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A Review of Organic, Inorganic, and Eutectics Phase Change Materials for Cooling Photovoltaic Solar Panels

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ABSTRACT

One of the most promising passive cooling techniques to lower thermal losses and boost solar energy conversion efficiency, particularly in high-temperature environments, is the integration of phase change materials (PCMs) into photovoltaic modules. This paper's primary goal is to provide a current analytical assessment of the four main types of PCM-based cooling systems, including hybrid, finned, composite, and pure PCM systems. According to the findings, pure PCM systems using paraffin wax (RT42) and hydrated salt (HS36) greatly increase photovoltaic (PV) electrical efficiency by preserving ideal operating temperatures. Composite PCM systems with thermally conductive additives like multiwall carbon nanotubes, graphene nano-platelets, and magnesium oxide (MgO) prove to be much better in terms of heat transfer enhancement and operational stability. Finned PCM systems with zinc nanoparticles or aluminum fins show higher capabilities for heat dissipation. Furthermore, hybrid PCM systems, like the graphene-integrated photovoltaic/thermal (PV/T)-RT35HC-based nano-fluids, demonstrated superior performance, along with efficiency gains. The findings reflect that the latest research trends are more focused on hybrid PCM systems owing to their increased potential for thermal management and PV efficiency improvement.

1. INTRODUCTION

Due to the detrimental effects of their use on the environment, the majority of the world's energy is generated from a small number of conventional sources [1]. Solar power is now among the most plentiful, sustainable, and practical energy sources for producing thermal and electrical energy. For many engineering applications, such as solar power plants, phase change materials (PCMs) offer a viable thermal energy storage (TES) alternative. However, the issue is that the majority of PCM types have extremely low heat conductivity. Some PCMs have demonstrated excellent thermal conductivity; however, because of their high reactivity, they frequently have some unfavorable characteristics like supercooling or corrosiveness. In order to get rid of these undesirable traits, enhancing these materials' heat conductivity has been the subject of extensive research [2]. Heat continues to be a limiting issue for photovoltaic (PV) cells and contributes considerably to a decrease in the amount of electrical energy produced, despite the significant advancements in solar cell technology. This is because semiconductors are inherently sensitive to temperature, which has a detrimental effect and lowers the overall energy generated. In the meantime, depending on the solar cell technology and environmental factors, an efficiency loss of 0.3% to 0.5% occurs for each degree Celsius that the panel temperature rises. By creating and enhancing cooling solutions for solar energy systems, a sizable team of researchers has concentrated on resolving and addressing this issue. In order to collect surplus thermal energy when the panel temperature reaches the PCM's melting point, they strategically integrate PCMs behind the PV panel. As a result, it keeps the working temperature within an ideal range. While separate reviews exist on individual classifications of PCMs (organic, inorganic, or eutectic) and certain improvement techniques (such as nanoparticles or fins), no comprehensive study exists that addresses both aspects and all four kinds of cooling systems (pure, composite, finned, or hybrid) as well as their improvement techniques and lifecycle issues. Moreover, there is no such review that critically analyzes various research findings that reported varying outcomes, particularly those that involved nano-enhancement of PCMs. This gap is filled through a comparative evaluation that allows performance analysis across categories and determines the root causes for the variation found in research outcomes.

The physical and thermal characteristics of organic, inorganic, and eutectic PCMs are reviewed in this work, with an emphasis on their performance in various applications and TES methods. The most recent advancements in improving these materials will also be covered, such as the encapsulation of PCMs to improve stability and the use of nanomaterials to improve thermal conductivity. We'll talk about the most recent advancements in the utilization of phase change materials as a practical cooling solution for solar panels and the impact these

materials have had on raising panel efficiency.

2. METHODOLOGY

In order to achieve a comprehensive review of PCM-assisted solar cooling technologies, an organised literature search and synthesis process was followed for the purpose of this review. The databases used were Scopus, Web of Science, Google Scholar, and ScienceDirect. The time period considered during the review process was from 2006 to 2025, but in order to capture any latest developments, papers after 2018 were prioritised. Some of the keywords used during the literature search include "PCMs, PV cooling, PCM + PV, TES + solar panel, nanofluid PCM, composite PCM, and finned PCM".

The following were the inclusion criteria:

•should consider the integration of PCM into PV thermal management.

•should include at least one metric in terms of temperature reduction, improvement in electrical efficiency, or increase in thermal conductivity.

•must have experimental or numerical data.

The following constituted the exclusion criteria:

•articles that do not consider PV thermal management.

•articles lacking quantifiable data.

•non-English language articles.

Around 129 articles were considered from more than 300 articles collected. The chosen literature was divided into four categories depending on the type of PCM-based cooling system employed, which included pure PCM, composite PCM (with addition), finned PCM, and hybrid PCM (PCM in combination with other cooling technologies). The following criteria were set for the comparative study: five important parameters that define the efficiency of the systems under consideration: "thermal conductivity increase, latent heat storage, PV temperature decrease, electrical efficiency increase, and cost factors".

3. FUNDAMENTALS OF PHASE CHANGE MATERIALS

Latent heat of fusion and thermal conductivity are the two most important thermo-physical properties of PCMs. The Latent heat is the energy released or taken in by a substance during its phase change at an almost constant temperature, which characterizes PCMs' capability to store and release a considerable amount of thermal energy. On the other hand, the rate of heat transport is explained by thermal conductivity. Within the material. Charging and discharging rates are directly influenced by thermal conductivity in TES applications. Therefore, a very high latent heat capacity is desired with a sufficiently high thermal conductivity for efficient TES applications. A typical temperature-energy diagram, Figure 1, depicts the transition of PCMs between solid and liquid phases in the phase change process. In this schematic, the horizontal plateau corresponds to the latent heat region where energy is stored or retrieved without a temperature rise, and the vertical segments of the curve correspond to sensible heat storage in solid and liquid forms. This isothermal plateau is what gives PCMs their unique thermo-physical property as thermal buffers. However, during such a process, the intrinsic thermal conductivity of the material has a significant impact on the energy exchange rate.

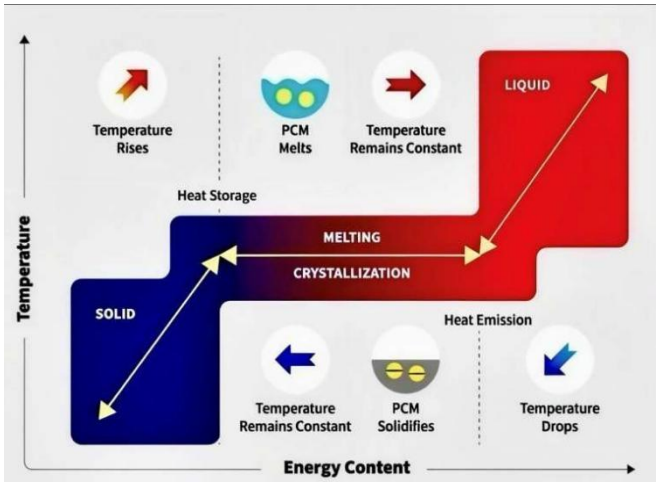

Figure 1. Energy-temperature relationship during phase change material (PCM) phase transition

Heat transfer is hindered by the low thermal conductivity of organic PCMs (mostly paraffins and fatty acids), which typically ranges from 150 to 250 kJ/kg [3]. With greater thermal conductivities of 0.5–4.0 W/(m·K), inorganic salt hydrate and metallic alloy PCMs provide latent heat values as high as 350 kJ/kg. Despite these benefits, these materials have a variety of disadvantages, including phase segregation, supercooling, and corrosion [4].

The creation of composite and nano-enhanced PCM has been extensively researched because of its poor thermal conductivity. For example, Jin et al. [5] found that adding 9 weight percent expanded graphite (EG) reduced the phase-change time by almost 30% and enhanced the thermal conductivity of the composite sodium acetate trihydrate–potassium chloride–urea by more than five times. Accordingly, Yang et al. [6] came to the conclusion that PCMs must be developed to meet the increased demands for power density and reliability in TES systems while maintaining the optimal latent heat values. The optimization of PCM characteristics is very context-dependent at the system level. For example, Belinson and Groulx [7] demonstrated computationally that although a higher thermal conductivity speeds up the system's reaction, it may also result in a decreased efficient use of latent heat if temperature gradients are not well controlled. Their research demonstrated that any overall performance gain must take into account improvements in thermal conductivity within the context of heat exchanger design, system geometry, and boundary conditions. Furthermore, Kant et al. [8] noted that composite and nano-enhanced PCMs can provide improved stability, latent heat retention, and thermal conductivity; however, this is frequently accompanied by increased material costs, synthesis complexity, and potential issues with dispersion or chemical stability after prolonged cycling.

4. CLASSIFICATION OF PHASE CHANGE MATERIALS

PCMs are mainly classified according to their chemical composition, which determines crucial characteristics including melting point, thermal stability, heat transmission characteristics, and suitability. Figure 2 summarizes that

PCMs fall into three primary categories: organic, inorganic, and eutectic.

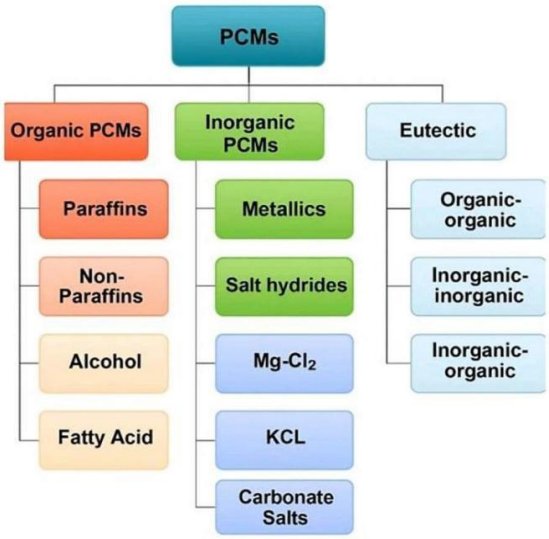

Figure 2. Classification of phase change materials (PCMs)

4.1 Organic phase change materials

PCMs can be categorized as either paraffin (such as paraffin wax) or nonparaffin (such as the family of fatty acids).

4.1.1 Paraffins

Straight-chain n-alkanes $CH_3–(CH_2)–CH_3$ make up the majority of paraffin wax. When the CH_3-chain begins to crystallize, a significant quantity of latent heat is produced. As the chain length increases, both the latent heat of fusion and the melting temperature do. Paraffin wax, polyaniline, n-Docosan, and paraffin purity are a few instances of these substances. Paraffin is cheaper, non-corrosive, non-poisonous, safe, reliable, and predictable. It has negligible volume changes at the melting point and is chemically inactive and stable below 500 ℃. Paraffins have high latent heat and a melting point between 35 ℃ and approximately 70 ℃ that could enable them to store 200–300 kJ/kg of energy in a lower bulk. In contrast, the disadvantages of paraffin are that it has low heat conductivity, is not compatible with plastic containers, and is weakly flammable. However, making minor changes to all of these harmful effects can partially be eliminated by the storage unit and wax.

4.1.2 Non-paraffins

The most common PCMs with a range of characteristics are non-paraffin organics. Each of these materials will have distinct qualities, in contrast to paraffin, which has several traits in common. There are the most potential materials for phase change storage in this category. Compared to paraffin, fatty acids have higher melting temperatures. Additionally, it consistently melts and freeze.

4.2 Inorganic phase change materials

Salt hydrates and metals are two more categories for inorganic materials.

4.2.1 Salt hydrates

With the generic formula salt compound nH_2O, salt hydrates, which include oxides, carbonates, sulfates, nitrates, and halides, are alloys that combine water and inorganic salts to create a unique crystalline solid. Their melting values, which range from 10 to 900 ℃, cover a wide variety of operating conditions. High latent heat of fusion per unit volume, little volume changes during melting, and comparatively high thermal conductivity, nearly double that of paraffin, are some of their advantageous properties. Numerous salt hydrates are reasonably priced for storage. However, their unfavorable traits include the potential for them to sink to the bottom of the container because of their higher density, a strong tendency toward supercooling (meaning that they may need considerable subcooling instead of starting to solidify at the point of solidification), incongruent melting, and extreme instability. Na_2CO_3 and magnesium oxide (MgO), sodium acetate trihydrate ($CH_3COONa·3H_2O$), sodium dodecyl sulfonate ($C_{12}H_{25}NaO_3S$), and carboxymethyl cellulose (CMC, $RnOCH_2COONa$) are a few examples of inorganic PCMs [9].

4.2.2 Metallic

Stable chemical and physical characteristics at elevated temperatures, strong thermal conductivities, the capacity to create custom alloys with specific melting points for specific applications, and generally low latent heat are the most important characteristics of metallic PCMs, which include low-melting metals [10].

4.3 Eutectics phase change materials

A eutectic is a minimum-melting composition made up of two or more components that, when they crystallize, simultaneously melt and freeze to form a mixture of the component crystals. Eutectics almost always melt and freeze without segregation because it forms a close-knit mixture of crystals with little opportunity for component separation. Separation is improbable since both components liquefy simultaneously during melting. Due to their beneficial properties of large latent heat and relatively high conductivity, as well as their durability and chemical inactivity with other solar panel components, these materials are most frequently utilized in solar panel research. Organic-organic, inorganic-inorganic, and organic-inorganic are the three types of eutectic materials.

5. ADVANTAGES AND DISADVANTAGES OF PHASE CHANGE MATERIALS

Most of the studies that have been done lately on PCMs have focused on their properties to identify advantages and disadvantages. The benefits of PCMs that are most frequently mentioned include their non-corrosiveness, high heat of fusion, non-toxicity, increased wetting capacity, lack of supercooling, self-nucleation, and lack of phase segregation. Flammability, low flash point, low density, poor phase transition enthalpy, and decreased latent heat storage capacity are the most commonly mentioned drawbacks. Among the most frequently cited disadvantages are flammability, low flash point, poor density, low phase transition enthalpy, and decreased latent heat storage capacity. These advantages and disadvantages define the applications of PCMs. Table 1 summarizes the advantages and disadvantages of various types of PCMs.

Table 1. Advantages and disadvantages of various types of phase change materials (PCMs) [11, 12]

Materials	Types	Advantages	Disadvantages
Organic Materials	Paraffins	• The heat of fusion can reach up to 258 kJ/kg. • The range of melting points is -4.9 ℃ to 74.9 ℃. • The thermal conductivity is 0.24 W/(m·K). • There is no toxicity. • There is no rusting. • Vapor pressure is lower in a molten state. • Up to 930 kg/m³ of density. • Technical grade is reasonably priced, with a maximum of USD 4 per kilogram. • Widespread accessibility. • The ability to wet is somewhat higher. • It is chemically inert below 500 ℃, but above this point it undergoes a variety of intricate processes, including dehydrogenation, aromatization, and cracking. • There is no super-cooling; self-nucleation takes place. • Chemically stable and recyclable. • There is good compatibility with various materials. • Phase segregation is absent. • The capacity to be immediately integrated. • Excellent thermal performance. • The capacity to melt congruently.	• Combustible. • The comparable melting point is between 6 and 37 ℃, while the flash point is between 108 and 170 ℃. • It is incompatible with plastic containers. The capacity of volumetric latent heat storage is reduced. • There is less thermal conductivity. • The change in relative volume is greater. • Certain paraffins do not dissolve in water. • The enthalpy of phase change is reduced. Because of the low density, more surface area is needed. • A high rate of heat transfer is necessary during freezing and is somewhat expensive.
	Non-Paraffins	• The heat of fusion can reach up to 258 kJ/kg. • The range of melting points is 7.7 ℃ to 127.1 ℃. • Because of its decreased thermal conductivity, it is suitable for building envelopes. • There was no supercooling. • There is a phase transition from one solid to another. • It is chemically stable. • Recyclable and well-compatible with other materials.	• Non-paraffin PCMs can be hazardous. • The majority of these PCMs are combustible. • The majority of them have lower flash points. • Impurities have a significant impact on the melting point. • They emit harmful vapors. • Some of them exhibit corrosion during thermal cycling; they are less sustainable in high temperatures, fires, and oxidizing chemicals. • Inconsistent melting. • Not easily reversible.
Inorganic Materials	Salt / Salt Hydrates	• The heat of fusion can reach up to 296 kJ/kg. • During a phase change, there is very little change in volume. • The density is higher (1641 kg/m³ for T_m = 25.9 ℃). • The average price is quite cheap ($0.18 per kg). • In comparison, thermal conductivity is greater. • It has a greater capacity to store heat and is non-flammable. • There was a sudden shift in phase. • The enthalpy of phase change is greater. • It is recyclable.	• Super-cooling took place. • It corrodes metals. • In a hot climate, thermal conductivity is higher. • A little poisonous. • There was dehydration. • The actual thermal conductivity is between 0.39 and 0.69 W/(m·K). • Phase separation is possible. • There is less thermal stability. • It weighs more. • Degradation tendencies. • Chemically unstable. • Incompatible with some building materials.
	Metallic	• There is more volumetric latent heat. • There is less vapor pressure. • The volume expansion is less at the phase changeover. • The boiling point is more than 2000 ℃. • There is a huge temperature difference between melting and boiling. • It is not combustible. • Phase separation doesn't happen.	• There is more thermal conductivity. • It is compatible with electrical conductivity. • There is moderate supercooling. • Expensive. • Incompatible with building materials
Eutectics		• The melting point is extremely low. • It has a high volumetric heat storage density. • Phase segregation is absent. • The phase change is congruent.	• There is insufficient test data to examine the thermophysical characteristics. • The availability is restricted. • There is less latent heat capacity overall. • Experience the supercooling effect. • Strong smell and more expensive.

6. LIFE CYCLE AND ENVIRONMENTAL IMPACT ASSESSMENT OF PHASE CHANGE MATERIALS

The environmental sustainability of PCMs has to be considered in a cradle-to-grave perspective, covering raw material sourcing, manufacturing, operational use, and end-of-life phases. Life cycle assessment (LCA) provides a harmonized method of measurement for these impacts across various application domains. Within the period from 2020 to 2025, several studies investigated the footprint of PCMs in buildings, energy systems, refrigeration, and industrial cooling, considering some important energy-saving vs. embodied impacts. To better understand these examples, Figure 3 depicts the usual life cycle stages of PCMs in thermal systems: extraction, synthesis, device integration, operational use, and, finally, disposal or recycling. These stages represent the environmental impact of a PCM system, related to key indicators such as Global Warming Potential (GWP), cumulative energy demand, and ecosystems.

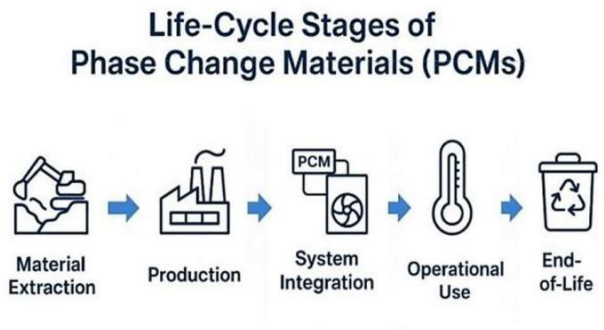

Figure 3. Life cycle stages of phase change materials (PCMs)

From 2020 to 2025, several LCA studies have been conducted with regard to the environmental performance of PCM-based systems in application fields such as power plant cooling, solar-assisted buildings, food preservation, and industrial heat exchangers. Hence, these studies give important information regarding the advantages and disadvantages of the use of PCMs, particularly related to embodied energy, efficiency, and sustainability. In cold chain logistics and off-grid refrigeration, Bozorgi et al. [13] investigated the thermoelectric refrigeration unit enhanced by organic PCM storage, working autonomously to maintain an internal temperature below 5 °C without the use of external electricity. The adopted unit achieved autonomy for almost 30% of the week without the use of external electricity, thus being suitable for any kind of remote or mobile applications. The LCA results showed a GWP of 1,190 kg CO_2 equivalent, relatively lower than that of magnetic and traditional refrigerator systems. Besides, it demonstrated superior behavior when compared to traditional alternatives in impact categories like the depletion of the ozone layer and smog formation. These results emphasize the potential of thermoelectric units integrated with PCMs toward sustainable temperature-sensitive transport and storage. While focusing on desalination technologies, Bahramei et al. [14] analyzed a solar-driven water purification system that was integrated with PCMs and geothermal support. Based on the results, it has been found that PCMs improved the efficiency of thermal storage by more than 10%, which has been validated by computational fluid dynamics (CFD). On the other hand, copper containment increases the aforementioned impact by 15.6% to GWP and over 60% to mineral resource depletion, thus emphasizing the choice of material. In building-integrated PV systems, Colarossi et al. [15] analyzed the adoption of PCMs in PV panels in peak shaving strategies of domestic hot water load. Smoothing thermal fluctuations, the PCM increased both energy storage and PV efficiency. LCA results showed an 11% reduction in the climate change impact, while the novel circularity index analysis according to UNI 1608856 provided a 45% material reuse potential, an interesting result considering the circular economy goals for the building sector. Complementary results were presented in the agricultural drying field by Mirzaee et al. [16]. This study analyzed an indirect solar dryer with incorporated PCM layers with the aim of stabilizing the drying temperature values. The thermal efficiency of the system approached 39% when the PCM was positioned on the lower trays. Lifecycle emissions and energy demand were significantly reduced compared with electric dryers, underlining the suitability of this system for low-carbon food processing in off-grid conditions. Extending to industrial applications, Ghasemi et al. [17] investigated a pillow plate heat exchanger that used microencapsulated PCM slurry for enhanced cooling in thermal management systems. A concentration of 15% enhanced the heat transfer by 6.2%, while LCA results highlighted the increase in related emissions due to encapsulation as marginal.

The overall environmental footprint remained low despite higher pressure drops, thus validating the use of PCM slurry as a next-generation coolant in electronics and industrial heat recovery. The advantages of using PCMs have also clearly come forth in solar drying configurations. Hao et al. [18] have conducted a comparative LCA of three solar dryer types, namely, direct, mixed mode, and PV thermal hybrid systems, each with and without integration with PCMs. While the highest thermal efficiency was achieved by the mixed-mode dryer, the hybrid system demonstrated the lowest environmental impact throughout its manufacture, transportation, and operation stages. In particular, its ReCiPe endpoint score of 0.0639 points per year was the best value, especially when lifetimes are longer or when such dryers operate under high solar radiation conditions.

Testing for the safety of PCMs involves considering the chemical composition, likely emissions, and any potential toxicity in various conditions. This therefore leads to presenting several studies conducted between 2020 and 2025 on organic, inorganic, eutectic, and bio-based PCMs in different thermal storage applications concerning environmental and health impacts. These highlight the trade-off among building, food storage, and high-temperature uses regarding performance, safety, and sustainability. Figure 4 describes the principal PCM types and related health and environmental hazards [19]. Vegetable oils and fatty acids are biodegradable with low toxicity but are flammable. Paraffins are flammable, not biodegradable, and their combustion could potentially emit harmful pollutants. Salt hydrates are irritants, whereas eutectic mixtures present risks according to their composition.

7. SELECTION CRITERIA FOR PHASE CHANGE MATERIALS

The development of Latent Heat Thermal Energy Storage (LHTES) systems inherently requires the proper selection of

PCMs, and engineers need to ensure that the phase transition temp of the material is within the range of operation of the intended application to ensure proper charging-discharging cycles. For high storage efficiency, PCMs are expected to have large specific and latent heat values with high thermal conductivity for the sake of quick heat transfer. Higher-density materials are always preferred since they will contribute to reduced system volume during design. Cost-effectiveness and wide availability will also represent crucial parameters from a practical point of view. However, because no single PCM has an optimum profile for all of these desired characteristics, selection will remain very dependent on the unique thermal bounds and operating requirements of each system [20]. The enthalpy of fusion and the melting points of low-temperature PCMs are presented in Figure 5, while salt hydrates and eutectics can be considered to be potential candidates for high-temperature applications due to their appropriate melting ranges.

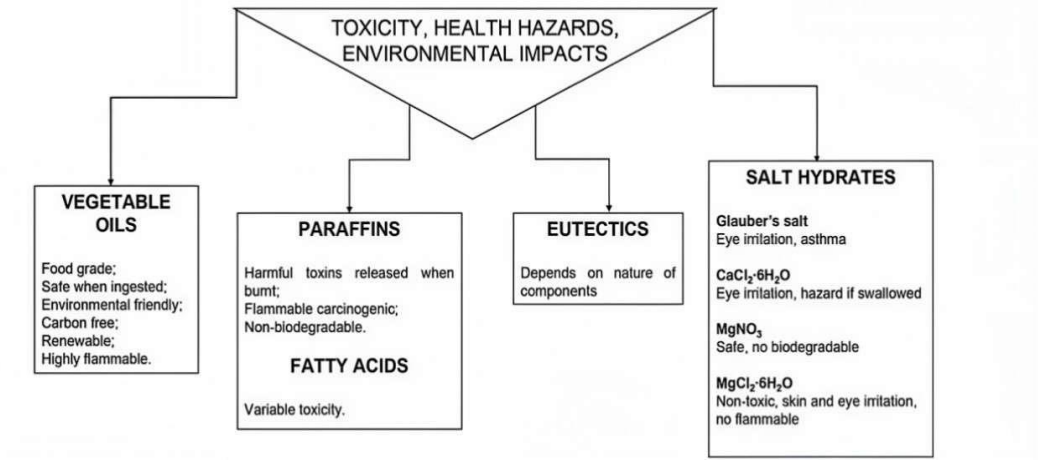

Figure 4. Toxicity, health risks, and environmental impacts of different phase change materials (PCMs) [19]

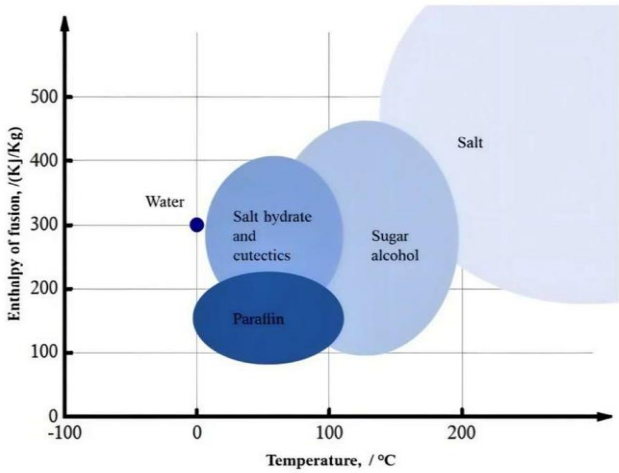

Figure 5. The melting temperature and latent heat of fusion of various phase change materials (PCMs) [21]

Table 2. Thermophysical properties of pure phase change materials **(**PCMs) used for photovoltaic (PV) cooling applications

No.	Authors	PCM	Solidification, °C	Liquefaction, °C	Density, kg/m^3 Solid	Density, kg/m^3 Liquid	Thermal Conductivity, W/(m·K)
1	Waqas et al. [22]	RT24	21	25	800	700	0.21
2	Hasan et al. [23]	Capric acid	-	30.2	886	158	0.15
3	Singh et al. [24]	Calcium chloride hexahydrate ($CaCl_2 \cdot 6H_2O$)	-	31	271	191	1.08
4	Sudhakar et al. [25]	OM 35	34	35	901	870	0.20–0.16
5	Xu et al. [26]	fatty acid	-	38	920	844	0.25–0.15
6	Akshayveer et al. [27]	OM32	-	36	870	153	0.15–0.22
7	Sarafoji et al. [28]	ROM05-P	-	6.1–5	764	242	0.37
8	Preet et al. [29]	RT-30	-	25	870	762	0.21
9	Hassan et al. [30]	RT-35HC	34	36	881	770	0.17–0.65
10	Li et al. [31]	35 paraffin wax	34.9	44	882	790	0.21
11	Abdelrahman et al. [32]	RT35HC	34	37	773	670	0.22
12	Nada et al. [33]	PCM RT55	53	57	881	770	0.21
13	Modjinou et al. [34]	Salt hydrate	-	142	673.5	182	0.21
14	Al-Waeli et al. [35]	Paraffin wax	-	49	930	830	0.22

15	Shastry and Arunachala [36]	OM-47	46	48	884	917	0.11–0.21
16	Bayrak et al. [37]	Biphenyi	-	69.2	-	-	0.12
		$CaCl_2 \cdot 6H_2O$	-	33	-	-	1.08
17	Klugmann-Radziemska and Wcisło-Kucharek. [38]	Paraffin 42–44	44	44	911	133	-
		RT 22	22	23	762	200	-
		Ceresin	-	61–78	910	784	-
18	Sardarabadi et al. [39]	Paraffin (Merck)	43	72	901	203–219	-
19	Stropnik and Stritih [40]	RT2HC	-	29	880	773	0.21
20	Atkin and Farid [41]	Paraffin	-	43	840	760	0.26
21	Maiti et al. [42]	Wax	-	56	912	765	0.41
22	Huang et al. [43]	RT25	-	26.6	787	745	0.18–0.19
23	Nehari et al. [44]	GR40	-	43	-	-	0.15
24	Jiang et al. [45]	Octadecylamine ($C_{18}H_{39}N$)	-	51.8	-	-	-
25	Ibrahim et al. [46]	Iraqi paraffin wax	-	42	-	-	-
26	Rabady and Malkawi [47]	Sodium thiosulfate pentahydrate	-	48	-	-	1.15
27	Sun et al [48]	Pure paraffin	-	26–28	-	-	0.36
28	Li et al. [49]	(SAT, $CH_3COONa \cdot 3H_2O$)	-	56.75	-	-	0.59
29	Zhang et al. [50]	RT100	-	88.28	-	-	-
30	Harish et al. [51]	Pristine lauric Acid ($C_{12}H_{24}O_2$)	-	44	-	-	0.22
31	Fan and Khodadadi [52]	Cyclohexane	-	6.5	850	779	-
32	Zeng et al. [53]	Tetradecanol (TD)/C14H30O	-	38	-	-	-
33	Weinstein et al. [54]	Paraffin Wax	-	56	-	-	0.25
34	Zeng et al. [55]	C14H30O (polyaniline)	-	35	-	-	-
35	Kim and Drzal [56]	n-Docosane	-	53–57	-	-	0.26
36	Wang et al. [57]	Pa, purity 98%	-	62.4	-	853	0.22
37	Wang et al. [58]	Paraffin wax	-	52–54	-	-	-
38	Yuan et al. [59]	Erythritol, purity 98%	-	125	-	-	-
39	Khudhair et al. [60]	Paraffin wax	-	62.7	-	-	-
40	Hu et al. [61]	Paraffin	-	56–58	-	-	0.25
41	Sharma et al. [62]	PCM RT42	38	44	883	174	0.22
42	Hasan et al. [63]	RT20	-	21.3–25.7	885	774	0.23
		Capric Lauric acid (C–L)	-	20.8–24.6	881	866	0.14
		Capric palmitic acid (PA) (C–P)	-	22.3–26.4	883	840	0.15
		Pure salt hydrate ($CaCl_2 \cdot 6H_2O$)	-	29.2–29.7	1711	213	1.08
		Commercial blend (SP22)	-	23–24.7	1491	1433	0.61

Table 3. Properties of additives, nanoparticles, porous media, and supporting materials used for phase change material (PCM) enhancement in photovoltaic (PV) cooling applications

No.	Authors	Enhancement Material	Material Type	Function in PCM System	Liquefaction, °C	Density, kg/m^3	Thermal Conductivity, W/(m·K)
1	Nada and El-Nagar [64]	Al_2O_3 nanoparticles powder	Nanoparticle	Thermal conductivity enhancement	-	3599	31
2	Sharma et al. [65]	Aluminium	Metal matrix	Heat dissipation enhancement	653	2710	222
		Epoxy Resin	Encapsulation material	Structural support and encapsulation	133	2091	1.24
3	Sardarabadi et al. [39]	Nano-particles Zinc-oxide	Nanoparticle	Thermal conductivity enhancement	-	5606	23.41
4	Atkin and Farid [41]	Infused graphite	Carbon additive	Heat transfer enhancement	45	-	16.51
5	Ibrahim et al. [46]	Nanoparticles (MgO)	Nanoparticle	Thermal conductivity enhancement	2852	-	50.11
		TiO_2	Nanoparticle	Thermal conductivity enhancement	1843	-	300–770
6	Li et al. [49]	Copper foam (DHPD + CMC)	Porous medium	Heat spreading and storage enhancement	36.71 + 300	-	0.59 + 0.18
7	Sharma et al. [62]	Polystyrene	Supporting material	Thermal insulation and encapsulation	240	-	0.032

Note: Aluminum Oxide (Al_2O_3); Magnesium Oxide (MgO); Titanium Dioxide (TiO_2); Disodium Hydrogen Phosphate Dodecahydrate (DHPD); Carboxymethyl CELLULOSE (CMC).

Functionally, PCMs act as storage media, absorbing and releasing latent heat during solid-liquid phase change. Ideally, they should have zero or very negligible supercooling and thermodynamically stable behavior. Table 2 summarizes selected studies on various PCMs, focusing on key properties such as the type of PCM, melting or liquefaction temperature, solidification temperature, thermal conductivity, and density.

This comparison study enables researchers to establish a trend of performance by material type, assists in the evaluation of the performance, and provides guidelines on the choice of suitable PCMs for various applications in TES and temperature regulation systems.

It is important to emphasize that in some cases, thermal conductivity enhancement materials such as metal oxides (MgO, titanium dioxide (TiO_2), aluminum oxide (Al_2O_3), zinc oxide (ZnO)), porous materials, graphite materials, metal

foams, and polymer substrates were used. The aforementioned enhancement materials do not work as PCMs but are used in PCM systems for improving their thermal conductivity, heat transfer properties, structural stability, and general performance related to TES. Hence, in order to distinguish between the phase transition temperature of PCM and properties of enhancement materials, the thermophysical properties of the former are discussed separately in Table 3, while Table 2 contains data on pure PCMs.

As shown in Table 4, their practical application is closely related to material availability, cost, and dependability in addition to thermal performance.

Table 4. Selection criteria for phase change material (PCM)

Properties	Characteristics of Property
Thermal conductivity	• The phase change temperature must fall within the intended range. • Heat transmission capacity should be strong. • Thermal conductivity and latent heat of fusion should be high.
Kinetic	• High nucleation rates are necessary to prevent supercooling. • High crystal growth is necessary to satisfy heat recovery requirements.
Physical	• Phase balance ought to be advantageous. • Density and specific heat should be high. • Phase transformation should result in very little volume change. • At working temperatures, vapor pressure should be low.
Chemical	• PCMs' chemical stability is a need for PCMs. • Melting congruently should occur. • They should not be toxic, corrosive, explosive, or flammable.
Economic	• They should be compatible with building materials. • They should be readily available, inexpensive, and abundant.

Figure 6 summarizes the general selection criteria, where thermo-physical properties are still at the top ranking. Short-listed materials are further evaluated in detail for suitability based on the application. Notably, user-oriented aspects such as safety, adaptability, and ease of integration are given high priority, since it is these features that determine competitiveness compared to conventional solutions.

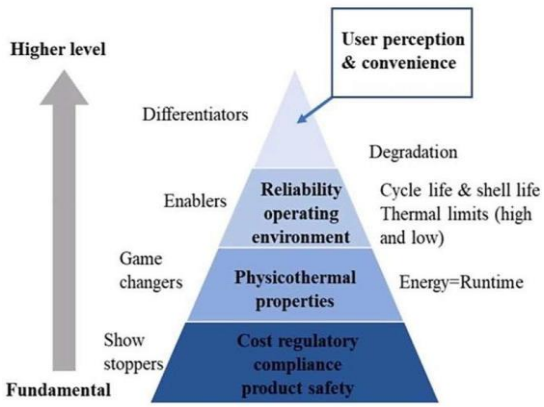

Figure 6. Phase change materials (PCMs) selection for thermal energy storage (TES) applications [10]

From a materials point of view, organic PCMs are very attractive because of their high latent heat, negligible supercooling, and long-term chemical stability. They are non-acidic and exhibit minimal degradation, further supporting their applicability in a wide range of thermal applications. Inorganic PCMs, represented mainly by salt hydrates and their eutectics, offer higher melting points and, therefore, are ideal for situations involving medium and high temperatures. However, their practical application is substantially hampered due to problems such as super-cooling, corrosiveness, and decomposition [66]. Consequently, while inorganic materials may remain suitable for particular applications involving high temperatures, organic PCMs have increasingly been favored in systems with demands for durability, safety, and high storage capacity.

8. INTEGRATION OF PHASE CHANGE MATERIALS IN PHOTOVOLTAIC SYSTEMS

Using PCMs in PV systems has become highly attractive and promising as a passive thermal management technique, which may alleviate the undesirable impacts of elevated operating temperatures on PV performance. During the melting process, PCMs absorb excess thermal energy and store it through physical change; later on, this thermal energy is released during the solidification process, keeping the temperature of the PV cell within a favorable operating range. This process will enhance electrical efficiency, reduce thermal stress, and also extend the operational life of the PV modules.

In the practical experiment carried out by Hasan et al. [67], when placed on the back side of a PV module, the paraffin wax was evaluated as a PCM with a melting point between 37 and 42 ℃ for each of the four seasons. In the autumn and spring, when the outside temperature is mild, the best parameters were extracted from the analysis. As a result, it permitted PCM to completely melt during the day and solidify at night. However, the hot temperatures in the summer prevented the PCM from completely solidifying, while the low temperatures in the winter prevented the PCM from completely melting. Compared to a PV module without PCM, the integration of the PV-PCM system increased energy output by 5%. Two capric-palmitic acid (PA) with calcium chloride hexahydrate ($CaCl_2 \cdot 6H_2O$) PCM cooling systems were compared by some earlier authors in both warmer and colder areas [68]. The results shown thatUtilizing the two PCMs lowered the temperature of the PV module from 48 ℃ to 44 ℃ and 41 ℃. Respectively, under colder conditions. On the contrary, in warm regions, this temperature decreased from 62 ℃ to 54 ℃ for capric-PA and to 43 ℃ for $CaCl_2 \cdot 6H_2O$, which reveals the economic feasibility of the PCM cooling systems in the hotter climes. RT28 was used as a PCM in an experiment by Stropnik and Stritih [40], and the results showed an increase in power output from 5.5% to 9.8% compared to an unmodified PV module. The cooling efficiency of a PV module was studied by Hachem et al. [69] using a PCM based on White petroleum jelly as opposed to a PCM made of a combination of white

petroleum jelly, copper, and graphite. By using PCM instead of only white petroleum jelly, the composite electrical efficiency rose by 5.5% instead of 3%. The concept of using PCMs: a proposal with building-integrated PV systems was presented by Hasan et al. [70]. Thus, the temperature went down by 21.8 ℃ while electrical output efficiency increased by 7.3%.

8.1 Photovoltaic panel cooling with pure phase change materials

Pure PCMs are capable of serving as an effective cooling system. When used for solar cell cooling, paraffin waxes provide several advantages. A PCM operates on the basis of gathering heat produced by solar cells at elevated temperatures, typically during the day's hottest hours and changing its state from solid to liquid while doing so at a steady temperature. As a result, the PCMs are able to control the PV panels' working temperature and avoid overheating. Pure PCMs do not experience any phase separation or degradation during their phase change, as might be expected when discussing composite PCMs in general. In addition, research about the application of pure PCMs in the cooling of solar systems is compiled in Table A1 (see Appendix) [71-75]. The methodology of the study and system configurations, along with the performance, efficiency, and operating temperature of the panel with respect to the cooling system, were researched. Among the researched PCMs were paraffin wax, hydrated salt, polyethylene glycol (PEG), and soybean wax-all of which demonstrated considerable decreases in operating temperatures and increases in electrical efficiency when tested to see whether they could cool if attached to the back surfaces of solar panels.

8.2 Photovoltaic panel cooling with composite phase change materials

Composite phase change materials (CPCMs) provide a number of advantages related to PV panel cooling. These materials combine the typical heat-absorbing properties of PCM with more enhancement provided by fibers or nanoparticles. It is expected that the addition of these nanoscale structures into the PCM matrix may significantly enhance its thermal conductivity and heat transport characteristics. This would, in turn, mean that when the PCM gains heat and undergoes direct phase change from solid to liquid, the generated heat can be successfully dissipated. The most pertinent studies that focused on using composite PCMs as a cooling solution for PV panels are summarized below in Table A2 (see Appendix) [76-81]. The PCM compositions and their combination techniques used to enhance PV panel efficiency and performance were considered during the summary of the available data. All of these experiments generally aimed at using phase-changing compounds on PV panels' rear surfaces to reduce excessive heat and raise energy output.

8.3 Photovoltaic panel cooling with finned phase change materials

An extremely effective and environmentally friendly method of cooling solar systems is to employ PCMs with finned heat exchangers. PCMs normally work as a thermal battery. Storing excess heat generated from solar cells during peak sun hours and releasing it when required. The primary purpose is to offer a constant and steady supply of electricity. By increasing the surface area, the fins increase the available area for heat exchange, thus enabling faster charging and discharging of the PCM. The efficiency of heat transmission. Besides, Table A3 (see Appendix) [82-86] presents a review of several recent studies aimed at improving the solar systems' cooling performance due to the use of finned PCMs. Various techniques, system configurations, and PCM options where scientists have often reported exceptional results via software models along with experimental settings. This is achieved by substituting copper fins and graphite with titanium and steel.

8.4 Hybrid photovoltaic/thermal systems with phase change material

For PV systems to have the best thermal management, PCM and hybrid cooling systems must be combined. The use of PCMs in hybrid cooling systems results in significant energy and financial savings in a number of areas, including transportation, buildings, and solar power. By lowering overall energy use, these technologies hope to make the world a greener place. Table A4 (see Appendix) [87-95] provides an overview of the latest research and enhancements in the phase change combination. Components of the hybrid and multiple cooling systems for solar energy panels. These materials can increase the efficiency of heat storage by using PCM systems under a range of environmental conditions, each with unique advantages. Researchers have studied various types and mixtures of PCMs to deliver sustainable energy. For example, encapsulated PCM balls can be used with both active and passive cooling. The different methods produced significantly higher thermal and electrical energy gains. Nano-PCMs and nanofluids showed improved temperature and heat- gain coefficient decreases when paired with microfin pipes. PV panel efficiency and electrical output have been increased significantly when PCMs are added with heat pipes, porous medium, and thermoelectric generators. As a result, the significance of integrated cooling systems in augmenting PCM-based renewable energy sources is recognized.

These combined studies, therefore, confirm the relevance of incorporating PCMs in a solar energy system for developing an efficient and environmentally friendly system.

9. ENHANCEMENT STRATEGIES

PCMs have been widely employed in the storage of thermal energy because of their elevated latent thermal capacity and nearly isothermal behavior in their phase change regions. However, practical applications have mostly been hindered by a number of problems such as very low thermal conductivity, volume variations on phase change, and other issues regarding material leakage during operation. In an effort to overcome these disadvantages, many methods have been suggested to enhance performance. For the purposes of readability, enhancement techniques are categorized into three types: material enhancement, structure enhancement, and hybrids.

9.1 Material-based enhancement

Material-based enhancement includes the addition of a highly thermally conductive additive like metal foams, nanoparticles, or carbon-based materials (graphene, carbon

nanotubes, EG), which has been widely adopted. They enhance internal heat transmission in the PCM matrix and hence speed up charging and discharging rates. In general, carbon-based materials increase the thermal conductivity of PCM composites between 50% and 250%, with EG being the best enhancer (as much as 500%) as per Jin et al. [5]. Nano-enhanced PCMs result in a reduction in the temperatures of operation of PV panels by 10–21 °C, with MgO and hybrid nanoparticles performing best in this respect.

9.2 Structural enhancement

Composite PCMs have been proposed, combining organic-inorganic or eutectic materials in order to optimize phase change enthalpy, thermal stability, and melting temperature ranges [96]. Porous structures, like metal foams or polymer matrices, are also used to stabilize the PCM and reduce volume changes in the melting-solidification process.

9.3 Hybrid approaches

Combined techniques, combining the use of nanoparticles, encapsulation, and composite material, have shown remarkable improvements in the thermal conductivity property and also cycling reliability. Combination cooling systems are combinations of more than one method of improvement, like the combination of nanoparticles and fins, the combination of encapsulation and porous matrix, and the combination of PCM with active cooling methods like water circulation and heat pipes and also thermoelectric generators. Combination systems show efficiency improvements from 14.5% to 30%, which is much higher than 2.8–17.5% by using pure PCM.

Recent experimental research on improving PCM performance by utilizing thermally conductive substances like carbon nanotubes, graphene, EG, and metal foams and the development of various porous or composite architectures is compiled in Table A5 (see Appendix) [45-48, 97-101]. The table provides more details about PCM kinds, additive materials, concentrations, manufacturing processes, and enhancements in thermal conductivity, energy storage density, and overall system efficiency. Together, these investigations show that adding highly conductive or structurally supporting additives greatly improves PCM performance for PV cooling and TES.

9.4 Comparative performance assessment

For an improved comparative performance analysis of various types of coolers based on PCM technology, Table 5 was developed as a comparative performance assessment tool. Although Tables A1-A5 contain results of independent experiments, Table 5 contains a summary of maximum values of all important performance indicators, namely the thermal conductivity improvement, the latent heat holding ability, the PV cell cooling effect, the increase in efficiency, and the economic benefits of implementation. This method allows evaluating the best cooling option and taking into account the relationship between thermal performance and economic factors.

Table 5. Comparison of parameters of the efficiency of a phase change material (PCM)-cooling system

System Type	Thermal Conductivity Improvement	Latent Heat Retention	Photovoltaic (PV) Temperature Reduction (°C)	Electrical Efficiency Gain (%)	Cost Implications
Pure PCM	Baseline (0.15–0.4 W/(m·K))	100% (baseline)	18–40	2.8–17.5	Low
Composite PCM (carbon additives)	150–500% increase	85–98% of pure PCM	21–26	8–21	Medium
Composite PCM (metal oxide additives)	20–50% increase	95–99% of pure PCM	13–21	2–30	Low–Medium
Finned PCM	Effective k increase of 2–10× (structural)	95–100%	4–47	3.7–18.2	Medium (fin material dependent)
Hybrid PCM (active-assisted)	Active cooling dominates	90–100%	20–45	11.5–19.3	High

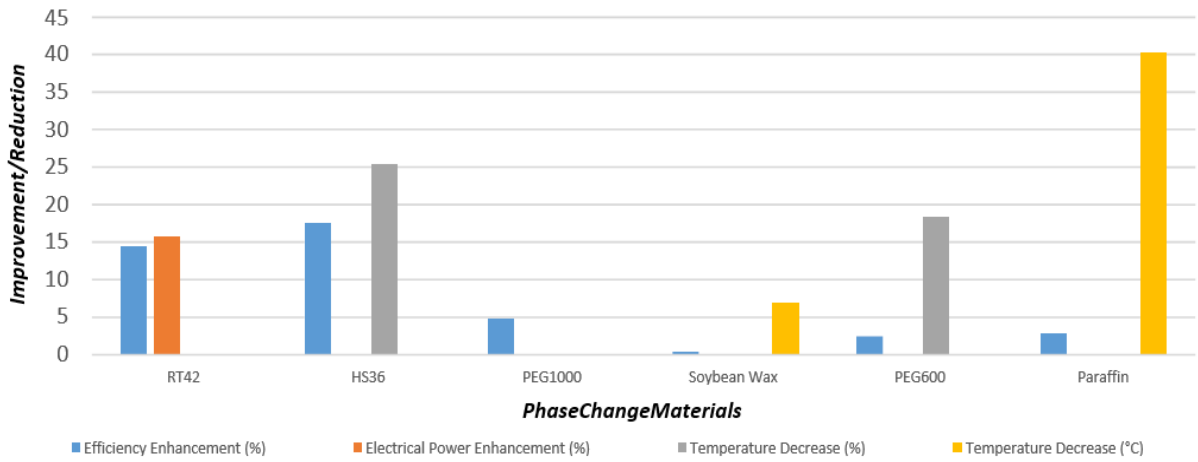

Figure 7. The different types of pure phase change material (PCM) cooling systems and their effects on the solar system

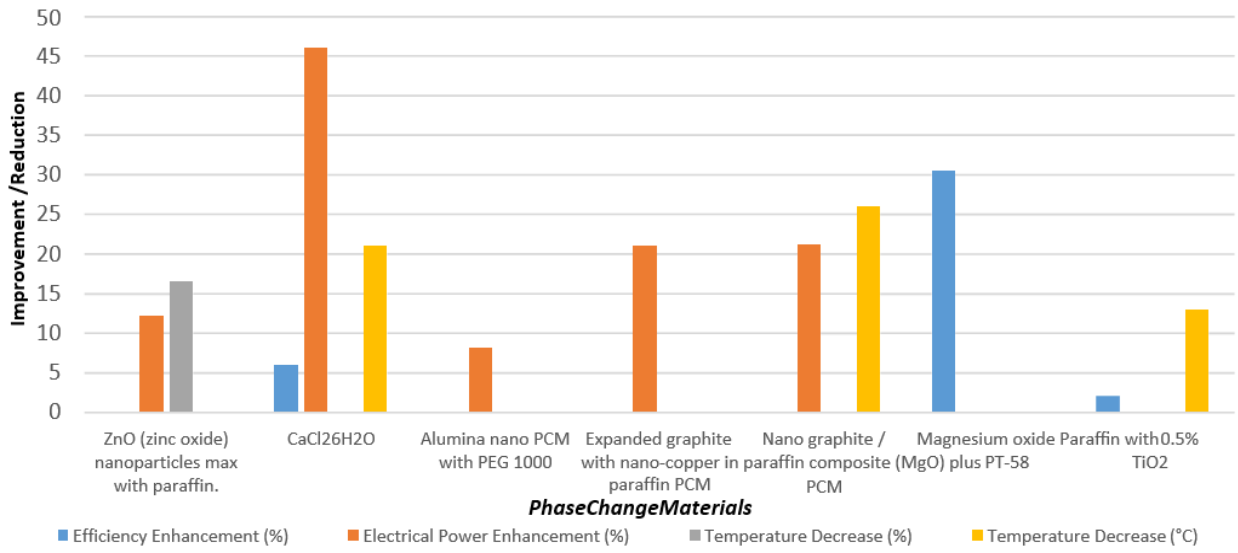

Figure 8. The different types of composite phase change material (CPCM) cooling systems and their effects on the solar system

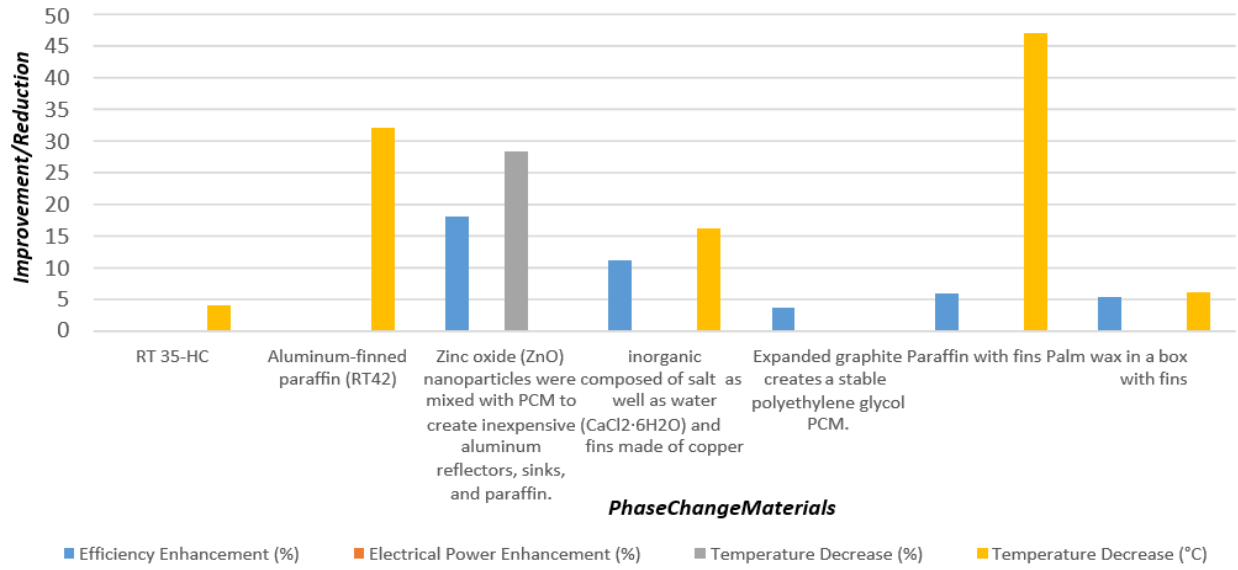

Figure 9. The different types of finned phase change material (PCM) cooling systems and their effects on the solar system

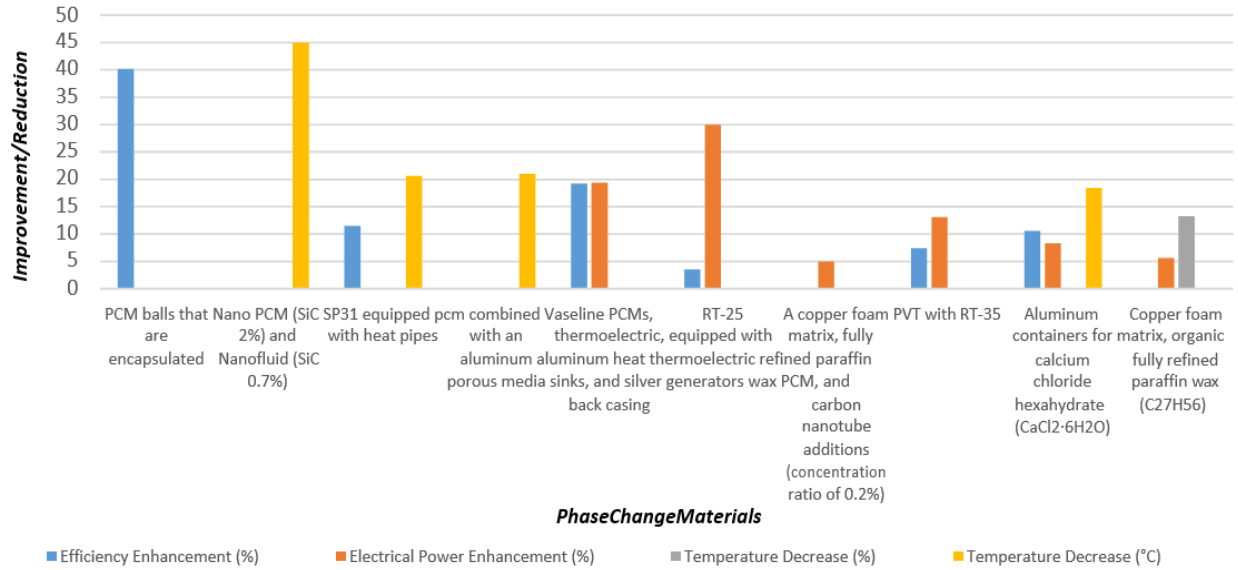

Figure 10. The different types of hybrid phase change material (PCM) cooling systems and their effects on the solar system

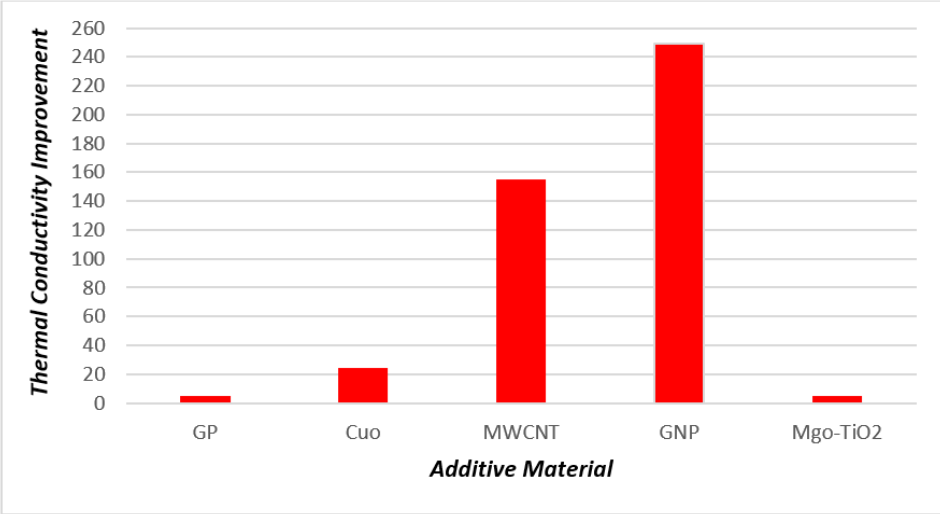

Figure 11. The different types of enhancement phase change material (PCM)

In the case of pure PCMs, there is a consistent decline in PV operating temperature from 18 to 40 °C along with an improvement in efficiency from 2.8% to 17.5%, as shown in the trends in Table A1 and Figure 7. Salt HS36 with hydration was found to produce the maximum decrease in temperature, i.e., 25.4%, and the maximum improvement in efficiency, i.e., 17.5%. Thus, in terms of performance in pure PCMs, salt hydrates can outperform paraffins despite facing problems with supercooling and phase separation. PEG 600 shows the least temperature decrease, i.e., 18.3%, but offers significant efficiency.

The results presented in Table A2 and Figure 8 show that there are repetitive trends in which composite PCMs prove to be superior to pure PCMs when it comes to improvement in efficiency and reduction in temperature. However, the maximum enhancement in energy output (by 46.11%, according to Baissi et al. [77]) and efficiency (by 30.45%, as reported by Jamil et al. [80] when using MgO/PT-58) proves to be much more than what pure PCMs can provide. There are also huge variations in efficiency increases (2.1%–30.45%) which depend on the type and quantity of additives used. In addition, the performance of metal oxide additives (such as ZnO, MgO, and Al_2O_3) appears to be somewhat unpredictable, as their reductions in temperature range from 13–21 °C, whereas carbon-based additives (EG and nano-graphite) produce a reliable reduction in temperatures ranging from 21 to 26 °C. It should be noted that sometimes adding nanoparticles leads to reduced latent heat.

As shown in Table A3 and Figure 9, fin-based PCMs have resulted in a temperature drop from 4 °C to 47 °C with efficiency improvement from 3.7% to 18.16%. It can be clearly seen that fins made of aluminum [83] provided a large temperature drop of 32 °C, whereas those made of copper [84] led to a 16.11 °C drop, with an increase of 11.19% in efficiency. Fin material has a substantial impact on heat transfer: graphite and copper have shown better performance than steel and titanium in providing about a 4 °C drop. Moreover, the combination of fins with nanoparticle-reinforced PCM [76] gave rise to maximum efficiency improvement among all fin-based PCMs (18.16%).

The performance of hybrid PCMs in Table A4 and Figure 10 is the best in comparison with other cooling mechanisms of PCM. The values of temperature difference lie in the range of 20.6 °C to 45 °C, whereas efficiency improvements vary from 2.5% to 19.32% in the case of electric efficiency alone. The overall efficiency value (thermal and electrical efficiencies added) is reported to be 76% [77]. An important point here is that hybrid active-assisted PCMs (which include water circulation, heat pipes, or TE coolers) perform better than hybrid passive PCMs. The maximum temperature difference value of 45 °C is reported by Bassam et al. [88], using a nano PCM with a microfin tube nanofluid, whereas the highest value of electric efficiency improvement of 19.32% is reported by Singh et al. [91], using PCM and TE coolers.

Figure 11 depicts the comparison of the thermal conductivity improvement obtained by different strategies of PCM enhancement, which are listed in Table A5. One may see from the picture that there is a great variety in the efficiency of the enhancement by means of different materials and structural modifications. Among the studied materials, carbon-based substances, namely graphene nanoplatelets (GNPs), multi-walled carbon nanotubes (MWCNTs), EG, graphite foam, and graphene particles, yield the greatest thermal conductivity improvement due to their initial high thermal conductivity and ability to form effective heat transfer paths in the PCM matrix. Metal oxide nanoparticles (MgO, CuO, TiO_2, CeO_2, SiO_2) show a modest improvement in thermal conductivity, but possess advantages in terms of stability, preparation procedure, and economy.

It can be seen from the findings that carbon-based additives always outperform most of the known enhancement materials. GNPs and MWCNTs showed thermal conductivity improvement over 150%, and EG even provided enhancement over 500% for some PCMs. Such high improvement of thermal conductivity can be explained by the formation of a conductive network that facilitates heat transfer through the material. This means that the rate of charging and discharging of PCMs will be higher for these additives.

Moreover, the structural enhancement methods such as porous structures, graphite foams, metal foams, encapsulation methods, and composites have shown significant enhancement in thermal behavior. In addition to increasing the heat transfer rate, these methods have shown improvement in shape stability, decreased leakage during melting, and increased reliability of the system. Therefore, the application of conductive additives along with structural enhancements could be considered as one of the most promising avenues in

PCM technology.

In conclusion, the comparison of various enhancement materials in the cooling system through the data depicted in Figure 11 clearly shows that the choice of enhancement materials is crucial in determining the performance of the system. These trends help us understand the reasons behind the recent tendency towards the use of carbon- based composite PCMs in research.

On balance, the comparative study carried out as shown in Table 5 reveals that there is a gradual increase in performance in cooling efficiency from simple PCM, through composite PCM, finned PCM, and eventually hybrid PCM. While hybrid systems offer improved thermal and electrical performance, they are relatively costly and more complicated. As such, choosing the right PCM cooling method depends on the interplay between thermal efficiency, economy, and stability.

The various performance metrics presented in Table 5 are the same metrics found in the scientific literature and need to be interpreted against the backdrop of the goals of the respective studies and system designs. Electrical efficiency improvement (%) is defined as the relative increase in PV electrical conversion efficiency when compared to a reference PV panel that operates under similar conditions. Power output increase (%) is defined as the amount of increase in electrical power production with respect to the respective reference system and is not the same as electrical efficiency improvement since it is affected by operation conditions, irradiation levels, and system dimensions. Total efficiency (%) is only applicable to photovoltaic/thermal (PV/T) systems and is indicative of the overall use of the incident solar energy in terms of both electrical conversion and heat recovery.

Temperature reduction figures will either be in the form of an absolute reduction in module temperature (°C) or a percentage reduction (%) compared with the reference system depending on whether the methodologies used were those of the original work. In addition, since the studies cited had different climatic conditions, irradiance levels, types of PCMs, cooling configurations, and reference systems, it must be noted that the data provided in Table 5 can only serve as comparative measures and not as equal ones. This table is meant to provide information about the relative performance of various PCM-cooling methods only.

10. TECHNICAL CHALLENGES AND DEPLOYMENT BOTTLENECKS

Although tremendous potential exists for PCMs in TES applications, a variety of critical challenges still must be overcome before large-scale deployments are realized, in terms of toxicity, environmental sustainability, and long-term stability. It is also important to resolve practical issues such as corrosion problems under high temperature conditions and meet the requirements for safety and environmental standards [12]. concluded that one of the major areas of ongoing research has been aimed at enhancing the thermo-physical properties of PCMs in order to establish a universal medium of storage. The most relevant technical barriers and corresponding research opportunities in accordance with a previous study are provided below.

10.1 Thermal conductivity limitations

Thermal conductivity is the dominating factor that influences the efficiency of the TES system. Unlike sensible or thermochemical materials, composite PCMs rely on their thermal conductivity for performance. For instance, embedding metallic structures such as metal wool can enhance thermal conductivity in solar heating [101], and the heat transfer is also affected by the geometry of encapsulation tubes. However, previous reviews only partially discussed the classification and evaluation of a high- thermal-conductivity additive. The main problems are that the interfaces between PCMs and heat-conducting matrices are random, which hinders the accurate prediction of the composite PCM conductivity. Besides, how the additive size, shape, or aspect ratio influences heat transport should be further explored. Although metal-based additives possess higher conductivity than carbon-based materials, their relatively high density reduces stability. Furthermore, the dispersion and aggregation of nanoparticles result in non-homogeneous distribution, which is another problem that has not been resolved yet [102].

Research opportunity: Creation of directional heat transfer systems through the use of aligned carbon fibers or oriented metal foam to establish preferential channels for heat transfer instead of random distribution. This would lead to increased thermal conductivity in the range of 500-1000%, utilizing reduced amounts of additives.

10.2 Heat transfer mechanisms

Conventional phonon models are unable to fully explain the heat conduction mechanisms in PCMs due to the complexity of their structures and physical/chemical properties. In most non-metallic systems, electrons are not available as heat carriers, and phonons typically dominate heat conduction in these materials.

Table 6. Comparison of various techniques for improving thermal conductivity [103]

Methods	Mechanisms	Limitations
The dispersion of highly conductive particles within the phase change material (PCM)	The incorporation of high thermal conductivity particles will enhance the thermal conductivity of the PCM.	The highly conductive particles may be sedimented, and these particles may not be generated within the heat transport network.
Multiple PCM methods	A rise difference in the average temperature.	This may not be useful in variable operating situations and is only appropriate for the design settings.
Microencapsulation of PCM	An increase in the heat transfer area.	Increased cost-mass reduction per PCM unit volume.
Extended surfaces such as fins	An increase in the heat transfer area.	The overall weight rose; PCM properties that are more expensive remain unchanged.
PCM integrated in porous matrices	PCM's increased thermal conductivity, expansion of the heat transfer area, and creation of a thermal transfer network.	Increased price boosts the overall weight drop in total heat storage capacity.

However, a large number of experimental results are inconsistent with purely phonon-based models, and it requires considering hybrid mechanisms such as phonon, electron, and photon contributions. Several enhancement strategies have been proposed, each with advantages and limitations, as summarized in Table 6.

10.3 Complexity of heat flow direction in composite matrices

The dominant pathways of heat flow in composite PCMs are especially difficult to determine, in particular for low-conductivity additives. Such advanced materials include graphene foams, graphitized carbon networks, and hexagonal boron nitride (HBN). However, there are substantial technical challenges with their preparation, mainly based on the tendency of such skeletons to collapse in certain reaction conditions; their preparation needs precise process control [102].

10.4 Phonon scattering and structural stability

The preparation of composite PCMs with improved performance requires reducing phonon scattering by widening the channels of heat transfer. Recent publications have discussed other new additives, including TiO_2 foams, 3D carbon architectures, and metal-organic frameworks (MOFs), among others. Accordingly, charging and discharging times are reduced, thereby improving the efficiency of the systems. Besides, composites have relatively low processing costs, compact designs, and adaptability for integration into a variety of thermal storage systems [102].

Research opportunity: Develop 3D thermally conductive structures (e.g., graphene aerogels, carbon foam networks) that maintain mechanical integrity through repeated phase changes. To achieve minimal phonon scattering during phase transitions, the lattice structure of the scaffold must match that of the PCM.

10.5 Nanoparticle-enhanced phase change materials

Nanoenhanced PCMs have received considerable attention because of their highly improved conductivity of heat and minimized supercooling effects. Nevertheless, there is still a lack of uniformity regarding latent heat storage: Whereas most studies find latent heat to be reduced upon the addition of nanoparticles, a few suggest that some kind of optimal particle loading may maximize latent heat [103]. The general thermal characteristics are strongly influenced by the dispersion of nanoparticles and nanoparticle structural changes during phase transitions. For example, van der Waals forces between nanoparticles weaken at high temperatures, which favors dispersion. On the other hand, solidification fosters nanoparticle aggregation and sedimentation, which can degrade performance after multiple cycles.

Research opportunity: Explore surface functionalization of nanoparticles to avoid aggregation and settling during repeated thermal cycling (>1000 cycles). Functionalized nanoparticles with suitable surface chemistry can also act as nucleation sites to suppress supercooling.

In short, balancing enhanced thermal conductivity, latent heat capacity, and long-term stability remains a key challenge for the further development of PCMs—one that must be addressed to achieve reliable, scalable, and sustainable TES.

11. APPLICATIONS OF PHASE CHANGE MATERIALS

While the primary focus of this review is PV thermal management, PCMs are being increasingly integrated into broader thermal energy systems due to their capacity to store and release massive latent heat around a consistent transition temperature. The following subsections on building applications, refrigeration, and industrial waste heat recovery are presented as supporting context for understanding PCM versatility, which informs material selection and system design for PV applications. For instance, long-term stability data from building applications and encapsulation techniques from refrigeration systems are directly transferable to PV cooling systems.

11.1 Phase change materials in building energy systems

Buildings account for a significant portion of the world's energy consumption, and PCMs are designed to improve both occupant comfort and thermal performance. To maintain interior temperatures within a specific range, PCMs are included in walls, roofs, floors, and even windows in passive systems. They reduce the need for heating and cooling by trapping heat during the day and releasing it at night. Especially in locations with significant daily temperature variations. PCMs are included in various heating, ventilation and air conditioning (HVAC) elements in active building systems, such as ceiling panels, ventilation air ducts, and radiant floor heating. These systems have PCM- based modules that buffer peak loads, stabilizing indoor air temperature and increasing system efficiency [104].

11.2 Phase change materials in solar thermal and photovoltaic applications

In solar energy systems, PCMs improve thermal energy capture and heat release time delay. PCMs are used in solar collectors and air heaters; for example, Extra solar energy is stored during peak hours and released when there is no sunlight. As a result, energy becomes more dependable and operates for longer. PCMs improve the efficiency of energy generation in PV/T systems by keeping the PV panels at ideal temperatures. Similar to this, PCMs in solar stills use stored heat from the day to continue desalination into the night [105].

11.3 Phase change materials in cold thermal energy storage and refrigeration

PCMs with sub-zero melting points can be used in cold chain systems to preserve temperature-sensitive products during transportation and storage, such as food, medicines, and vaccines. They are utilized in thermal packaging materials, cooling packs, and insulated containers [105]. PCM-integrated refrigeration systems reduce the need for electrical refrigeration systems by enabling the manufacture of ice, medical cold storage, and vaccine preservation in low-energy and off-grid places. PCMs that are encapsulated or nano-enhanced provide even greater stability and reusability in cold storage [106].

11.4 Phase change materials in industrial waste heat recovery

Industry sectors such as petrochemicals, cement, and metallurgy produce large amounts of waste heat. This kind of medium-to-low-grade thermal energy can be recovered by PCMs for use in process preheating, steam production, and space heating. To improve thermal cycling and boost waste heat usage efficiency, several pipe-assisted heat storage units and modular heat exchangers with embedded PCMs are presently being developed. Salt hydrates or metallic PCMs, which provide extremely high thermal conductivity with stability in repeated cycling, are commonly utilized for this application [107].

12. CONCLUSIONS

PCM incorporation with PV systems has emerged as a viable and efficient way to reduce thermal loss and improve solar energy conversion efficiency. According to the review done for this research, systems of pure, composite, finned, and hybrid PCMs are the main PCM-based cooling solutions that have the ability to greatly enhance both electrical performance and thermal regulation.

These efficiency improvements include the following:

•Pure PCMs, such as calcium chloride hexahydrate ($CaCl_2 \cdot 6H_2O$) and paraffin wax RT42, offer a straightforward, passive cooling method that can increase efficiency by up to 17.5%. Efficiency levels that would be achieved by using pure PCMs would fall between 2.8% and 14.4%, and the typical average is around 8–10%.

•Composite PCMs, which achieve efficiency gains of more than 30% (maximum reported: 30.45% using MgO/PT-58) by using thermally conductive material additives such as graphene nano-platelets, carbon nanotubes, and MgO. The mean efficiency increase in studies involving composite PCMs is estimated to be 15% to 20%. Carbon-containing fillers show superior results over metal oxides by a range of 5% to 10%, while having a lower latent heat value.

•Finned PCM designs have also shown cost-effective gains in thermal performance of about 18.16%. In finned PCMs without the nanoparticles, efficiency improvement ranges from 5% to 11%, showing the synergistic effect of fins and nanoparticles.

•The hybrid PCM systems that combine PCMs with advanced technologies such as thermoelectric generators and nano-fluids give efficiency improvements of 19.3% electrical efficiency and even a total efficiency of 76% (thermal & electrical), accord Such hybrid PCM systems seem to be the most promising technology of the future regarding the cooling of PV systems.

Some of the recurrent themes from the literature review are that increased efficiency scales with increases in thermal conductivity; however, there is marginal improvement after a certain level of additive concentration. Reductions in temperature of 10 to 20 ℃ increase efficiency by 5 to 15%. Hybrid active-passive systems perform significantly better than pure passive systems.

13. RECOMMENDATIONS AND FUTURE WORK

Based on the findings of this review, the following are future research directions for investigation:

•Design of Nano-Composites: Fabricate NEPCMs having ultra-high thermal conductivity (in excess of 5 W/(m·K)) and optimize nucleation agents in order to overcome the issue of supercooling. The next step would be to use surface-functionalized nanoparticles to minimize aggregation during multiple thermal cycling (≥1000 cycles), besides developing hybrid nanoparticles with both thermal conductivity enhancement and nucleating properties.

•Bio-based and Sustainable PCMs: Consider recent research pertaining to bio-based PCMs from 2024–2025, such as vegetable oils, fatty acid esters, and agricultural wastes, among others. As sustainable and bio-friendly options, bio-based PCMs have significant potential in terms of lowering the environmental impact of the system without compromising thermal performance for moderate temperature PV applications.

•MXene-based and Advanced Composites: Study MXene-based nano-composites, known to exhibit superior thermal conductivity of up to 500 W/(m·K) along with tuneable surface chemistry. Studies conducted in 2024–2025 reveal that the thermal conductivity of MXene/PCM composites could be increased by 300% to 600% without a significant loss of latent heat capacity.

•AI-based PCM Material Selection and Optimization: Machine learning and AI technology can be used to hasten PCM material selection and optimize additive levels. Using AI systems that have learned from existing databases of the thermophysical properties of different PCMs, predictions could be made regarding thermal conductivity, thermal capacity, and thermal cycling behavior of novel formulations that require no physical testing.

•LCA and Lifetime Evaluation of Behavior: Perform standard LCA experiments incorporating the PCM and the enclosure. Moreover, evaluate the thermal degradation over an operational life span of 25 years. In particular, special consideration must be given to the modeling of thermal cycling stability, since most research does not provide information beyond 100 thermal cycles.

•Economic Analysis and Scalability: Comprehensive techno-economic feasibility studies must be carried out with a particular emphasis on bio-based and renewable materials in order to evaluate large-scale production costs and their effects on the Levelized Cost of Electricity (LCOE).

•Hybrid Integration: Research how PCMs can be integrated with active cooling systems to create hybrid solutions that maximize the system's overall efficiency.

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NOMENCLATURE

ΔT	Temperature difference
Cp	Specific heat
K	Thermal conductivity
L	Latent heat
Tm	Melting temperature
ρ	Density
α	Thermal diffusivity
μm	Micrometer

Abbreviations

PCM	Phase Change Material
BN	Boron Nitride
CMC	Carboxymethyl Cellulose
CPCM	Composite Phase Change Material
CuO	Copper Oxide
DHPD	Disodium Hydrogen Phosphate Dodecahydrate
EG	Expanded Graphite
GO	Graphene Oxide
GP	Graphite Powder
MWCNTs	Multi-Walled Carbon Nanotubes
NC	Nano Coconut Shell Charcoal
NG	Nano Graphite
nm	Nanometer
PA	Palmitic Acid
PEG	Polyethylene Glycol
PV	Photovoltaic
PV/T	Photovoltaic/Thermal
TD	Tetradecanol
TES	Thermal Energy Storage
LCA	Life Cycle Assessment
GWP	Global Warming Potential
LHTES	Latent Heat Thermal Energy Storage
CPCMs	Composite phase change materials
HBN	Hexagonal boron nitride
MOFs	metal-organic frameworks
HVAC	Heating, ventilation and air conditioning
LCOE	Levelized Cost of Electricity

APPENDIX

Tables A1-A5 summarize detailed experimental data from the literature reviewed in Sections 8 and 9.

Table A1. Performance comparison and synthesis of pure phase change material (PCM) cooling systems in photovoltaic applications

No.	Authors	PCM Used	Methods	Configuration	Results
1	Maghrabie et al. [71]	Wax Paraffin (RT42)	Exp.	PCM is affixed to the panel's back surface, and Investigations are carried out at different degrees of tilt and PCM densities.	Electrical power and efficiency increased by 15.8% and 14.4%, respectively, at a thickness of 4 cm and a tilt angle of 32°.
2	Prakash et al. [72]	Latent heat of 167 kJ/kg in hydrated salt (HS36)	Exp.	An experimental setup was designed and installed at the top of an institution at a tilt angle of 11.5° in accordance with the latitude location.	The panel's electrical efficiency rose by 17.5% while its operating temperature dropped by 25.4% to 16.98 ℃.
3	Sheik et al. [73]	Polyethylene glycol (PEG) or polyethylene glycol 100 melts between 33 and 39 ℃.	Exp.	Using PCM to absorb excess heat from solar panels' backs can increase energy efficiency.	A 4.82% increase in the electrical efficiency of the system.
4	Arifin et al. [74]	Soybean wax	Num.	Using a PCM container as a passive cooling device, on the back plate of solar panels, 52 Wp polycrystalline solar cells were placed, both with and without soybean wax.	Increasing maximum efficiency by 0.42% at 900 W/m^2 intensity and reducing the optimal photovoltaic (PV) temperature from 61.7 ℃ to 55.7 ℃ at 1050 W/m^2 intensity.
5	Firoozzadeh et al. [75]	PEG 600	Exp.	PEG 600 is colorless, non-toxic, odorless, and non-acidic, with melting temperatures between	Efficiency increases by 2.45% while the temperature decreases by 18.3%.

	Paraffin	Exp.	23 and 26 ℃ and positioned behind a 60 W PV panel. PCM is odorless, non-acidic, colorless, and non-toxic, with melting points between 57 and 59 ℃ and positioned on the rear of a 60 W PV panel.	Efficiency increases by 2.8% while the temperature decreases by 40.2 °C.

Table A2. Comparative overview of structural enhancement (finned) and multi-technology hybrid phase change material (PCM) cooling configurations for photovoltaic (PV) applications

No.	Authors	PCM Used	Methods	Configuration	Results
1	Praveen Kumar et al. [76]	PCM was combined with zinc oxide (ZnO) nanoparticles in paraffin.	Exp.	Applying ZnO nanoparticles and paraffin wax (PCM) to the rear of a 50 W solar panel.	16.5% lower temperature and 12.18% higher output power in contrast to an uncooled panel.
2	Baissi et al. [77]	$CaCl_2 \cdot 6H_2O$	Exp.	lowering the operational temperature of the back of the PV module's surface.	When PCM is used, the average operating temperature drops by up to 21 ℃, the average power output increases by 46.11%, and the electrical efficiency improves by 6%.
3	Sheik et al. [73]	Alumina nano PCM (polyethylene glycol (PEG) 1000)	Exp.	The excess heat from the backs of solar panels is absorbed by PCM.	8.1% increase in the electricity efficiency of the system.
4	Fang et al. [78]	Expanded graphite (EG) with nano-copper in paraffin PCM	Exp. and Num.	Between 62 and 64 ℃, the paraffin PCM melted. The EG had an 80 mesh size, a surface area of around 40 m^2/g, and an expansion rate of 250 mL/g. Cu nanoparticles are 101 nm in size.	Cu greatly improved the phase-change performance of the composite PCMs, increasing the storage and release heat response rates by 153% and 99%, respectively. Electrical power increased by 21%.
5	Rostami et al. [79]	Nano graphite (NG)/paraffin composite PCM	Exp.	To stop the PCM from melting, a finned tube heat-melting exchanger was installed. PCM is mixed with graphite nanoparticles (0.002–0.012 (w/v)) after a PV. In the first stage, panels are cooled using a paraffin heat exchanger and a pure finned tube.	With the greatest water flow rate (Q = 100 mL s1) and PCM nanographite with = 0.01 (w/v), the average temperature at the mean temperature at the PV module's surface is reduced from 337 to 311 K. The PV/nanoPCM combination's power generation rose by the most, 21.2%, when efficient parameters were used.
6	Jamil et al. [80]	Magnesium oxide (MgO) plus PT-58 (PureTemp)	Exp.	PCM integration on the panel's back side.	The electrical power output increased by 30.45%.
7	Kumar et al. [81]	Paraffin with 0.5% titanium dioxide (TiO_2) volume	Exp.	Two solar PV panels with similar layouts were examined in this study; one had nano PCM integrated beneath the panel, while the other did not.	The panel's daily efficiency increased by 2.1% while its average surface temperature decreased by 13 ℃.

Table A3. Synthesis of experimental and numerical studies on finned phase change material (PCM) configurations for solar panel cooling

No.	Authors	PCM Used	Methods	Configuration	Results
1	Chibani et al. [82]	RT 35-HC (240,000 J/kg of latent heat)	Num.	PCM (RT35HC) is set up. Utilizing a pair of fins composed of steel, copper, graphite, and titanium. The model is carried out at zero inclinations, 35, 50, 65, and 90 degrees.	When steel and titanium were swapped out for graphite and copper, the solar panel's average temperature dropped by 4 ℃. The temperature was maintained at about 40 ℃ on average.
2	Bria et al. [83]	Aluminum-finned paraffin (RT42)	Num.	The model consists of PCM layers with an aluminum rectangular fin affixed to the panel's back.	There is a 32 ℃ drop in temperature. Additionally, it has been demonstrated that increasing PCM thickness further lowers the PV temperature.
3	Praveen Kumar et al. [76]	ZnO nanoparticles were mixed with PCM to create inexpensive aluminum reflectors, sinks, and paraffin	Exp,	combining PCM (paraffin wax)/ZnO nanoparticles and a cheap aluminum reflector. The experiment was conducted in an outdoor setting at latitude 56.84 °N and longitude 60.64 °E using a 50 W Delta-SM-12 M solar panel.	18.16% more electricity was produced and the temperature dropped by 28.3%.
4	Zhang et al. [84]	Inorganic PCM, composed of salt as well as water ($CaCl_2 \cdot 6H_2O$) and fins made of copper	Num.	The solar collector, which has an angle of 30° inclination, includes a plexiglass shelter, copper sheet, panel, and plexiglass with a layer of insulation. Eleven fins were used.	The efficiency was 11.19% higher and the average temperature was 48.58 ℃ instead of 64.69 ℃.
5	Marudaipillai et al.	Expanded graphite (EG)	Exp.	This technique preserved the panel's	The improved PV panel efficiency of

	[85]	creates a stable PEG PCM		shape and provided a sufficient thermal interface between the PCM and the panel when it is melting and cooling.	3.7% is higher than the conventional cooling method's efficiency of 1.072% (heat sink).
6	Firoozzadeh et al. [75]	Paraffin with fins	Exp.	Melting points between 56 and 58 ℃. PCM is odorless, non-acidic, colorless, and non-toxic. Positioned below a 60 W PV panel.	Efficiency increases by 5.94% and the temperature decreases by 47 ℃.
7	Wongwuttanasatian et al. [86]	Palm wax in a box with fins	Exp.	The PCM box was fastened to the back surface of a 20 W polycrystalline PV module at a 15° southward slope.	There was a 5.3% gain in module efficiency and a 6.1 °C drop in temperature.

Table A4. Summary of research on hybrid and combined phase change material (PCM) cooling strategies in PV applications

No.	Authors	PCM Used	Methods	Configuration	Results
1	Hamada et al. [87]	PCM balls that are encapsulated	Exp.	Comparing passive and active cooling methods at a 2.8 L/min flow rate of cooling water.	The photovoltaic/thermal (PV/T)-PCM panel cooled through the active method generated the highest electrical and thermal energy gain, with a total efficiency of 76% as opposed to 35.8% for the passive cooling strategy.
2	Bassam et al. [88]	Nano PCM (SiC 2% Vol) and Nanofluid (SiC 0.7% Vol)	Exp.	The cooling nanofluid flow system, including an inner-grooved microfin pipe coated in nano PCM, is placed in a controlled environment using an indoor solar simulator.	There was a nearly 45 °C drop in temperature. The proposed system outperformed a conventional circular tube without micro-fins in terms of thermal efficiency by 77.5%. Additionally, the system generates 14.5 W of power as opposed to the PV panel's 10.49 W.
3	Gad et al. [89]	SP31 equipped with heat pipes	Num.	In summer, a 3 cm thickness test was conducted.	11.5% improvement in electrical efficiency and a 20.6 ℃ decrease in temperature.
4	Firoozzadeh and Shiravi [90]	Phase-change materials combined with an aluminum porous medium	Exp.	2 cm porous medium thickness.	21 ℃ reduction in temperature.
5	Singh et al. [91]	Vaseline PCMs, thermoelectric, aluminum heat sinks, and silver back casing	Num.	A 10.5 W polycrystalline PV panel is the subject of the study.	The biggest gains in panel efficiency and electrical performance are 19.32% and 19.4%, respectively.
6	Metwally et al. [92]	RT-25 equipped with thermoelectric generators	Num.	A hybrid cooling system uses phase change material and a thermoelectric generator to dissipate heat from solar panels.	In favorable conditions, panel efficiency increases by 2.5%, while in sunny situations, it increases by 3.5%. Furthermore, electrical power generation rises by 20% in favorable conditions and by 30% in bright weather.
7	Abdulmunem et al. [93]	A copper foam matrix, fully refined paraffin wax PCM, and carbon nanotube additions (concentration ratio of 0.2%)	Exp.	In a case study in a hot temperature zone, the performance of PV panels was examined experimentally.	rise in the PV panels' typical electrical efficiency ranges from 5% to 22%.
8	Carmona et al. [94]	PV/T with RT-35 PCM and Rubitherm	Exp.	the simultaneous operation of a conventional PV module and a hybrid PV/T-PCM panel.	The two solar modules that were used have the same brand, model, and technical specs. The hybrid PV/T-PCM outperformed the standard PV module in terms of daily electrical efficiency by 7.43%. Furthermore, the PV module's daily electrical efficiency is 13.12%, whereas the PV/T-PCM module's daily hybrid efficiency is 31.35%.
9	Singh et al. [95]	Aluminum containers for calcium chloride hexahydrate ($CaCl_2 \cdot 6H_2O$)	Exp.	Outside, the panel was exposed to the sun. On days with clear weather on January 26, 2019, and June 15, 2019, the experiment was carried out from 6:00 a.m. to 7:00 p.m. The panel had a 17° tilt and faced south.	In January, the maximum PV temperature dropped from 65.7 ℃ to 47.3 ℃, and in June, it dropped from 78.2 ℃ to 54.9 ℃. Throughout the middle of the day, the electrical efficiency increased from 9.45% to 10.57%. In January and June, daily power generation increased by 6.2% and 8.3%, respectively.

Table A5. An overview of improved phase change material (PCM) composites using structural alterations and additive materials

No.	Authors	PCM Material and Properties	Additive Material, Properties, Dimensions, and Concentration of Additive Material	Characterization and Type Eutectic PCMs	Results
1	Gu et al. [97]	Tm = 60 ℃, L = 217 J/g.	Graphite powder (GP), not available, 3–5% by mass	First, mullite was roasted for six hours at 120 degrees to eliminate the water content in the drying oven. Second, the PA was heated to 80 ℃ in the	Compared to pure PA, PA/mullite/GP has better chemical and thermal reliability and is a viable option for solar energy storage

				water bath to liquefy it. Using the simple impregnation technique, the PA/mullite composites were made by mixing the liquid PA into the mullite pore region. Following an hour of stirring and twenty minutes of ultrasonication, GP was then distributed throughout the composites. Organic-Organic.	applications. The enhanced thermal conductivity of 5% has caused the manufactured PA/mullite/GP's thermal conductivity to rise from 0.27 to 0.54 W/(m·K).
2	Safaei et al. [98]	Paraffin wax, Tm: 45 °C, k: 0.24 W/(m·K) L: 236 kJ/kg.	Graphene oxide (GO), density:3610 kg/m^3, k: 3020 W/(m·K), not available, 0.2, 0.4 and 0.6% by weight dispersed in paraffin	At 45 °C, GO in varying concentrations was mixed into melted paraffin. Organic-organic.	A larger Nusselt number and, thus, a higher heat transfer coefficient were obtained when more GO was added to PCM, suggesting a considerable potential for a noticeable decrease in heating times.
3	Wang et al. [99]	Paraffin wax, L = 198 kJ/kg. Tm = 51–53 °C	Copper oxide (CuO) nanopartile, k = 37 W/(m·K) at 25 °C, specific surface area of 13.1 m^2/g. Changing mass fractions of 0.3, 0.6, 0.9, and 1.2%, with an average particle size of 30 nm.	There was a two-phase approach. Paraffin is melted and combined with various mass fractions in a water bath. After adding the dispersant Span-80 and mixing the nanoparticles in a 1:1 ratio, the materials are put through a 42-hour ultrasonic oscillator minutes. Natural and non-organic.	The PCMs' thermal conductivity rises by 24.4% and the latent falls by 1.5% with 1.2% CuO.
4	Pasupathi et al. [100]	Paraffin wax, k = 0.181 W/(m·K) Tm = 64.74 °C	SiO_2 nanoparticles (k = 1.51 W/(m·K), Tm = 1717 °C) and CeO_2 nanoparticles (k = 13 W/(m·K), Tm = 2611 °C) make up the hybrid nanoparticles. CeO_2 nanoparticles have a mean size of 25 nm, while SiO_2 nanoparticles have a mean diameter of 25 nm. 0, 0.49, 1, and 3% of hybrid nanoparticles by mass	A hot water bath was used to melt the paraffin wax. The previously mentioned molten paraffin wax was mixed with hybrid nanoparticles of the necessary mass at a constant pace while it was heated and stirred in order to produce a homogeneous mixture. To achieve a fine dispersion of the nanoparticles in paraffin, the composite mixture was subjected to 61 minutes of sonication utilizing an ultrasonicator.	Confirmed that hybrid nanoparticles can boost paraffin's thermal conductivity and thermal storage properties when in contrast to the next highest pure paraffin mass percent.
5	Prieto et al. [101]	Epoxy resin	Stainless steel wool AISI 421 steel, density 198.9 kg/m^3, k = 41 W/(m·K). The fibers had a diameter of 11 and 301 µm. The mineral wool was placed inside metal resins and containers were included with 11% and 91% epoxy and fiber resin.	The second type of sample was made by vacuum infiltration and the first one by casting techniques. In the first sample, mineral wool was introduced into a metal vessel heated to 140 °C and compressed with a PCM after the fibers had been preheated for ten minutes at 170 °C to ensure the resin was hardened properly. For the second sample, the metal wool was enclosed within a plastic bag, and a vacuum was generated to form the composite. After creating the vacuum, the resin was infiltrated and heat-treated for curing. Inorganic.	By employing metal wool that was infiltrated into the resin under vacuum, the PCM thermal conductivity that is effective was brought up to the industry-required values of around 5 W/(m·K).
6	Jiang et al. [45]	Octadecylamine ($C_{18}H_{39}N$), Tm: 51.8 °C, L: 196.5 J/g.	The template method is used to prepare graphite foam. After dissolving 25.7 g of resorcinol in 41 mL of DI water and 41 mL of 100% ethanol, 2.6 m of 37% by weight hydrochloric acid was added. Next, a dropwise addition of 18.72 g of a 37% by weight formaldehyde solution was made. Then, 22 g of nickel nitrate was added after a specific mass ratio of GP. The produced graphite foam has several interpenetrating pore structures that offer PCMs numerous adsorption sites. 5, 10, and 15% by weight graphite particles are included in graphite foam.	25 grams of octadecylamine were melted, followed by the addition of 10 × 5 × 10 mm of graphite foam. The combination was subsequently positioned in a vacuum drying oven maintained at 81 °C for a duration of 24 hours.	Because of their superior performance, octadecylamine/graphite foam CPCMs have strong thermal characteristics and are much more competitive in the energy storage market.
7	Ibrahim et al. [46]	Iraqi paraffin wax k: 0.2 W/(m·K) L: 195 kJ/K	Magnesium oxide (MgO) nanoparticles, Purity 98%, Tm = 2862 °C, k = 50.1 W/(m·K). Titanium dioxide (TiO_2), purity	Subsequent to storing liquid paraffin, particular mass fractions of nanoparticles were added, and the mixture was stirred for 60 minutes	Particularly for the hybrid nanoparticles, the products' thermal conductivity was greatly enhanced. 4.6% was the biggest improvement.

		Tm: 42 °C.	98.87%, Tm = 1843 °C, k = 299-769 W/(m·K). 0.25, 0.51, 0.72 and 1.2% by mass. With the same mass fractions, the two types were mixed with 49.9% each.	using an ultrasonic vibrator. Organic-Inorganic.	The products' heat capacity marginally increased.
8	Rabady and Malkawi [47]	Sodium thiosulfate pentahydrate, Tm: 48 °C k: 1.15 W/(m·K)	Multi-walled carbon nanotube (MWCNT) and GNP nanoparticles. Purity >95%, diameter 40 nm. MWCNT, purity >90%, diameter 50–80 nm.GNP. 1, 3, 5, and 7% by mass.	Sodium thiosulfate pentahydrate, or pure PCMs, are placed on a heated plate inside a water beaker that is between 50 and 60 °C. Following the addition of the given amount of nanofillers to liquid PCMs, the Composites were produced by 20 minutes of shear mixing using a magnetic stirrer and then 50 minutes of ultrasonic shaking.	Thermal conductivity improved significantly as a result of the nanoparticles' higher mass fraction. Thermal conductivity rose by 155.3 and 249.61%, respectively, for 7% mass fractions of GNP-PCMs and Carbon Nanotubes-PCMs.
9	Sun et al. [48]	Pure paraffin, L = 232.2 J/g, Ks = 0.37 W/(m·K) Tm = 26–28 °C	Nano graphite (NG) plus nano coconut shell charcoal (NC). 99.9% purity. The graphite was between 20 and 500 nm in size. In the lab, the NC was made. NG and NC were added to CPCMs at weight percentages of 0.02, 0.06, and 0.1%.	The CPCMs were prepared using two different methods, one with and one without dispersant, using a two- step process. A magnet was used to stir the mixture after the NC and NG were combined with 52 °C heated pure liquid paraffin.	Compared to pure paraffin, CPCMs had a lower latent heat. As the nanomaterial's concentration rose, in terms of PCM melting efficiency, nanographite performs better than nanococoshell charcoal.