

Original Article

# Phase Change Materials for Thermal Energy Storage: Materials, Methods of Enhancements, Applications with Future Prospects and Challenges

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**Abstract** - The growing need to use clean energy worldwide has increased the level of attention to effective energy storage systems capable of resolving the fluctuations of renewable energy sources like solar and wind. Phase Change Materials (PCMs) have become a promising technology among thermal energy storage technologies since they can take up and give up large quantities of latent heat during phase changes at nearly constant temperatures. The review focuses on the key PCM types that are organic, inorganic, eutectic, and polymer-based materials and evaluates the appropriateness of these materials in renewable energy applications. Special focus is made on some of the crucial thermophysical characteristics, such as melting temperature, latent heat capacity, thermal conductivity, cycling stability, and environmental compatibility, since they have a significant impact on the efficiency of thermal storage. The review also points out the latest advances in PCM improvement methods, including nano-enhanced materials, composite PCMs, and novel encapsulation mechanisms, which enhance heat transfer, reliability, and the performance of the system, in general. Moreover, the application of PCMs to renewable energy technologies, such as solar thermal collectors, photovoltaic-thermal systems, building energy management, electronics cooling, and thermal storage units, is mentioned. Despite the fact that supercooling, phase separation, leakage, and cost remain the major obstacles in the way of adopting it, PCMs still hold significant promise in enhancing thermal management, renewable energy use, and enabling the shift to more sustainable energy systems.

**Keywords** - Phase Change Material, Renewable Energy System, Thermal Energy Storage, Latent Heat, Nanoencapsulation, Energy Efficiency.

## 1. Introduction

Latent heat storage is a sophisticated thermal energy management method that exploits the substantial energy absorbed or released when a material changes its physical state, such as from solid to liquid. This process, known as a phase change, occurs at an almost constant temperature, offering superior energy density and temperature stabilization compared to simply heating or cooling a material within a single phase.

Phase change materials are substances that can absorb and release large amounts of thermal energy in their change between solid and liquid phases, taking advantage of the latent heat of fusion, to store energy at a near-steady temperature. This is because of the ability of PCMs to retain thermal energy in a significantly more efficient way compared to standard sensible heat storage materials, which can only store energy as changes in temperature. The global shift to sustainable energy infrastructure requires optimization of renewable energy

systems to reduce climate change and minimize dependence on exhaustible fossil fuel reserves [1]. Again, the nature of the intermittency of natural sources like solar and wind power requires the use of strong energy storage networks to fill the difference between the supply and demand [2, 3]. Thermal energy storage (especially the use of phase change materials) has become one of the solutions of great concern to overcome the time difference between the production and consumption of energy by storing the surplus thermal energy to be used later [4]. These materials work by absorbing and releasing latent heat over phase changes, normally between solid and liquid phases, and hence can store large amounts of energy within them relative to sensible heat storage systems [6, 7]. The given capability enables PCMs to keep the temperature almost constant throughout the charging and discharging process, which is necessary to stabilize the output of variable renewable energy sources and enhance the overall stability of the power supply [8]. These storage systems make grid balancing in real-time, minimize excess renewable generation



curtailment, and provide demand-side flexibility [9]. Moreover, PCMs can be integrated into the energy systems to enable the excess thermal energy to be collected during high renewable availability that can later be discharged during dips in the generation to balance the supply and stabilize the grid [10].

The primary problems with renewable energy include efficiency and intermittency since renewable sources such as solar and wind energy rely on stochastic environmental conditions, and it is challenging to have a reliable and stable energy flow without efficient storage options or grid enhancements [11, 12]. The inherent variability of these resources causes a time lag between the high generation levels and the real consumer demand, and this requires the implementation of advanced storage systems that provide a buffer against the changes and maintain the supply of power at all times [13]. This time lag is especially severe in solar and wind generating systems, where the generation capacity of the energy is highly sensitive to the weather conditions and varies independently of the patterns of the consumer demand, requiring a well-developed storage system to maintain an uninterrupted energy supply [14, 15]. To overcome these difficulties, thermal energy storage technologies have been developed as an essential element of overcoming the discrepancy between energy supply and demand, especially the latent heat capacity of PCMs to store and release thermal energy at a certain temperature [16]. Latent heat thermal energy storage systems take advantage of this process to store and release energy via the melting and solidification processes to offer a flexible solution to the intermittency of solar energy supply at night or when it is overcast [17]. This ability is effective in averting the problems that are related to the intermittency, dispersion, and inefficiency of solar energy [18].

The thermal energy storage systems are crucial in the balancing of energy supply and demand, especially in areas that use PCMs in domestic hot water supply, space heating, space cooling, etc., where the latent heat stored in the PCM during the phase change process is released [19]. PCMs are able to offer high storage density in a narrow temperature range by retaining a constant temperature during phase transitions, which allows their application in thermal storage of energy and passive temperature regulation [20]. PCMs have been proven to support solar thermal power by storing surplus heat to be used later, have been shown to enhance the use of wind-linked storage with thermal buffering, and have been shown to be used in conjunction with biomass and geothermal to stabilize power output and allow compact thermal mass in building envelopes to produce more energy efficiency [21]. These materials are especially beneficial in lightweight constructions where thermal mass would be constrained because they have more heat storage density and isothermal characteristics when charging and discharging cycles occur [22]. Environmentally, PCMs can be used to reduce

greenhouse gas emissions through the reduction of the use of fossil fuels. Economically, PCMs have a chance to save money through reducing the need to add more energy infrastructure, as well as improving the efficiency of already-existing renewable-energy installations. The efficiency to store energy can also delay the process of upgrading the grid at high costs, as well as lower the expense of energy to the consumer [23].

The purpose of this review is to compare and contrast various classes of phase change materials utilized in renewable energy systems, with a particular emphasis placed on the impact of PCM selection and integration on the energy system in general. It lists and discusses reported thermophysical properties, performance results, and factors of practical implementation in the fields of solar, wind-hybrid, biomass, geothermal, waste heat recovery, and building-integrated applications of renewable uses. The literature review also covers the improvement strategies, such as encapsulation, composite formulations, and heat transfer augmentation, to overcome the typical PCM drawbacks. Another goal is to determine the most appropriate PCM alternatives within certain operating temperature and system needs at the expense of cost, safety, durability, compatibility, and environmental influences. Lastly, the review identifies the existing challenges and gaps in the research and suggests future research and work directions that can help achieve reliable, scalable, and efficient PCM-based thermal energy storage in renewable energy systems.

### **1.1. Novelty of Work**

- All valuable aspects related to properties of phase change material have been extensively reviewed from the existing context of Literature and focused on highlighting the same in the present research.
- Current field of application, Problems encountered there, and Specific solutions for each challenge have been rigorously reviewed and reflected in the context of this research.
- Selection of a particular phase change material for a unique and specific application has been emphasized with due focus on its affordability, safety, durability, compatibility, and environmental impact.
- Active Judgement over existing research gaps has given greater emphasis to minimizing the gap, and the future scope of work has been enlightened.

## **2. Fundamentals of Phase Change Materials**

PCMs are those materials that experience changes in phase (solid to solid, solid to liquid, liquid to gas, or solid to gas) by absorbing, storing, and releasing large amounts of latent heat without a change of temperature [24, 25]. Alteration in environmental conditions has an influence on these materials that alters the material properties during phase transition. This material was discovered and incorporated in

the 1970s [26]. A PCM cycle is not complicated. At temperatures higher than the phase change temperature, the PCM absorbs heat during melting, and absorbs it at nearly constant temperature until the phase change has almost finished. As the temperature decreases, the PCM gives up the heat stored in it and freezes at a temperature close to the same temperature. The cyclic process in PCMs to store thermal energy is illustrated in Figure 1. These materials can be considered to be the rechargeable batteries of nature to absorb, store, and release heat to make the environment comfortable and energy-efficient.

Figure 1 shows the cyclic process in PCMs to store thermal energy. These materials act like nature’s rechargeable batteries to absorb, store, and release heat to keep the environment comfortable and energy-efficient.

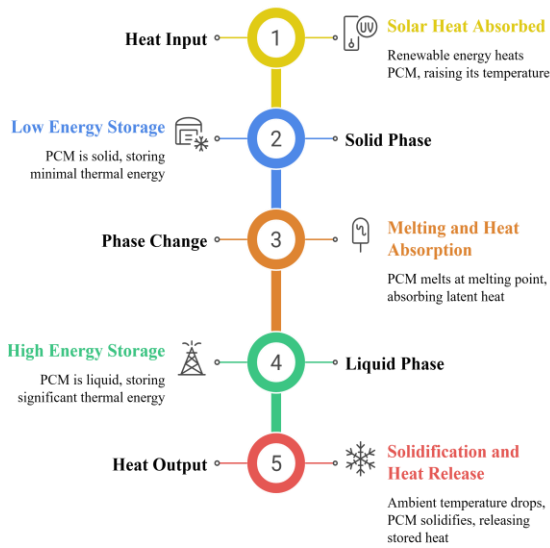


Fig. 1 Thermal energy storage process in PCM

Latent heat storage is based on the absorption and release of thermal energy in a phase change (melting, solidification) at a comparatively constant temperature and can store 5-14 times as much heat per unit volume as sensible heat storage materials like water, masonry, or rock [12, 13, 27]. This enhanced storage capability has made PCMs a leading method in passive cooling and heating systems in buildings, and among its advantages are constant regulation of temperatures, peak load minimization, and enhanced envelope energy efficiency [28]. When PCMs are incorporated into the building structures, the PCMs are able to absorb excess heat when the building is melting, thus postponing the heat transfer process and causing low temperatures of the interiors, and the latent heat that was stored is then released when they solidify at night. The PCMs are able to maintain thermal comfort and reduce cooling energy use [29]. Table 1 shows the comparative differences between sensible heat storage and latent heat storage (PCM) in their energy storage mechanisms and temperature change during the charging and discharging process.

Table 1. Latent vs. Sensible heat storage: Comparative analysis

Parameter	Sensible Heat Storage	Latent Heat Storage (PCM)
Energy Mechanism	Temperature change within a single phase (solid, liquid, or gas).	Phase transition (e.g., solid–liquid) at a constant temperature.
Temperature Profile	Continuous temperature increases during charging and decreases during discharging.	Presence of a temperature plateau during the phase change process.
Energy Density	Moderate; depends on the material's heat capacity and achievable temperature swing.	High; dominated by the latent heat of fusion, allowing more energy storage per unit volume.
Primary Materials	Water, rock, concrete.	Organic PCMs (paraffin, fatty acids), Inorganic PCMs (salt hydrates), Eutectic mixtures.

For example, paraffin wax PCMs can store 150–250 kJ/kg as latent heat during melting, while water would require a large temperature increase to store a comparable amount of energy sensibly. This enables PCM-based systems to achieve the same thermal storage capacity in a significantly smaller volume than water-based systems.

The solid-liquid transition is a complicated heat transfer process in which the substance absorbs latent heat at a fixed temperature during melting to create a moving boundary interface called the melting front [30]. In the process, the conductivity of the PCM is a major factor in regulating the rate at which heat can pass through the storage system since low conductivity may reduce the power density of the storage system, even though the material may have a high energy storage capacity [31]. To counter this drawback, different types of enhancement methods of heat transfer have been devised, like the addition of metal foams, fins, or nanoparticles, in order to augment the effective thermal conductivity of the composite system [9]. Such improved heat transfer rates and better thermal response of the storage unit make PCMs more feasible in real-life applications, where fast charging and discharging are needed [32]. Despite this, a major drawback of most PCMs is their low thermal conductivity, which is a fundamental constraint hindering their capacity to absorb or release heat in a reasonable time, causing long charging and discharging times that impair the operation of latent heat thermal energy storage units [33]. The most common solid-liquid PCMs like paraffin and inorganic salts have transition temperatures between 10 and 200°C, but often have low thermal conductivities between 0.1 and 0.4

W/m.K in organic forms, which grossly limits their charge and discharge rates [34]. Table 2 gives a clear look at the most

important properties of PCMs. It also points out the way each property affects the intended functions.

**Table 2. Important properties of PCMs and their engineering importance**

PCM property	Importance
Melting or phase change temperature range	Must match the system operating temperature so the PCM stores and releases energy at the right time. Typical Range: 0-120°C (class dependent)
Latent heat of fusion	Higher latent heat stores more energy per kg, improving storage capacity and overall efficiency. Typical Range: 150-350 kJ/kg
Specific heat capacity	Adds sensible heat storage and improves temperature buffering outside the phase change range. Typical Range: 1.5 to 4 J/g.K
Thermal conductivity	Controls charging and discharging speed; low values cause slow response and lower usable power. Typical Range: 0.2-1.2 W/m.K (solid/liquid)
Density	It affects the energy stored per unit volume and the size and weight of the storage unit. Typical Range: 800-1600 kg/m <sup>3</sup>
Volume change during phase change	Large expansion can create stress, leakage risk, and container damage over repeated cycles. <10%
Supercooling degree	Delays solidification and heat release, reducing performance when energy is needed. <1-5°C (mitigated)
Phase separation tendency	Reduces repeatability and degrades storage capacity over cycles, especially in salt hydrates and mixtures.
Cycling stability	Indicates whether properties remain stable over many melt-freeze cycles, which is critical for long-term use.
Chemical stability	Prevents decomposition or oxidation, maintaining consistent performance in real operating conditions. Non-aggressive
Thermal stability limit	Sets the safe maximum operating temperature and avoids breakdown during high-temperature charging.
Compatibility and corrosion	Ensures the PCM does not react with container materials, preventing corrosion, leaks, and contamination.
Viscosity in the liquid phase	Affects natural convection and heat transfer; higher viscosity can slow melting and charging.
Flammability and toxicity	Determines safety needs, indoor suitability, handling, and regulatory compliance.
Cost and availability	Drives feasibility for large-scale deployment and whether efficiency gains justify the investment.
Environmental impact and recyclability	Matters for sustainable adoption, disposal, and life cycle benefits.

One of the basic selection criteria is the melting temperature, which should be compatible with the particular working range of the application to make the phase change at the necessary thermal threshold to have a high energy storage and release rate [35]. Thermal conductivity is also important, as it decides the speed of the process of heat absorption or loss in the process of the phase transition, which directly affects the power density and responsiveness of the storage system [36]. Another important parameter is the latent heat capacity, which is a measure of the thermal energy that is stored per unit mass of the phase transition and has a direct influence on the overall energy storage density of the system [37]. Such factors as thermophysical stability and compatibility are also critical since they allow for guaranteeing that the material will be able to endure multiple melting and solidification cycles without any drastic degradation or phase segregation throughout the range of operation of the system. Moreover, the supercooling and phase separation propensity of inorganic materials, as well

as leaking liquids in organic materials, pose further reliability problems that should be overcome by developing material formulations and encapsulation solutions [38]. An example is the addition of expanded graphite into the paraffin-based matrices, which has shown the capability to raise thermal conductivity to 7.654 W/m.K with a latent heat of 141.74 J/g, but the addition of conductive fillers tends to reduce overall storage capacity slightly [39]. Eutectic mixtures, e.g., potassium nitrate-sodium nitrate, provide a sharp melting point to control temperature closely with latent heat values of 150 to 300 J/g and moderate thermal conductivity of 0.5 to 1.5 W/m.K [7]. However, the slow thermal conductivity of organic PCMs is still a major constraint that limits their charge and discharge rate in thermal energy storage systems despite this moderate conductivity [30]. To overcome this limitation, researchers have determined that a minimum thermal conductivity of 20 W m<sup>-1</sup> K<sup>-1</sup> is necessary to utilize the entire storage capacity of a PCM when heat must be rejected at a 1C-

rate, or lower power densities of about  $2.5 \text{ W m}^{-1} \text{ K}^{-1}$  are needed when lower power densities are needed [40]. As a result, a common method of increasing thermal conductivity is by the incorporation of thermally conductive fillers or matrices, which is bound to decrease the overall storage capacity, since the filler replaces a section of the active phase change material [40]. Indicatively, addition of ultrathin-graphite foams at volume fractions between 0.8 and 1.2 vol% has demonstrated to enhance thermal conductivity by up to 18 times to a value of  $1.28 \text{ Wm}^{-1} \text{ K}^{-1}$  [32]. Equally, addition of expanded graphite to molten salt mixtures has been shown to enhance thermal conductivity in molten salt mixtures significantly, one study indicating that a composite PCM has a thermal conductivity of  $4.884 \text{ W/m}^3\text{K}$ , though with a loss in overall latent heat of approximately 11.0% [41].

During the solid-liquid transition, density change and volume expansion take place, which may cause mechanical stress on the containment systems that have to be accommodated by proper design and allocation of void space. Another major challenge is supercooling, especially in inorganic PCMs, in which the material will be in a liquid state below its freezing point before suddenly solidifying, implying that it will take longer to produce energy and decrease the reliability of the system [39]. Long-term performance requires cycling stability and chemical compatibility because repeated phase transition may lead to degradation of thermophysical properties, phase separation in hydrated salts, or leakage in organic substances, reducing long-term storage capacity [42]. The capability of PCM to preserve its thermophysical characteristics and latent heat capacity through many melting and solidification cycles without major degradation is known as cycling stability [39]. The chemical stability of a material is important because it is not allowed to decompose or react adversely with the containment materials during extended thermal exposure, and compatibility with encapsulation matrices and heat exchanger hardware is important to avoid corrosion or leakage and the resultant disintegration of the system [16, 43]. Safety factors such as flammability, toxicity, and corrosion are important selection factors that dictate the environmental performance and operating safety of phase change materials in real-world applications. Long-term performance requires cycling stability, chemical stability, and compatibility since repeated phase transitions may lead to degradation of thermophysical properties, phase separation in hydrated salts, or leakage in organic materials, which reduce storage capacity with time [44]. The storage system may be unstable in the long term because of inadequate stability of material properties when subjected to extensive thermal cycling and corrosion or chemical incompatibility between the PCM and its container [45]. The stability of cycling is especially important where cycling will be used in concentrated solar power plants, where it is anticipated that the storage system will complete a total of over 8,500 charge and discharge cycles during a 25-year operating lifetime, and where materials should be developed that will not lose their

storage capacity over this time period [45]. This gradual decrease in the latent heat is usually witnessed in substances such as erythritol, myo-inositol, galactitol, and D-mannitol as a result of polymorphism and oxidation when exposed to air [46]. In order to evaluate these degradation processes, thermal cycling tests are performed to evaluate performance degradation. Fourier transform infrared spectroscopy and thermogravimetric analysis are undertaken to determine the limits of thermal decomposition and chemical stability, respectively [47].

### 3. Classifications of PCM

PCM classification is the grouping of phase change materials into families based on their chemical nature and melting behavior. The most common grouping is organic, inorganic, and eutectic. PCMs used for latent heat thermal energy storage fall into distinct classes, depending on phase transformation technique, as detailed in the classification given in Figure 2. Comparison of different thermal energy storage based on sensible, latent, and chemical thermal energy is represented in Figure 3.

A brief insight into the temperature range of operation, commercial viability with its status and durability, and storage density of thermal energy storage is highlighted in Figure 4. It is evident from the given status that the durability of sensible heat storage materials is approximately 20 years, related to latent heat storage materials, which is about one-fourth of that, and thermos chemical energy storage is found to be one-tenth of the lifetime of sensible heat storage materials.

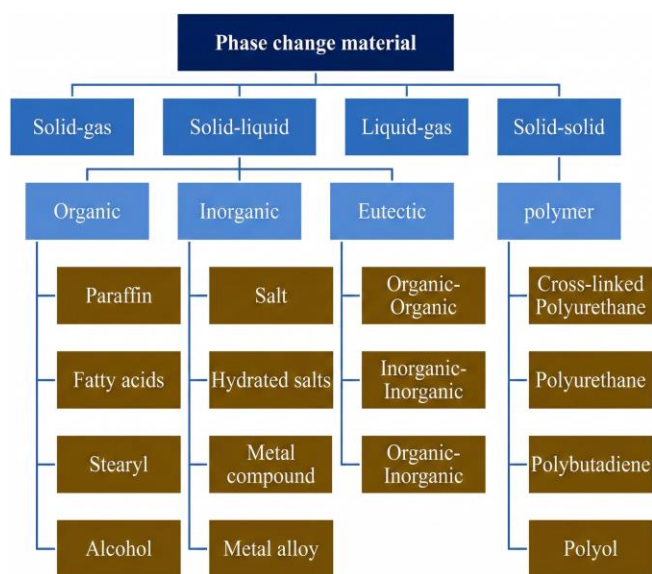


Fig. 2 Phase change material classifications

#### 3.1. Organic PCM

These materials (e.g., paraffins, fatty acids, and polyethylene glycols) are characterized by large latent heat capacity, low supercooling, and congruent melting behaviour, making them useful in a variety of applications, including

solar energy systems, building insulation, and textiles used to regulate temperature (48,49). Although these materials have these benefits, they are characterized by low thermal conductivity and the tendency to leak in the molten state, which can be addressed through the addition of conductive

fillers or by encapsulation methods [50, 51]. Paraffin (by-products of crude oil refining) is characterized by substantial heat storage capacity, non-toxicity, and commercial availability, but has disadvantages such as low thermal conductivity (approximately 0.2 W/m.K).

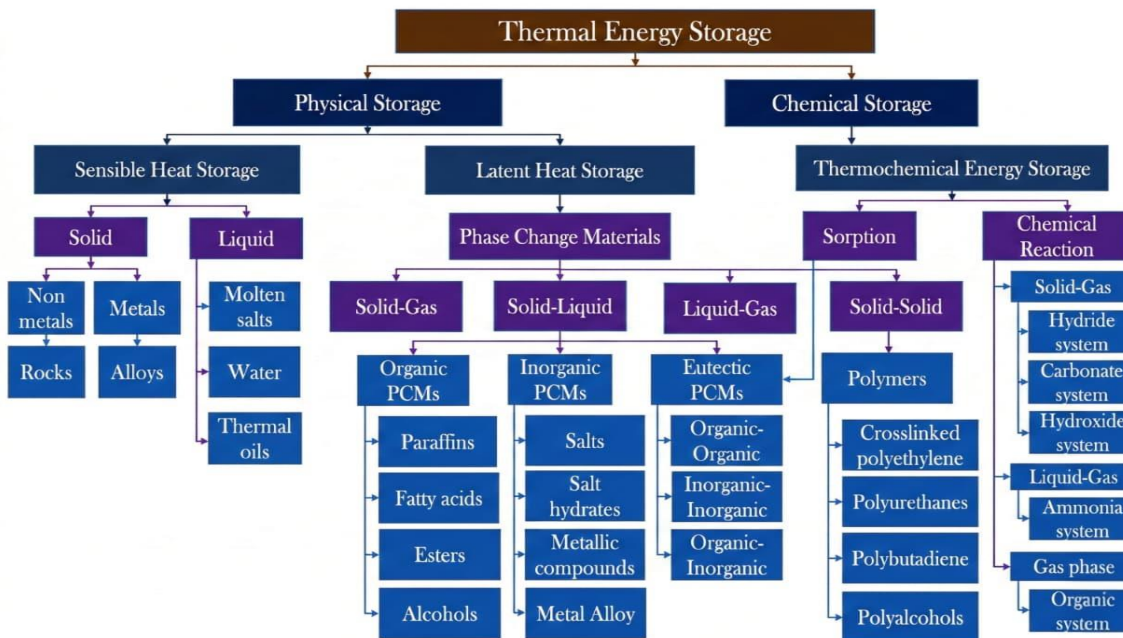


Fig. 3 Classification of PCMs for thermal energy storage

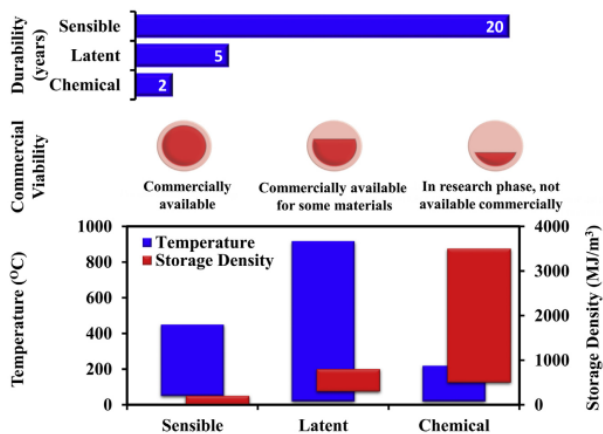


Fig. 4 Comparison of PCMs for thermal energy storage

Fatty acids are an alternative, more important type of organic PCM, with their own unique benefits of high heat capacity, very minimal supercooling, and low vapor pressure [52]. These are bio-based compounds, such as stearic and palmitic acid, that are produced using renewable sources and have a high level of chemical stability even after repeated melting and freezing [53, 54]. Still, issues concerning flammability and thermal conductivity usually require the incorporation of additives or composite construction to improve the performance and safety [55, 56]. In order to

overcome these drawbacks, researchers have come up with composite materials that incorporate organic PCMs with porous matrices or high-conductivity nanoparticles to enhance thermal response and eliminate leakage during phase changes [57, 58]. It has become especially evident that microencapsulation methods are especially useful for the confinement of organic PCM between protective shell materials to ensure that leakage does not occur and that the risk of combustion is minimized without compromising thermal storage density [53]. In this method, the core material is encased by a polymer or an inorganic shell to increase thermal stability and the life cycle of the substance undergoing phase change [29, 53]. In addition, the choice of the right shell materials plays a significant role in maximizing the mechanical strength and thermal conductivity of the microcapsules, and recent research has shown the effectiveness of organic and inorganic hybrid shells in improving the overall functionality [53].

The organic PCMs are carbon-based materials, most of them originating as hydrocarbons, e.g., paraffins (linear alkanes) and non-paraffin organics, e.g., fatty acids. Paraffin Compounds are hydrocarbons that have a better use in cooling systems because of their capacity for retaining heat. They typically melt between 20 70°C. Fatty Acids are greener substitutes, and their melting points are usually between 20 °C and 50 °C.

#### Advantages

- Chemically stable with good long-term cycling stability.
- Exhibit little to no supercooling.
- Non-corrosive to most container materials.
- Compatible with many building materials.

#### Limitations

- Low thermal conductivity (around  $0.2 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$ ), which limits heat transfer rates unless enhanced with fillers.
- Flammability is a concern, particularly for paraffins.
- Generally, have a lower volumetric energy density than inorganic PCMs.
- It can be more expensive than some inorganic options.

### 3.2. Inorganic

The main types of inorganic PCMs include hydrated salts, molten salts, metals, and alloys that have a characteristic wide range of phase transition temperatures, high thermal conductivity, non-flammable, and relatively low costs in contrast to their organic counterparts [59, 60]. One of the most commonly studied classes of inorganic PCMs is salt hydrates, which are ionic compounds containing water of crystallization in the crystal lattices and are usually characterized by a large volumetric latent heat storage density [50, 53]. Again, common practical issues with these materials include the incompatibility of melting, phase segregation, and substantial supercooling of the solidification process [61, 35]. Supercooling may cause poor heat recovery and inefficiency of the system, and phase segregation may cause a decrease in latent heat storage capacity with repeated thermal cycles [53, 62]. To reduce the problem, scientists have considered the addition of nucleating agents and thickening materials to facilitate congruent melting and avoid sedimentation in the salt hydrate matrix [63]. Although these changes have been made, salt hydrates are mostly incompatible with metallic containers because they are corrosive and, therefore, require the application of protective finishes or special encapsulation techniques to guarantee the long-term stability of systems [64, 65]. In addition to salt hydrates, molten salts and metallic alloys are also major types of inorganic PCMs, especially when high temperature thermal energy storage is required in concentrated solar power plants [59, 45]. These systems prefer molten salts (e.g., nitrates, chlorides, carbonates, etc.) as they are highly thermally stable, possess low vapor pressure, and can be used at temperatures above  $500 \text{ }^\circ\text{C}$ , matching the demands of steam turbines and other high-temperature power generation cycles [45]. Another type of inorganic PCMs, which are also known as metallic alloys, possess a high thermal conductivity and volumetric heat storage density, which makes them usable in the context of applications with a high heat transfer rate [65]. However, the inherent limitations of inorganic PCMs that hinder their extensive application include corrosiveness, low nucleation rates that cause supercooling, and large volume change during the transition of the phase [45, 66]. These changes in volume may cause

mechanical stress on the containment vessels, which may cause structural failure or release of the storage medium [45]. Moreover, inorganic PCM encapsulations pose further challenges in engineering, with microcapsule coats being fragile and having low latent heat, and macro-encapsulation designs having to consider that the material will tend to melt or dehydrate incongruently during long-term thermal cycling [59, 67]. Therefore, the thermal reliability and cyclability over the long term of inorganic PCMs is still a significant issue that needs to be optimized further on materials and improved engineering solutions to enable their wider use in actual thermal energy storage systems [68, 69]. Alternative materials like metallic PCMs have been proposed as possible alternatives to the inorganic salts to use in high temperature operation with high thermal conductivity, low subcooling, but with high density and oxidizability, have to be encapsulated to achieve sustainable operation [45].

This category includes salt hydrates, anhydrous salts, and metallic alloys. They generally offer higher thermal conductivity and volumetric storage density than organic PCMs. Salt hydrates are compounds of salt and water (e.g., sodium sulfate decahydrate). They are used in a wide temperature range, commonly from  $8$  to  $120^\circ\text{C}$ . Metals are though less common due to cost, metallic PCMs offer extraordinarily high thermal conductivity.

#### Advantages

- Non-flammable.
- High thermal conductivity and latent heat storage capacity.
- Often available at low cost.
- Low volume change during phase transition.

#### Limitations

- Prone to supercooling, where the material remains liquid below its freezing point
- It can suffer from phase segregation and incongruent melting, leading to performance degradation.
- Corrosive to many metals, requiring careful container selection.
- May exhibit chemical instability and lack of thermal stability over many cycles.

### 3.3. Eutectic

Eutectic phase change materials are prepared through two or more constituents to form a mixture with the lowest melting temperature and have the benefit of a sharp melting point and high volumetric heat storage density [1]. These mixtures are accordingly melted and solidified at a lower temperature than the components, offering a large selection of operational temperatures and high latent heat of fusion as well as excellent chemical and thermal stability [1]. In spite of these advantages, issues like liquid leakage, phase separation,

supercooling, and low thermal conductivity continue to be encountered in their real-life application [2]. To overcome these limitations, researchers have examined encapsulation and shape-stabilization technologies whereby the PCM core is enclosed in a protective shell to avoid leakage and still achieve thermal performance [3]. Organic-organic, organic-inorganic, or inorganic-inorganic mixtures can be designed to fit particular thermal needs by making eutectic mixtures, which are immiscible in the solid state and non-reactive between the components [3, 4]. This customizability enables the accurate control of melting points and latent heat values, and therefore, eutectic PCMs can find various applications, including building envelopes and solar energy storage [5, 6]. An example is that varying weight proportions of constituents can be used to easily change the melting point; that is, at each temperature range, a number of possible eutectic PCM mixtures can be achieved to promote the selection of the most desirable in the specific application [3]. Despite this, the natural constraints of pure eutectic mixtures, including low thermal conductivity and phase separation, require the creation of new high-tech composite phase change materials by chemical modification or the addition of functional additives [8]. One of such strategies has been the integration of carbon-based nanomaterials, as it has been found promising to dramatically improve the thermal conductivity of inorganic salt hydrate-based eutectic PCMs, which are highly sought after in low-temperature applications such as those with high melting enthalpy [4]. As an illustration, addition of expanded graphite has been reported to enhance thermal conductivity by up to 200 percent and at the same time lowering the possibility of leakage due to the ability of the material to maintain its shape even after melting [5, 9]. On the same note, polyurethane coating application has also been effectively used to create form-stable PCM based on eutectic mixtures of hydrated salts, which, in turn, showed no supercooling and high thermal reliability when cycling tests were performed [4].

One fundamental benefit of phase change materials (PCMs) is that eutectic mixtures can have sharp and well-defined phase boundaries. This property can be well illustrated using Differential Scanning Calorimetry (DSC) data, which gives an insight into the melting temperature and the steepness of the phase transition range. Eutectic mixtures may also have a distinct, sharp melting point at a given temperature. Indicatively, one study identifies a eutectic composition, which exhibits one sharp melting event at the lowest temperature observed in all the compositions. Such sharp melting characteristics are characteristic of eutectic systems, and all components liquefy at the eutectic point [70].

$\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O} + \text{Na}_2\text{CO}_3 \cdot 10\text{H}_2\text{O}$  eutectic mixture, in a 50:50 wt% ratio, melts at 25.18 °C with a high melting enthalpy of 187.46 J/g. The DSC data of this system shows that the melting range is well defined and narrow, which is crucial to the efficient storage and retrieval of thermal energy. Eutectic mixtures have sharp melting behavior, which is

frequently retained through several thermal cycles. As an example, it was found that 78 percent of the melting enthalpy could be recovered after 10 melt/freeze cycles in a eutectic mixture which exhibited consistent phase transition behaviour [71]. A binary eutectic salt with a melting point of 76.4 °C and a latent heat of 189.4 J/g is another example. The DSC results establish a sharp phase transition, which makes it appropriate for solar power storage systems. An eutectic salt of  $\text{NH}_4\text{Al}(\text{SO}_4)_2 \cdot 12\text{H}_2\text{O}$  and  $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$ , with optimum performance at 55 wt AASD content, and a melting point of 76.4 °C and latent heat of 189.4 J/g [67].

#### Advantages

- Provide great flexibility to tune the phase change temperature for specific applications.
- Generally, avoid the phase segregation problems seen in some salt hydrates due to congruent melting.
- Offer high volumetric thermal storage density and a sharp melting point.

#### Limitations

- Can have a strong odor and be costly.
- May have a lower total latent heat capacity compared to single-component materials.
- Their properties depend strongly on the constituent mix and require experimental verification for long-term stability.

### 3.4. Polymers

Polymer PCMs employ phase changes (primarily solid-liquid) to store and release thermal energy. These changes are accomplished at some temperatures, which enable them to absorb additional heat during increases and release it during decreases. Polymers have emerged very eminent as PCMs owing to their possible use in storage of thermal energy, temperature control in buildings, textiles, electronics and even in medical use. Polymer-based PCMs have a versatile form, better thermal characteristics, and increased durability in comparison to the conventional PCMs, such as paraffin wax and salt hydrates.

Polyurethane, polyacrylates, and polyolefins are popular polymers because of their high mechanical strength, high thermal stability, chemical resistance, and ability to be compatible with other PCMs. These polymers stop the leakage of the PCM in case of phase transitions, which is a key matter in practice, and keep the latent heat storage capacity [72]. The PCM is trapped in a polymer matrix that allows the polymer to maintain its shape in the melting and solidification processes, and this increases the durability and cyclability of the composite. This method is especially significant in the case of organic PCMs such as paraffins and fatty acids, which are likely to melt when melted [73]. The latest studies have been on Solid-Solid Phase Change Materials (SSPCM) using polymers, which do not transform into a liquid during a phase transition. Such materials have the benefits of the elimination

of leakages and increased mechanical strength. Flexible SSPCMs made of polymers have been of interest for use in flexible electronics and wearable thermal management systems. Polymer SSPCMs can be used in different temperature ranges and applications, with phase transition temperature and enthalpy being controllable via polymer chemistry modifications [74].

PCM encapsulating materials are greatly employed as polymers to create micro- or nano-encapsulated composites. Encapsulation improves thermal stability, chemical stability, and safety of PCMs to hand. As an illustration, High-Density Polyethylene (HDPE) has been found to be an especially suitable polymer matrix for organic PCMs because it is compatible and has low leakage rates as compared to other plastics such as low-density polyethylene or polypropylene [73-75]. Nanocomposite approaches, where polymeric matrices are infused with nanoparticles that have a high thermal conductivity, such as graphene, carbon nanotubes, or TiO<sub>2</sub> nanoparticles, have been discovered to show a significant increase in thermal conductivity and storage capacity. Such enhancements address the low thermal conductivity of polymers that is inherent in the functionality of PCM and is one of the main limitations [76, 77]. To capitalize on the flexibility and processability of polymers, thermo-regulating fabrics have been made through polymer-based PCM that is embedded into the fabric. These materials are thermal comfort materials that absorb and emit heat and can therefore be applied in wearable devices and smart clothes [78]. Shape-stabilized PCM made with polymers is a promising solution to energy efficiency in the construction industry since it regulates changes in indoor temperature. They are applied on walls, ceilings, and floors to offer passive

thermal regulation, which reduces heating and cooling load [72].

**Advantages**

- Shape stability due to crosslinked polymer networks.
- Chemical stability and good resistance to corrosion
- Good mechanical strength to be molded into sheets, panels, foams, and coatings.
- Tailorable Properties
- Safety
- Good Cycling Stability

**Disadvantages**

- Lower Latent Heat
- Low Thermal Conductivity
- Flammability
- Expensive
- Limited high-temperature applications
- High volume change compared to liquid PCMs

To choose the right PCM, several thermophysical, chemical, and economic properties have to be balanced. The characteristics of a desirable thermodynamic material are the appropriate melting temperature, high latent heat of fusion, high thermal conductivity, low volume change, and congruent melting. Significant chemical characteristics include non-corrosiveness, non-toxicity, and long-term operating cycle stability. Table 3 indicates the comparative differences between sensible heat storage and latent heat storage (PCM) in their energy storage mechanisms and temperature change during the charging and discharging process.

**Table 3. Comparative characteristics of organic, inorganic, and eutectic phase change materials**

Characteristic	Organic PCMs	Inorganic PCMs	Eutectic PCMs
Primary Examples	Paraffin waxes, Fatty acids	Salt hydrates, Metals	Organic–organic mixtures, Salt–salt mixtures
Latent Heat	Moderate (150–250 kJ·kg <sup>-1</sup> )	High (200–350 kJ·kg <sup>-1</sup> )	Variable
Thermal Conductivity	Low (≈ 0.2 W·m <sup>-1</sup> ·K <sup>-1</sup> )	Moderate to High (0.5–50 W·m <sup>-1</sup> ·K <sup>-1</sup> )	Variable
Supercooling	Minimal	Significant	Moderate
Flammability	Flammable	Non-flammable	Variable
Corrosiveness	Non-corrosive	Corrosive	Variable
Cost	Moderate to High	Low to Moderate	High
Cycling Stability	Good	Can degrade	Requires verification

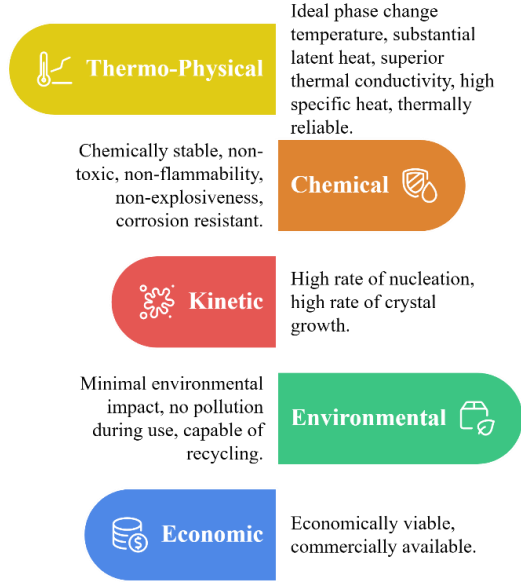
**4. Properties of PCM**

Their unique thermophysical properties make them highly effective for thermal energy storage and temperature regulation applications. Table 4 shows the key properties that define and influence the performance of PCMs. Figure 5

shows the major categories of PCM properties that influence their performance in thermal energy storage systems.

PCMs are characterized by a combination of thermophysical, safety, environmental, economic, and

performance properties [79]. The ideal PCM for a given application should have:



**Fig. 5 Properties of PCMs**

- A melting point matching the operating temperature range.
- High latent heat for efficient energy storage.
- Good thermal conductivity to enable fast heat transfer.

- Minimal volume change and low supercooling for mechanical stability and reliable phase transitions.
- Thermal and cycling stability for long-term use.
- Non-toxic, non-flammable, and environmentally friendly.
- Cost-effectiveness and availability for scalability.

Precise measurement of the PCM properties is a fundamental requirement for materials selection and system design. Standardized characterization methods include:

- Differential Scanning Calorimetry (DSC) is the most common technique used in the determination of the latent heat of fusion and the melting/solidification temperature range.
- Thermal Conductivity can be measured using various techniques, including the hot-disk method or laser flash analysis.
- Cycling Stability Tests involve subjecting the PCM to hundreds or thousands of controlled melting-freezing cycles and periodically measuring key properties like latent heat and melting point to assess degradation.

These are the main characteristics that need to be balanced when choosing a PCM with regard to the particular needs of the application in the trade-offs between energy density and heat transfer: price, long-term stability, safety, and performance.

**Table 4. Properties of Phase Change Materials**

Property	Description	Importance / Impact
Melting Point	The temperature at which PCM changes phase (solid ↔ liquid)	Should match application temperature for effective thermal regulation; maintains nearly constant temperature.
Latent Heat of Fusion	Amount of energy absorbed/released during phase change without temperature change	Higher values mean greater energy storage capacity per unit mass.
Specific Heat Capacity	The heat required to raise the temperature by 1°C in the solid or liquid phase	Influences sensible heat storage outside phase change; complements latent heat storage.
Thermal Conductivity	Rate of heat transfer through the PCM	Low conductivity limits charging/discharging speed; often enhanced with additives or composites.
Density	Mass per unit volume in solid and liquid phases	Affects volumetric energy storage and system sizing.
Volume Change	Expansion or contraction during phase transition	Minimal volume change is preferred to avoid mechanical stress and containment issues.
Supercooling Tendency	Delay in crystallization below the melting point	Low supercooling ensures reliable and repeatable phase transitions.
Thermal & Chemical Stability	Ability to maintain properties and integrity over many thermal cycles	Critical for long-term durability and consistent performance
Non-Toxicity & Safety	Environmental and health safety aspects	Important for building, textile, and consumer applications; non-flammable and eco-friendly preferred.
Cost & Availability	Economic feasibility and material accessibility	Influences scalability and commercial adoption.

### 5. Applications of PCM

The majority of the most advantageous applications of PCMs in various industrial applications and other widely used forms are given below.

- Storage of thermal energy, especially in solar thermal applications.
- Heating and cooling applications (especially in the construction industry and logistics).
- Heat release in electronic devices and transportation.
- Textile industry usage.
- Regulation of food and pharmaceutical preservation temperature.
- Energy management

In addition to buildings, PCMs are crucial in cold chain logistics and medical uses, and a high degree of temperature control is needed when transporting sensitive pharmaceuticals and biological materials. Also, PCMs are used in thermal control of electronic and battery devices as well as textiles to enhance performance and safety, reducing temperature extremes. The ability of PCM to be flexible to a wide variety of melting points and thermal conductivities enables it to be customized to fit a variety of applications, including small-scale cooling-packs (personal data) and large-scale district energy storage. Although these benefits exist, to implement them successfully, it is necessary to pay attention to system integration and consider such factors as thermal conductivity,

stability during cycling, and cost. In general, PCMs are a promising technology to increase energy efficiency and allow sustainable energy systems, and enhance thermal management in a variety of fields. Table 5 shows the major sectors of PCM applications along with quantified performance gains.

A major application is in energy management, with a PCM being a part of a Li-ion battery thermal management system to improve energy efficiency [80]. The use of PCM behaviour in multi-physics simulations of battery degradation can be used to obtain more accurate simulations of battery performance and life in the real world. The advanced strategies of coupling, multi-scale modeling, and the consideration of PCM properties and their interactions with battery systems are required in this integration. Such models have the ability to optimize PCM-enhanced battery designs, and this ensures that they have better thermal management and lower degradation rates. In order to incorporate Phase Change Material (PCM) behaviour in multi-physics battery degradation simulations, thermal dynamics of PCMs have to be coupled with electrochemical, thermal, and mechanical processes that take place in the battery. This is possible by coupled electro-chemo-thermo-mechanical models that are already employed to model battery performance and degradation pathways with different operating conditions [81].

**Table 5. Applications of PCMs and their performance benefits**

Sector	Application Example	Performance Benefit
Building & Construction	PCM walls, ceilings, floors, windows	15–30% HVAC energy savings, up to 25% total energy savings
HVAC	PCM-enhanced systems, AI optimization	Up to 44% energy savings, 85% improved comfort
Electronics	Battery packs, high-heat electronics	Improved lifespan, reduced overheating
Textiles	Smart clothing, sportswear	Stable latent heat after 500 cycles
Automotive	Cabin comfort, battery management	Downsized cooling, improved battery life
Aerospace	Spacecraft thermal regulation	Extreme temperature management
Renewable Energy	Solar/thermal energy storage	Uninterrupted power, load balancing
Biomedical	Vaccine/medicine transport, drug delivery	Maintains cold chain, safe delivery

Cycling stability and supercooling are significant issues in the utilization of PCMs since they may lead to a reduction in the reliability and efficiency of thermal storage in the long run. Also, full-coupled models, which solve the PCM behaviour and the degradation of the battery, may be computationally expensive, and simplified models may need to be used in practice. PCM material, organic, inorganic, or eutectic, also has a significant impact on performance and should be selected to fit a particular battery system in order to achieve thermal management optimization and durability. PCMs and Metal Insulator Transition (MIT) materials show great potential in temperature-dependent electrical switching

with their reversible switch ability between high and low resistance states. Such materials, especially chalcogenide PCMs such as Ge<sub>3</sub>Sb<sub>2</sub>Te<sub>6</sub> and In<sub>3</sub>SbTe<sub>2</sub>, and MIT materials such as VO<sub>2</sub>, demonstrate enormous changes in their properties at phase transitions. PCMs have non-volatile switching properties, and MIT materials have volatile switching properties, which are thermally-controlled [82]. Recent developments have made it possible to characterize the dynamics of phase transitions at nanoseconds with indirectly heated phase-change switches, with a high level of precision in measuring resistance variations under thermal cycling over the melting point. These materials fill the performance gap

between MEMS and semiconductor switches, with low insertion loss, small size, and reliability [83]. They can be used in applications that require reconfigurable RF/mmWave devices and intelligent temperature regulation systems, which use latent heat, optical modulation, and mechanical deformation properties.

Modulators and switches with enhanced modulation efficiency, lower power consumption, and reduced footprints in optical transceivers are built using heterogeneously-integrated optical phase shifters on silicon photonics platforms [84]. To manage thermal behavior, smart power modules utilize a number of thermal monitoring methods, such as sensing, thermal estimators, and observers to signal real-time thermal data with low phase lag that can be actively controlled with enhanced reliability [85]. Superconducting terahertz metamaterials exhibit multifunctional applications as temperature sensors, thermo-optical modulators, and magnetic switches with their special electromagnetic characteristics [86]. Also, liquid crystal technology allows reconfigurable millimeter-wave devices such as tunable phase shifters, filters, and steerable antennas over dielectric waveguides, and demonstrations have been made of phased array antennas and beam steering devices [87]. All these technologies are driving smart electrical systems in terms of increased tunability, sensing, and thermal control.

PCMs have been shown to be useful in Thermal Energy Storage (TES) applications, especially in smaller-scale storage such as building envelopes or solar-thermal collectors. Nevertheless, the extension of PCM systems towards the district or seasonal storage scales also presents special issues that should be evaluated critically.

The thermal cycling stability of the PCM systems on long-term scales is one of the main issues considered by PCM systems at the district or seasonal scales. These systems often involve a single charge/discharge cycle for seasonal storage, with heat stored in the summer and released during the winter. In the course of such long periods of time, PCMs are required to retain their latent heat capacity and phase transition properties without deterioration. Research has indicated the necessity of practical experimentation to determine the stability of PCMs in the long term in these conditions [87]. The thermal conductivity of PCMs is usually low, and this can be a major constraint in their use in large systems. At the scale of the district or season (where the storage volume is large), the low heat transfer rates may result in inefficient charging and discharging processes. This limitation needs to be overcome by some improvements, including the inclusion of high-conductivity materials (e.g., graphene or metal foams) or by using more advanced Heat Transfer Fluids (HTFs) [88]. Theoretically, PCM systems can be scaled, although, in practice, modular and flexible designs are necessary to provide service on a district or seasonal basis. The proposed modular TES solutions, which have been proposed in the

recent literature, can be integrated more easily into the district heating networks and grid-scale energy storage systems. The cost of materials used and complexity of materials integration into a cohesive system can, however, limit the scalability of PCM systems [87]. Economic viability of PCM systems on a district or seasonal basis is also a major obstacle. Although PCMs can be highly competitive in energy density over conventional sensible heat storage systems, their material costs and the additional requirements of advanced encapsulation or thermal conductivity additions can render them less competitive. This requires detailed cost-benefit studies in order to establish whether they are viable on a large-scale basis. In order to circumvent scalability challenges, computational modeling and AI-based optimization are being applied more often to design and simulate PCM-based TES systems. Such tools can be used to maximize system settings, forecast long-term performance, and determine the possible points of failure before a large-scale adoption.

## 6. Challenges Associated with PCMs

Several challenges continue to limit their wide application. One of the key issues is their low thermal conductivity, which reduces their efficiency in the heat transfer during phase transitions and leads to the use of thermal conductivity enhancers. In addition, temporal stability also remains a challenge since repeated phase transitions can lead to materials loss, such as phase segregation in salt hydrates or physical integrity of organic PCMs. Supercooling and leaking in phase transitions are also an issue that brings them challenges of performance and reliability. Beyond these technical hurdles, environmental and biological safety considerations, particularly for bio-derived or eutectic formulations, require meticulous material selection and fine-tuning [88-90]. Therefore, in order to address these problems, there is a need for continuous research and improvements in PCM formulation through advancements in material science and system cost and efficiency that can lead to commercially sustainable phase change materials for various applications. Table 6 indicates the major issues related to PCMs, description of the problems, the most affected PCMs, and the engineering solutions to enhance their performance in thermal energy storage systems. Transitioning from laboratory-scale demonstrations to commercial-scale deployment reveals several critical challenges that must be addressed for widespread PCM adoption.

The system integration barriers are:

- Heat transfer limitations (low thermal conductivity)
- Encapsulation requirements (effective containment to prevent leakage, maintain material integrity, and facilitate heat transfer)
- Long-term performance
- Control system complexity (managing the phase change front and energy flow effectively).

## 7. Fundamental Impact of PCMs on Renewable Energy Storage

Phase Change Materials (PCMs) play a transformative role in renewable energy storage by leveraging their unique ability to store and release thermal energy during phase transitions. The table explores the fundamental impacts [35], [91-94]. Table 7 shows the impacts of PCMs on renewable systems. The basic effect of PCMs on renewable energy storage is that it effectively stores and release thermal energy, balances demand and supply, and works well with the renewable energy systems. They are a very important element in the development of sustainable energy solutions, considering their versatility, scalability, and environmental advantage. One practical point is that PCM-based thermal storage is compared to the traditional sensible heat storage in water.

Advantages of PCMs over water storage are:

- Higher energy storage density per unit volume, leading to smaller storage units.
- Ability to store and release heat at a relatively constant temperature.
- Can reduce the operating cycles (and associated emissions) of backup heating or cooling generation units.

Disadvantages of PCMs compared to water storage are:

- Higher initial investment costs.
- Limited peak discharge power due to thermal conductivity constraints.
- Less established long-term operational experience.
- Risks related to the stability of the PCM solution and deterioration of encapsulation materials.

**Table 6. Challenges of PCMs and proposed improvement strategies**

Challenge	Problem Description	PCMs Most Affected	Proposed Solutions
Low Thermal Conductivity	Many PCMs exhibit low intrinsic thermal conductivity, which slows heat charging and discharging and reduces TES effectiveness.	Mainly organic (paraffins, fatty acids), some polymeric and PEG-based PCMs.	Add high-conductivity structures (metallic fins, foams), carbonaceous additives (graphite, CNTs), or nanoparticles; design compact HX geometries with reduced PCM thickness.
Supercooling	Particularly in salt hydrates, the material cools below its freezing point without crystallizing, delaying or preventing latent heat release.	Inorganic salt hydrates, some eutectic salt mixtures.	Use nucleating agents, seeding, and micro/macro-encapsulation to promote crystallization and reduce supercooling.
Phase Separation	Incongruent melting causes separation of salt and water phases, leading to reduced latent heat and poor cyclic stability.	Inorganic salt hydrates and eutectic salt systems.	Apply encapsulation, thickening/stabilizing agents, and composition optimization to maintain homogeneity during cycling.
High Cost	High-purity or specially formulated PCMs and advanced composites can be expensive, limiting large-scale deployment.	Advanced organic and inorganic composites, nano-enhanced and encapsulated PCMs.	Develop hybrid/composite PCMs with cheaper fillers, utilize waste-based PCMs, and use scalable, low-cost manufacturing and encapsulation methods.
Material Degradation	Thermal and chemical degradation during repeated cycles reduces latent heat, changes the melting point, or causes leakage.	Organic PCMs (paraffins, fatty acids, PEG) and some inorganic salts at high temperature.	Improve stability using antioxidants and stabilizers, suitable encapsulation shells, and compatible container materials; optimize the operation temperature window.
Volume Expansion	Significant volume change across a phase transition induces mechanical stress, risking container deformation or failure.	Many organics (paraffins, fatty acids) and some inorganic PCMs have a large density change between phases.	Design flexible or compliant containment, leave expansion gaps, and use encapsulation geometries that accommodate swelling.
Flammability	The combustibility of many organic PCMs creates fire safety concerns in buildings	Organic PCMs (paraffins, some fatty acids, and polymers).	Incorporate flame retardants, use fire-resistant encapsulation shells, or replace with non-flammable

	and industrial systems.		inorganic or bio-based PCMs where feasible.
Environmental Impact	Petroleum-based PCMs and some inorganic salts raise sustainability, toxicity, and end-of-life disposal concerns.	Fossil-derived organics, some synthetic polymers, and certain inorganic salts.	Develop bio-based/biodegradable and waste-derived PCMs, establish recycling and recovery strategies, and select low-toxicity salts.
Difficulty in Large-Scale Implementation	System-level integration faces issues in heat transfer, encapsulation reliability, and control of charging/discharging in large TES units.	All PCM classes are used in building TES, industrial, and district-scale applications.	Use advanced modelling, optimization, and control, improved HX design, and robust encapsulation to ensure uniform temperature and reliable operation at scale.

Table 7. Major effects of PCMs on renewable energy storage

Aspect	Description
Energy Storage Efficiency	Incorporation of PCMs in applications such as building envelopes and solar thermal collectors has shown notable improvement in overall energy storage performance and thermal regulation behaviour.
Thermal Management and Stability	PCMs provide effective thermal management by maintaining near-constant temperatures during phase change, which is critical for systems requiring controlled operating conditions. This is particularly valuable in battery thermal management for electric vehicles.
Environmental Sustainability	Lowering reliance on fossil fuel-based backup systems and enhancing storage performance, PCMs facilitate the transition to cleaner energy portfolios and align with international climate mitigation and sustainable development strategies.
Economic Viability	PCMs improve economic viability by increasing the effectiveness of existing renewable installations, thereby reducing the requirement for additional generation and storage infrastructure. Their enhanced storage capability can delay or reduce the need for costly grid reinforcement and capacity upgrades, resulting in potential cost savings for both end-users and energy providers.

## 8. Trend and Future Scope of PCMs

The future of PCMs is extensive as it extends into various disciplines such as data storage, photonics, thermal management, and energy storage. The applications and developments of PCMs in the future in various areas are discussed below.

### 8.1. Data Storage and Memory Devices

PCM is a non-volatile memory technology that is still new, but has already passed the research phase to become a storage-class memory [95]. PCM has distinct benefits, as it provides fast storage and large memory, which can be used in new applications in big data analytics and Artificial Intelligence machines [96]. The application of Phase Change Materials (PCMs) in data storage and memory devices is gaining popularity as they are the only material that can be switched between amorphous (non-crystalline) and crystalline states, which is equivalent to binary data (0 and 1). This conversion process is initiated by controlled heating, usually through electrical pulses, and has a number of benefits compared to conventional memory technologies such as flash memory.

Features of PCM in data storage and memory are,

- High-speed switching
- Non-volatile memory
- Endurance and longevity
- Scalability
- Multi-level Storage

PCM has been used in Storage Class Memory (SCM) to achieve a combination of the high speed of DRAM with the long life of NAND flash, which is needed in embedded systems and has to provide fast and reliable memory. Moreover, PCM technology is currently under exploration as next-generation computing, especially in neuromorphic computing and AI, because it can simulate synaptic behaviour [97].

The reversible phase change of amorphous to crystalline has made PCMs revolutionary materials in photonics and optical applications. The transition in this phase is linked by drastic alterations in their optical characteristics, including refractive index and optical absorption, making them convenient in dynamic and reconfigurable optical devices.

**Table 8. Applications of PCMs in photonics and optics**

Application Area	Specific Technology	Role of PCM	Example
Optical Data Storage	Rewritable optical discs	Enables reversible phase transition between amorphous and crystalline states for binary data encoding	Ge–Sb–Te (GST) used in DVDs and Blu-ray discs
Tunable Photonic Devices	Reconfigurable meta-surfaces	Dynamically alters optical properties such as beam steering, focusing, and spectral filtering.	Active beam shaping and adaptive optics
	Tunable waveguides	Controls refractive index to modulate light propagation in integrated photonic circuits	Optical communication systems
Neuromorphic Photonics	Photonic synapses	Mimics biological synaptic behaviour using multi-level phase states for optical signal processing and memory.	Optical neural networks
Display Technologies	Reflective displays	Controls light reflection via phase transition	Low-power e-paper type displays
	Smart windows	Modulates light transmission and reflectivity	Energy-efficient buildings
Optical Modulators & Switches	High-speed optical switching	Enables ultra-fast modulation of optical signals via refractive index contrast	Telecommunication networks
Infrared Optics	Thermal imaging systems	Controls and modulates infrared radiation	IR sensors and defense applications

### 8.2. Photonics and optical applications

PCMs are highly efficient substances in photonics and optical applications since they can undergo reversible phase changes between crystalline and amorphous. The transition in this phase is linked by drastic alterations in their optical characteristics, including refractive index and optical absorption, making them convenient in dynamic and reconfigurable optical devices.

They are versatile and are therefore essential to optical devices of the next generation, such as displays, modulators, and neuromorphic computing systems. Current innovations in material science and engineering of devices will continue to unlock their potential in the use of optical technologies on a large scale [98].

Properties of PCMs in photonics are,

- Refractive index modulation
- Non-volatile switching
- Fast switching speed
- Broadband optical response

The challenges related to the use of Phase Change Materials (PCMs) are stability of the material since continued cycling causes degradation, power consumption since a large amount of thermal energy is needed to make phase transitions, and scalability because the phase change materials are difficult to incorporate into complex photonic circuits. Nevertheless, there exists a chance due to the current research to find new PCMs with superior optical contrast, low-power requirements, and improved cycling stability [99]. Table 8 summarizes applications in photonics and optics, through reversible phase transitions that control optical properties.

### 8.3. Space Exploration

The application of phase change materials in space exploration is mainly in the accurate thermal control, thermal storage of energy, and in the astronaut comfort system in the harsh orbital environment. They are the best materials to use in the stabilization of thermal conditions in spacecraft and other space systems due to their capacity to absorb and release a lot of latent heat during phase changes. Other materials, such as molten silicon and boron, are undergoing tests in order to improve satellite propulsion systems through offering an effective thermal energy storage technology [100-103].

The advantages of PCMs for space exploration are,

- Passive and reliable
- High energy density and mass efficiency
- Temperature stability

Important applications of PCMs in space systems are,

- Satellite thermal control and energy storage
- Avionics and electronics cooling
- Thermal control of instruments (imagers, sensors)
- Spacecraft transport and ground systems
- Spacesuits and textiles

The choice of materials in PCMs, including paraffin and water-ice, is a trade-off of thermal characteristics, mass, and stability to withstand space. The long-term exposure to space may lead to deterioration of PCM properties, thus necessitating a high level of protection and materials. Moreover, void formation during the phase transitions of water-ice systems should be controlled to avoid the expansion damage. Future studies aim at coming up with an improved PCM composite with improved thermal characteristics,

durability, and resistance to space-specific problems. These technologies will also increase the contribution of PCMs to the possibility of sustainable and efficient space exploration.

#### **8.4. Next-Generation Energy Storage**

PCMs are becoming a building block of the next-generation energy storage systems. This characteristic renders PCMs very effective in Thermal Energy Storage (TES), which allows sustainable and dependable solutions to energy [35]. They are especially essential in the renewable energy systems where intermittent sources of energy like solar and wind are subjected to efficient storage technologies in order to have a stable supply of energy. Phase Change Materials (PCMs) are very important in energy storage. In Thermal Energy Storage (TES) systems, they absorb the heat in CdTe plants, storing it during the day and releasing it through the night. They also assist in the integration of renewable energy by storing the excess energy from solar panels and wind turbines to be used in the future to reduce the problem of intermittency. The PCMs incorporated within materials are used in the construction of energy management, reducing the level of consumption through the storage of surplus heat. They are also involved in battery thermal management, whereby they control the temperature to increase battery life. Finally, PCMs allow the storage of seasonal energy, which allows thermal energy storage during the summer and winter periods [104].

Studies on PCMs have been associated with a number of challenges, such as low thermal conductivity, which reduces the efficiency of heat transfer. Continued research is being done to improve thermal properties using nano-enhanced or composite materials. Another issue is the cycling stability because repeated phase changes may deteriorate the PCM performance; hence, it is essential to enhance the durability. The choice of materials is aimed at the identification of cost-effective, non-toxic, and sustainable PCMs that fit within certain temperatures. Moreover, cost-cutting measures such as increasing the scale of production and effective manufacturing methods are needed to make PCM-based energy storage systems cheaper.

#### **8.5. Biomedical and Healthcare Applications**

The potential of PCMs in biomedical and healthcare applications is great due to their thermal energy storage capacity and biocompatibility. PCMs are widely applicable in four areas, namely cold chain storage of vaccines and medicines, drug delivery systems, thermotherapy, and medical dressing [105]. The two PCMs that are the most researched are paraffin wax and polyethylene glycol, which are considered low in toxicity, biocompatible, and thermostable [89]. To increase the level of safety and to avoid the leaking of liquids, different encapsulation techniques have been established, such as microencapsulation, electrospinning technology, and porous framework encapsulation [106]. PCMs have the potential to realize the ability to release drugs in response to temperature in tumour therapy and can be used

in diagnostics with thermal therapy and imaging [107]. Although it promises to be better, the challenges that it currently faces are biosafety concerns and engineering challenges that are yet to be addressed through research and development. The healthcare PCMs have a number of benefits, such as the ability to control temperature precisely, which is necessary in highly sensitive medical cases, non-invasive solutions, such as wearables and thermal packs, energy efficiency, such as passive thermal regulation, and scalability to a number of medical uses. The major issues in developing PCMs to be used in biomedical applications are the biocompatibility, improvement of thermal conductivity, stability, and durability under thermal cycling, costs, and accessibility to make PCMs widely used.

#### **8.6. Thermal Management of Electronics**

Thermal management of electronic devices is an area where PCMs are becoming popular in overcoming the challenges of ever-increasing power densities and miniaturization requirements. These are successful in dealing with transient thermal profiles by the use of latent heat of fusion, and this offers thermal inertia and more stable operating temperatures. It has been determined that PCM integration can help decrease the number of hot spots by 6-10 percent and have more uniform temperature distributions in electronic components. Its uses are in many areas such as portable electronics, power batteries, and spacecraft avionics.

More than 200 PCMs with 0-100 °C operating temperature have been discovered to be used in electronic cooling. The general adoption is, however, not without problems, especially low intrinsic thermal conductivity. These limitations have been overcome by enhancement methods based on internal fins, nanomaterials, and metal foams. Although it has potential, further experimental studies are required to determine practical design processes and to prove the long-term performance [108-110].

PCMs are applied in other electronics engineering studies by controlling heat dissipation, increasing device life, and thermal control. They are installed in the electronic enclosures to absorb the surplus heat and avoid overheating. Heat sinks have PCMs that assist in controlling the transient thermal loads, reducing the thermal stress, and prolonging the life of devices—high-performance electronics. Advanced composite PCMs, such as graphite, maximize heat dissipation. Liquid Metal PCMs (LMPCMs) are highly thermal conducting in small spaces in devices, although with a reduced latent heat.

Generally, PCMs are also significant in cooling small gadgets like cell phones and laptops, where thermal solutions are important. Difficulties that PCMs have encountered are low thermal conductivity, which is a deterrent to the effectiveness of heat transfer, and there has been research on composite PCMs with better qualities. Also, stability of the materials is a factor, and repeated phase changes may impair

performance, so improvements in cycling stability are required. Other economic reasons that hinder widespread use include the high price of the advanced PCMs and their inability to be scaled to mass production. In order to improve thermal control, new designs such as PCM-based structures with metallic pin fin structures are being designed [111].

### 8.7. Nano-Enhanced PCMs (NePCMs)

Although traditional PCMs have a high latent heat storage capacity, they have poor thermal conductivity that limits their heat transfer capacity. This is achieved by integrating nanoparticles in the PCM matrix to improve thermal performance. Indicatively, TiO<sub>2</sub> nanoparticles may be synthesized through the application of continuous spray pyrolysis processes and dispersed in the PCM matrix by using the latest wet impregnation processes to create NePCMs [112]. This outcome has led to the fact that the nano-enhanced PCMs can now store and release a massive amount of heat over brief periods of time, which is quite applicable to thermal storage systems and serves to supplement and enhance their performance [113].

Such materials load 1-2% nanoparticle dispersions, and 700-900% thermal conductivity gains on form-stable PCMs are realized, but with a decrease in the heat storage enthalpy at high concentrations (5-20%) [114]. NePCMs facilitate quicker charging and discharging of thermal energy storage apparatus, and are useful in solar energy use, thermal management of structures, and electronic cooling [113]. Popular nanoparticle materials are Al<sub>2</sub>O<sub>3</sub>, copper, and carbon, and paraffin is the most studied PCM base material [17]. NePCMs have a specific promise in domestic heating at temperatures of 20-70 C, but further experimental research in real-world applications is required instead of merely studying the properties of the materials [115].

NePCMs have a number of advantages, among which is high thermal conductivity that is enhanced up to 300 percent, and high charging/ discharging rates of above 40. Nanoparticles contribute to the enhancement of the efficiency of heat transfer, making it possible to have faster and more homogeneous heat absorption and release. These materials are also efficient in controlling transient heat loads, which keeps the operating temperatures at the optimal levels. Additionally, PCMs based on GNP contribute to the solar energy collection, increasing the voltage of thermoelectric output by approximately 36 percent, which demonstrates their contribution to the enhancement of thermal energy storage. Many nanoparticles have been shown to improve the performance of phase change material (PCM), such as metal oxide nanoparticles (TiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, CuO) to improve thermal conductivity and stability, carbon-based nanomaterials (graphene nanoplatelets, carbon nanotubes, expanded graphite) to increase thermal conductivity greatly, and metallic nanoparticles (Cu, Ag, Au) to be excellent thermal transport materials.

Some of the challenges encountered by NePCMs are nanoparticle agglomeration, cost, long-term stability, optimization of nanoparticle loading, and scalability. Sophisticated methods of dispersion are being formulated to fight agglomeration. Good nanoparticles are more expensive, and therefore cannot be used in large quantities.

A major concern is to ensure that the performance remains consistent on the thermal cycles, as it is now under evaluation by using both computational and experimental analyses. Also, the concentration of nanoparticles is vital in performance, and the problem with nanoparticles is shifting from the laboratory to industrial applications.

### 8.8. Advanced Encapsulation Techniques

Improved phase change materials (PCM) encapsulation methods have become important solutions to improving thermal management in different applications. There are five common types of encapsulations, which include direct mixing, imbibing, shape-stabilization, macro-, and micro-encapsulation [27].

In the case of inorganic PCMs, two major techniques prevail, including the core-shell encapsulation and shape-stabilized PCM systems, whereby core-shell techniques involve in situ polymerization, solvent evaporation, and sol-gel processes [116]. The parameters of encapsulation have a strong influence on the performance, and the thermal conductivity of shell materials has an effect on the interaction of heat transfer and PCM-heat transfer fluids [117].

The thickness of encapsulation is very important, with high encapsulation thickness offering minimum quality against low encapsulation thickness. Current developments are carbon nanotube-based PCMs and nano-enhanced encapsulated PCMs, which offer better thermal control [117, 118]. Although macro-encapsulation is predominant in the commercial applications, micro/nano-encapsulation is considered a promising technology that needs further improvement [27].

Figure 6 displays the various encapsulation methods of PCMs to improve stability and thermal characteristics. Polymer-based microencapsulation has been one of the most successful methods since PCMs get covered in polymer shells using the methods of mini emulsion polymerization, in situ polymerization, interfacial polymerization, and suspension polymerization.

These techniques enable a high degree of control over the size of capsules and shell thickness, with a high potential for thermal control and capsule energy storage. As an example, encapsulation efficiency can be maximized by optimizing the core-to-shell mass ratio [119].

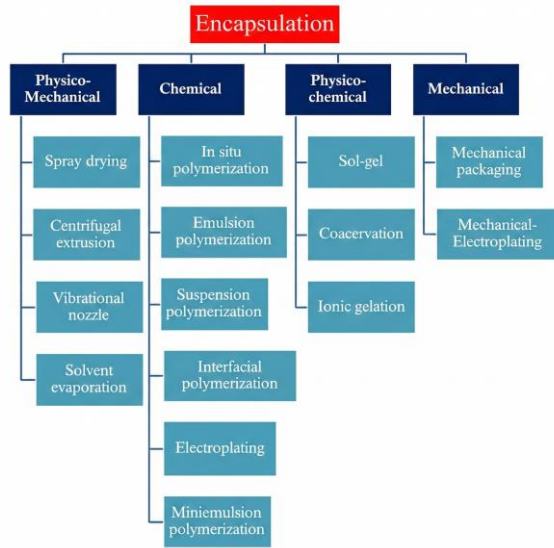


Fig. 6 Encapsulation methods of various PCMs (inorganic)

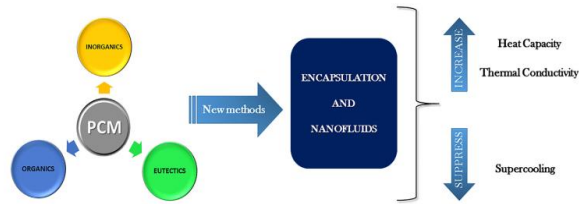


Fig. 7 PCM performance enhancement

Some advanced methods of encapsulation have tried to avoid PCM leakage during phase change and chemical stability in numerous thermal cycles. This includes the choice of shell materials, which are impervious and compatible with the PCM core in terms of chemistry. Moreover, other approaches, including dual encapsulation whereby a secondary shell or skeleton material such as TiO<sub>2</sub> is employed, have also been invented to enhance cyclic strength and mechanical strength [120]. Microencapsulation in the modern world can create capsules of 1-10 micrometers in diameter, a value where the heat transfer rates are much higher than those of bulk PCMs. Microcapsule thermal conductivities could be as high as 0.5-0.8 W/m.K, which is better than conventional PCM forms. Nevertheless, the shell permeability is still an issue, because there may be some leakage during prolonged thermal cycling [121]. Figure 7 shows the enhancement in PCM performance with the use of new techniques like encapsulation and nanofluids that increase the amount of heat capacity, thermal conductivity, and decrease the influence of supercooling.

Encapsulation is divided into physical and chemical encapsulation. Physical techniques comprise the spray cooling, spray drying, and fluidized bed techniques, which aim at coating or embedding Phase Change Materials (PCMs). Chemical techniques include in-situ polymerization (interfacial polycondensation, suspension, and emulsion

polymerization), complex coacervation, sol-gel techniques, and solvent extraction/evaporation, which are customizable in shell properties and better encapsulation efficiency. Recent studies discuss nanomodified and bio-sourced encapsulation shells as a way of enhancing environmental sustainability and thermal performance. As an example, in more advanced systems, nanoporous microparticles can be incorporated in boiling intensification or bio-based polymers can be used as shell materials to improve thermal energy storage and efficiency [122].

8.9. Photovoltaic Thermal (PVT) Systems

Photovoltaic Thermal (PV/T) systems are a potential source of renewable energy that can be used to provide both electricity and thermal energy using solar radiation. Recent studies emphasize a number of major trends that define the future of PV/T systems. Nanomaterials, especially nanofluids and nano-enhanced phase change materials (NEPCMs), have a high potential of enhancing thermal performance, and research has shown that nanomaterials have 8.3% higher capacity to store heat energy during charging and 25.1% higher capacity to give up heat energy during discharging [123]. PV/T collectors are taking three major forms, namely air-cooled, liquid-cooled, and heat pipe systems, each with specific application benefits [124]. PV/T technology is coupled with the heat pump systems; therefore, the possibilities of increased energy efficiency and reduced emissions, and the potential to avoid 911 tons of CO<sub>2</sub> emissions per year, in contrast to the traditional PV systems [123]. The future is built on technological innovation, cost minimization, and expanding the market, but issues are still in the field of thermal energy storage capabilities and optimization of the system [125].

Photovoltaic-Thermal (PVT) systems have been technologically advanced on Spectral Beam Splitting (SBS) to improve the efficiency of the system by separating useful amounts of solar wavelengths to PV cells and the rest to thermal collectors, thereby minimizing heating and maximizing outputs. Thermal energy storage and stability of a system are enhanced with the integration of Phase Change Materials (PCMs). Also, there are bifacial solar panels that absorb sunlight on both sides and, coupled with highly developed thermal collectors, energy production is further enhanced [126]. PVT systems are now being incorporated into building envelopes in Building-Integrated Photovoltaics (BIPV) and Building-Added Photovoltaics (BAPV) systems, such as autonomous switchable glazing and low heat loss glazing. These combinations enhance the efficiency of building energy since they offer both thermal and electrical comfort. Electric vehicles (EVs) are also on the increase, which makes the development of PVT systems as a component of the charging infrastructure where thermal energy can be utilized to heat or cool EV batteries or buildings of interest [127]. Solar thermal and PVT systems will be used in large numbers to achieve ambitious climate objectives. To

illustrate, the International Energy Agency (IEA) estimates that hundreds of millions of solar thermal systems will be installed by 2030, and this will probably involve the use of PVT technologies. There is also a development of concentrated PVT (CPVT) and high-concentration PVT (HCPVT), with the concentrating device, tracking, and cooling technologies now allowing increased efficiencies and new uses.

Based on the current landscape of PCM technology, the following are some interrelated research priorities that are essential for advancing the field:

- Long-term stability and reliability: Structured investigation of degradation mechanisms of PCMs over thousands of thermal cycles alongside the development of standard durability testing protocols.
- Cost reduction and scalability: Assessment of low-cost raw materials, scalable composites, encapsulants manufacturing processes, and sustainable lifecycle approaches.
- Standardization and certification: Formulation of industry-wide standards for characterization, performance testing, and safety certification to increase confidence and accelerate market adoption.
- Comprehensive system integration: Synergizing PCM-container interaction, thermal interface materials, and development of intelligent control systems in order to charge and discharge optimally.
- Advanced characterization: Establishment of in-situ and non-destructive monitoring techniques to track PCM behaviour during phase transitions under actual operating conditions.

Enhancing the synergy between phase-change materials and their enclosures, selecting appropriate heat-transfer coupling agents, and developing smart regulatory frameworks that govern the most efficient energy storage and release cycles.

## 9. Conclusion

- The use of Phase Change Materials has also been an encouraging alternative to thermal storage of energy in renewable energy systems due to their property of storing and releasing high levels of latent heat almost at constant temperatures.
- PCMS could greatly minimize the effects of intermittency in renewable power sources like solar and wind because

the supply and demand of thermal energy could be balanced in a more efficient way.

- The various types of PCMs, such as organic, inorganic, eutectic, and polymer-based materials, have different strengths and weaknesses, and therefore, the choice of the material must be greatly influenced by the intended use.
- The chemical stability and low supercooling behaviour of organic PCMs are considered to be more preferable, whereas the inorganic PCMs have better thermal conductivity and higher volumetric heat storage capacity.
- Eutectic and composite PCMs offer prospects of customized thermal functionality, enhanced structural integrity, and leakage that increase their usefulness in energy systems.
- Recent innovations, including nano-enhancement, encapsulation technologies, and the use of high-conductivity additives, have made PCM-based storage systems significantly better in terms of thermal conductivity, durability, and reliability.
- In spite of these developments, low intrinsic thermal conductivity, phase separation, supercooling, leakage, and high material cost are some of the challenges that are still limiting the large-scale commercialization of PCMs.
- The future study must aim at coming up with cost-effective, environmentally friendly, and high-performance PCM formulations that have superior thermal conductivity and long-term cycling stability.
- In general, PCMs have great potential to enhance thermal management, increase the use of renewable energy, and aid in the creation of efficient and sustainable energy storage technologies.

## Conflict of interest

The authors declared that there is no conflict of interest.

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## Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author, to retain the privacy ethics of research. Also, most of the data is available within the article.

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