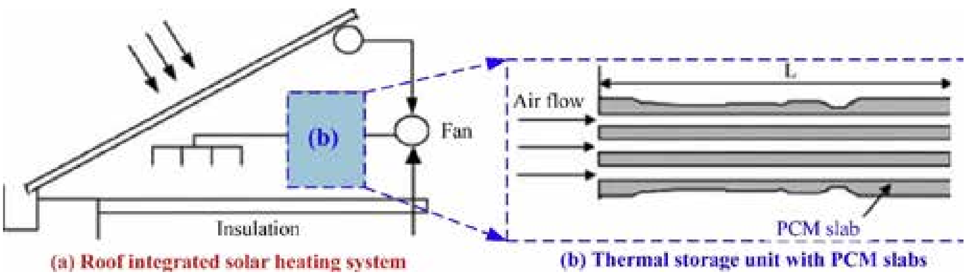
3.1 Thermal Regulation and Energy Efficiency

Phase Change Materials (PCMs) play a pivotal role in thermal regulation and enhancing energy efficiency in buildings. By leveraging their ability to store and release large amounts of heat during phase transitions, PCMs effectively mitigate temperature fluctuations within buildings. During periods of excess heat, such as sunny days, PCMs absorb thermal energy, preventing overheating of indoor spaces. Conversely, during colder periods, PCMs release stored heat, helping to maintain comfortable indoor temperatures. This process reduces reliance on traditional heating and cooling systems, leading to significant energy savings and lower utility costs.

Ultimately, integrating PCMs into building designs contributes to sustainable and environmentally friendly practices, promoting energy-efficient structures.

Saman et al. (2005) introduced a roof integrated solar heating system, featuring PCM slabs as its thermal energy storage (TES) unit, depicted in Fig. 4. The study observed that the effects of sensible heat led to a notable rise in outlet air temperature during the initial stages of melting, followed by a rapid decline during freezing. This resulted in a substantial warming effect during the initial air delivery for heating purposes, thereby enhancing indoor thermal comfort. Clearly, this offers an advantageous scenario from the perspective of maintaining comfortable indoor temperatures.

Figure 4. Roof integrated solar heating system and TES unit

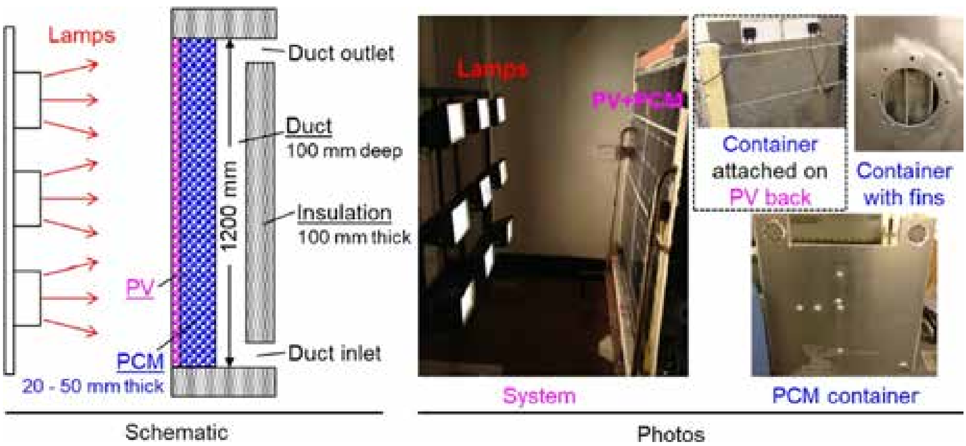


(Saman et al. 2005)

Phase Change Materials (PCMs) play a crucial role in enhancing thermal regulation and energy efficiency in buildings, as evidenced by various studies. Pasupathy et al. (2008) highlighted PCM-based building architecture's efficacy in managing thermal fluctuations in residential and commercial establishments, emphasizing PCM's potential in reducing energy consumption. Similarly, Zhou et al. (2012) provided a comprehensive review, underscoring PCM's versatility and effectiveness in building applications for thermal energy storage. Ma et al. (2015) focussed on PCM integration in photovoltaic systems, showcasing its dual benefits in thermal regulation and electrical efficiency improvement. Additionally, Yuan et al. (2020) and Wang et al. (2022) discussed advancements in PCM engineering and critical aspects for sustainable building design, respectively. Song et al. (2018) and Frigione et al. (2019) further emphasized PCM's role in enhancing building energy performance and efficiency through their comprehensive reviews. Overall, these references collectively emphasize PCM's significant contributions to sustainable and energy-efficient building practices, advocating for its widespread adoption in the construction industry.

In laboratory conditions, a PVT-PCM solar panel (Fig. 5) was tested by Gan & Xiang (2020), featuring ducting and a PCM layer as part of its specific design. Air served as the primary coolant, with PLUSICE S25 chosen as the PCM material. Various PCM layer thicknesses (20 mm, 30 mm, and 50 mm) were explored, along with fins to enhance heat transfer. The system prioritized high thermal conductivity, utilising thermal grease, albeit potentially raising costs. A rectangular air duct behind the PCM layer ensured adequate air circulation, while Celotex insulation provided thermal insulation. Experimentation revealed a potential 10% improvement in PV electrical performance, with optimal PCM layer capacities between 20 mm and 50 mm at a 25°C melting temperature.

Figure 5. Schematic of PVT-PCM panel and experimental setup



(Gan & Xiang (2020)

3.2 HVAC Systems and Thermal Energy Storage

Phase Change Materials (PCMs) play a crucial role in enhancing energy efficiency and thermal regulation in buildings, particularly in HVAC systems and thermal energy storage. They offer a sustainable solution by storing and releasing thermal energy during phase transitions, effectively mitigating temperature fluctuations. PCMs integrated into building envelopes, insulation, or HVAC systems help reduce peak energy demand, optimise thermal comfort, and enhance overall building performance. Through PCM-based thermal energy storage, excess energy can be stored during off-peak periods and utilised during peak demand, promoting energy conservation and reducing reliance on conventional heating and cooling systems.

Phase Change Materials (PCMs) offer significant advantages in HVAC systems and thermal energy storage applications, as highlighted by recent studies. De Gracia & Cabeza (2015) emphasized their role in enhancing building energy efficiency, particularly in passive cooling and heating. Bourne & Novoselac (2016) discussed improved performance of tube-encapsulated PCM thermal energy stores, essential for HVAC systems. Tan et al. (2020) conducted a techno-economic evaluation of PCM-based cold storage in office buildings, demonstrating their feasibility and cost-effectiveness. Nie et al. (2020) and Muzhanje et al. (2022) explored performance enhancements and applications of PCM-based thermal energy storage in air conditioning. Said and Hassan (2019) analysed PCM incorporation into air conditioning condensers, showcasing improved unit performance. Additionally, Selvnes et al. (2021) and Yun et al. (2019) discussed PCM applications in refrigeration systems and floor heating for efficient thermal energy storage, respectively. These studies collectively underscore the versatile and promising role of PCMs in HVAC systems and thermal energy management.

To activate a building thermally, a liquid (typically water) functions as the heat transfer medium, circulating through a network of pipes integrated into the ceiling, roof, walls, floors, or various combinations thereof within the building structure. Groundwater or absorption/compression chillers serve as natural or artificial cold sources for cooling purposes. Figure 11 illustrates the distinctions between buildings equipped with conventional HVAC systems and those incorporating Thermally Activated Building Systems (TABS) with PCM in their structural partitions. It showcases how TABS with PCM can effectively mitigate indoor temperature fluctuations, ensuring consistent thermal comfort throughout the day when optimally installed.

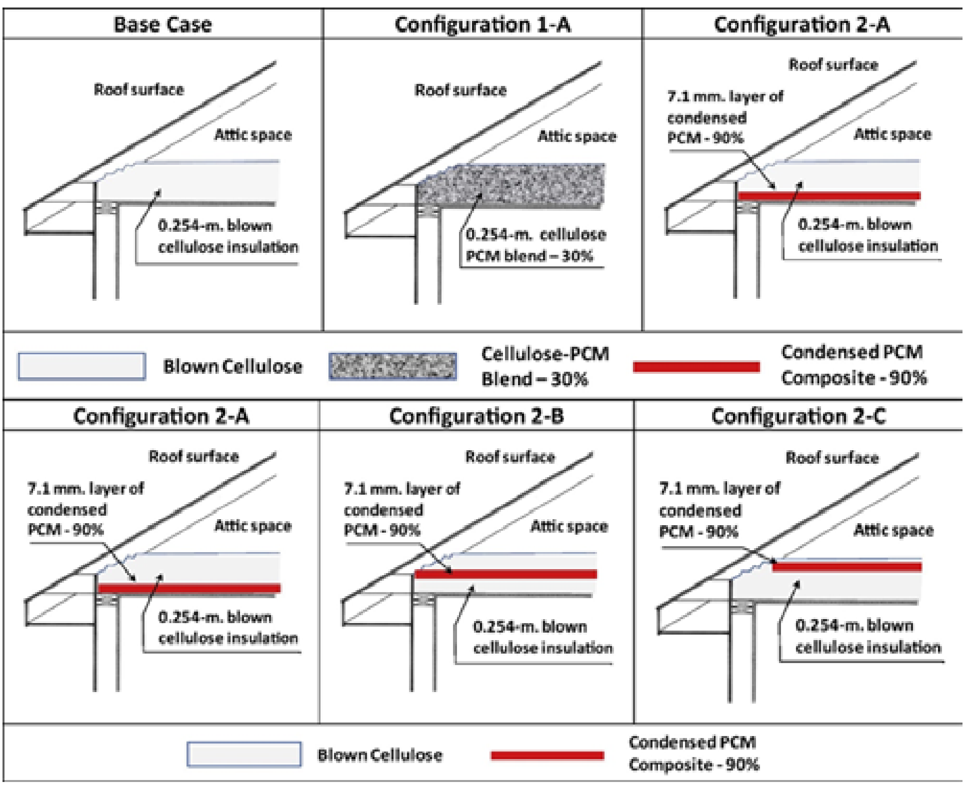
Figure 6. Schematic showing the difference between (a) conventional HVAC cooled office and (b) an office integrated with TABS and PCM (Faraj et al. 2020)

3.3 Passive Building Design and PCM Integration

Passive Building Design leverages natural elements to minimise energy consumption, emphasizing insulation, orientation, and ventilation. By strategically placing windows for solar gain and employing thermal mass materials, buildings regulate internal temperatures passively. Integrating Phase Change Materials (PCM) enhances this approach. PCM stores and releases heat during phase transitions, stabilizing indoor temperatures. In summer, PCM absorbs excess heat, reducing reliance on air conditioning, while in winter, it releases stored heat, cutting heating needs. This synergy between Passive Building Design and PCM integration not only reduces energy consumption but also ensures comfortable indoor environments, fostering sustainability and efficiency in construction.

Kośny et al. (2014) explored passive cooling potential by integrating PCM-enhanced insulation into residential attics in Phoenix, Arizona. They utilised two PCM types: a 30% PCM blend with fibre insulation and a 90% PCM blend with plastic composite, both with a melting point of 26.5°C. Through ESP-r simulations (depicted in Fig. 7), various scenarios were examined. Results indicated that concentrated PCM in attic insulation yielded lower cooling loads compared to PCM-enhanced cellulose. Configurations 2-A and 2-B demonstrated superior cooling energy savings (6.8% and 6.6%) compared to dispersed PCM (Configuration 1-A, 3.1%). The study suggests optimal PCM integration strategies, favouring PCM placement at the bottom or middle of attic floor insulation.

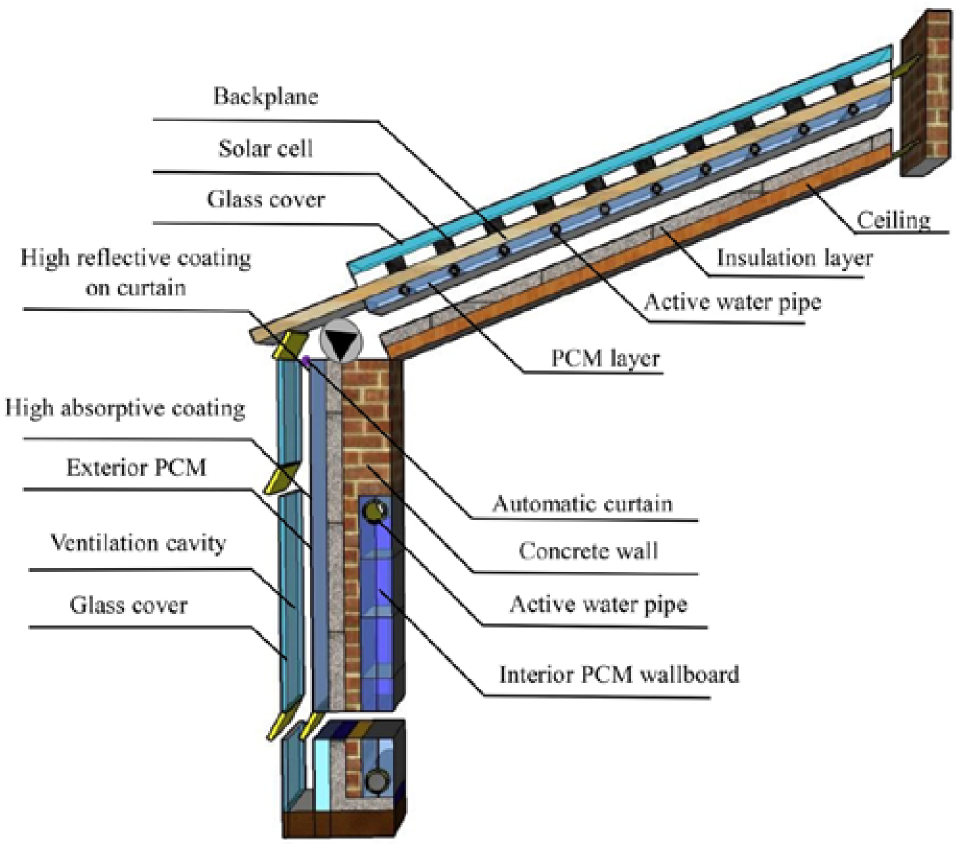
Figure 7. Different scenarios of PCM-enhanced cellulose insulation & concentrated PCM into attic envelope



(Kośny et al. 2014)

Zhou et al. (2019) introduced a novel renewable system integrating phase change materials (PCMs) for cooling and heating, depicted in Fig. 8. The system operates based on weather conditions, toggling between natural or mechanical ventilation for solar cell heat dissipation. Additionally, an active cooling water system enhances PV cell cooling. Six ventilation vents, along with active devices, are flexibly controlled. This intelligent design combines passive and active modes, leveraging their respective advantages while mitigating disadvantages. Smart control strategies optimise renewable utilisation, PCM storage efficiency, and reduce energy consumption. Challenges include heat accumulation in PCMs, control signal transitions, and enhancing daytime radiative cooling capacity.

Figure 8. One example of the integrated system with combined passive and active designs



(Zhou et al. 2020)

Integration of Phase Change Materials (PCM) in passive building design offers a sustainable solution for thermal control, as evident from various studies. Akeiber et al. (2016) discussed PCM's role in passive cooling, emphasizing its potential in building envelopes. PCM's ability to absorb and release thermal energy enables temperature regulation, reducing the need for active cooling systems and enhancing energy efficiency. Kenisarin & Mahkamov (2016) highlight PCM's application in residential buildings for passive thermal control. By incorporating PCM into building materials, such as walls or ceilings, they demonstrate effective temperature stabilization, improving indoor comfort without relying heavily on mechanical cooling. Alam et al. (2017) compared different passive and free cooling methods using PCM in residential buildings. Their study evaluates PCM's effectiveness in reducing peak temperatures and energy consumption, providing valuable insights for sustainable building design.

Saffari et al. (2017) reviewed the integration of PCM in passive cooling strategies using whole-building energy simulation tools. They emphasize the importance of accurate modelling for assessing PCM's impact on energy performance and comfort conditions. Lizana et al. (2019) critically analysed implementation alternatives for passive cooling through PCM in buildings. They discuss various factors influencing PCM effectiveness and propose strategies for optimising its integration in building design. Stritih et al. (2018) explored the integration of passive PCM technologies for net-zero energy buildings. Their study underscores PCM's role in achieving energy efficiency targets by reducing heating and cooling loads, contributing to sustainable building practices. Younsi & Naji (2020) conducted numerical simulations to evaluate the thermal performance of hybrid brick walls embedded with PCM. Their findings demonstrate the potential of PCM-enhanced building components in passive applications, offering effective thermal regulation and energy savings.

Carlucci et al. (2021) modelled the benefits of active and passive PCM integration in building envelopes across different building types and climates. Their study highlights the versatility of PCM in adapting to diverse environmental conditions and optimising energy usage. Obergfell et al. (2021) assessed the long-term functionality of passive PCM building applications. Their investigation reveals the durability and reliability of PCM systems over more than a decade of operation, affirming their suitability for sustainable building design. Overall, these studies collectively underscore PCM's significance in passive building design, offering an effective and sustainable solution for thermal energy management and enhancing building performance.

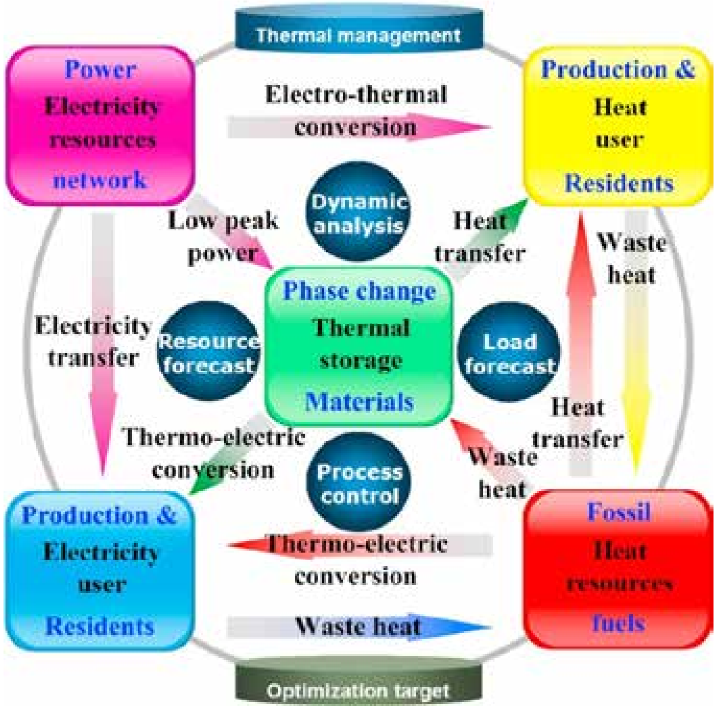
3.4 Heat Recovery and PCM Applications

Phase Change Materials (PCMs) play a pivotal role in enhancing heat recovery systems. By capturing and storing excess heat during peak periods, PCMs offer a means of thermal energy storage. When integrated into heat recovery systems, PCMs efficiently store surplus heat for later use, minimising energy wastage and maximising system efficiency. During off-peak hours or when demand rises, PCMs release stored heat, supplementing heating requirements. This application of PCMs facilitates a more sustainable and economical approach to heat recovery, contributing to reduced energy consumption and environmental impact in various industrial and residential settings.

Phase Change Materials (PCMs) are increasingly applied in building heat recovery systems to enhance energy efficiency. Studies by Jelle and Kalnæs (2017) and Kalnaes & Jelle (2015) highlighted their effectiveness in regulating indoor temperatures by storing and releasing thermal energy. Xu et al. (2019) discussed various heat recovery technologies for buildings, emphasizing PCM integration's potential. Du et al. (2018) reviewed PCM applications in cooling, heating, and power generation across temperature ranges, showcasing their versatility. De Gracia & Cabeza (2015) further underlined PCM's role in thermal energy storage for buildings. Alazwari et al. (2021) demonstrated PCM's efficacy in reducing energy demand in air handling units, particularly in high solar-irradiance regions.

The industrial waste heat recovery system utilising Phase Change Material (PCM) thermal storage operates by dynamically managing thermal energy. As outlined by Li et al. (2019), the system absorbs excess heat generated during industrial processes using PCM (Fig. 9). During periods of low demand or when the process generates excessive heat, PCM stores this thermal energy efficiently. Subsequently, during peak demand or when the process requires additional heat, PCM releases stored energy, supplementing heating requirements. This dynamic operation ensures optimal utilisation of waste heat, enhancing overall energy efficiency and reducing environmental impact in industrial settings.

Figure 9. Operation principle of industrial waste heat recovery system based on PCM thermal storage



(Li et al. 2019)

4. TYPES OF PHASE CHANGE MATERIALS AND THEIR SELECTION

Phase Change Materials (PCMs) come in various types, each suited to specific applications. Organic PCMs like paraffin offer high latent heat storage and low cost, ideal for building applications. Inorganic PCMs like salt hydrates possess excellent thermal conductivity, suitable for industrial processes. Bio-based PCMs provide sustainable alternatives derived from renewable sources. Selection depends on factors such as operating temperature, thermal conductivity, and compatibility with the application. PCM encapsulation, such as microencapsulation or macroencapsulation, further influences selection, affecting durability and handling. Understanding these distinctions ensures optimal PCM choice for efficient heat storage and release in diverse contexts, from buildings to industrial processes.

4.1 Organic PCMs

Organic Phase Change Materials (PCMs) represent a versatile and promising category of materials that find wide-ranging applications in thermal energy storage and management systems. Unlike their inorganic counterparts, organic PCMs are derived from organic compounds, offering unique advantages such as tunable phase transition temperatures, high latent heat storage capacities, and compatibility with various building materials. One of the primary advantages of organic PCMs is their ability to undergo phase transitions at temperatures suitable for building applications, typically ranging from room temperature to around 100°C. This enables their integration into building envelopes, HVAC systems, and other thermal energy storage solutions to effectively manage indoor temperatures and reduce energy consumption.

Additionally, organic PCMs often exhibit excellent thermal stability, ensuring long-term reliability and performance in diverse operating conditions. Their chemical composition can be tailored to meet specific requirements, such as thermal cycling stability, compatibility with other materials, and environmental sustainability. Furthermore, organic PCMs offer advantages in terms of safety and environmental impact. Many organic compounds used as PCMs are non-toxic, biodegradable, and derived from renewable sources, making them environmentally friendly alternatives to traditional thermal energy storage materials.

In building applications, organic PCMs can be incorporated into various forms, including encapsulated microcapsules, dispersed within matrices, or even directly applied as coatings. This flexibility allows for seamless integration into construction materials such as plaster, concrete, insulation, and even textiles, offering tailored solutions for specific building requirements. Research in the field of organic PCM continues to advance, with ongoing efforts focused on developing novel materials with enhanced properties, improving manufacturing techniques, and optimising integration strategies. As the demand for energy-efficient and sustainable building solutions grows, organic PCMs are expected to play an increasingly important role in meeting these challenges and shaping the future of building design and construction.

4.2 Inorganic PCMs

Inorganic Phase Change Materials (PCMs) represent a crucial class of materials utilised for thermal energy storage and management in various applications, particularly within the built environment. Unlike organic PCMs, which are derived from organic compounds, inorganic PCMs are typically composed of salts, metals, or other inorganic substances. One of the key advantages of inorganic PCMs is their high thermal conductivity and stability, making them suitable for applications requiring rapid heat transfer and repeated phase transitions. Additionally, inorganic

PCMs often exhibit high latent heat storage capacities, enabling them to store and release large amounts of thermal energy during phase transitions.

Inorganic PCMs are commonly used in applications where high-temperature stability and durability are essential, such as solar thermal energy storage systems, building insulation, and thermal energy storage tanks. Their robust nature allows them to withstand harsh operating conditions and extended service lifetimes. Moreover, inorganic PCMs offer advantages in terms of cost-effectiveness and availability, as many of the materials used are abundant and relatively inexpensive. This makes them attractive options for large-scale energy storage systems and commercial building applications.

In building construction, inorganic PCMs can be integrated into various components, including walls, ceilings, and floors, to regulate indoor temperatures, reduce energy consumption, and enhance thermal comfort. They can be incorporated into construction materials such as concrete, plaster, and insulation to create energy-efficient and sustainable building envelopes. Despite their numerous advantages, inorganic PCMs also pose some challenges, including potential corrosion issues, phase separation during cycling, and limited phase change temperatures compared to organic PCMs. However, ongoing research and development efforts are focused on addressing these challenges and optimising the performance of inorganic PCM-based systems.

4.3 Eutectic Mixes

Eutectic mixes, also known as eutectic alloys or eutectic systems, are a type of Phase Change Materials (PCMs) that exhibit a unique phenomenon called eutectic behaviour. In eutectic mixes, two or more components are combined in specific proportions to form a mixt with a lower melting point than any of the individual components alone. This results in a sharp and well-defined melting point, making eutectic mixes highly desirable for thermal energy storage applications. One of the key advantages of eutectic mixes is their precise and predictable melting behaviour, which allows for accurate control over the release and absorption of thermal energy. This makes them particularly suitable for applications requiring precise temperature regulation, such as in building HVAC systems, solar thermal storage, and thermal comfort solutions. Eutectic mixes can be composed of various combinations of metals, salts, or other substances, depending on the desired melting temperature and specific application requirements. Common examples include mixes of salts like potassium nitrate and sodium nitrate, as well as metal alloys such as bismuth-tin and lead-tin.

In building applications, eutectic mixes can be integrated into construction materials such as plaster, concrete, or insulation to provide thermal energy storage capabilities. They can also be incorporated into thermal storage tanks or containers for use in solar thermal systems or district heating and cooling networks. Additionally, eutectic mixes offer advantages such as high thermal conductivity, which facilitates efficient heat transfer during the phase change process. They are also often cost-effective and readily available, making them attractive options for large-scale energy storage systems and commercial building applications.

4.4 Bio-based PCMs

Bio-based phase change materials (PCMs) are a promising innovation in materials science, offering a sustainable alternative to conventional PCMs derived from fossil fuels. These materials undergo a phase transition between solid and liquid states at specific temperatures, efficiently storing and releasing thermal energy in the process. Bio-based PCMs are sourced from renewable biomass such as plant oils, fatty acids, carbohydrates, and proteins.

These materials offer several advantages over their petroleum-based counterparts. Firstly, they are derived from renewable feedstocks, reducing dependence on finite fossil fuel resources. Additionally, many bio-based PCMs are biodegradable, providing environmentally friendly end-of-life solutions. They also exhibit low toxicity, making them safer for handling and disposal. As production processes mature and scale up, bio-based PCMs have the potential to become cost-competitive with conventional PCMs. Furthermore, their thermal properties can be tailored through modifications in feedstock composition and processing techniques. Common sources for bio-based PCMs include fatty acids like palm oil, soybean oil, and coconut oil. These oils undergo chemical modifications or encapsulation processes to enhance their thermal properties and stability. Bio-based polymers and carbohydrates, such as starch and cellulose derivatives, also show promise as PCM materials.

Applications of bio-based PCMs span various industries. They can be incorporated into building materials to enable passive thermal regulation, reducing the need for active heating and cooling systems. In textiles, bio-based PCMs can create temperature-regulating clothing for comfort in diverse environments. They can also be used in thermal management systems for electronic devices and in automotive applications to regulate battery temperature in electric vehicles. Research and development in bio-based PCMs continue to advance, focusing on improving thermal performance, scalability, and cost-effectiveness. As society seeks sustainable solutions, bio-based phase change materials offer a promising avenue for enhancing energy efficiency and reducing environmental impact across diverse industries.

4.5 Selection Criteria for PCMs in Building Applications

Selecting the appropriate Phase Change Material (PCM) for building applications necessitates careful consideration of several key criteria. Firstly, the PCM's melting temperature should align with the building's climate and intended thermal performance. Compatibility with the construction materials and integration methods is crucial for effective implementation. PCM's latent heat capacity, thermal conductivity, and stability over repeated cycles are vital for sustained performance. Additionally, factors such as cost-effectiveness, environmental impact, and availability should be evaluated. Balancing these criteria ensures optimal PCM selection, facilitating efficient thermal management, energy conservation, and comfort enhancement in buildings while meeting specific project requirements and sustainability goals. Table 3 provides a structured overview of the selection criteria, their descriptions, importance levels, and examples to guide PCM selection in building applications.

Table 3. Selection Criteria for Phase Change Materials (PCMs) in Building Applications

Criteria	Description	Importance	Examples
Melting Temperature	PCM's melting point should match building's climate for efficacy	High	18°C for cooling, 24°C for heating
Compatibility	PCM should integrate well with building materials and methods	High	Compatible with concrete, gypsum, insulation, etc.
Thermal Properties	Consider latent heat capacity and thermal conductivity	High	Latent heat: 150 kJ/kg, Thermal conductivity: 0.5 W/mK
Stability and Reliability	PCM should remain stable over repeated thermal cycles	Medium-High	No phase separation, degradation over time
Cost-effectiveness	Assess total cost including procurement, installation, & maintenance	Medium-High	$10/kg upfront, but saves $X/year in energy costs
Environmental Impact	Prefer eco-friendly options to minimise environmental impact	Medium	Bio-based PCM, non-toxic formulations
Availability	Consider availability and accessibility from reliable suppliers	Medium	Widely available from reputable manufacturers

5. ENHANCING THE PERFORMANCE OF PHASE CHANGE MATERIALS

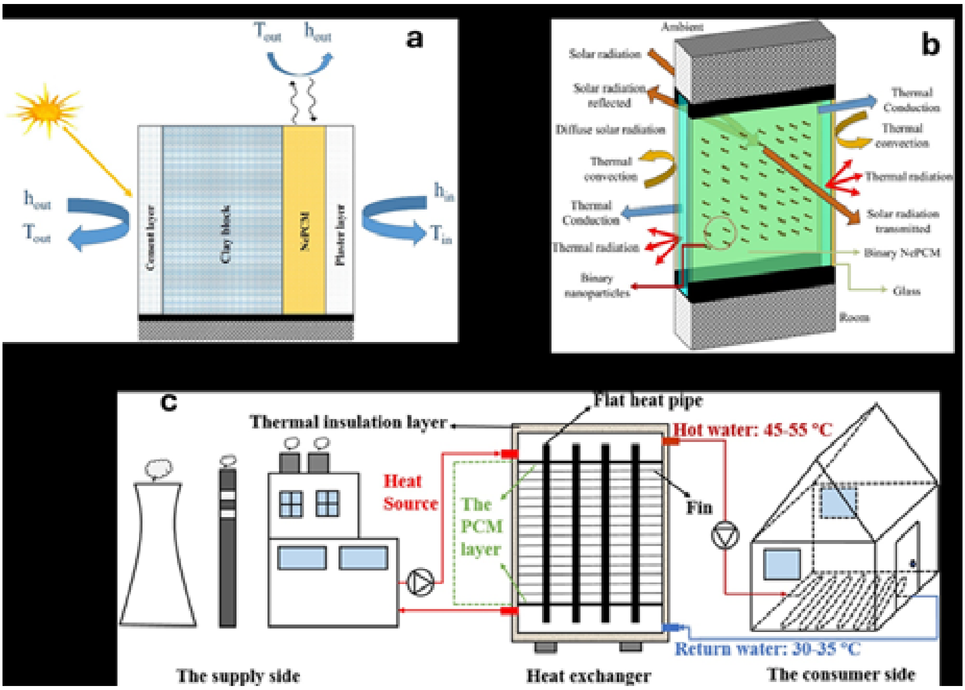
Enhancing the performance of Phase Change Materials (PCMs) in buildings involves various strategies to optimise their thermal storage and release capabilities. Firstly, selecting PCMs with suitable melting temperatures and high latent heat capacities ensures efficient energy absorption and release. Secondly, improving PCM dispersion within building components enhances heat transfer rates and overall effectiveness. Additionally, integrating PCM with passive and active cooling or heating systems maximises energy efficiency. Employing advanced encapsulation techniques and incorporating PCM into innovative building designs further enhances performance. Moreover, continuous research and development efforts focus on enhancing PCM stability, durability, and environmental sustainability, ensuring their reliable and long-term contribution to building energy efficiency and thermal comfort.

5.1 Nano-Enhanced PCMs

Nano-enhanced phase change materials (NEPCMs) integrate nanoparticles into phase change material (PCM) matrices, enhancing thermal properties. Nanoparticles offer superior thermal conductivity and high surface area-to-volume ratios, facilitating efficient heat transfer, vital for faster charging and discharging in thermal cycling. NEPCMs augment latent heat storage, ideal for high energy density applications. Tuning phase change temperatures is possible by adjusting nanoparticle composition and concentration, catering to specific needs. NEPCMs find utility in diverse sectors like building materials, solar energy storage, electronics cooling, and thermoregulatory textiles. Despite challenges like dispersion and stability, ongoing research ensures NEPCMs' potential to revolutionize energy storage with sustainable and efficient solutions.

Nano-enhanced phase change materials (NEPCMs) enhance building energy management and are commonly integrated into walls, glass, roofs, and other structural components. Research indicates that NEPCMs enhance building energy storage by reducing energy consumption, cooling to lower temperatures, minimising temperature fluctuations, and ensuring internal thermal stability (Keshteli & Sheikholeslami, 2019). Figure 10 illustrates the utilisation of NEPCMs in these building elements.

Figure 10. Application of NEPCMs in buildings: (a) wall; (b) glass windows; (c) radiant floor heating system



(a) (Sarrafha et al. 2021); (b) (Ma et al. 2021); (c) (Fang et al. 2020)

Leong et al. (2019) provided a comprehensive review of NEPCMs, emphasizing their thermo-physical properties and diverse applications. This foundational review underscores the potential benefits of NEPCMs in building systems, including reduced energy consumption and improved thermal stability. Xiong et al. (2020) focussed on numerical simulations to analyse the behaviour of NEPCMs under various conditions. Their study contributes valuable insights into the computational modelling of NEPCMs, aiding in the optimisation of building designs and energy management strategies. Ma et al. (2016) delved into the practical implications of NEPCMs in buildings, emphasizing their role in enhancing building performance. By discussing real-world applications and case studies, they highlight the potential of NEPCMs to contribute to energy savings and indoor comfort improvements.

Martin et al. (2019) and Barreneche et al. (2019) provided experimental insights into the development and characterization of NEPCMs at the lab scale. These studies offer valuable data on the performance of NEPCMs under controlled conditions, laying the groundwork for further research and practical implementation in buildings. Tunçbilek et al. (2022) investigated the impact of NEPCMs on building envelope thermal performance and energy consumption. Their findings underscore the potential of NEPCMs to enhance building energy efficiency and mitigate thermal losses, particularly in regions with extreme climates.

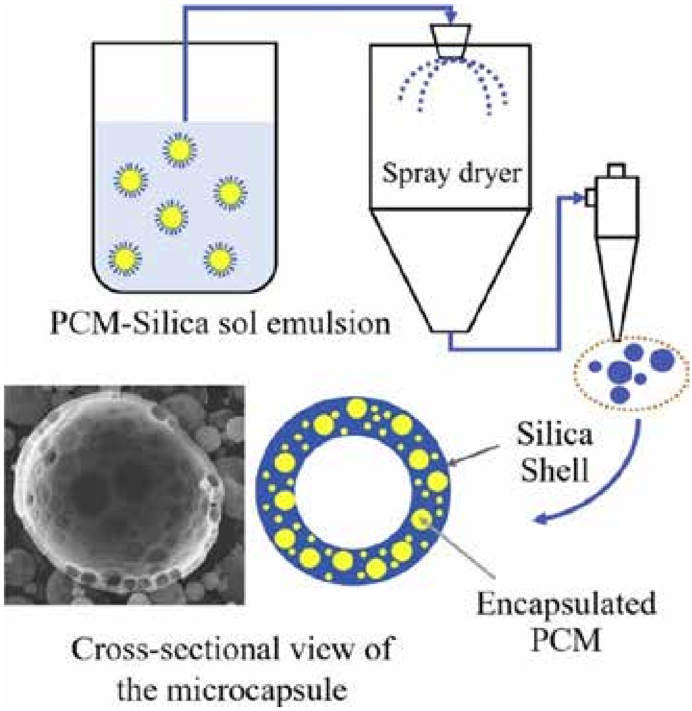
While the cited references collectively demonstrate the promise of NEPCMs in improving building energy efficiency and thermal performance, several challenges and considerations warrant attention. These include issues related to nanoparticle dispersion, long-term stability, cost-effectiveness, and scalability of production methods. Additionally, the practical implementation of NEPCMs in building systems requires careful consideration of factors such as material compatibility, installation requirements, and regulatory considerations. Moreover, gaps in knowledge exist regarding the long-term performance and environmental impacts of NEPCMs, underscoring the need for further research and development. Addressing these challenges will be crucial in realizing the full potential of NEPCMs to contribute to sustainable building practices and mitigate the environmental impact of energy consumption in the built environment.

5.2 Microencapsulation Techniques

Microencapsulation techniques offer a versatile approach to incorporating phase change materials (PCMs) into building materials, enhancing their thermal performance and energy efficiency. In the context of buildings, microencapsulated PCMs (MPCMs) provide a means to regulate indoor temperatures, reduce energy consumption, and improve occupant comfort. Various microencapsulation methods are employed to encapsulate PCM within a protective shell, ensuring compatibility with building materials and enabling seamless integration into construction components.

1. **Spray Drying**: This technique involves atomizing a PCM solution or dispersion into fine droplets, which are then dried to form solid microcapsules as can be seen in Fig. 11. Spray drying offers scalability and versatility, making it suitable for large-scale production of MPCMs. The resulting microcapsules can be incorporated into building materials such as plaster, concrete, or coatings.

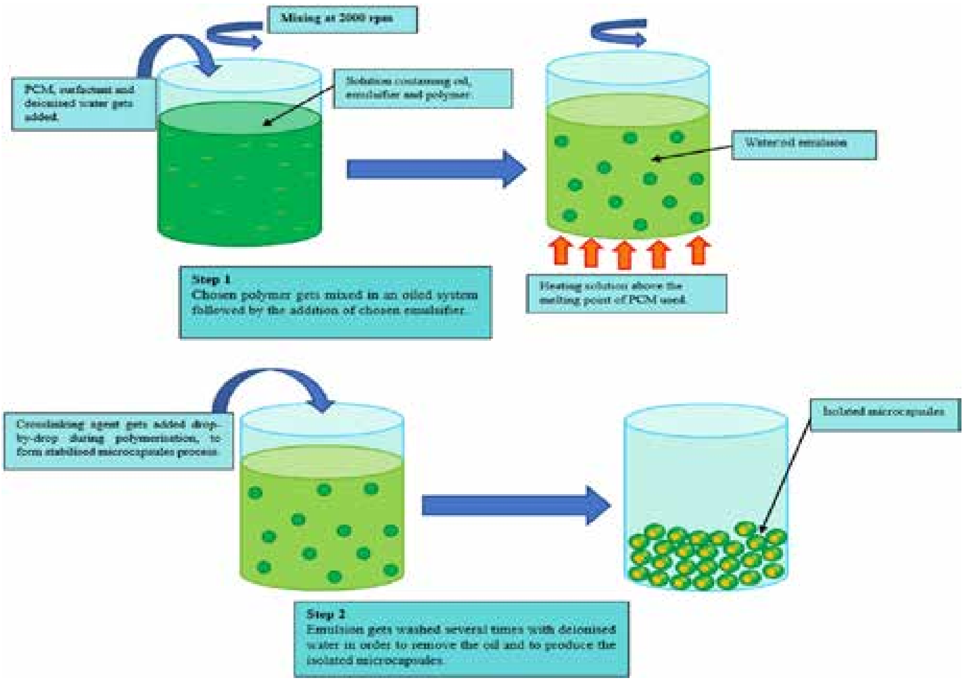
Figure 11. Spray dying process



(Methaapanon et al. 2020)

2. **Emulsion Polymerization**: In this method, PCM is emulsified within a polymer solution, followed by polymerization to form a solid shell around the PCM droplets (Fig 12). Emulsion polymerization allows for precise control over the size and morphology of the microcapsules, enabling tailored thermal properties and compatibility with building materials.

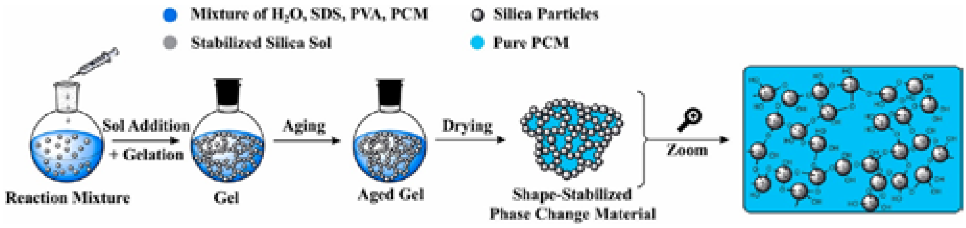
Figure 12. Basic steps involved in the emulsion polymerisation method



(Sivanathan et al. 2020)

3. **Sol-Gel Encapsulation**: Sol-gel encapsulation involves the hydrolysis and condensation of precursors to form a gel network around PCM droplets (Fig. 13). This method offers precise control over the composition and properties of the shell material, enabling customization for specific building applications. Sol-gel encapsulated MPCMs exhibit high thermal stability and compatibility with building materials.

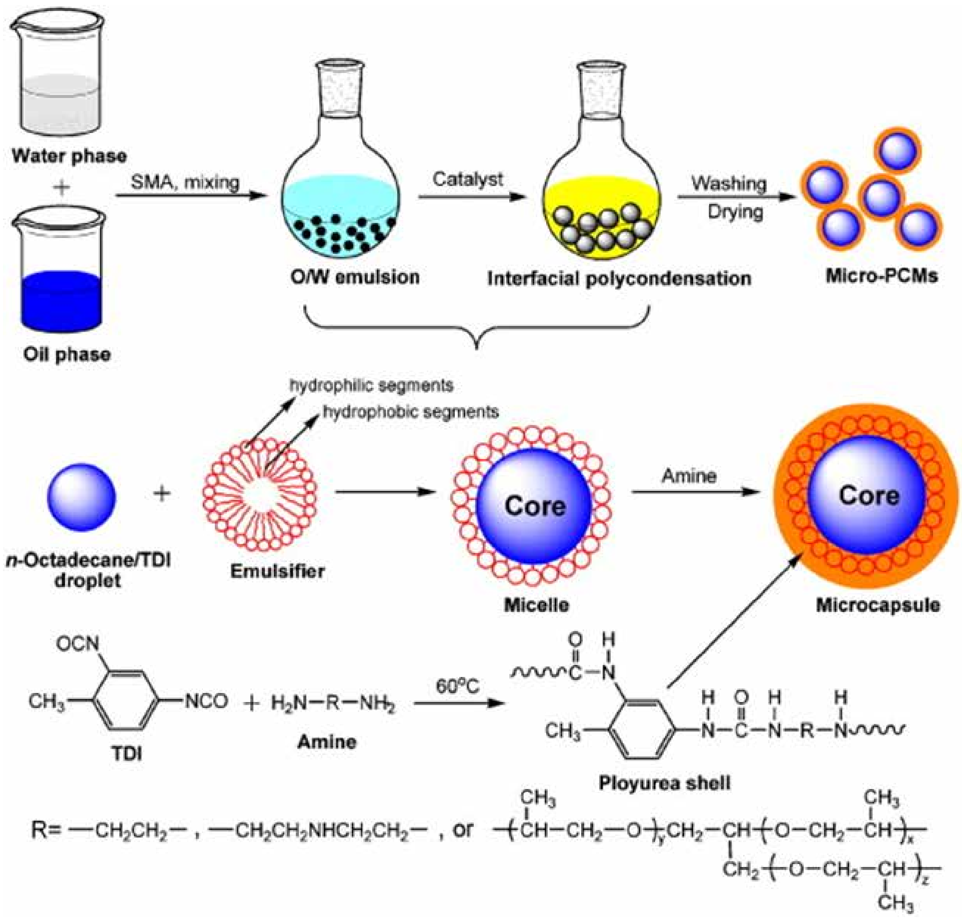
Figure 13. Schematic synthesis of shape-stabilized phase change materials (ss-PCMs) by sol-gel with water, sodium dodecyl sulphate (SDS), poly(vinyl alcohol) (PVA), phase change materials (PCMs) and silica sol



(Marske et al. 2022)

4. **Interfacial Polymerization**: Interfacial polymerization involves the reaction of monomers at the interface between two immiscible phases, typically aqueous and organic (Fig. 14). This results in the formation of a polymer shell around the PCM droplets. Interfacial polymerization offers high encapsulation efficiency and can be used to produce MPCMs with uniform particle size distributions.

Figure 14. Microcapsule manufactured by interfacial polycondensation



(Zhang & Wang, 2009)

5. **Coacervation**: Coacervation involves the phase separation of a polymer solution into a polymer-rich phase and a polymer-poor phase, with PCM dispersed in the former. The polymer-rich phase solidifies to form a shell around the PCM droplets. Coacervation is a versatile technique suitable for encapsulating a wide range of PCMs and can be adapted for incorporation into building materials.

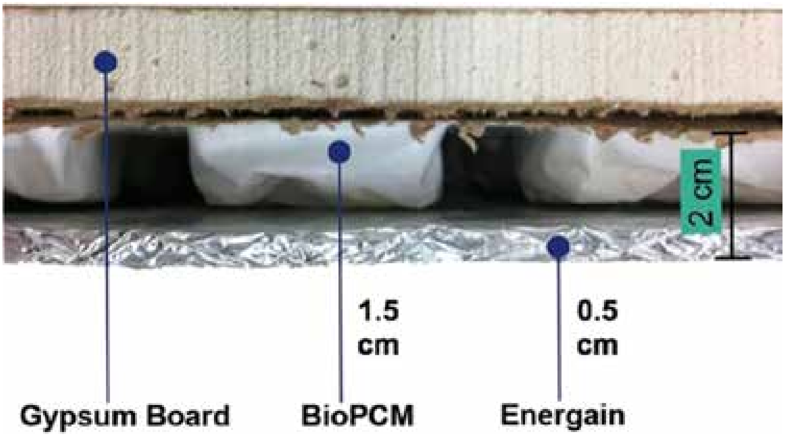
In buildings, MPCMs find applications in various components such as walls, ceilings, and floors to regulate indoor temperatures and reduce heating and cooling loads. By absorbing and releasing thermal energy during phase transitions, MPCMs help maintain comfortable indoor conditions while reducing reliance on mechanical heating and cooling systems. Additionally, the incorporation of MPCMs into building materials improves thermal inertia, reducing temperature fluctuations and enhancing energy efficiency.

5.3 Composite PCMs

Composite phase change materials (CPCMs) merge phase change materials (PCMs) with supporting matrices, offering diverse applications in energy storage, construction, and electronics cooling. These innovative materials combine the high thermal storage capacity of PCMs with the structural support and tailored properties of matrix materials. CPCMs can be macroscopic, with PCM particles dispersed within a solid matrix, or micro- and nanostructured, with PCM integrated at microscopic levels. The integration of high thermal conductivity additives like carbon nanotubes enhances overall thermal conductivity, enabling faster heat transfer during phase transitions. This property makes CPCMs valuable in thermal energy storage systems, building materials for temperature regulation, and electronics cooling. Additionally, CPCMs offer design flexibility, allowing engineers to customize properties such as thermal conductivity and melting point to suit specific applications. Challenges including cost-effectiveness, durability, and scalability remain, driving ongoing research to improve fabrication techniques and integration methods. Despite these challenges, CPCMs hold promise for enhancing energy efficiency, sustainability, and thermal comfort across various industries. Continued innovation and research are key to unlocking their full potential.

Berardi et al. (2019) investigated the impact of integrating a composite PCM wallboard on a test cell's thermal performance. The composite wallboard consisted mainly of two commercial PCMs with distinct melting temperatures (Fig. 15): BioPCM at 25°C and Energain PCM at 21.7°C. Installed between gypsum board and insulation, the composite PCM underwent testing from July to October in Toronto. Analysing cell orientation, shading, and night cooling effects, they recorded indoor air and wall surface temperatures. Results indicated a temperature peak reduction of up to 6°C with the composite PCM. Night ventilation facilitated PCM solidification and rapid discharge. This study supports the advantageous use of composite PCMs with varied melting temperatures in building envelopes.

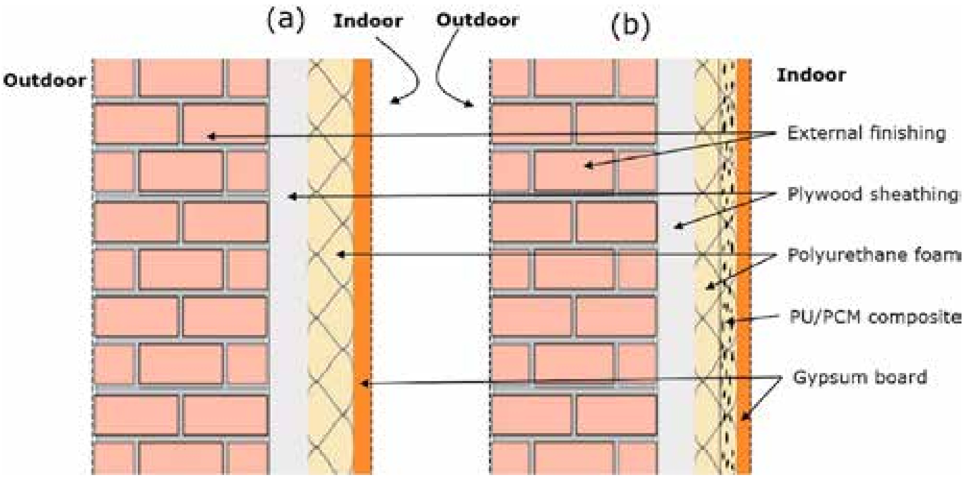
Figure 15. Composite PCM wall



(Berardi et al. 2019)

For optimal heat transfer management akin to PCM and PU foam synergy, incorporating a thin layer near the interior of building walls (Fig. 16) is recommended (Ikutegbe et al. 2020). This setup facilitates rapid PCM charging with excess indoor heat, releasing stored heat when indoor temperatures drop below PCM solidification levels. As depicted in Fig. 18, the PCM-free PU foam layer acts as a barrier, preventing heat flow between the building interior and exterior. This integration optimises energy efficiency, enhancing both thermal comfort and insulation effectiveness within the building structure.

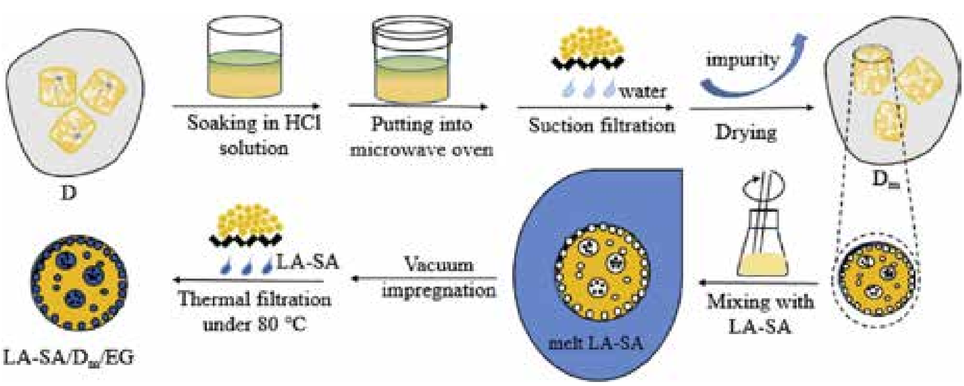
Figure 16. Sketch of building assembly (a) conventional wall, (b) wall with an additional PCM composite layer



(Ikutegbe et al. 2020)

Li et al. (2020) developed a composite PCM, detailed in Fig. 17. Initially, to enhance diatomite's loading capacity for PCM, raw diatomite underwent microwave-acid treatment. This involved mixing 16.0 g of diatomite with an 8% HCl solution (48.0 g) in a 500 ml beaker, irradiating at 700 W for 5 min in a microwave oven, washing with distilled water until chlorine ions were undetectable, followed by vacuum suction filtration and drying at 105 °C for 15 h, yielding the labelled sample, D_m. Experimental trials at various microwave powers and durations were conducted, with optimum efficacy observed at 700 W for 5 min.

Figure 17. Preparation schematic for the LA-SA/D_m composites PCMs



(Li et al. 2020)

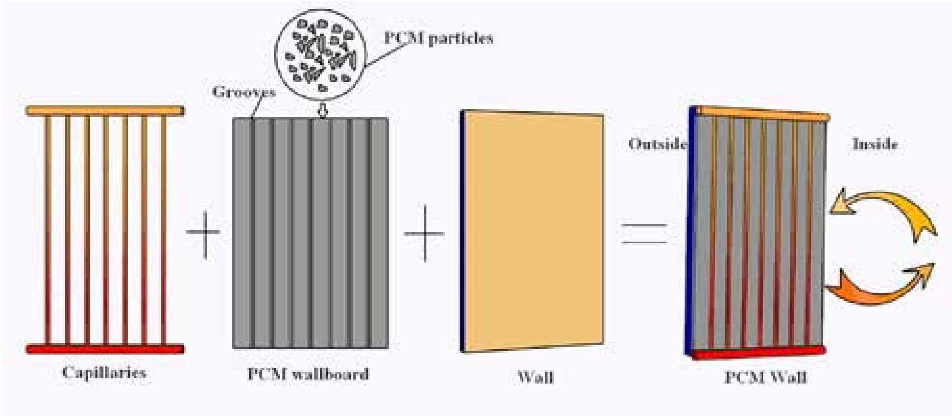
5.4 Hybrid PCMs

Hybrid phase change materials (HPCMs) represent an innovative class of materials that combine the advantageous properties of different PCM types or PCM with other functional materials. These hybrids aim to enhance the overall performance and applicability of PCM systems in various fields such as energy storage, thermal management, and building materials. One common approach in HPCMs involves combining two or more PCM types with complementary melting/freezing points. This allows for a broader operating temperature range and improved thermal energy storage capacity. For instance, combining paraffin-based PCMs with salt hydrates can create HPCMs with enhanced thermal properties suitable for different temperature requirements. Moreover, HPCMs can incorporate other functional materials such as nanoparticles, carbon-based materials, or polymers to enhance specific properties like thermal conductivity, stability, or mechanical strength. For example, the incorporation of graphene or carbon nanotubes into PCM matrices can significantly improve thermal conductivity, enabling faster heat transfer during the phase change process.

The applications of HPCMs are diverse, ranging from thermal energy storage in renewable energy systems to temperature regulation in textiles and electronics cooling. In building materials, HPCMs are utilised to improve energy efficiency by storing and releasing heat to maintain indoor thermal comfort. Despite their promising advantages, challenges such as cost-effectiveness, scalability, and long-term stability need to be addressed to facilitate widespread adoption of HPCMs. Continued research and development efforts are crucial to unlock the full potential of these hybrid materials in addressing the growing demand for efficient thermal management solutions.

Kong et al. (2020) presented a pioneering hybrid PCM wall design for winter heating, featuring a coupled solar thermal system and shape-stabilized PCM wallboard (Fig. 18). Two experimental cells (1.7 m × 1.7 m × 2 m) were constructed to validate its performance. Three experiments were conducted to assess indoor thermal comfort and energy consumption. Results demonstrated a substantial reduction (approximately 44%) in daily energy usage compared to conventional buildings lacking PCM integration. Despite promising findings, further techno-economic analysis is imperative to gauge its broader feasibility and economic viability.

Figure 18. Hybrid PCM wall



(Kong et al. 2020)

6. INTEGRATION AND DESIGN CONSIDERATIONS FOR PCM IN BUILDINGS

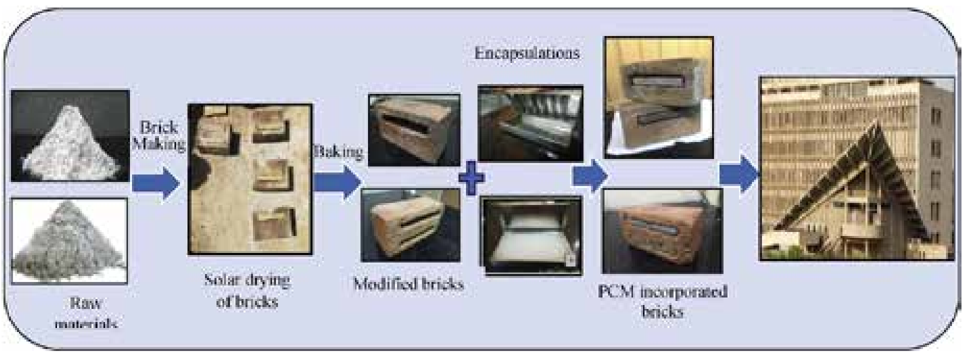
Integration and design considerations for Phase Change Materials (PCM) in buildings are pivotal for optimising thermal performance. Efficient integration involves careful placement of PCM within building envelopes, considering factors such as insulation, construction materials, and airflow. Design considerations encompass selecting PCM types tailored to specific climate conditions, ensuring compatibility with existing HVAC systems, and addressing structural implications. Moreover, incorporating PCM into building design necessitates meticulous attention to detail, including proper sealing, encapsulation, and maintenance procedures. By seamlessly integrating PCM into building design and addressing associated considerations, such as heat transfer mechanisms and thermal mass distribution, buildings can achieve enhanced energy efficiency and thermal comfort.

6.1 Incorporating PCM into Building Materials

Incorporating Phase Change Materials (PCMs) into building materials represents a cutting-edge approach to enhancing thermal performance and energy efficiency in construction. By seamlessly integrating PCMs into various building components, such as walls, roofs, and floors, these materials serve as dynamic thermal energy storage systems, actively regulating indoor temperatures and reducing energy consumption. One notable advantage of incorporating PCM into building materials is its ability to effectively manage thermal loads. During periods of excessive heat, PCM absorbs and stores thermal energy as it transitions from solid to liquid phase, preventing overheating within the building. Conversely, when ambient temperatures drop, PCM releases stored energy, providing a natural source of warmth and reducing the need for mechanical heating systems.

Additionally, PCM integration offers the potential to mitigate temperature fluctuations within buildings, enhancing occupant comfort and well-being. By stabilizing indoor temperatures, PCM-infused materials create a more consistent and pleasant living or working environment throughout the day, regardless of external weather conditions. Incorporating Phase Change Materials (PCMs) into bricks proves to be an efficient strategy for augmenting the thermal mass of constructed elements, thereby regulating daily temperature variations. Figure 19 presents a proposed practical methodology for manufacturing PCM-based bricks, facilitating their integration into construction projects.

Figure 19. Preparation of PCM-incorporated conventional bricks

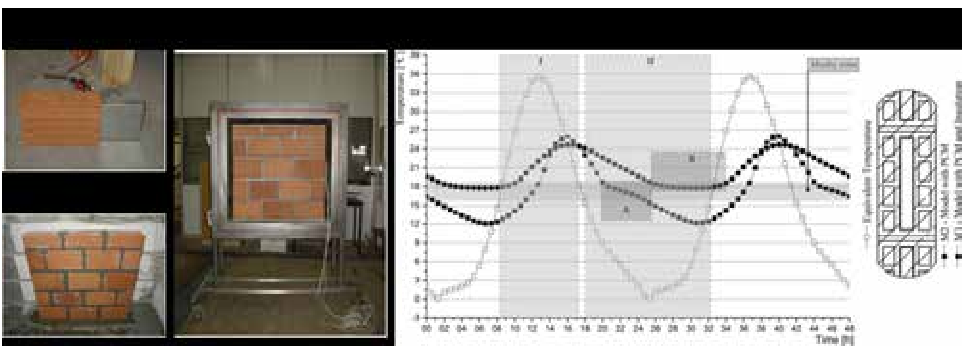


(Saxena et al. 2020)

Furthermore, PCM incorporation can contribute to overall energy savings and sustainability goals in building design. By reducing reliance on traditional heating and cooling systems, PCM-enabled materials help decrease energy consumption and carbon emissions associated with building operation. This not only benefits the environment but also reduces utility costs for building owners and occupants. In terms of implementation, PCM can be embedded within a variety of building materials, including insulation, plaster, concrete, and even textiles. Advanced manufacturing techniques, such as microencapsulation or macroencapsulation, allow for precise integration of PCM into these materials without compromising their structural integrity or performance. Overall, incorporating PCM into building materials offers a promising avenue for enhancing thermal comfort, energy efficiency, and sustainability in construction. As research and development in this field continue to advance, PCM-enabled buildings are poised to become integral components of the future built environment, promoting greener, more resilient, and more comfortable living and working spaces.

Combining insulation materials with the latent heat properties of Phase Change Materials (PCMs) can significantly improve the thermal performance of PCM bricks. Vicente et al. (2014) conducted a study comparing the thermal inertia of PCM hollow brick walls with conventional masonry walls. The PCM incorporation method and wall specimens were depicted in Figures 20 (a) and (b), respectively. Tests were conducted in a climatic chamber, as shown in Figure 20 (c). Results indicated that PCM walls exhibited thermal amplitudes approximately 50% (M2) and 80% (M3) lower than those of conventional masonry walls. Moreover, compared to conventional walls, PCM brick walls demonstrated a 2-hour increase in thermal lag, as illustrated in Figure 20 (d).

Figure 20. (a) and (b) PCM filling of the macro capsule; (c) Wall specimen; (d) Temperatures profiles obtained in the interior of the macro capsules with PCM



(Vicente & Silva, 2014)

Incorporating Phase Change Materials (PCMs) into building materials presents a promising avenue for enhancing thermal performance, energy efficiency, and occupant comfort in construction projects. Several studies have shed light on the critical aspects and potential benefits of PCM integration: Marani & Nehdi (2019) conducted a critical review, emphasizing the significance of PCM integration in construction materials. They highlighted the importance of understanding PCM properties, compatibility with other materials, and manufacturing processes to ensure effective utilisation in building applications. Al-Yasiri and Szabó (2021) provided a comprehensive analysis of PCM incorporation into building envelopes. Their study underscored the potential of PCM-enhanced envelopes for improving thermal comfort and energy savings in buildings, offering insights into design considerations, performance evaluation, and practical applications.

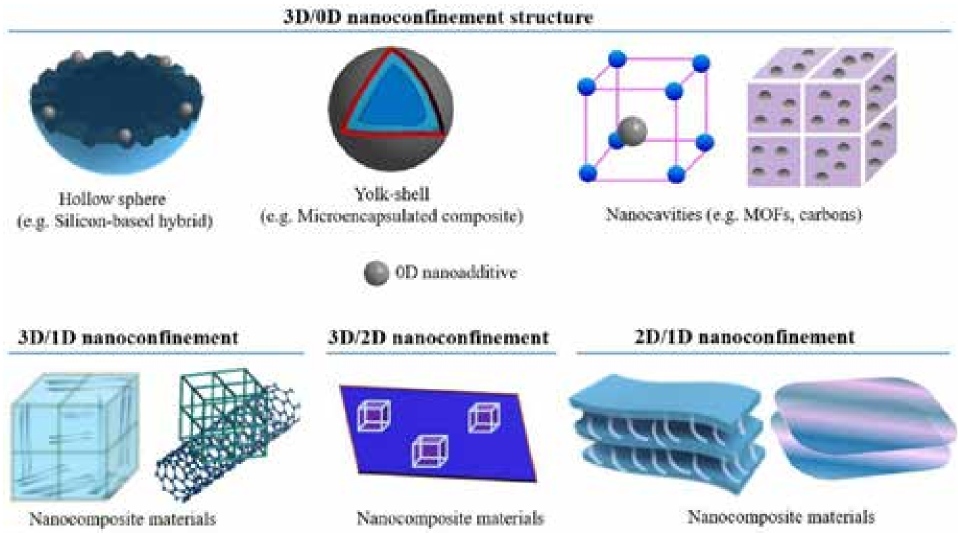
Memon (2014) offered a state-of-the-art review focusing on PCM integration in building walls. The study highlighted various PCM types, integration methods, and their impact on thermal regulation and energy consumption in buildings, providing valuable insights for researchers and practitioners in the field. Li et al. (2022) examined the incorporation of PCMs into glazing units for building applications. Their research highlighted current progress, challenges, and opportunities in leveraging PCM-enhanced glazing for enhancing building energy efficiency and occupant comfort. Gao and Meng (2023) conducted a comprehensive review of PCM integration in building bricks. Their study covered methods, performance evaluation, and applications of PCM-enhanced bricks, offering valuable insights into the potential of PCM bricks for enhancing thermal inertia and energy efficiency in buildings. Collectively, these studies underscore the significance of PCM integration in building materials and provide valuable insights into methods, performance evaluation, and applications across various building components. As research in this field continues to advance, PCM integration is expected to play a pivotal role in shaping the future of sustainable and energy-efficient building design and construction.

6.2 Architectural Integration and Design Strategies

Architectural integration and design strategies of phase change materials (PCMs) involve seamlessly incorporating these materials into building structures to optimise thermal performance and energy efficiency. Several key approaches are employed to achieve effective integration and design. Choosing the appropriate PCM type based on the specific requirements of the building and its climate is crucial. PCMs with suitable melting points and thermal properties are selected and integrated into building elements such as walls, ceilings, or floors to regulate indoor temperatures effectively.

Individual 3D nano-additives effectively address organic PCM challenges like leakage, thermal conductivity, and supercooling. The favourable intrinsic structure of these nano-additives contributes to their efficacy. However, achieving multi-responsive composite PCMs (e.g., electrical conductivity, electromagnetic property, and photoabsorption ability) with a single 3D nano-additive is challenging. Integrating different nano-additives to form 3D nanocomposites (e.g., 3D/0D, 3D/1D, and 3D/2D) promotes sustainable energy infrastructures. For instance, porous Al2O3/graphite foams synthesized by a particle-stabilized foaming method exhibit high paraffin loading (66%) and thermal conductivity (0.76 W/m·K), withstanding 200 heating-cooling cycles. Variations in size and uniformity of nanocomposites extend beyond the depicted scheme (Fig. 21), contingent on material composition and design techniques.

Figure 21. Schematic illustrations of 3D hybrid materials employed for PCMs nanoconfinement



(Atinafu et al. 2021)

Careful consideration is given to the configuration and placement of PCMs within the building envelope. Strategic placement in areas experiencing high thermal loads, such as south-facing walls or roofs, maximises their effectiveness in absorbing and releasing heat.

PCM encapsulation ensures their stability, prevents leakage, and facilitates integration into building materials. Microencapsulation, macroencapsulation, and shape-stabilization techniques are employed to encapsulate PCMs within matrices such as polymers or composites.

PCMs are integrated with passive design strategies such as natural ventilation, shading devices, and thermal mass to optimise building performance. This integration enhances indoor thermal comfort while reducing reliance on mechanical heating and cooling systems (Soares et al. 2013; Abuelnour et al. 2018; Prabhakar et al. 2020; Zhan et al. 2023). Computational tools and simulations are utilised to assess the performance of PCM-integrated buildings under various climatic conditions. This allows architects and engineers to optimise design parameters for maximum energy savings and occupant comfort. By integrating PCMs into architectural design, buildings can achieve higher levels of energy efficiency, reduced environmental impact, and enhanced occupant comfort, contributing to sustainable building practices and green building certifications.

6.3 Modelling and Simulation of PCM Integration

Modelling and simulation are indispensable tools in the realm of integrating phase change materials (PCMs) into building systems, offering a comprehensive approach to understand and optimise their thermal behaviour within architectural contexts. One of the primary functions of modelling is to develop mathematical representations of PCM systems, encapsulating their complex thermal dynamics. These models take into account various factors such as the physical properties of the PCM (e.g., melting point, latent heat), heat transfer mechanisms (conduction, convection, radiation), building geometry, and environmental conditions (temperature, humidity) (Dutil et al. 2011; Caggiano et al. 2018 ; Rucevskis et al. 2020 ; Al-Nahhar et al. 2022). By capturing these intricate interactions, models provide a theoretical framework to predict how PCM-integrated systems will perform under different scenarios.

Simulation tools, including Computational Fluid Dynamics (CFD) software and building energy simulation programs, are then employed to translate these mathematical models into actionable insights. CFD simulations, for instance, allow for the detailed analysis of airflow patterns and temperature distributions within PCM-integrated building envelopes (Gowreesunker et al. 2013; Bouhal et al. 2018; Pandey et al. 2021; Khattari et al. 2022). Energy simulation programs provide a broader perspective by assessing overall energy consumption, indoor thermal comfort, and potential energy savings associated with PCM integration (Saffari et al. 2017; Xie et al. 2018; Morovat et al. 2019; Beiranvand & Mohaghegh, 2021). Parametric studies within simulation frameworks enable exploration of the impact of varying design parameters on PCM performance (Wang et al. 2020; Zeinelabdein et al. 2020; Mohseni & Tang, 2021). By systematically adjusting factors such as PCM type, thickness, placement, and building orientation, designers can identify optimal configurations that maximise energy efficiency and occupant comfort. Moreover, model validation against experimental data derived from PCM test setups or real-world building installations is crucial to ensure the accuracy and reliability of simulation results. This iterative process of model refinement and validation enhances confidence in simulation outcomes, enabling stakeholders to make informed decisions regarding PCM integration strategies.

In essence, modelling and simulation provide a robust platform for evaluating PCM integration within building designs, offering insights into thermal performance, energy efficiency, and sustainability. By leveraging these tools effectively, architects, engineers, and researchers can drive innovation in green building practices and contribute to the advancement of environmentally conscious design solutions.

7. FUTURE DIRECTIONS AND EMERGING TRENDS

Future directions and emerging trends in Phase Change Materials (PCMs) encompass advancements in material science, integration methods, and application domains. Nanotechnology holds promise for developing novel PCM formulations with enhanced thermal properties and stability. Integration trends focus on smart building systems, leveraging PCM's potential for dynamic thermal management and energy optimisation. Additionally, there's a growing emphasis on multifunctional PCM systems, combining thermal energy storage with other building functions like moisture control or air purification. Furthermore, research explores PCM integration in renewable energy systems and urban infrastructure for sustainable urban development. These trends signify a shift towards innovative PCM solutions that address evolving challenges in energy efficiency and climate resilience.

7.1 Advancements in PCM Technology

Over the years, researchers have developed new PCM formulations with enhanced thermal properties. These formulations often involve encapsulating PCM within microcapsules or integrating them into various matrices to improve their stability, thermal conductivity, and compatibility with building materials (Konuklu et al. 2015; Drissi et al. 2019; Suresh et al. 2022). Advanced PCMs can now withstand multiple phase change cycles without significant degradation, ensuring long-term effectiveness.

Initially, PCMs were primarily used for thermal energy storage in buildings, but advancements have led to their integration into various building components and systems. PCMs are now incorporated into walls, ceilings, floors, roofs, and even windows to regulate indoor temperatures effectively (Souayfane et al. 2016; Akeiber et al. 2016; Kasaeian et al. 2017; Berardi & Soudian, 2019). Additionally, they are utilised in HVAC systems, solar collectors, and building envelopes to optimise energy efficiency throughout the entire building lifecycle. Modern PCM technologies offer superior thermal performance compared to conventional insulation materials. By storing excess heat during peak hours and releasing it when ambient temperatures drop, PCMs help maintain a comfortable indoor environment without the need for constant heating or cooling. This not only reduces energy consumption but also minimises temperature fluctuations, improving occupant comfort and productivity.

Researchers and manufacturers are now developing PCM solutions tailored to specific climate conditions and building requirements (Marin et al. 2016; Nghana & Tariku, 2016; Ahangari & Maerefat, 2019; Lagou et al. 2019). By selecting PCMs with appropriate melting temperatures and latent heat capacities, designers can optimise thermal comfort and energy savings based on factors such as local climate, building orientation, and occupancy patterns. Customized PCM solutions offer flexibility and efficiency, allowing for sustainable building designs in diverse environments. PCMs complement renewable energy systems such as solar and wind power by providing thermal energy storage capabilities (Belmonte et al. 2016; Chen et al. 2019; Wang et al. 2022b; Gurbuz et al. 2023). In buildings equipped with solar panels or solar thermal collectors, PCMs store excess heat generated during the day for use during the night or cloudy periods, ensuring continuous energy supply and reducing dependence on fossil fuels. This integration maximises the efficiency of renewable energy sources and promotes sustainable building practices.

Advancements in sensor technology and building automation have enabled the development of smart PCM systems that adapt to changing environmental conditions and occupancy patterns (Wei et al. 2018; de Gracia et al. 2020; Zhou et al. 2020). Smart PCM systems use real-time data to adjust the activation and deactivation of PCM-based thermal storage, optimising energy usage and comfort levels dynamically. These systems may also incorporate predictive algorithms to anticipate future thermal loads and pre-emptively adjust PCM settings for optimal performance. As sustainability becomes a primary concern in building design and construction, researchers are conducting comprehensive lifecycle assessments of PCM technologies to evaluate their environmental impact. By considering factors such as manufacturing processes, energy consumption, and end-of-life disposal, stakeholders can make informed decisions about the adoption of PCM solutions and their contribution to overall sustainability goals.

7.2 Cross-disciplinary Research Opportunities

Cross-disciplinary research opportunities on phase change materials (PCMs) in building design and construction present a fertile ground for innovation and collaboration among various fields. Integrating expertise from materials science, engineering, architecture, environmental science, and beyond, researchers can address complex challenges and unlock new possibilities for sustainable building practices.

Researchers in materials science and chemistry play a crucial role in developing novel PCM formulations with optimised thermal properties, stability, and compatibility with building materials. Cross-disciplinary collaborations can focus on synthesising PCM composites, exploring new encapsulation techniques, and enhancing PCM performance through nanostructuring or functionalization (Zhou

& Liu, 2023; Zhou & Zheng, 2024). By understanding the molecular structure and behaviour of PCM materials, scientists can tailor their properties to meet specific building requirements. Engineers leverage principles of thermodynamics and heat transfer to design efficient PCM-based thermal energy storage systems for buildings. Cross-disciplinary research in this area can explore advanced heat exchanger designs, optimal placement of PCM elements within building envelopes, and integration with HVAC systems for seamless operation. Collaborative efforts between mechanical, electrical, and civil engineers can lead to innovative solutions for enhancing energy efficiency and thermal comfort in buildings.

Architects and building designers are increasingly incorporating PCM technologies into their projects to achieve sustainable and energy-efficient designs (Rodriguez-Ubinas et al. 2012; Bohórquez-Órdenes et al. 2021; Jaradat et al. 2023). Cross-disciplinary collaborations between architects, engineers, and materials scientists can explore the aesthetic integration of PCM elements into building envelopes, optimising daylighting and passive heating/cooling strategies. Research in this area can also focus on developing design guidelines and tools for architects to effectively incorporate PCM solutions into their projects while maintaining architectural integrity. Environmental scientists contribute valuable insights into the lifecycle analysis and environmental impact assessment of PCM technologies in buildings. Cross-disciplinary research opportunities involve evaluating the overall sustainability of PCM-based building solutions, considering factors such as embodied energy, carbon footprint, and resource depletion. Researchers can also investigate the potential benefits of PCM-enabled buildings in reducing greenhouse gas emissions and mitigating the urban heat island effect, promoting environmentally conscious urban development.

Cross-disciplinary collaborations between experts in renewable energy systems and building integration explore synergies between PCM technologies and solar, wind, or geothermal energy sources (Powell et al. 2017; Nazir et al. 2019; Mourad et al. 2022). Researchers can develop integrated building energy management systems that optimise the utilisation of renewable energy and PCM-based thermal storage, maximising energy efficiency and grid resilience. By studying the dynamic interactions between building energy demand, renewable energy generation, and PCM storage, interdisciplinary teams can identify opportunities for enhancing overall system performance and reliability. With the advent of smart building technologies and IoT (Internet of Things) sensors, data science plays a crucial role in optimising PCM-enabled building systems. Cross-disciplinary research in this area involves developing predictive analytics models, machine learning algorithms, and building automation strategies to intelligently control PCM activation and maximise energy savings. Collaborations between data scientists, building engineers, and HVAC specialists can lead to innovative approaches for adaptive thermal management in buildings, improving occupant comfort and operational efficiency.

PCM technologies not only impact energy performance but also influence indoor environmental quality and occupant health and well-being (Amoatey et al. 2022; Roumi et al. 2023). Cross-disciplinary research opportunities involve investigating the effects of PCM materials on indoor air quality, humidity levels, and thermal comfort. Researchers can explore the potential benefits of PCM-enabled buildings in mitigating indoor air pollutants, reducing thermal stress, and promoting occupant productivity and satisfaction. Interdisciplinary approaches that integrate expertise from public health, psychology, and building science can provide holistic insights into the human-centred aspects of PCM applications in buildings.

7.3 Policy and Industry Implications

The integration of phase change materials (PCMs) into buildings has significant policy and industry implications, impacting various stakeholders ranging from policymakers and manufacturers to building developers and end-users. These implications extend beyond technical considerations to encompass regulatory frameworks, market dynamics, and socio-economic factors. Policymakers at local, national, and international levels play a crucial role in shaping energy efficiency regulations and standards for buildings. The adoption of PCMs can influence these policies by promoting innovative thermal energy storage solutions that contribute to reducing energy consumption and greenhouse gas emissions. Policymakers may incentivise the use of PCM technologies through tax credits, subsidies, or building code revisions that recognise their contribution to energy efficiency and sustainability goals.

Industry-driven building certification and rating systems, such as LEED (Leadership in Energy and Environmental Design) or BREEAM (Building Research Establishment Environmental Assessment Method), provide benchmarks for sustainable building practices. The incorporation of PCMs into buildings can enhance their performance in categories related to energy efficiency, thermal comfort, and indoor environmental quality, leading to higher certification levels and market differentiation. Industry stakeholders may leverage PCM technologies to meet or exceed certification requirements and appeal to environmentally conscious consumers. The adoption of PCM technologies in buildings creates opportunities and challenges for manufacturers and suppliers across the supply chain. Manufacturers of PCM materials, encapsulation technologies, and building products must scale up production capacity, optimise manufacturing processes, and ensure product quality and reliability. Industry collaborations and research partnerships can drive innovation in PCM manufacturing, leading to cost reductions, performance improvements, and market competitiveness.

Market adoption of PCM technologies in buildings depends on consumer awareness, acceptance, and willingness to invest in innovative building solutions. Policymakers, industry associations, and advocacy groups can play a role in educating consumers about the benefits of PCMs in terms of energy savings, comfort enhancement, and environmental impact. Market research and consumer surveys can provide insights into consumer preferences, perceptions, and willingness to pay for PCM-enabled buildings, guiding marketing strategies and product positioning efforts.

Architects, engineers, and building developers are key influencers in the adoption of PCM technologies through their design and construction practices. Integration of PCMs into building envelopes, HVAC systems, and interior finishes requires collaboration among design professionals, contractors, and manufacturers to ensure proper installation, performance optimisation, and long-term durability. Industry standards and best practices for PCM implementation can facilitate knowledge sharing and capacity building within the construction industry.

Financial incentives, such as grants, loans, and rebates, can accelerate the adoption of PCM technologies by reducing upfront costs and improving return on investment for building owners and developers. Policymakers may partner with financial institutions and industry stakeholders to develop innovative financing mechanisms that incentivize investments in PCM-enabled buildings. Moreover, PCM technologies can attract private investment in research and development, manufacturing facilities, and commercialization efforts, fostering entrepreneurship and job creation in the emerging green building sector.

The global market for PCM technologies is influenced by trade policies, tariffs, and international agreements that affect the flow of raw materials, components, and finished products across borders. Policymakers may negotiate trade agreements or harmonize technical standards to facilitate the international trade of PCM materials and products. Industry stakeholders must navigate regulatory compliance requirements and market access barriers in different regions, adapting their strategies to local market conditions and competitive dynamics.

8. CONCLUDING REMARKS

In this comprehensive chapter, Phase Change Materials (PCMs) emerge as pivotal elements in revolutionising building design and energy management. By providing a detailed exploration, the chapter serves as a foundational resource for understanding the diverse applications and implications of PCMs in the built environment. Beginning with an insightful overview of PCM fundamentals, the chapter delves into the intricacies of different PCM types, elucidating their phase change mechanisms and essential properties. This foundational understanding sets the stage for a deeper exploration into practical applications across various domains within building construction and operation.

A key highlight of the chapter is its thorough examination of PCM integration within building systems and design methodologies. From enhancing thermal regulation and energy efficiency to optimising HVAC systems and facilitating thermal energy storage, PCMs offer multifaceted solutions to longstanding challenges in building performance. Moreover, the chapter not only discusses theoretical concepts but also provides real-world examples and case studies illustrating successful PCM implementations. By showcasing the effectiveness of PCMs in diverse contexts, it underscores their versatility and adaptability in addressing the evolving needs of modern building design and operation. Furthermore, the chapter critically evaluates strategies for enhancing PCM performance, such as nano-enhancements, microencapsulation, and hybrid solutions. These innovative approaches hold promise for further advancing the efficacy and applicability of PCMs in building applications.

As the chapter draws to a close, it offers valuable insights into future directions and emerging trends in PCM research and application. By identifying potential areas for innovation and emphasizing the importance of sustainable building practices, it provides a roadmap for leveraging PCMs to create more energy-efficient, comfortable, and environmentally friendly built environments. In essence, this chapter serves as an indispensable resource for researchers, practitioners, and stakeholders seeking to harness the transformative potential of Phase Change Materials in shaping the future of building design and construction.

REFERENCES

Abuelnuor, A. A., Omara, A. A., Saqr, K. M., & Elhag, I. H. (2018). Improving indoor thermal comfort by using phase change materials: A review. *International Journal of Energy Research*, 42(6), 2084–2103. DOI:10.1002/er.4000

Ahangari, M., & Maerefat, M. (2019). An innovative PCM system for thermal comfort improvement and energy demand reduction in building under different climate conditions. *Sustainable Cities and Society*, 44, 120–129. DOI:10.1016/j.scs.2018.09.008

Akeiber, H., Nejat, P., Majid, M. Z. A., Wahid, M. A., Jomehzadeh, F., Famileh, I. Z., Calautit, J. K., Hughes, B. R., & Zaki, S. A. (2016). A review on phase change material (PCM) for sustainable passive cooling in building envelopes. *Renewable & Sustainable Energy Reviews*, 60, 1470–1497. DOI:10.1016/j.rser.2016.03.036

Al-Najjar, H. M. T., & Mahdi, J. M. (2022). Novel mathematical modeling, performance analysis, and design charts for the typical hybrid photovoltaic/phase-change material (PV/PCM) system. *Applied Energy*, 315, 119027. DOI:10.1016/j.apenergy.2022.119027

Al-Yasiri, Q., & Szabó, M. (2021). Incorporation of phase change materials into building envelope for thermal comfort and energy saving: A comprehensive analysis. *Journal of Building Engineering*, 36, 102122. DOI:10.1016/j.jobe.2020.102122

Alam, M., Sanjayan, J., Zou, P. X., Ramakrishnan, S., & Wilson, J. (2017). Evaluating the passive and free cooling application methods of phase change materials in residential buildings: A comparative study. *Energy and Building*, 148, 238–256. DOI:10.1016/j.enbuild.2017.05.018

Alazwari, M. A., Abu-Hamdeh, N. H., Khoshaim, A., Almitani, K. H., & Karimipour, A. (2021). Using phase change material as an energy-efficient technique to reduce energy demand in air handling unit integrated with absorption chiller and recovery unit–Applicable for high solar-irradiance regions. *Journal of Energy Storage*, 42, 103080. DOI:10.1016/j.est.2021.103080

Amoatey, P., Al-Jabri, K., & Al-Saadi, S. (2022). Influence of phase change materials on thermal comfort, greenhouse gas emissions, and potential indoor air quality issues across different climatic regions: A critical review. *International Journal of Energy Research*, 46(15), 22386–22420. DOI:10.1002/er.8734

Bao, X., Yang, H., Xu, X., Xu, T., Cui, H., Tang, W., Sang, G., & Fung, W. H. (2020). Development of a stable inorganic phase change material for thermal energy storage in buildings. *Solar Energy Materials and Solar Cells*, 208, 110420. DOI:10.1016/j.solmat.2020.110420

Barreneche, C., Martín, M., Calvo-de la Rosa, J., Majó, M., & Fernández, A. I. (2019). Own-synthetize nanoparticles to develop nano-enhanced phase change materials (NEPCM) to improve the energy efficiency in buildings. *Molecules (Basel, Switzerland)*, 24(7), 1232. DOI:10.3390/molecules24071232 PMID:30934832

Baylis, C., & Cruickshank, C. A. (2023). Review of bio-based phase change materials as passive thermal storage in buildings. *Renewable & Sustainable Energy Reviews*, 186, 113690. DOI:10.1016/j.rser.2023.113690

Beiranvand, M., & Mohaghegh, M. R. (2021). Energy analysis and simulation of PCM-enhanced building envelopes in commercial buildings: A case study. *Energy Storage*, 3(4), e246. DOI:10.1002/est2.246

Belmonte, J. F., Izquierdo-Barrientos, M. A., Molina, A. E., & Almendros-Ibáñez, J. A. (2016). Air-based solar systems for building heating with PCM fluidized bed energy storage. *Energy and Building*, 130, 150–165. DOI:10.1016/j.enbuild.2016.08.041

Berardi, U., & Soudian, S. (2019). Experimental investigation of latent heat thermal energy storage using PCMs with different melting temperatures for building retrofit. *Energy and Building*, 185, 180–195. DOI:10.1016/j.enbuild.2018.12.016

Bohórquez-Órdenes, J., Tapia-Calderón, A., Vasco, D. A., Estuardo-Flores, O., & Haddad, A. N. (2021). Methodology to reduce cooling energy consumption by incorporating PCM envelopes: A case study of a dwelling in Chile. *Building and Environment*, 206, 108373. DOI:10.1016/j.buildenv.2021.108373

Bouhal, T., Meghari, Z., El Rhafiki, T., Kousksou, T., Jamil, A., & Ghoulam, E. B. (2018). Parametric CFD analysis and impact of PCM intrinsic parameters on melting process inside enclosure integrating fins: Solar building applications. *Journal of Building Engineering*, 20, 634–646. DOI:10.1016/j.jobe.2018.09.016

Bourne, S., & Novoselac, A. (2016). Improved performance in tube-encapsulated phase change thermal energy stores for HVAC applications. *Building and Environment*, 98, 133–144. DOI:10.1016/j.buildenv.2015.12.023

Boussaba, L., Foufa, A., Makhlouf, S., Lefebvre, G., & Royon, L. (2018). Elaboration and properties of a composite bio-based PCM for an application in building envelopes. *Construction & Building Materials*, 185, 156–165. DOI:10.1016/j.conbuildmat.2018.07.098

Caggiano, A., Mankel, C., & Koenders, E. (2018). Reviewing theoretical and numerical models for PCM-embedded cementitious composites. *Buildings*, 9(1), 3. DOI:10.3390/buildings9010003

Carlucci, F., Cannavale, A., Triggiano, A. A., Squicciarini, A., & Fiorito, F. (2021). phase change material integration in building envelopes in different building types and climates: Modeling the benefits of active and passive strategies. *Applied Sciences (Basel, Switzerland)*, 11(10), 4680. DOI:10.3390/app11104680

Chandel, S. S., & Agarwal, T. (2017). Review of current state of research on energy storage, toxicity, health hazards and commercialization of phase changing materials. *Renewable & Sustainable Energy Reviews*, 67, 581–596. DOI:10.1016/j.rser.2016.09.070

Chen, X., Zhang, Q., Zhai, Z. J., & Ma, X. (2019). Potential of ventilation systems with thermal energy storage using PCMs applied to air conditioned buildings. *Renewable Energy*, 138, 39–53. DOI:10.1016/j.renene.2019.01.026

de Gracia, A., & Cabeza, L. F. (2015). Phase change materials and thermal energy storage for buildings. *Energy and Building*, 103, 414–419. DOI:10.1016/j.enbuild.2015.06.007

de Gracia, A., Tarragona, J., Crespo, A., & Fernández, C. (2020). Smart control of dynamic phase change material wall system. *Applied Energy*, 279, 115807. DOI:10.1016/j.apenergy.2020.115807

Drissi, S., Ling, T. C., Mo, K. H., & Eddhahak, A. (2019). A review of microencapsulated and composite phase change materials: Alteration of strength and thermal properties of cement-based materials. *Renewable & Sustainable Energy Reviews*, 110, 467–484. DOI:10.1016/j.rser.2019.04.072

Du, K., Calautit, J., Wang, Z., Wu, Y., & Liu, H. (2018). A review of the applications of phase change materials in cooling, heating and power generation in different temperature ranges. *Applied Energy*, 220, 242–273. DOI:10.1016/j.apenergy.2018.03.005

Dutil, Y., Rousse, D. R., Salah, N. B., Lassue, S., & Zalewski, L. (2011). A review on phase-change materials: Mathematical modeling and simulations. *Renewable & Sustainable Energy Reviews*, 15(1), 112–130. DOI:10.1016/j.rser.2010.06.011

Fang, Y., Su, J., Fu, W., Liang, X., Wang, S., Gao, X., & Zhang, Z. (2020). Preparation and thermal properties of NaOAc· 3H2O-CO (NH2) 2 non-eutectic binary mixture PCM for radiant floor heating system. *Applied Thermal Engineering*, 167, 114820. DOI:10.1016/j.applthermaleng.2019.114820

Faraj, K., Khaled, M., Faraj, J., Hachem, F., & Castelain, C. (2020). Phase change material thermal energy storage systems for cooling applications in buildings: A review. *Renewable & Sustainable Energy Reviews*, 119, 109579. DOI:10.1016/j.rser.2019.109579

Faraj, K., Khaled, M., Faraj, J., Hachem, F., & Castelain, C. (2021). A review on phase change materials for thermal energy storage in buildings: Heating and hybrid applications. *Journal of Energy Storage*, 33, 101913. DOI:10.1016/j.est.2020.101913

Frigione, M., Lettieri, M., & Sarcinella, A. (2019). Phase change materials for energy efficiency in buildings and their use in mortars. *Materials (Basel)*, 12(8), 1260. DOI:10.3390/ma12081260 PMID:30999615

Gan, G., & Xiang, Y. (2020). Experimental investigation of a photovoltaic thermal collector with energy storage for power generation, building heating and natural ventilation. *Renewable Energy*, 150, 12–22. DOI:10.1016/j.renene.2019.12.112

Gao, Y., & Meng, X. (2023). A comprehensive review of integrating phase change materials in building bricks: Methods, performance and applications. *Journal of Energy Storage*, 62, 106913. DOI:10.1016/j.est.2023.106913

Gowreesunker, B. L., Tassou, S. A., & Kolokotroni, M. (2013). Coupled TRNSYS-CFD simulations evaluating the performance of PCM plate heat exchangers in an airport terminal building displacement conditioning system. *Building and Environment*, 65, 132–145. DOI:10.1016/j.buildenv.2013.04.003

Gürbüz, H., Demirtürk, S., Akçay, H., & Topalcı, Ü. (2023). Experimental investigation on electrical power and thermal energy storage performance of a solar hybrid PV/T-PCM energy conversion system. *Journal of Building Engineering*, 69, 106271. DOI:10.1016/j.jobe.2023.106271

Ikutegbe, C. A., & Farid, M. M. (2020). Application of phase change material foam composites in the built environment: A critical review. *Renewable & Sustainable Energy Reviews*, 131, 110008. DOI:10.1016/j.rser.2020.110008

Jaradat, M., Al Majali, H., Bendea, C., Bungau, C. C., & Bungau, T. (2023). Enhancing Energy Efficiency in Buildings through PCM Integration: A Study across Different Climatic Regions. *Buildings*, 14(1), 40. DOI:10.3390/buildings14010040

Jelle, B. P., & Kalnæs, S. E. (2017). Phase change materials for application in energy-efficient buildings. Cost-effective energy efficient building retrofitting, 57-118.

Jeong, S. G., Wi, S., Chang, S. J., Lee, J., & Kim, S. (2019). An experimental study on applying organic PCMs to gypsum-cement board for improving thermal performance of buildings in different climates. *Energy and Building*, 190, 183–194. DOI:10.1016/j.enbuild.2019.02.037

Junaid, M. F., Rehman, Z., Čekon, M., Čurpek, J., Farooq, R., Cui, H., & Khan, I. (2021). Inorganic phase change materials in thermal energy storage: A review on perspectives and technological advances in building applications. *Energy and Building*, 252, 111443. DOI:10.1016/j.enbuild.2021.111443

Kalnaes, S. E., & Jelle, B. P. (2015). Phase change materials and products for building applications: A state-of-the-art review and future research opportunities. *Energy and Building*, 94, 150–176. DOI:10.1016/j.enbuild.2015.02.023

Kapsalis, V., Maduta, C., Skandalos, N., Bhuvad, S.S., D'Agostino, D., Yang, R.J., Parker, D. and Karamanis, D., (2024) Bottom-up energy transition through rooftop PV upscaling: remaining issues and emerging upgrades towards NZEBs at different climatic conditions. Renewable and Sustainable Energy Transition, 100083.

Karaipekli, A., & Sarı, A. (2016). Development and thermal performance of pumice/organic PCM/gypsum composite plasters for thermal energy storage in buildings. *Solar Energy Materials and Solar Cells*, 149, 19–28. DOI:10.1016/j.solmat.2015.12.034

Karthick, A., Murugavel, K. K., Ghosh, A., Sudhakar, K., & Ramanan, P. J. S. E. M. (2020). Investigation of a binary eutectic mixture of phase change material for building integrated photovoltaic (BIPV) system. *Solar Energy Materials and Solar Cells*, 207, 110360. DOI:10.1016/j.solmat.2019.110360

Kasaeian, A., Pourfayaz, F., Khodabandeh, E., & Yan, W. M. (2017). Experimental studies on the applications of PCMs and nano-PCMs in buildings: A critical review. *Energy and Building*, 154, 96–112. DOI:10.1016/j.enbuild.2017.08.037

Kenisarin, M., & Mahkamov, K. (2016). Passive thermal control in residential buildings using phase change materials. *Renewable & Sustainable Energy Reviews*, 55, 371–398. DOI:10.1016/j.rser.2015.10.128

Keshteli, A. N., & Sheikholeslami, M. (2019). Nanoparticle enhanced PCM applications for intensification of thermal performance in building: A review. *Journal of Molecular Liquids*, 274, 516–533. DOI:10.1016/j.molliq.2018.10.151

Khattari, Y., Arid, A., El Ouali, A., Kousksou, T., Janajreh, I., & Mahjoub Ben Ghoulam, E. (2022). CFD study on the validity of using PCM in a controlled cooling ceiling integrated in a ventilated room. *Developments in the Built Environment*, 9, 100066. DOI:10.1016/j.dibe.2021.100066

Kong, X., Wang, L., Li, H., Yuan, G., & Yao, C. (2020). Experimental study on a novel hybrid system of active composite PCM wall and solar thermal system for clean heating supply in winter. *Solar Energy*, 195, 259–270. DOI:10.1016/j.solener.2019.11.081

Konuklu, Y., Ostry, M., Paksoy, H. O., & Charvat, P. (2015). Review on using microencapsulated phase change materials (PCM) in building applications. *Energy and Building*, 106, 134–155. DOI:10.1016/j.enbuild.2015.07.019

Kośny, J., Fallahi, A., Shukla, N., Kossecka, E., & Ahbari, R. (2014). Thermal load mitigation and passive cooling in residential attics containing PCM-enhanced insulations. *Solar Energy*, 108, 164–177. DOI:10.1016/j.solener.2014.05.007

Lagou, A., Kylili, A., Šadauskienė, J., & Fokaides, P. A. (2019). Numerical investigation of phase change materials (PCM) optimal melting properties and position in building elements under diverse conditions. *Construction & Building Materials*, 225, 452–464. DOI:10.1016/j.conbuildmat.2019.07.199

Leong, K. Y., Rahman, M. R. A., & Gurunathan, B. A. (2019). Nano-enhanced phase change materials: A review of thermo-physical properties, applications and challenges. *Journal of Energy Storage*, 21, 18–31. DOI:10.1016/j.est.2018.11.008

Li, C., Wang, M., Xie, B., Ma, H., & Chen, J. (2020). Enhanced properties of diatomite-based composite phase change materials for thermal energy storage. *Renewable Energy*, 147, 265–274. DOI:10.1016/j.renene.2019.09.001

Li, D., Wang, J., Ding, Y., Yao, H., & Huang, Y. (2019). Dynamic thermal management for industrial waste heat recovery based on phase change material thermal storage. *Applied Energy*, 236, 1168–1182. DOI:10.1016/j.apenergy.2018.12.040

Li, D., Yang, R., Arıcı, M., Wang, B., Tunçbilek, E., Wu, Y., Liu, C., Ma, Z., & Ma, Y. (2022). Incorporating phase change materials into glazing units for building applications: Current progress and challenges. *Applied Thermal Engineering*, 210, 118374. DOI:10.1016/j.applthermaleng.2022.118374

Lizana, J., de-Borja-Torrejon, M., Barrios-Padura, A., Auer, T., & Chacartegui, R. (2019). Passive cooling through phase change materials in buildings. A critical study of implementation alternatives. *Applied Energy*, 254, 113658. DOI:10.1016/j.apenergy.2019.113658

Ma, M., Xie, M., & Ai, Q. (2021). Numerical simulation on photo-thermal properties of double glazing unit filled with TiN-Al2O3 binary nanoparticles enhanced phase change material. *Sustainable Energy Technologies and Assessments*, 48, 101676. DOI:10.1016/j.seta.2021.101676

Ma, T., Yang, H., Zhang, Y., Lu, L., & Wang, X. (2015). Using phase change materials in photovoltaic systems for thermal regulation and electrical efficiency improvement: A review and outlook. *Renewable & Sustainable Energy Reviews*, 43, 1273–1284. DOI:10.1016/j.rser.2014.12.003

Ma, Z., Lin, W., & Sohel, M. I. (2016). Nano-enhanced phase change materials for improved building performance. *Renewable & Sustainable Energy Reviews*, 58, 1256–1268. DOI:10.1016/j.rser.2015.12.234

Marani, A., & Nehdi, M. L. (2019). Integrating phase change materials in construction materials: Critical review. *Construction & Building Materials*, 217, 36–49. DOI:10.1016/j.conbuildmat.2019.05.064

Marin, P., Saffari, M., de Gracia, A., Zhu, X., Farid, M. M., Cabeza, L. F., & Ushak, S. (2016). Energy savings due to the use of PCM for relocatable lightweight buildings passive heating and cooling in different weather conditions. *Energy and Building*, 129, 274–283. DOI:10.1016/j.enbuild.2016.08.007

Marske, F., Haupt, C., Birkemeyer, C., Bacia, K., Hahn, T., & Enke, D. (2022). Shape-stabilization of organic phase change materials as mechanically stable silica boards with high latent heats synthesized via sol-gel route. *Journal of Building Engineering*, 60, 105198. DOI:10.1016/j.jobe.2022.105198

Martin, M., Villalba, A., Fernández, A. I., & Barreneche, C. (2019). Development of new nano-enhanced phase change materials (NEPCM) to improve energy efficiency in buildings: Lab-scale characterization. *Energy and Building*, 192, 75–83. DOI:10.1016/j.enbuild.2019.03.029

Meethaapanon, R., Kornbongkotmas, S., Ataboonwongse, C., & Soottitantawat, A. (2020). Microencapsulation of n-octadecane and methyl palmitate phase change materials in silica by spray drying process. *Powder Technology*, 361, 910–916. DOI:10.1016/j.powtec.2019.10.114

Mehrizi, A. A., Karimi-Maleh, H., Naddafi, M., & Karimi, F. (2023). Application of bio-based phase change materials for effective heat management. *Journal of Energy Storage*, 61, 106859. DOI:10.1016/j.est.2023.106859

Memon, S. A. (2014). Phase change materials integrated in building walls: A state of the art review. *Renewable & Sustainable Energy Reviews*, 31, 870–906. DOI:10.1016/j.rser.2013.12.042

Mohseni, E., & Tang, W. (2021). Parametric analysis and optimisation of energy efficiency of a lightweight building integrated with different configurations and types of PCM. *Renewable Energy*, 168, 865–877. DOI:10.1016/j.renene.2020.12.112

Morovat, N., Athienitis, A. K., Candanedo, J. A., & Dermardiros, V. (2019). Simulation and performance analysis of an active PCM-heat exchanger intended for building operation optimization. *Energy and Building*, 199, 47–61. DOI:10.1016/j.enbuild.2019.06.022

Mourad, A., Aissa, A., Said, Z., Younis, O., Iqbal, M., & Alazzam, A. (2022). Recent advances on the applications of phase change materials for solar collectors, practical limitations, and challenges: A critical review. *Journal of Energy Storage*, 49, 104186. DOI:10.1016/j.est.2022.104186

Muzhanje, A. T., Hassan, M. A., & Hassan, H. (2022). Phase change material based thermal energy storage applications for air conditioning. *Applied Thermal Engineering*, 214, 118832. DOI:10.1016/j.applthermaleng.2022.118832

Nazir, H., Batool, M., Osorio, F. J. B., Isaza-Ruiz, M., Xu, X., Vignarooban, K., Phelan, P., & Kannan, A. M. (2019). Recent developments in phase change materials for energy storage applications: A review. *International Journal of Heat and Mass Transfer*, 129, 491–523. DOI:10.1016/j.ijheatmasstransfer.2018.09.126

Nghana, B., & Tariku, F. (2016). Phase change material's (PCM) impacts on the energy performance and thermal comfort of buildings in a mild climate. *Building and Environment*, 99, 221–238. DOI:10.1016/j.buildenv.2016.01.023

Nie, B., Du, Z., Zou, B., Li, Y., & Ding, Y. (2020). Performance enhancement of a phase-change-material based thermal energy storage device for air-conditioning applications. *Energy and Building*, 214, 109895. DOI:10.1016/j.enbuild.2020.109895

Obergfell, T., Guzman, J. S., Haussmann, T., Gschwander, S., & Wagner, A. (2021). Long-term functionality of a passive phase-change materials building application after more than a decade of operation. *Energy and Building*, 249, 111213. DOI:10.1016/j.enbuild.2021.111213

Pandey, B., Banerjee, R., & Sharma, A. (2021). Coupled EnergyPlus and CFD analysis of PCM for thermal management of buildings. *Energy and Building*, 231, 110598. DOI:10.1016/j.enbuild.2020.110598

Pasupathy, A., Velraj, R., & Seeniraj, R. V. (2008). Phase change material-based building architecture for thermal management in residential and commercial establishments. *Renewable & Sustainable Energy Reviews*, 12(1), 39–64. DOI:10.1016/j.rser.2006.05.010

Powell, K. M., Rashid, K., Ellingwood, K., Tuttle, J., & Iverson, B. D. (2017). Hybrid concentrated solar thermal power systems: A review. *Renewable & Sustainable Energy Reviews*, 80, 215–237. DOI:10.1016/j.rser.2017.05.067

Prabhakar, M., Saffari, M., de Gracia, A., & Cabeza, L. F. (2020). Improving the energy efficiency of passive PCM system using controlled natural ventilation. *Energy and Building*, 228, 110483. DOI:10.1016/j.enbuild.2020.110483

Raj, C. R., Suresh, S., Bhavsar, R. R., & Singh, V. K. (2020). Recent developments in thermo-physical property enhancement and applications of solid-solid phase change materials: A review. *Journal of Thermal Analysis and Calorimetry*, 139(5), 3023–3049. DOI:10.1007/s10973-019-08703-w

Rathore, P. K. S., & Shukla, S. K. (2021). Enhanced thermophysical properties of organic PCM through shape stabilization for thermal energy storage in buildings: A state of the art review. *Energy and Building*, 236, 110799. DOI:10.1016/j.enbuild.2021.110799

Reddy, V. J., Ghazali, M. F., & Kumarasamy, S. (2024). Advancements in phase change materials for energy-efficient building construction: A comprehensive review. *Journal of Energy Storage*, 81, 110494. DOI:10.1016/j.est.2024.110494

Rodriguez-Ubinas, E., Ruiz-Valero, L., Vega, S., & Neila, J. (2012). Applications of phase change material in highly energy-efficient houses. *Energy and Building*, 50, 49–62. DOI:10.1016/j.enbuild.2012.03.018

Roumi, S., Zhang, F., Stewart, R. A., & Santamouris, M. (2023). Weighting of indoor environment quality parameters for occupant satisfaction and energy efficiency. *Building and Environment*, 228, 109898. DOI:10.1016/j.buildenv.2022.109898

Ručevskis, S., Akishin, P., & Korjakins, A. (2020). Parametric analysis and design optimisation of PCM thermal energy storage system for space cooling of buildings. *Energy and Building*, 224, 110288. DOI:10.1016/j.enbuild.2020.110288

Saffari, M., de Gracia, A., Ushak, S., & Cabeza, L. F. (2017). Passive cooling of buildings with phase change materials using whole-building energy simulation tools: A review. *Renewable & Sustainable Energy Reviews*, 80, 1239–1255. DOI:10.1016/j.rser.2017.05.139

Said, M. A., & Hassan, H. (2019). A study on the thermal energy storage of different phase change materials incorporated with the condenser of air-conditioning unit and their effect on the unit performance. *Energy and Building*, 202, 109353. DOI:10.1016/j.enbuild.2019.109353

Saman, W., Bruno, F., & Halawa, E. (2005). Thermal performance of PCM thermal storage unit for a roof integrated solar heating system. *Solar Energy*, 78(2), 341–349. DOI:10.1016/j.solener.2004.08.017

Sarrafha, H., Kasaeian, A., Jahangir, M. H., & Taylor, R. A. (2021). Transient thermal response of multi-walled carbon nanotube phase change materials in building walls. *Energy*, 224, 120120. DOI:10.1016/j.energy.2021.120120

Saxena, R., Rakshit, D., & Kaushik, S. C. (2020). Experimental assessment of Phase Change Material (PCM) embedded bricks for passive conditioning in buildings. *Renewable Energy*, 149, 587–599. DOI:10.1016/j.renene.2019.12.081

Selvnes, H., Allouche, Y., Manescu, R. I., & Hafner, A. (2021). Review on cold thermal energy storage applied to refrigeration systems using phase change materials. *Thermal Science and Engineering Progress*, 22, 100807. DOI:10.1016/j.tsep.2020.100807

Shilei, L., Neng, Z., & Guohui, F. (2006). Eutectic mixtures of capric acid and lauric acid applied in building wallboards for heat energy storage. *Energy and Building*, 38(6), 708–711. DOI:10.1016/j.enbuild.2005.10.006

Sivanathan, A., Dou, Q., Wang, Y., Li, Y., Corker, J., Zhou, Y., & Fan, M. (2020). Phase change materials for building construction: An overview of nano-/micro-encapsulation. *Nanotechnology Reviews*, 9(1), 896–921. DOI:10.1515/ntrev-2020-0067

Soares, N., Costa, J. J., Gaspar, A. R., & Santos, P. (2013). Review of passive PCM latent heat thermal energy storage systems towards buildings' energy efficiency. *Energy and Building*, 59, 82–103. DOI:10.1016/j.enbuild.2012.12.042

Song, M., Niu, F., Mao, N., Hu, Y., & Deng, S. (2018). Review on building energy performance improvement using phase change materials. *Energy and Building*, 158, 776–793. DOI:10.1016/j.enbuild.2017.10.066

Souayfane, F., Fardoun, F., & Biwole, P. H. (2016). Phase change materials (PCM) for cooling applications in buildings: A review. *Energy and Building*, 129, 396–431. DOI:10.1016/j.enbuild.2016.04.006

Srinivasaraonaik, B., Singh, L. P., Sinha, S., Tyagi, I., & Rawat, A. (2020). Studies on the mechanical properties and thermal behavior of microencapsulated eutectic mixture in gypsum composite board for thermal regulation in the buildings. *Journal of Building Engineering*, 31, 101400. DOI:10.1016/j.jobe.2020.101400

Stritih, U., Tyagi, V. V., Stropnik, R., Paksoy, H., Haghighat, F., & Joybari, M. M. (2018). Integration of passive PCM technologies for net-zero energy buildings. *Sustainable Cities and Society*, 41, 286–295. DOI:10.1016/j.scs.2018.04.036

Sun, W., Zhang, Y., Ling, Z., Fang, X., & Zhang, Z. (2020). Experimental investigation on the thermal performance of double-layer PCM radiant floor system containing two types of inorganic composite PCMs. *Energy and Building*, 211, 109806. DOI:10.1016/j.enbuild.2020.109806

Suresh, C., Hotta, T. K., & Saha, S. K. (2022). Phase change material incorporation techniques in building envelopes for enhancing the building thermal Comfort-A review. *Energy and Building*, 268, 112225. DOI:10.1016/j.enbuild.2022.112225

Tan, P., Lindberg, P., Eichler, K., Löveryd, P., Johansson, P., & Kalagasidis, A. S. (2020). Thermal energy storage using phase change materials: Techno-economic evaluation of a cold storage installation in an office building. *Applied Energy*, 276, 115433. DOI:10.1016/j.apenergy.2020.115433

Teggar, M., Arıcı, M., Mert, M. S., Mousavi Ajarostaghi, S. S., Niyas, H., Tunçbilek, E., Ismail, K. A., Younsi, Z., Benhouia, A. T., & Mezaache, E. H. (2022). A comprehensive review of micro/nano enhanced phase change materials. *Journal of Thermal Analysis and Calorimetry*, 147(6), 3989–4016. DOI:10.1007/s10973-021-10808-0

Tunçbilek, E., Arıcı, M., Krajčík, M., Li, Y., Jurčević, M., & Nižetić, S. (2022). Impact of nano-enhanced phase change material on thermal performance of building envelope and energy consumption. *International Journal of Energy Research*, 46(14), 20249–20264. DOI:10.1002/er.8200

Vicente, R., & Silva, T. (2014). Brick masonry walls with PCM macrocapsules: An experimental approach. *Applied Thermal Engineering*, 67(1-2), 24–34. DOI:10.1016/j.applthermaleng.2014.02.069

Wang, H., Lu, W., Wu, Z., & Zhang, G. (2020). Parametric analysis of applying PCM wallboards for energy saving in high-rise lightweight buildings in Shanghai. *Renewable Energy*, 145, 52–64. DOI:10.1016/j.renene.2019.05.124

Wang, L., Guo, L., Ren, J., & Kong, X. (2022b). Using of heat thermal storage of PCM and solar energy for distributed clean building heating: A multi-level scale-up research. *Applied Energy*, 321, 119345. DOI:10.1016/j.apenergy.2022.119345

Wang, X., Li, W., Luo, Z., Wang, K., & Shah, S. P. (2022a). A critical review on phase change materials (PCM) for sustainable and energy efficient building: Design, characteristic, performance and application. *Energy and Building*, 260, 111923. DOI:10.1016/j.enbuild.2022.111923

Wei, F., Li, Y., Sui, Q., Lin, X., Chen, L., Chen, Z., & Li, Z. (2018). A novel thermal energy storage system in smart building based on phase change material. *IEEE Transactions on Smart Grid*, 10(3), 2846–2857. DOI:10.1109/TSG.2018.2812160

Williams, J. D., & Peterson, G. P. (2021). A review of thermal property enhancements of low-temperature nano-enhanced phase change materials. *Nanomaterials (Basel, Switzerland)*, 11(10), 2578. DOI:10.3390/nano11102578 PMID:34685017

Xie, J., Wang, W., Liu, J., & Pan, S. (2018). Thermal performance analysis of PCM wallboards for building application based on numerical simulation. *Solar Energy*, 162, 533–540. DOI:10.1016/j.solener.2018.01.069

Xiong, T., Zheng, L., & Shah, K. W. (2020). Nano-enhanced phase change materials (NePCMs): A review of numerical simulations. *Applied Thermal Engineering*, 178, 115492. DOI:10.1016/j.applthermaleng.2020.115492

Xu, Q., Riffat, S., & Zhang, S. (2019). Review of heat recovery technologies for building applications. *Energies*, 12(7), 1285. DOI:10.3390/en12071285

Younsi, Z., & Naji, H. (2020). Numerical simulation and thermal performance of hybrid brick walls embedding a phase change material for passive building applications. *Journal of Thermal Analysis and Calorimetry*, 140(3), 965–978. DOI:10.1007/s10973-019-08950-x

Yuan, K., Shi, J., Aftab, W., Qin, M., Usman, A., Zhou, F., Lv, Y., Gao, S., & Zou, R. (2020). Engineering the thermal conductivity of functional phase-change materials for heat energy conversion, storage, and utilization. *Advanced Functional Materials*, 30(8), 1904228. DOI:10.1002/adfm.201904228

Yun, B. Y., Yang, S., Cho, H. M., Chang, S. J., & Kim, S. (2019). Design and analysis of phase change material based floor heating system for thermal energy storage. *Environmental Research*, 173, 480–488. DOI:10.1016/j.envres.2019.03.049 PMID:30986650

Zeinelabdein, R., Omer, S., & Mohamed, E. (2020). Parametric study of a sustainable cooling system integrating phase change material energy storage for buildings. *Journal of Energy Storage*, 32, 101972. DOI:10.1016/j.est.2020.101972

Zhan, H., Mahyuddin, N., Sulaiman, R., & Khayatian, F. (2023). Phase change material (PCM) integrations into buildings in hot climates with simulation access for energy performance and thermal comfort: A review. *Construction & Building Materials*, 397, 132312. DOI:10.1016/j.conbuildmat.2023.132312

Zhang, H., & Wang, X. (2009). Synthesis and properties of microencapsulated n-octadecane with polyurea shells containing different soft segments for heat energy storage and thermal regulation. *Solar Energy Materials and Solar Cells*, 93(8), 1366–1376. DOI:10.1016/j.solmat.2009.02.021

Zhou, D., Zhao, C. Y., & Tian, Y. (2012). Review on thermal energy storage with phase change materials (PCMs) in building applications. *Applied Energy*, 92, 593–605. DOI:10.1016/j.apenergy.2011.08.025

Zhou, Y., & Liu, Z. (2023). A cross-scale 'material-component-system' framework for transition towards zero-carbon buildings and districts with low, medium and high-temperature phase change materials. *Sustainable Cities and Society*, 89, 104378. DOI:10.1016/j.scs.2022.104378

Zhou, Y., & Zheng, S. (2024). A co-simulated material-component-system-district framework for climate-adaption and sustainability transition. *Renewable & Sustainable Energy Reviews*, 192, 114184. DOI:10.1016/j.rser.2023.114184

Zhou, Y., Zheng, S., Liu, Z., Wen, T., Ding, Z., Yan, J., & Zhang, G. (2020). Passive and active phase change materials integrated building energy systems with advanced machine-learning based climate-adaptive designs, intelligent operations, uncertainty-based analysis and optimisations: A state-of-the-art review. *Renewable & Sustainable Energy Reviews*, 130, 109889. DOI:10.1016/j.rser.2020.109889

Zhou, Y., Zheng, S., Liu, Z., Wen, T., Ding, Z., Yan, J., & Zhang, G. (2020). Passive and active phase change materials integrated building energy systems with advanced machine-learning based climate-adaptive designs, intelligent operations, uncertainty-based analysis and optimisations: A state-of-the-art review. *Renewable & Sustainable Energy Reviews*, 130, 109889. DOI:10.1016/j.rser.2020.109889

Zhou, Y., Zheng, S., & Zhang, G. (2019). Study on the energy performance enhancement of a new PCMs integrated hybrid system with the active cooling and hybrid ventilations. *Energy*, 179, 111–128. DOI:10.1016/j.energy.2019.04.173