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Review Article

Nano-material based composite phase change materials and nanofluid for solar thermal energy storage applications: Featuring numerical and experimental approaches

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ABSTRACT

Continuously raising the photovoltaic thermal (PVT) module's cell temperature reduces the system's electrical efficiency, reducing its effectiveness. Therefore, one of the ways to maintain the desired efficiency is to install a hybrid PVT system with the incorporation of Phase Change Material (PCM). The utilization of PCM has been identified as a promising method of storing thermal energy in a thermal energy storage (TES) system. However, the effective usage of PCM is restricted due to their low thermal conductivity attribute that prevents their efficient applications in the practical world. The dispersion of nanoparticles into the base-fluid (nanofluid) and PCM has been regarded as a promising method for improving the thermal conductivity of PCMs and thus reducing thermal energy charging and discharging duration. This work aims to critically and fully investigate the research on nanoparticle incorporation in PCMs and the preparation of nanofluids for the improvement in thermophysical properties for both. Some studies showed that the increment reached over 1000 % and carbon-based nanoparticles triumphed over the performance of metal-based nanoparticles. The usage of graphite-based nanoparticles with 7.5 % and 10 % by weight increased the thermal conductivity by around 620 % and 1100 % respectively. The review also considers the environmental impact of using nanofluid and NEPCM, reducing the CO_2 emission by around 448 kg/m^2.yr with the utilization of carbon-based nanofluid (CNT/water) in the hybrid PVT system. This review also provides in-depth information about the perspective benefits, environmental impacts, and challenges of implementing nanotechnology as nanofluid and NEPCM, and it highlights the significance of continuing research and development in this area to push forward the solar energy conservation and conversion process to be uplifted.

1. Introduction

In the last hundred years, energy dependency has crossed quite a high margin and it is predicted that the non-renewable sources will deplete soon. An increase in per capita income and switching to more comfortable lifestyles using digital devices, refrigerators, acute use of transportation services, air conditioning for heating and cooling, home appliances, and others have fuelled to consumption of more energy on a daily basis. Over the past two centuries, harnessing fossil fuels has been invaluable for making a huge uplift in our standard of living. Climate change is considered one of the primary concerns for humanity in the 21st century [1]. The greenhouse gases such as CO_2, CH_4, CFCs, N_2O, peroxyacetyl-nitrate, and ozone and their increasing concentration in the atmosphere are likely to trap heat radiating from the earth's surface [2]. If the efficient utilization of renewable sources in the actual meeting path is promoted, there is ample scope to degrade the rate of emission of greenhouse gases [3–5].

Conventional energy resources can be split into three categories: fossil fuels, renewable, and nuclear resources. Coal, oil, and gas basically constitute almost 80 % of the world's recent energy demand. [6]. On the contrary, renewable energy sources include biomass, wind, solar, hydropower, geothermal, and tidal energies are considered as green energy resources [7–9]. The uplift and familiarisation of using renewable energy sources can enhance supply markets of energy, will help to reduce local and global energy impacts, will secure long-term sustainable energy supplies, and open various opportunities [10]. The promise of low-cost renewable fuel generation is offered by the conversion of

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Nomenclature

Q_s	Sensible Heat (J)
Q_l	Latent Heat (J)
H_{fg}	Specific Latent Heat (J/kg K)
Q	Heat Stored (J)
m	Mass flow rate of storage medium (kg/s)
C_{eff}	Effective heat capacity
Δh_T	Latent heat (kJ)
$C_{p,l}$	Specific heat of liquid NEPCM (kJ/kg K)
$C_{p,s}$	Specific heat of solid NEPCM (kJ/kg K)
k_{eff}	Effective Thermal Conductivity (W/m K)
k_{np}	Thermal conductivity of nanoparticles (W/m K)
k_{pcm}	Thermal conductivity of PCM (W/m K)
k_{base}	Thermal conductivity of base matrix (W/m K)
T_i	Initial Temperature (K)
T_f	Final Temperature (K)
B	Boltzmann constant (J/K)
$\dot{C}$	Empirical constant
u	Fluid velocity (m/s)
f	Liquid fraction of NEPCM
d	Diameter of nanoparticle (nm)

Symbols

$\varnothing$	Volume fraction of additives
δ	Metal foam porosity
ρ	Density of NEPCM (kg/m^3)
α	Thermal diffusivity
μ_{np}	Dynamic viscosity of nanoparticles
γ	Fraction of the liquid volume travelling with the nanoparticle
β_k	Empirical function of Brownian motion
β	Superficial expansion factor
ξ	Correction factor for Brownian motion
δ	The metal foam porosity
$\varnothing_{wt}$	Weight fraction of the additives

Abbreviation

ANN	Artificial Neural Network
CNT	Carbon nanotubes
CNF	Carbon nano-fiber
HDPE	High-density polyethylene
PV	Photovoltaic
PVT	Photovoltaic Thermal System
EG	Expanded Graphite
CFC	Chlorofluorocarbon
GNP	Graphene nanoplatelet
NPVT	Nanofluid based PVT system
FESEM	Field emission scanning electron microscopy
IEA	International Energy Agency
MSS-PCM	Manganese-based organic-metallic solid solid PCM
NEPCM	Nano enhanced PCM
PCM	Phase Change Material
TES	Thermal Energy Storage
MWCNT	Multi-walled carbon nanotubes
XRD	X-ray diffraction
FTIR	Fourier transform infrared spectroscopy
SEM	Scanning electronic microscope
EDX	Energy dispersive X-ray spectroscopy
TCA	Thermal conductivity analysis
DSC	Differential scanning calorimetry
TGA	Thermogravimetric analysis
Vis	Visible
UV	Ultra-violet
LPM	Liter per minute

photoelectrochemical solar energy from abundant sunlight and water [11]. In addition, solar energy possesses the irreplaceable attributes of cleanness, sustainability, and abundance [12,13]. Among many others, solar energy is considered one of the best options for the future world. Sun emits power at the rate of 3.8×10^{23} kW out of which approximately 1.8×10^{14} kW is intercepted by the earth itself [14]. After

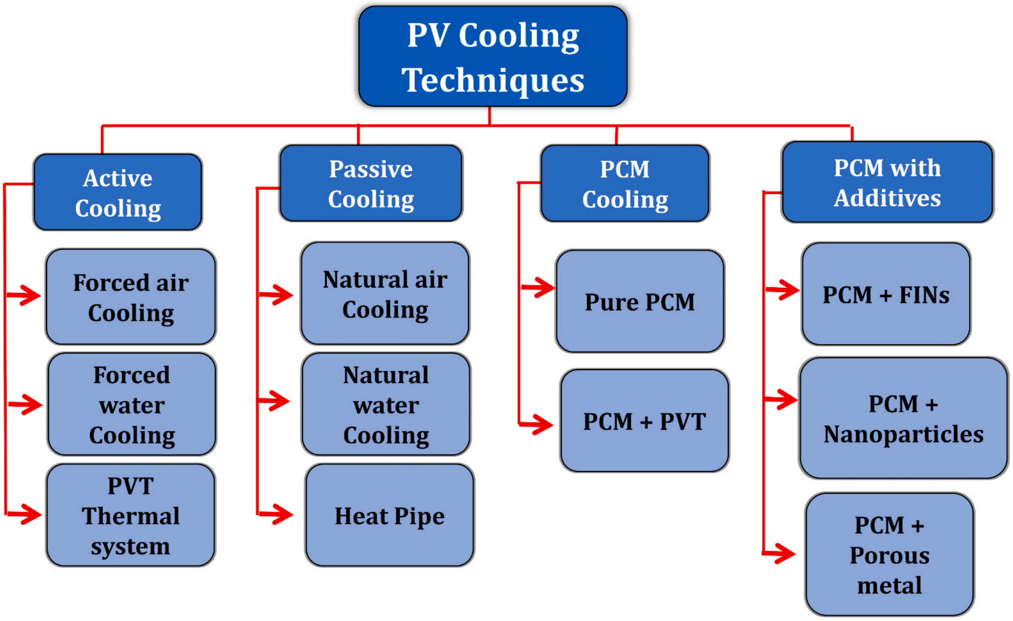


Fig. 1. Different cooling techniques of PV module.

reaching the earth in various forms like heat and light, the majority of the portion is lost by scattering, absorption and reflection and its availability in nature makes it an emerging source of energy [15,16].

Compared to other temperate countries, Asian countries are observed to have the largest potential for solar irradiation due to their relatively longer annual sunshine hours [17,18]. A PV cell is a mechanically-free gadget that directly generates electricity from sunshine. But the thing of concern is that the efficiency of the solar system, in particular, PV arrangement is generally low. The surfaces continuously in contact with direct sunlight tend to degrade the output of the PV module adversely due to the rise in temperature. However, solar cell efficiency degrades by almost 0.5 % for each increment of surface temperature about 1^0C [19,20]. Therefore, using cooling techniques can be a suitable solution to reduce the excessive heat generated in PV panels and enhances efficiency [21]. Fig. 1 Shows various cooling techniques of PV panels.

Scientists are working on active and passive cooling techniques to reduce solar cell temperature. A suitable coolant like air or water is necessary for active cooling which involves a fan or pump power. In contrast, passive cooling requires no specialized power equipment to cool down PV cells. The cooling process of Phase Change Materials (PCM) is a kind of passive conductive cooling. PCM are materials that can absorb or release a sizable quantity of so-called “latent” heat, hence restricting thermal energy and maintaining thermal stability. In addition, integrated PCM has significant daytime heat absorption qualities and so it would become a superior option for PV modules [22]. There are numerous PCMs including paraffin wax, hydrated salts, and organic/inorganic compounds can be also utilized in the TES system for charging and discharging phenomena. However, their practical applications are being restricted due to their low thermal conductivity attributes. It degrades the rate of heat extraction from the PV panel as well as reduces the charging and discharging time of the TES system. Many researchers have addressed this issue by the insertion of highly conductive nanoparticles, metal foam, metal fins, and porous material into the various PCMs [23]. Hence, due to their high thermal conductivity and superior heat transfer capability, nano-PCM and nanofluids have attracted a lot of attention from the research community [24]. In recent years, a heat transfer fluid, containing a dispersion of nano-sized solid particles (nanoparticles) with a typical diameter of the order of 1–100 nm, called nanofluid, and nanoparticles have appeared in the scientific community with exceptional qualities such as a high surface-to-volume ratio, superior thermal conductivity, improved stability, decreased viscosity, and pumping power [25]. Transportation, microelectronics, refrigeration, photovoltaic (PV), medicinal, power generation, space, and nuclear technologies are just a few of the potential uses for nanofluids. The fabrication of thermal fluids based on nanotechnology to optimize energy systems increases the effectiveness of conversion processes and has significant effects on the economy and the environment [26].

To review the updated literature, keyword-based search methods have been applied using major online platforms such as Science Direct (https://www.sciencedirect.com/), Scopus (https://www.scopus.com/), and Google Scholar (https://scholar.google.com/). The keywords such as “Nano-enhanced PCM (NEPCM)”, “Nanofluid-based PVT system”, “economic and environmental perspective based on NEPCM”, and “numerical analysis methods in PVT systems” are used. Based on the previously conducted reviews, as given in Table 1, it was established that a comprehensive review on NEPCM and nano-fluids for the hybrid PVT and TES applications along with the details environmental and economic perspective has not reported yet. This review article gives in-depth analysis to comprehend the importance utilization of nanoparticles into base-fluid (nanofluid) and NEPCMs to improve the thermophysical properties including thermal conductivity, latent heat, and the phase change temperature of the PCMs and their suitability for the real-world applications, especially in the hybrid PVT and TES systems. The aim of this study is to present the overall environmental and economic perspective, challenges of utilizing nanofluid and Nano-enhanced PCM with substantial explanation and future directions for the development to the researchers in developing their knowledge on this field. In addition, most of the numerical approaches have also been highlighted along with the considering variables. The sections are structured as follows: Section 2 discusses PCM including its classification and PCM selection criteria. Section 3 elucidates the reason behind using nanoparticles with PCM and sub-sections express the effect of nanoparticles on thermal conductivities, latent heat, and phase change temperature of PCM. Section 4 expatiates the different cooling techniques of PV panels using single PCM, nano-enhanced PCM, PCM with nanofluid, nanofluid-based PVT system, and hybrid nanofluid based system. Section 5 discusses the expressions regarding the numerical investigation of nano-enhanced PCM. Section 6 elucidates numerical and experimental approaches of NEPCM in TES. Sections 7 and 8 present the environmental and economical perspective of using nanofluid and nano-enhanced PCM respectively. Section 9 presents challenges of using NEPCM and nanofluid and section 10 draws a conclusion with future recommendations. It is possible to conduct a thorough examination and comparison of the steps involved in creating NEPCM and nanofluid, and to form a conclusion by contrasting certain modern environmentally friendly synthesis methods with more traditional ones.

Table 1
Comparison between previously published and recent review paper.

Ref.	Main objective
[27]	The thermophysical properties of nano-enhanced PCM were reviewed.
[28]	The preparation, thermophysical properties of NEPCM, and the selection criteria of PCM were reviewed by this review article for building application.
[29]	The methods of enhancing the thermal conductivity of the PCMs were reviewed by the addition of conductive substance or encapsulated PCM and PCM application.
[30]	This study discussed various PCMs, their nanoencapsulation technologies, phase change fibers, and their effective applications in energy-storing devices.
[31]	This review article examines the synthesis, characterization, and impact of nanoparticles (NPs) on the thermophysical characteristics, stability, and applications of nanoparticle-enhanced phase change materials (NEPCM).
[32]	This research examines the methodology for making NEPCMs, explores the thermal conductivity of NEPCMs in solar heat collecting, and investigates their many applications in diverse domains.
Present Review	This study investigates the effect on thermophysical properties of NEPCM and the comprehension study of the applications of NEPCM and nano-fluid based hybrid PVT and TES systems for enhancing their performance along with the challenges and environmental impact associated with the utilization of nanoparticles.

2. About PCMs

Larger storage devices are required to store massive quantities of energy since the lower energy storage density of sensible thermal energy storage materials like brick, rock, concrete and soil limits their potential uses. In contrast, PCM is a material that undergoes phase transition. As seen in Fig. 2, the primary benefit of PCMs is their large potential for energy storage. A substantial amount of latent heat can be absorbed, stored, and released by PCMs within a specific temperature range, as shown in Fig. 3. Even after thousands of phase change cycles, PCMs possess the potential to retain latent heat energy without any changes [33]. The sensible and latent heat which are stored by PCM can be expressed by Eqns. (1) and (2) [34].

$$Q_s = m\, c_p\, \Delta T \tag{1}$$

$$Q_l = m\, h_{fg} \tag{2}$$

where, Q_s represents the sensible heat, $Q_l$the latent heat, m the mass, ΔT

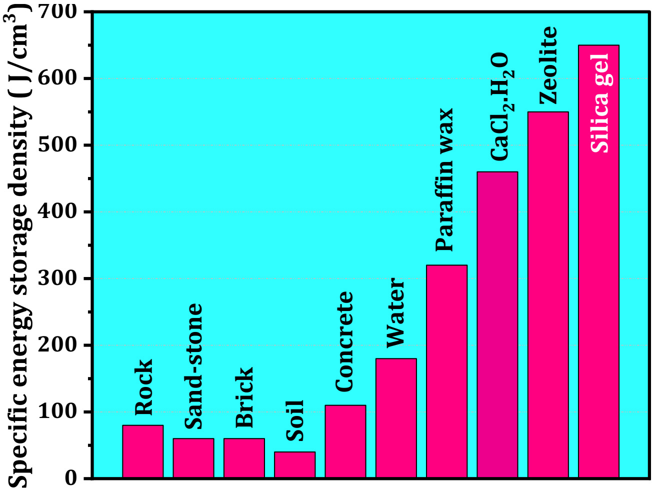


Fig. 2. Comparison of specific energy storage density of sensible and latent heat storage materials [36,37].

the temperature changes, h_{fg} the specific latent heat. When the PCMs are used indoors, large amounts of heat are exchanged with the surrounding environment through consecutive cycles involving melting and freezing due to extreme changes in air temperature [35].

PCM fumbles a lot due to its lower thermal conductivity in most frequent cases. This results in a reduction in thermal performance and overall efficiency. Various techniques are adopted to overcome these sorts of inappropriate economic justifications including microcapsules PCMs [39–41], using extended surfaces like fins [42–44], and using nanoparticles with PCM [45–47].

2.1. Classification of PCMs

For PCMs phase transitions are taken place in solid–solid, solid–gas, liquid–gas, and solid-liquid states. PCMs are generally categorized into three and sometimes four main groups [45]. They are organic PCMs, inorganic PCMs, and eutectics of organic and inorganic compounds, and are depicted in Fig. 4. Paraffins and non-paraffins are in the subcategory of organics. The chemical formula of paraffin is C_nH_{2n+2}.They are derived from oil and belong to the enriched hydrocarbon family. The groups containing $n \leq 5$ are gas at 25^0C. Similarly, groups with $n = 5$ and $n = 15$ exhibit liquid properties, while the remaining groups are solid. Paraffin possesses lower thermal conductivity properties and acts as an insulator. Therefore, the insertion of materials is needed to enhance the thermal conductivity of paraffin [48]. In contrast, non-organic paraffin contains lower melting temperature with a chemical composition of $CH_3(CH_2)_{2n}COOH$. Salt hydrates and metals are in the inorganic division. Salt hydrates are often regarded as alloys of some kind of inorganic salts (AB) and water (H_2O). This results in an emblematic crystalline solid having a general formula of $AB.xH_2O$ [43].

That means inorganic salt hydrate is basically an ionic compound and a number of water molecules are attracted by the ions causing it enclosed within its crystal lattice. The general formula is represented as follows, $M_xN_y.nH_2O$. Equation for congruent dehydration [49]:

$$M_xN_y.nH_2O + \Delta H_1 \rightarrow M_xN_y + nH_2O \tag{3}$$

This type of phase change transition is really thought to be the dehydration or hydration of the salt, while it can also be thought of as the compound melting or freezing [50,51]. Because of the property of non-flammability salt hydrates are a better alternative to organic PCMs. Apart from the advantage, salt hydrates make the environment corrosive and another concern of the density variation in solid and liquid states. There is a lacking conducting a study on salt hydrates for cooling PV panels due to its inherent limitations like very high sub-cooling. Eutectics, may exist in various types, and they are made by combining several materials [52]. Among them, an organic eutectic PCM is basically a combination of several organic PCMs. It serves as an individual component and freezes to a familiar crystal mixture and melts contemporarily without separation. For TES systems, a decent number of organic eutectics may be implied at almost any desired melting point [53]. The chemical nature and anticipated function of a PCM determine its temperature range. The respective temperature ranges of several PCM types are displayed in Fig. 5. The precise formulation and purity of the PCM can affect these estimated temperature ranges. Furthermore, a PCM's efficiency and applicability for a certain application are determined by a number of criteria, including cost, stability, latent heat of fusion, thermal conductivity, and stability at a given temperature.

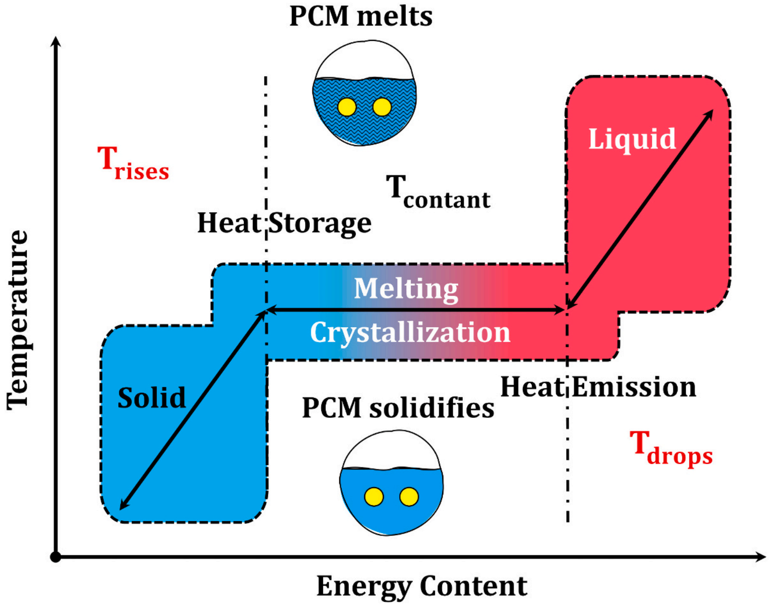


Fig. 3. Phase transition diagram of PCM [38].

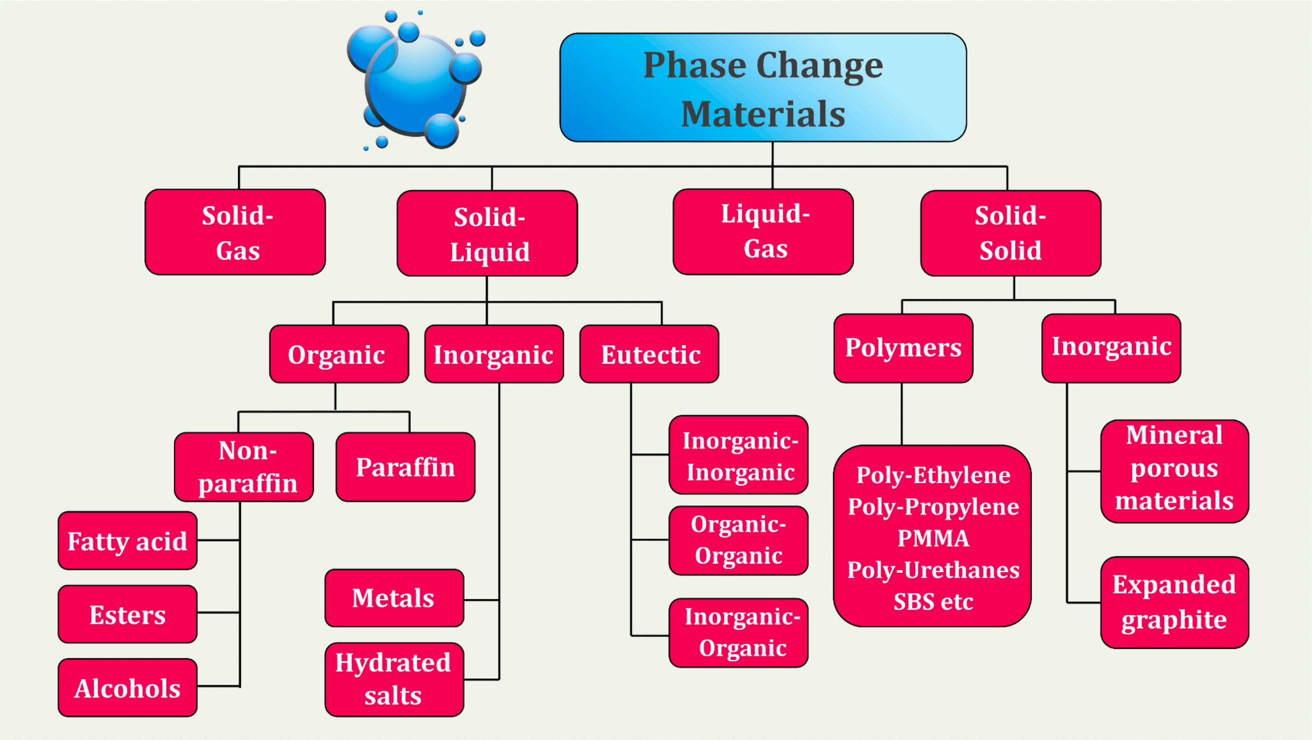


Fig. 4. Classification of phase change materials.

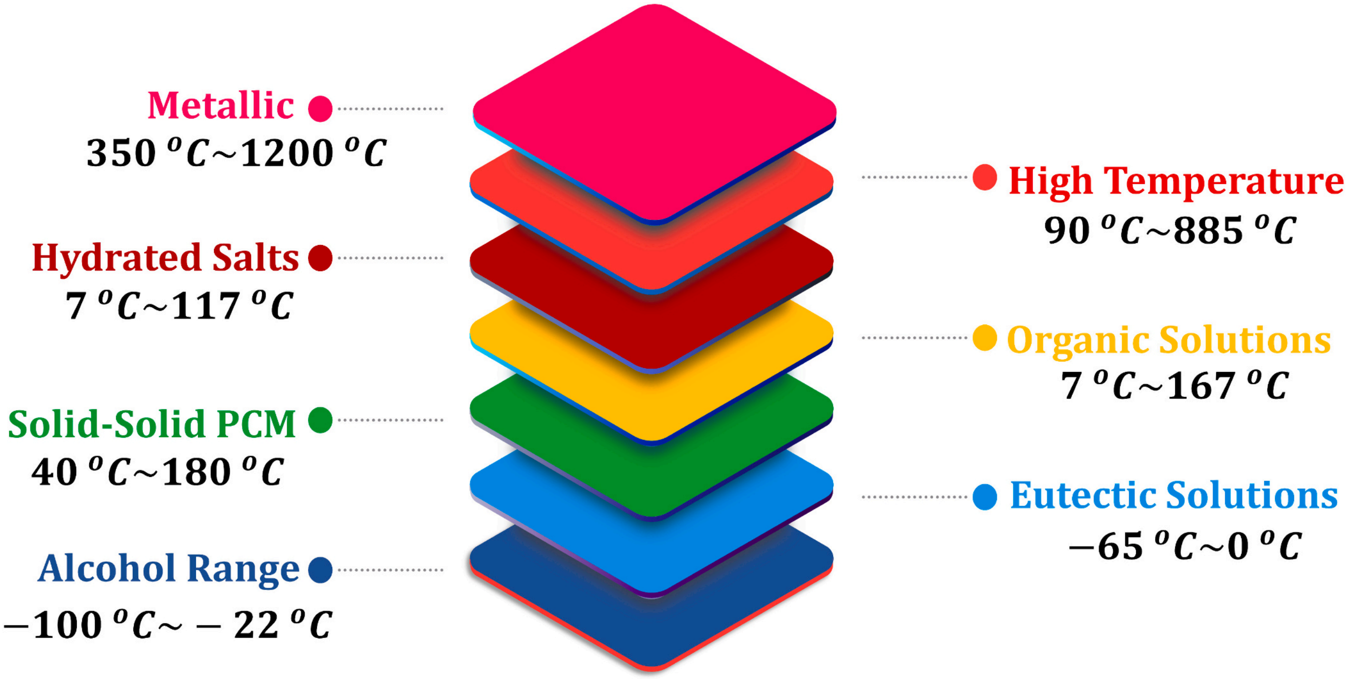
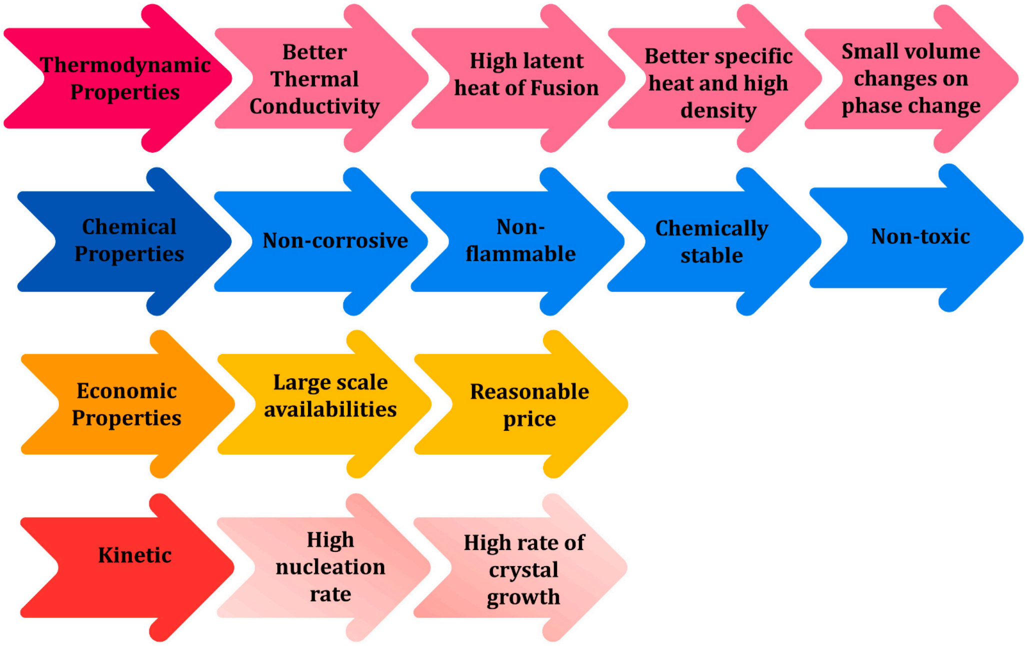


Fig. 5. Temperature ranges of PCMs [54].

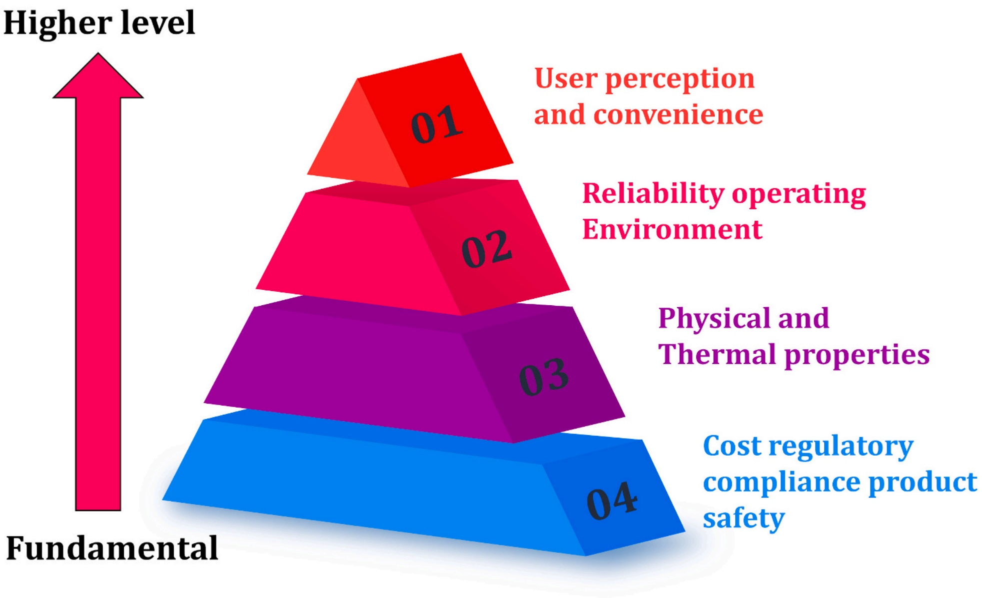
2.2. PCM selection criteria

After reviewing several literature, a suggestion can be made of utilizing multiple PCMs having different melting points would be a better solution to implement on conventional PV panels for cooling performance. Therefore, a balance has to be executed among the parameters like PCM melting temperatures, thickness, and obtained efficiency. According to Fig. 6, researchers have proposed (a) several selection criteria for appropriate PCMs based on numerous parameters and for (b) energy storage. Fig. 7(a) depicts the summary of produced nanoparticles. Fig. 7 (b) presents the essential properties of PCM that should be considered during the selection of PCM.

PCMs can be utilized in the PV panels to regulate the temperature of the cell and used as the storing material in the TES system. When this material is employed in both systems, it absorbs and releases the thermal energy during the phase change and thus it reduces the cell temperature



(a)



(b)

Fig. 6. (a) PCM selection criteria based on several parameters [54], (b) PCM selection characteristics for energy storage.

of the PV panel for improving the energy conversion efficiency. The selection of proper PCM is critical and researchers have figured out that the selection criteria depend on the operating temperature of the system and the weather conditions [55]. An important consideration in selecting the PCM is that the phase change temperature of the PCM should be lower than the cell temperature for the effective flow of heat and in the hot and dry climate conditions, the phase change temperature of PCMs should be above 40 °C [56]. The PCMs need to have high latent heat of fusion to effectively capture the generated heat from the system as the higher values of latent heat refer to the higher ability to store heat during the phase change process [57]. PCMs having a higher thermal conductivity attribute are preferable for applying in the PV panels and TES system to enhance the rate of heat extraction from PV panels and to reduce the charging and discharging time of the TES system. However, most of the PCMs, especially the organic paraffin, have a lower value of thermal conductivity by around 0.21 W/m K and can be enhanced to the

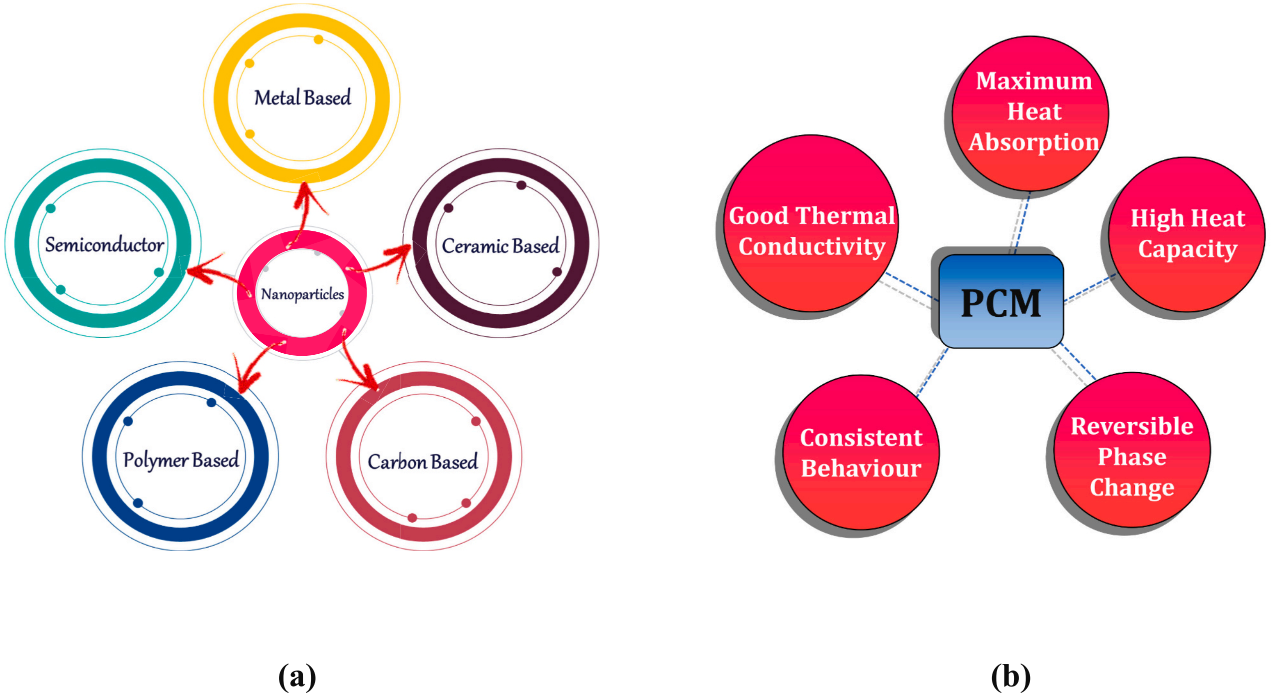


Fig. 7. (a) Summary of produced nanoparticles, (b) Properties of PCM should have.

expected values of 1.101 W/m K by incorporating expanded graphite nanoparticles [58].

Furthermore, the selection of PCMs depends on the thermophysical properties of the PCMs which can be determined by adopting the differential thermal analysis and differential scanning calorimetry (DSC) methods. Additionally, there should be a lower volume expansion coefficient of the PCMs as there is a limitation of storing a convective amount of PCM in either a solid or liquid state. Based on the study, if the value of the subcooling is zero ($\Delta T_{sub} = 0$) and the temperature is below the solidification point, PCM is regarded as in a solid state [59]. If ΔT_{sub} is not equal to zero solidification will not occur at that point. Moreover, PCMs should have higher values of phase change enthalpy to store huge amounts of energy in a small volume, resulting in a greater energy density. It should also meet some requirements to safely utilize in the PV panels and TES system, for instance, non-corrosive, non-flammable, non-toxic, chemically stable, and compatible with other system materials. It should be cost-effective and the price of PCMs must be in a reasonable range. Finally, PCMs must be available in large quantities [60].

3. Reasons behind choosing nano-PCMs

As mentioned, the thermal conductivity of most PCMs is low which restricts their utilization in the practical applications, especially, in the PVT and TES applications. Many researchers have adopted many techniques to resolve the problem of having lower thermal conductivity of PCMs including the usage of extended surfaces fin [61], heat pipes [62], utilization of metal foams [63], single and hybrid nanoparticles [64–66], and nanofillers [67].

The weight of the PCM increases with the addition of metallic foams and extended surface fins. Additionally, it also increases the fabrication cost of the system. These two problems can be addressed by employing the nanoparticles in the PCMs. Many research articles proved that the incorporation of nanoparticles has tremendously improved the thermal conductivity of the various PCMs due to having high surface area, strong interaction with PCMs, excellent retention of thermal conductivity, and higher inherent thermal conductivity of nanoparticles. It is evident that the carbon-based nanoparticles (graphite, GNP, and CNT) exhibit better performance in case of improving the thermal conductivity rather than using metals (Ag, Cu, Al, Fe, Ni) and metallic oxides (Al_2O_3, CuO, ZnO, TiO_2, MgO, SiO_2) nanoparticles [68,69]. For instance, Arshad et al. [70] incorporated carbon-based additives with a constant 1 % mass fraction of multi-wall carbon nanotube (MWCNT), graphene oxide (GO), reduced graphene oxide (rGO), and graphene nanoplatelet (GNP) into PCM (RT-35HC) and characterized all samples. The results found the enhancement of 66 %, 77 %, 74.9 %, and 77.7 % in TC by the addition of MWCNTs GNP, GO, and rGO nanoparticles, respectively, and a slightly 10 % decrease in the energy storage capacity was observed. Fig. 8(a) presents the different nanoparticles used in PCMs. However, there is an issue with making clusters of nanoparticles as they have a high tendency for adhesion due to the existence of van der Waals force between the nanoparticles, and the problem related to the cluster of nanoparticles can be resolved by using the methods shown in Fig. 8(b).

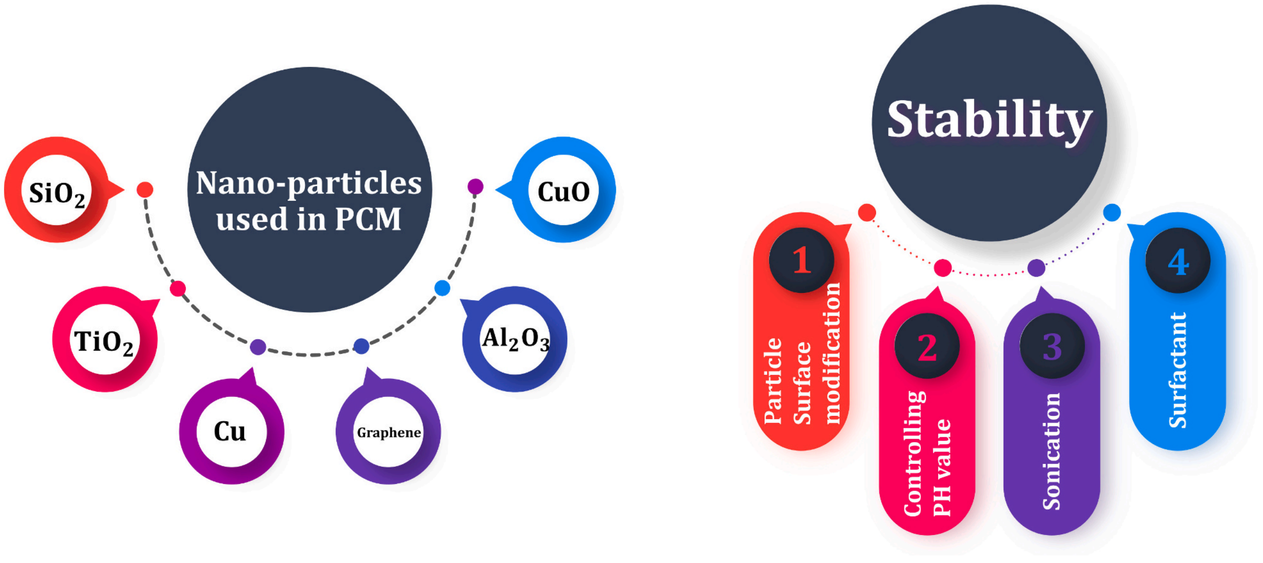
However, it should be noted that the addition of nanoparticles in various PCMs does not only affect on the thermal conductivity property, but it also impacts on the attribute of phase change temperature and latent heat of fusion which is tabulated in Table 2.

3.1. *Nanoparticles and their effects*

3.1.1. *Effects on thermal conductivity*

The addition of nanoparticles into circulating fluids to enhance heat transfer rate has always been a major concern for researchers due to its high demand in several industries [24,71–74]. Nanoparticles having higher surface area ensure a higher heat transfer rate, thus improving the thermal conductivity of PCMs. In several studies, it is found that a particle of size 3 nm contains 50 % of its particles on the surface whereas, for a particle of the size of 30 nm, 5 % of its particles are on the surface. Lin and Al-Kayiem [75] implemented hexagonal-shaped almost 15 nm to 125 nm-sized Copper nanoparticles with paraffin wax and found improved thermal conductivity from 14 to 46.3 % by varying the weight from 0.5 % to 2 %.

Krishna et al. [76] employed Al_2O_3 nanoparticles at a concentration of 0.5 % to 2 % by vol. in combination with Tricosane ($C_{23}H_{48}$) and observed a significant increase in the thermal conductivity of the PCM by up to 32 %. Colla et al. [77] found that the addition of 1 % by weight



(a)

(b)

Fig. 8. (a) Nanoparticles used in PCMs, (b) Different techniques for stabilization of nanoparticles.

of black carbon nano particles along with Al_2O_3, to RT20 and RT25, resulted in a 35 % increase in thermal conductivity and black carbon exhibited better result than Al_2O_3 nanoparticle. Soni et al. [78] experimented on Cu, Al, TiO_2, SiO_2 of 2.5 % by volume with Erythritol and found that Cu and Al nanoparticles show better effects on increasing thermal conductivity. Furthermore, the addition of carbon-based nanoparticles triumph over the performance of metal-based nanoparticles in the case of thermal conductivity enhancement of PCM. It was observed by Bahiraei et al. [79] that the inclusion of graphite-based nanoparticle into the paraffin wax with 7.5 % and 10 % by weight incremented the thermal conductivity by around 620 % and 1100 % respectively. Different steps associated with the preparation of nano-PCM are shown in Fig. 9. Variation of thermal conductivity in PCM by loading different types of nanoparticles are depicted in Fig. 10. Mathematical model of thermal conductivity of different nano-enhanced PCM developed by the authors are shown in Table 3.

3.1.2. *Effects on latent heat*

Some authors have suggested that the addition of nanoparticles in a specific manner enhances the latent heat. Nevertheless, some researchers have discovered that the existence of nanoparticles leads to a reduction in the volume of PCM, thereby diminishing its latent heat capacity. In contrast, alternative research has shown that a small proportion of nanoparticles has a beneficial influence on the latent heat, while a large proportion has the opposite consequence. Rufuss et al. [131] incorporate TiO_2, Cuo and GO into paraffin and conduct observations. Graphene decreases thermal latency. In contrast, some individuals have a tendency to augment it. Singh et al. [132] study various nanoparticles including Cu, Al, Ni, Ag nano metal oxide, CuO, Al_2O_3, TiO_2, SiO_2, Graphene nanoplatelets with eutectic salt $(LiNO_3 - KCl; 50 : 50)$. They find that graphene exhibits the least reduction in specific and latent heat in nano-PCM and the greatest enhancement in thermal conductivity. Saeed et al. [133] incorporated platelets graphene, comprising 10 % of the total weight, into PCMs such as $(C_{17}H_{34}O_2)$ and Lauric Acid $(C_{12}H_{24}O_2)$. They observed that the addition of nanoparticles reduced the latent heat from 177.9 J/g to 165.6 J/g. Fig. 11 shows the variation of latent heat with the loading of different nanoparticles.

3.1.3. *Effects on phase change temperature*

Mohamed et al. [134] observed a reduction of 2.2 °C in the phase change temperature when using α-Al_2O_3 in petroleum waxes. Harikrishnan et al. [135] incorporated SiO_2 in Myristic Acid and found that the melting temperature increased by 0.7 °C and the solidification temperature increased by 0.6 °C. Wang et al. [136] used MWCNT in paraffin wax and results in decrease of phase change temperature about 1 °C. Fig. 12 shows the effect of inserting nanoparticles on phase change temperature.

4. Different cooling techniques of PV panel

4.1. *Nano and Composite-PCM integrated with PV*

PCM thermal conductivity is less and therefore, the rate of heat extraction is also less. To improve the rate of heat extraction, additional nanoparticle is dispersed on PCM, or composite PCM is used, shown in Fig. 13. Kazemian et al. [138] found that the electrical efficiency of the system increased as the mass fraction of nanoparticles in the PCM increased. They estimated the maximum values for electrical power, thermal power, and thermal exergy to be approximately 136.93 W/m^2, 377.87 W/m^2, and 2.91 W/m^2, respectively. The reduction in cell temperature along with the enhancement in electrical efficiency was observed with increasing the number of nanoparticles in PCM. Abdelrazik et al. [139] numerically investigated that the Addition of 10 % GNPs with a thermal system enhanced the electrical efficiency around 22 % than conventional PV panel. Sharma et al. [140] numerically investigated that the usage of nano-PCM reduced the cell temperature by about 11.2 °C whereas only PCM reduced by about 9.6 °C. It was also estimated that nano-PCM could enhance the thermal conductivity of PCM by about 0.35 %. Manoj et al. [141] performed an investigation of the thermophysical properties of nano-ZnO dispersed on paraffin at different compositions and estimated the thermal conductivity. The result found that the addition of 2 wt% of ZnO nanoparticles on paraffin had better output and it was around 41.67 %. The thermal conductivity of the PCM was enlarged by infusing the graphite nanoparticle on it and it had been experimentally proven the increment of thermal conductivity from 0.25 W/m K to 16.6 W/m K by Atkin and Farid [142]. Table 4 shows the several Nano Particles dispersed with PCM in PVT application from different literatures.

Table 2
Summary of the previously performed studies to improve the thermophysical properties of PCM using nanoparticles.

PCM	Matrix	Method	Characterization	Enhancement of thermal conductivity (W/m K)	Changes of latent heat from (J/g)	Changes of melting temperature (°C)	Key findings	Ref.
Paraffin wax	EG	Vacuum impregnation	FTIR, SEM, UV–Vis, TGA, DSC, TCA, Leakage test	0.21 to 1.101	154 to 132.7	47.1 to 47.4	The addition of 15 wt% of EG exhibited no traces of leakage with a 447 % improvement in thermal conductivity as well as achieved 61.89 % electro-thermal conversion efficiency.	[58]
Lauric acid and Stearic acid	SiC	Two-step	SEM and EDX, AFM, FTIR, TCA, DSC, XRD, TGA	0.211 to 0.371	121.8 to 125.2	41.6 to 41.6	The maximum increment of thermal conductivity was observed by about 75.8 % at 0.075 wt% of SiC.	[80]
Commercial grade paraffin	MWCNT, GNP, TiO_2	Two-step	FTIR, XRD, DSC, TGA, TCA	0.29 to 0.864	248.4 to 230.9	28.92 to 28.96	The inclusion of 1 wt% of MWCNT+GNP improved the thermal conductivity of 170 % at 25 °C and maximum reduction of latent heat was observed for TiO_2-based mono and hybrid nanoparticles at 1 wt%.	[64]
Capric acid and Stearic acid	SiO_2, SiO_2-EG, SiO_2-CuO	Melt impregnation	SEM, FTIR, XRD, DSC, Leakage test, TGA and DTG, Thermal cycling, TCA	0.231 to 0.929	165.00 to 156.50	28.75 to 30.62	EG exhibited excellent thermal conductivity enhancer and the addition of 0.6 g and 0.2 g of SiO_2 and EG improved the maximum thermal conductivity of 302.1 % with the reduction of latent heat of 5.15 %.	[81]
Paraffin wax	MWCNT, SiO_2	Two-step	FE-SEM, XRD, FTIR, TGA, DSC, TCA, TEM	0.24 to 0.45	189 to 176.83	62.7 to 59.7	The incorporation of 1 wt% of MWCNT+ SiO_2 enhanced the thermal conductivity by 46 % with the reduction of latent heat and melting temperature.	[82]
Paraffin	SiO_2, Al_2O_3, MgO	Two-step	Charging and discharging, Viscosity, TCA	0.20 to 0.26	260 to 258.3	43 to 33.28	SiO_2 outperformed in the case of enhancing thermal conductivity and exhibited a 29.32 % improvement with a lesser and higher reduction of latent heat and melting temperature at 0.5 wt%.	[83]
RT-35HC	MWCNT, GO, rGO, GNP	Two-step	ESEM, FTIR, XRD, DSC, TGA, TCA	0.214 to 0.443	255.88 to 230.82	36.09 to 36.17	The addition of 1 wt% of GNP + MWCNT improved the thermal conductivity by 185.3 % with the reduction of latent heat by around 9.8 % and the enhancement of specific heat of capacity by around 13.75 %.	[70]
Paraffin wax	Ag	Two-step	SEM and EDX, FTIR, UV–Vis, TCA, DSC, TGA, Thermal cycling	0.212 to 0.44	157.5 to 159.1	54 to 53.5	The engagement of Ag nanoparticle improved thermal conductivity by around 107.5 % with the slight difference in melting temperature of PCM which is considerably <1.0 °C.	[84]
$Mg(NO_3)_2.6H_2O$	TiO_2, ZnO, Fe_2O_3, SiO_2	Melt-mixing	SEM and EDX, FTIR, XRD, TCA, DSC, TGA, Thermal cycling	0.4 to 0.99	146 to 134	91.5 to 91.8	TiO_2 performed better than other nanoparticles and the maximum thermal conductivity was achieved for TiO_2 by about 147.5 % with optimum 0.5 wt%.	[85]
Paraffin wax	SiO_2, CeO_2	Two-step	FESEM, FTIR, DSC, TGA, TCA	0.18 to 0.26	140.2 to 133.7	63.74 to 62.81	The addition of 1 wt% of hybrid nanoparticles improved the thermal conductivity and selected as the optimum number with the maximum reduction of supercooling by around 35.81 %.	[86]
Paraffin	Gr, Ag	Two-step	SEM and EDX, FTIR, UV–Vis, TCA, DSC, TGA, Thermal cycling	0.212 to 0.326	157.5 to 152.2	–	The addition of *Gr*:Ag nanoparticles with 0.8 wt% improved the thermal conductivity by around 53.85 % with the reduction of latent heat values <3 %.	[87]
Myristic acid	GNP, MWCNT, NG	Two-step	SEM, FTIR, TCA, DSC, TGA, Thermal cycling	0.2186 to 0.6039	194.90 to 187.19	54.4 to 54.3	GNP nanoparticle exhibited better performance in case of enhancing thermal conductivity which is around 176.26 % at 3 wt% than other nanoparticles	[88]

(*continued on next page*)

Table 2 (*continued*)

PCM	Matrix	Method	Characterization	Enhancement of thermal conductivity (W/m K)	Changes of latent heat from (J/g)	Changes of melting temperature (°C)	Key findings	Ref.
							with the maximum reduction of latent heat.	
Polyethylene Glycol 1500	GNP, CuO	Two-step	FESEM, DSC, TCA, Viscosity	0.234 to 0.45	178.35 to 168.70	43.1 to 38.9	The addition of 3 wt% of hybrid mixture of GNP-CuO improved the thermal conductivity by about 91.3 % with the reduction of 5.41 % and 4.2 °C of latent heat and melting temperature.	[89]
Lauryl alcohol and Capric acid	GNP-Al_2O_3, GNP-CuO, GNP-TiO_2	Two-step	SEM, XRD, FTIR, UV–Vis, DSC, TCA, TGA, Thermal cycling	0.148 to 0.238	170.7 to 159.1	4 to 3.8	GNP-Al_2O_3 hybrid nanoparticle into binary mixture of LA-CA improved the thermal conductivity of 60.8 % with the maximum deviation in melting temperature of 8 %.	[90]
Paraffin wax	CNF, GNP, Graphite nano-powder	Two-step	TCA, DSC, Viscosity, SEM	0.25 to 3	119.3 to 110	–	The addition of 7.5 % and 10 % by weight of graphite-based nanoparticles leads to an increase in the thermal conductivity of the solid phase by 620 and 1100 %, respectively.	[79]
Stearic acid	Expanded graphite (EG)	Melting impregnation	XRD, SEM, FTIR, DSC, TCA	0.26 to 2.5	189.7 to 163.5	52.91 to 53.51	The thermal conductivity enhancement took place 9.6 times that of pure SA with an excellent short of melting time of 63.3 % compared to that pure SA.	[91]
Commercial grade paraffin	ZnO	Two-step	SEM, FTIR, TGA, TCA	0.18 to 0.255	–	–	2 wt% of ZnO nanoparticle improved the thermal conductivity by around 41.67 % and proved the chemical compatibility of ZnO into PCM.	[92]
Paraffin wax	Nano-graphene (NG)	Two-step	FESEM, EDX, DSC, TCA	0.123 to 0.303	230.08 to 216.1	29.83 to 28.12	The thermal conductivity of NG-based composite PCM exhibited a maximum of 146 % improvement with a maximum of 3 % reduction in latent heat at 3 % concentration of NG.	[93]
Paraffin wax	Al_2O_3, CuO, TiO_2	Two-step	SEM, FTIR, TCA, DSC, TGA, Charging and discharging	0.238 to 0.586	116.75 to 110.78	62.54 to 63.56	TiO_2-based PCM exhibited better performance than other nanoparticles. The maximum thermal conductivity improved of 59.38 % for TiO_2-based nanoparticles compared to pure encapsulated paraffin with the less reduction of latent heat of 5.4 %.	[94]
RT-35HC	TiO_2	Two-step	ESEM and EDS, FTIR, XRD, TGA and DTG, DSC, TCA, Thermal images	0.21 to 0.48	255.88 to 227.74	36.09 to 36.05	The maximum thermal conductivity was achieved at phase transition temperature for 2 wt% of TiO_2 which is around 128.57 % with maximum reduction of latent heat and melting temperature.	[95]
Polyethylene glycol	SWCNT	Melting impregnation	SEM, TEM, FTIR, DSC, TGA and DTG, TCA, Thermal cycling	0.24 to 0.87	188.1 to 109.8	62.1 to 59.6	The inclusion of 2 wt% of SWCNT improved the thermal conductivity by around 260 % with the highest reduction in melting temperature of 4.03 %.	[96]
$MgCl_2$-NaCl-KCl	EG-SiO_2	Three-step	Leakage test, SEM and EDS, DSC, XRD, TCA, Thermal cycling	0.59 to 6.55	202.2 to 123.7	383.5 to 381.7	The enhancement of thermal conductivity was recorded 23.2 times that of mixed ternary chloride and maximum reduction of latent heat and melting point was observed for nano-SiO_2/ $MgCl_2$-NaCl-KCl /EG composite.	[97]
Li_2CO_3-Na_2CO_3-K_2CO_3	Mg	Statistical mixing	SEM and EDX, TCA, DSC, TGA and DTGA	1.328 to 1.93	166.4 to 160.1	393.60 to 387.61	The addition of 2 wt% of Mg nanoparticle into molten salt improved thermal conductivity by about 45.11 % with the highest reduction in melting temperature and latent heat of 5.99 °C and 3.79 %.	[98]

(*continued on next page*)

Table 2 (*continued*)

PCM	Matrix	Method	Characterization	Enhancement of thermal conductivity (W/m K)	Changes of latent heat from (J/g)	Changes of melting temperature (°C)	Key findings	Ref.
$NaNO_3$, KNO_3, $NaNO_3$-KNO_3	CuO	Statistical mixing	SEM, FTIR, DSC, TCA	–	186 ± 4 to 186 ± 4 91 ± 6 to 87 ± 2 124 ± 3 to 120 ± 6	306.21 ± 0.03 to 306.14 ± 0.05 334.48 ± 0.02 to 333.90 ± 0.06 220.52 ± 0.04 to 220.35 ± 0.03	The thermal conductivity improved by 20 %, 44 %, and 72 % respectively.	[99]
Erythritol	Graphene	Two-step	SEM, FTIR, XRD, DSC, TCA, Thermal cycling	0.733 to 1.122	311 to 338.60	127.52 to 120.01	The incorporation of 1 wt% of graphene improved thermal conductivity by about 53.1 % with the reduction of melting temperature by about 5.8 %.	[100]
Paraffin wax	Al_2O_3, CuO	Two-step	DSC, TCA	0.18 to 0.289	140 to 134	64 to 62.2	The maximum enhancement of thermal conductivity was recorded for 1 wt% of CuO of 60.55 % with the highest reduction of latent heat and melting temperature of 4.29 % and 1.8 °C.	[101]
Chloride salts ($MgCl_2$-KCl-NaCl)	Al_2O_3, CuO, ZnO	Solution evaporation	SEM, DSC, TGA, TCA	0.35 to 0.57	283.3 to 276.5	399.7 to 398.8	Al_2O_3 nanoparticles exhibited the highest thermal conductivity enhancer and maximum enhancement was achieved by around 62.59 % with the reduction of latent heat and melting temperature.	[102]
Paraffin wax	SiC, Ag	Two-step	FESEM, DSC, TCA	0.248 to 0.392	206.94 to 70	53 to 49.3	SiC exhibited better performance in enhancing thermal conductivity compared to Ag nanoparticle and the maximum enhancement was reported by about 58.2 % at 15 wt% with the reduction of melting temperature and latent heat.	[103]
Beeswax	Graphene	Two-step	SEM, XRD, FTIR, DSC, TCA, Viscosity	0.25 to 2.89	141.49 to 186.74	62.28 to 62.42	The addition of 0.3 wt% of graphene improved the value of thermal conductivity by about 1056 % with the increment of latent heat of 22.5 %.	[104]
Lauric acid	MWCNT, SWCNT, GNP	Two-step	SEM, TCA	0.215 to 0.694	–	–	Carbon-based nanofillers exhibited higher performance in thermal conductivity enhancement in solid phase compared to liquid phase. The maximum enhancement was recorded by about 223 %, 171 %, and 27 % for GNP, MWCNT and SWCNH respectively at a loading of 1 vol%.	[105]

Ahmadi et al. [143] conducted an experiment using the composite-PCM and estimated that using composite-PCM minimized the cell temperature by up to 6.8 % and enhanced the electrical efficiency by up to 14 %. Klemm et al. [144] combined metallic fiber structure with PCM for enhancing thermal conductivity and reduced the cell temperature by about 20 K.

4.2. Water-based hybrid PVT/PCM system

Radziemska and Kucharek [145] performed an experiment with PCM at different thicknesses of 2 cm, 3 cm, and 4 cm. They used water at different flow rates (32 dm^3/h and 80 dm^3/h) for the cooling agent at the rear of the PV panel. They obtained better results on the performance of PV panels at 2 cm thickness and 32 dm^3/h flow rate. However, the PV/PCM with water cooling seemed so expensive due to some difficulties to maintain the flow of water, and around 7 °C temperature was made to reduce by using only PCM without water cooling. Browne et al. [146] executed an experiment with 4 systems including PVT/PCM, PVT, PV with a container, and conventional PV, and compared the performance among them. The water-cooling system with PCM obtained a 5.5 °C higher temperature than PVT without PCM. Preet et al. [147] compared three systems consisting of conventional PV panels, water-based PVT, and water-based PVT/PCM systems. Water was passed through the copper tube underneath the PV panel with flow rates of 0.013 kg/s, 0.023 kg/s, and 0.031 kg/s. At a mass flowrate of 0.031 kg/s, the water-based PVT/PCM system was able to reduce the cell temperature by roughly 53 %, whilst the water-based PVT system was able to do so by 47 %. Gaur et al. [148] numerically examined PVT systems with PCM and without PCM in Lyon, France. The incorporation of PCM into the PVT system resulted in a decrease in the maximum cell temperature and an improvement in both the electrical power output and efficiency. The influence of parameters such as the mass of PCM, the thickness of PCM, and the mass flow rate of water on the performance of the PV panel was observed to be significant. The optimal values were

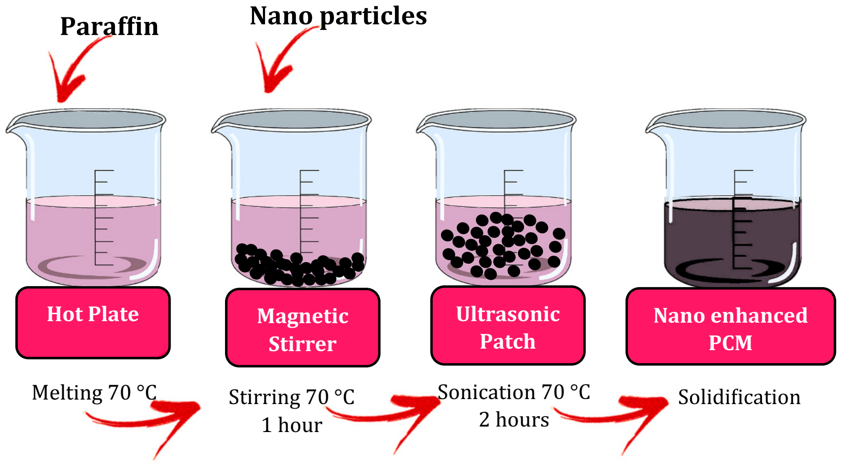


Fig. 9. Steps for preparing nano-PCM.

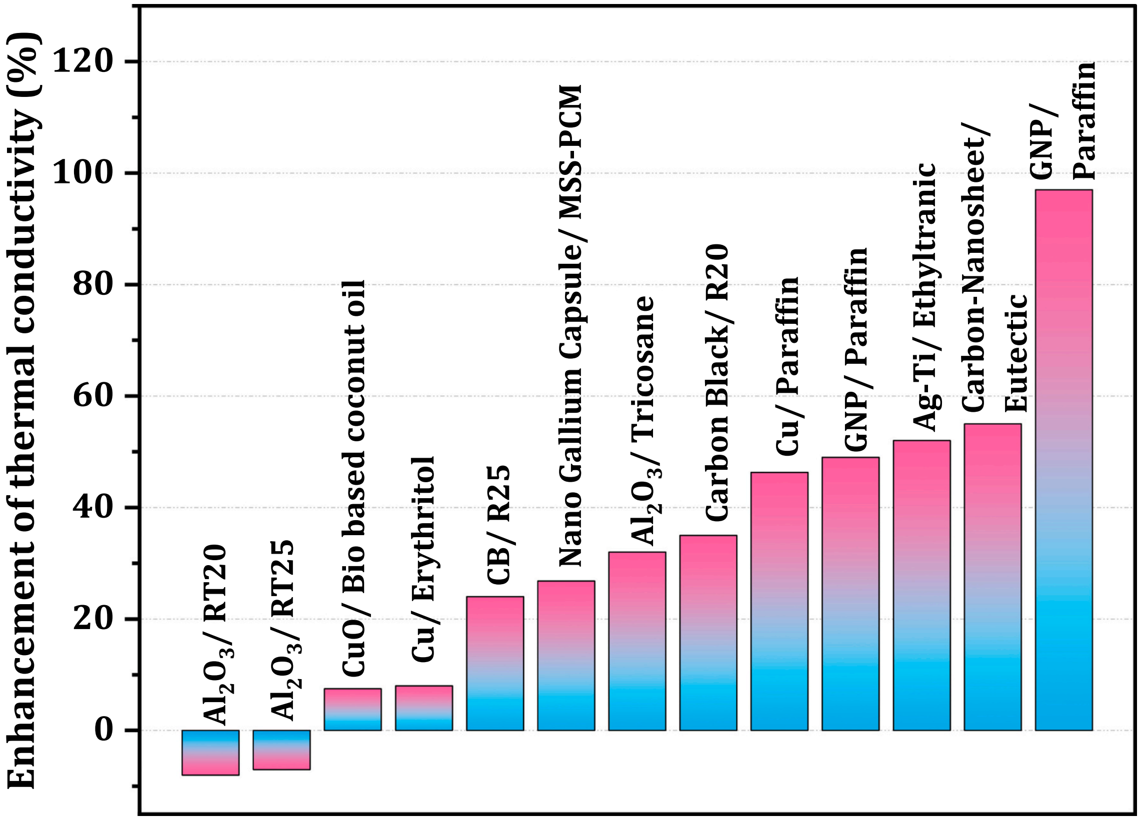


Fig. 10. Thermal conductivity variation of PCM owing to loading nanoparticles [54].

determined to be 30 kg for the mass of PCM, 15 mm for the thickness of PCM, and 0.04 kg/s for the mass flow rate of water. *Imam* et al. [149] found that the total efficiency of PVT/PCM performance with CPC was 10 % higher on clear days compared to semi-cloudy days. Zhou et al. [150] examined how the water flow rate and inlet temperature of the water impact the performance of PV panels. Various flowrates (0.25 kg/s, 0.5 kg/s, 1 kg/s, 5 kg/s, 10 kg/s) and inlet temperatures (10 °C, 15 °C, 20 °C, 25 °C) were examined and demonstrated that augmenting the mass flow rate and reducing the inlet temperature of the flowing water enhanced the efficiency of the PV panel. Yang et al. [151] made a comparative analysis between the conventional PVT system and PVT/PCM system. Capric acid was used as PCM, and water was allowed to flow in a copper pipe situated rear of the PV panel. The difference in temperature between the two cases was recorded 15.8 °C and 1.18 % higher electrical efficiency was observed for PVT/PCM system than the PVT system. Ho et al. [152] designed a MEPCM-PV panel with MEPCM situated back of the PV panel that floats on water. 2 different layer thicknesses (5 cm and 3 cm) and melting points (28 °C and 30 °C) of MEPCM were selected for this application. The best performance was observed for 5 cm and 30 °C MEPCM which indicated a 1.8 °C reduction in panel temperature and generation output 2.1 % higher than untreated PV. Ho et al. [153] added two layers of MEPCM behind the PV panel to create an MEPCM module that can float on water. The dimensions are 5 cm by 5 cm, and the temperature range is from 30 °C to 26 °C. The

Table 3
Mathematical models for thermal conductivity of nano-enhanced/PCM.

Model developer	Model used for	Formulation	Remarks
Maxwell [106]	Eicosane/Ag [107] Eicosane/CuO [108] Octadecane/Cu [109] PCM around cylindrical capsule [110]	$k_{eff} = k_{pcm}\left[\frac{k_{NP}+2k_{PCM}-2\varnothing(k_{PCM}-k_{NP})}{k_{NP}+2k_{PCM}+\varnothing(k_{PCM}-k_{NP})}\right]$	$k_{PCM}(T) = k_{solid}+\left(k_{liquid}-k_{solid}\right)B(T)$ $B(T) = \begin{cases} 0, T<(T_m-\Delta T) \\ \frac{T-T_m+\Delta T}{2\Delta T}, (T_m-\Delta T)\leq T<(T_m-\Delta T) \\ 1, T>(T_m+\Delta T) \end{cases}$ $\varnothing = \frac{\varnothing_{wt}\,\rho_{PCM}}{\varnothing_{wt}\,\rho_{PCM}+(1-\varnothing_{wt})\rho_{NP}}$
Nan et al. [111,112]	Eicosane/Graphite [113] Eicosane/Graphene [114]	$k_{eff} = k_{PCM}\left[\frac{3+\varnothing[2\beta_{xx}(1-L_{xx})+\beta_{zz}(1-L_{zz})]}{3-\varnothing[2\beta_{xx}(L_{xx})+\beta_{zz}(L_{zz})]}\right]$	$L_{xx} = \frac{a^2}{2(a^2-1)}+\frac{a}{2(1-a^2)^{3/2}}\cos^{-1}a$ $L_{zz} = (1-2L_{xx})$ $\beta_{xx} = \frac{k_{f,xx}-k_{PCM}}{k_{PCM}+L_{xx}\left(k_{f,xx}-k_{PCM}\right)}$ $\beta_{zz} = \frac{k_{f,zz}-k_{PCM}}{k_{PCM}+L_{zz}\left(k_{f,zz}-k_{PCM}\right)}$ $k_{f,xx} = \frac{d_{NP}}{2R_{eff}+d_{NP}/k_{f,in-plane}}$
Yu et al. [115]	Eicosane/xGnP [116]	$k_{eff} = k_{PCM}\left[1+\frac{\varnothing a}{3}\frac{k_{NP}/k_{PCM}}{a+\frac{2a_k}{\delta}\times\frac{k_{NP}}{k_{PCM}}}\right]$	$a_k = R_k\,k_{PCM}$
Maxwell [106]	Organic PCM/Graphene [117]	$k_{eff} = 5\times10^4\beta_k\varnothing\xi(\rho c_p)_{PCM}\sqrt{\frac{B_0T}{\rho_{NP}d_{NP}}}f(T,\varnothing)$	$f(T,\varnothing) = \left(2.8217\times10^{-2}\varnothing+3.917\times10^{-3}\right)\frac{T}{T_{ref}}+\left(-3.0669\times10^{-2}\varnothing-3.91123\times10^{-3}\right)$ (Considering the Brownian motion in molten nano-enhanced/PCM)
Parker et al. [118]	Octadecane/GA [119]	$k = a\times c_p\times\rho$	The thermal conductivity was measured by using laser flash apparatus.
Mesalhy et al. [120]	Organic PCM/Foam [121]	$k_{eff} = \frac{\left[k_s+\pi\left(\sqrt{\frac{1-\delta}{3\pi}}-\frac{1-\delta}{3\pi}\right)(k_f-k_s)\right]\left[k_s+\frac{1-\delta}{3\pi}(k_f-k_s)\right]}{k_s+\left[\frac{4}{3}\sqrt{\frac{1-\delta}{3\pi}}(1-\delta)+\pi\sqrt{\frac{1-\delta}{3\pi}}-(1-\delta)\right](k_f-k_s)}$	Applicable for the nanoparticles having high thermal conductivity and high porosity.
Corcione [122]	Effective thermal conductivity of the nanofluid	$\frac{k_{eff}}{k_{PCM}} = 1+4.4\,Re^{0.4}Pr^{0.66}\left(\frac{T}{T_{fr}}\right)^{10}\left(\frac{K_{NP}}{K_{PCM}}\right)^{0.03}\varnothing^{0.6}$	
Gharagozloo et al. [123]		$\frac{k_{NEPCM}}{k_{PCM}} = 1+C\varnothing$	20 to 120 for NEPCM containing organic solvents and CNTs
Hamilton and Crosser [124]		$k_{NEPCM} = \frac{-(k_{PCM}-k_{NP})m\varnothing+(k_{NP}-k_{PCM})\varnothing+mk_{PCM}+k_{NP}+k_{PCM}}{mk_{PCM}+(k_{PCM}-k_{NP})\varnothing+k_{NP}+k_{PCM}}$	
Patel et al. [125]		$k_{NEPCM} = k_{PCM}+k_s\frac{A_S}{A_{PCM}}+CP_e\frac{A_S}{A_{PCM}}$	$\frac{A_S}{A_{PCM}} = \frac{d_S}{d_{PCM}}\frac{\varnothing}{(1-\varnothing)}, P_e = \frac{U_Sd_S}{\alpha}, U_S = \frac{2BT}{\pi\mu_{PCM}d_p^2}$

(continued on next page)

Table 3 (*continued*)

Model developer	Model used for	Formulation	Remarks
Koo and Clement [126]	PCM/Al_2O_3	$k_{eff} = k_{PCM}\left[\frac{k_{NP}+2k_{PCM}-2\varnothing(k_{PCM}-k_{NP})}{k_{NP}+2k_{PCM}+\varnothing(k_{PCM}-k_{NP})}\right]$ $5\times10^4\beta_k\xi\varnothing(\rho c_p)_{PCM}\sqrt{\frac{B_0T}{\rho_{NP}d_{NP}}}f(T,\varnothing)$ $\beta_k = \begin{cases}0, T < T_{Freezing}\\ 1, T > T_{Melting}\end{cases}$	Numerical simulation for thermal energy storage of solidification of nano-enhanced/PCM at 0 °C [127–129]. (Solidification of water/CuO) $\frac{k_{eff}}{k_{base}} = 1 - 3\frac{\left(-\frac{k_{NP}}{k_{base}}+1\right)\varnothing}{\left(1-\frac{k_{NP}}{k_{base}}\right)\varnothing+\left(\frac{k_{NP}}{k_{base}}+2\right)} + 5\times10^4\varnothing\rho_{base}c_pf\sqrt{\frac{k_{base}T}{\rho_{NP}d_{NP}}}g(d_{NP},T,\varnothing)$ [130] $g(d_{NP},T,\varnothing) = \Big[a_1 + a_2ln(d_{NP}) + a_3ln(\varnothing) + a_4ln(\varnothing)ln(d_{NP}) + a_5ln(d_{NP})^2ln(T) + \Big(a_6 + a_7ln(d_{NP}) + a_8ln(\varnothing) + a_9ln(\varnothing)ln(d_{NP}) + a_{10}ln(d_{NP})^2\Big]\ \{Condition\varnothing \le 0.04, 300k \le T \le 325k\}$ $\{(a_1........a_{10}) = Co-efficient\ value\ of\ water/CuO\}$ [130].

k_{PCM}= Thermal conductivity of PCM (W/m K); k_{NP}= Thermal conductivity of nanoparticle (W/m K); k_{base}= Thermal conductivity of base matrix(W/m.K); $\varnothing$= Volume fraction of the additives.
$\varnothing_{wt}$= weight fraction of the additives; ρ= density of the discrete (kg/m^3); k_{eff}= Effective thermal conductivity of nano-enhanced/PCM (W/m K); *PCM*= Phase Change Material.
NP= Nanoparticle; k_{solid} *and* k_{liquid}= Thermal conductivity of PCM in solid *and* liquid phase;T_m *and*ΔT= Melting temperature and transition range of PCM (K); *d*= Diameter.
β_k= Empirical function of Brownian motion; ξ= Correction factor for Brownian motion; c_p= Specific heat capacity (kJ/kg K); B_0= Boltzmann constant 1.381×10^{-23} (J/K); *T*= Temperature (K).
T_{ref}= Reference temperature (K); *a*= aspect ratio of NP; α= Thermal diffusivity(m^2/s); R_{eff}= Effective interfacial thermal resistance; $k_{f,in-plane}$= In-plane thermal conductivity of NP (W/m K).
k_f= Thermal conductivity of the metal foam (W/m K); δ= The metal foam porosity; $k_{f,xx}$= Modified in-plane thermal conductivity of NP (W/m K); $k_{f,zz}$= Out-of-plane thermal conductivity of NP (W/m K).
m = shape factor representative nanoparticle.

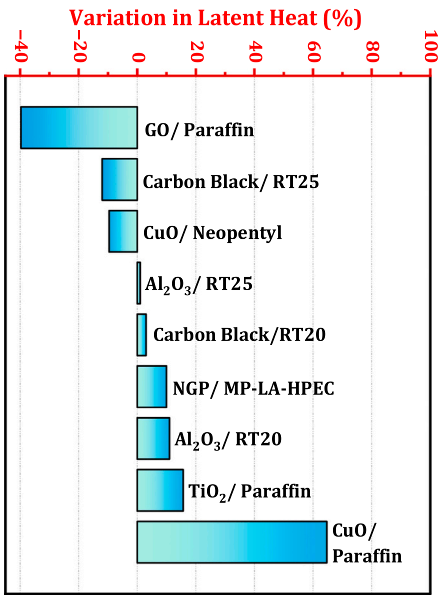


Fig. 11. The effect of inserting nanoparticles on the variation of latent heat [54].

generation efficiency of the MEPCM-PV module increased by 2.03 %, compared to the 3 cm/3 cm–30 °C/26 °C condition. The MEPCM-PV module exhibited a 1.48 % enhancement compared to the untreated PV module. Fig. 14 shows the water-based PVT/nano-PCM system.

4.3. Nanofluid in PVT system

In order to accelerate the rate of heat extraction from the PV panel, nanoparticles are dispersed in base fluid and flow through the tube. The mass flow rate of the nanofluid affects the rate of heat extraction. Generally, nanofluid acts as a heat absorber and it enhances the thermal conductivity of base-fluid. These attributes of the nanofluid absorb more heat and cause the cooling effect of the PV panel. It further enhances electrical efficiency as well as thermal efficiency. The absorbing characteristics of nanofluid will be discussed in the following subsection performed by a different researcher. The performance observation of Nanofluid-based PVT/PCM and PVT/NEPCM are presented in Table 5.

4.4. Nanofluid acts as a thermal absorber

Sardarabadi et al. [154] experimented with a nanofluid-based PCM system and estimated that using 0.2 wt% of ZnO in water can reduce the 16 % of cell temperature to that of a water-based system. The increment of electrical efficiency is recorded at 13 % in the case of PCM/nanofluid system than a conventional PV panel and also thermal energy output is recorded at 48 % than a water-based system which is only 42 %. AL-Musawi et al. [155] performed a numerical investigation on the performance of PV panels using SiO_2 nanofluid and proved the positive impact on electrical and thermal efficiency. For 1 % and 3 % of SiO_2 nanofluid, electrical efficiency nearly stays the same, but thermal efficiency rises by 3.51 % and 10.40 %. In an experimental examination, Al-Waeli et al. [156] used water and 3 wt% of SiC to increase the thermal conductivity by 8.2 %, indicating an improvement in the thermophysical parameters. The performance of a PV panel can be promoted more by a nanofluid-based PVT system than by a traditional one, and the usage of 3 wt% SiC increased electrical efficiency by up to 24.1 %. Sardarabadi and Passandideh-Fard [157] made the comparison between different metal-oxides/water nanofluid including TiO_2, ZnO, and Al_2O_3 for the development of electrical efficiency and cooling process. The average enhancement of electrical efficiency was recorded around 6.54 %, 6.46 %, and 6.36 % for TiO_2/water, ZnO/water, and Al_2O_3/water respectively compared with the conventional PV panel. ZnO/water nanofluid exhibited better thermal efficiency than other nanofluids. Hamdan and Kardasi [158] performed an experiment for the cooling of the PV panel using Al_2O_3 nanofluid and CuO nanofluid in the backside and estimated that CuO nanofluid showed better performance in the case of PV

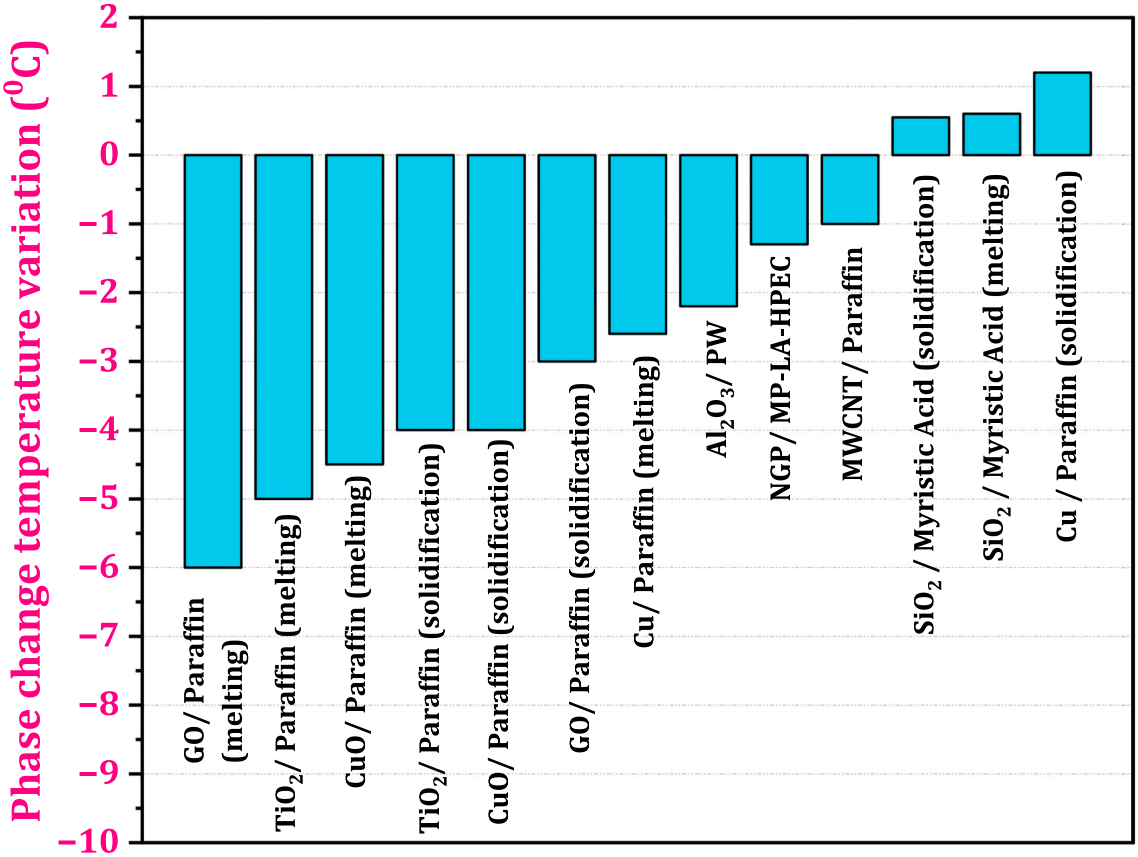


Fig. 12. Phase change temperature variation owing to loading nanoparticles [54,137].

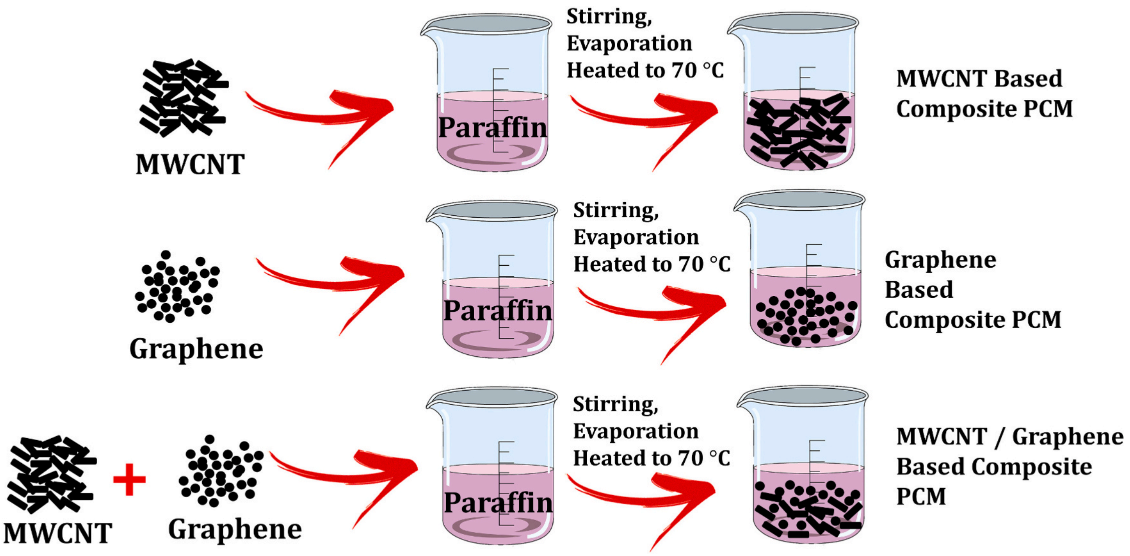


Fig. 13. Preparation of PCMs to disperse nano particles.

efficiency than Al_2O_3 nanofluid. CuO nanofluid increased the efficiency by 2.34 % whereas Al_2O_3 increased by only 2 %. Ghadiri et al. [159] used ferrofluid (Fe_2O_3-water) with two different concentrations (1 wt% and 3 wt%) under two different solar radiations (1100 W/m^2 and 600 W/m^2) to experimentally test the performance of a PV panel. An alternating magnetic field with a 50 Hz frequency and the addition of ferrofluid at a 3 wt% concentration led to increased performance and an increase in system efficiency of roughly 79 %. Al-Waeli et al. [160] performed a comparison of the performance of the PV/T system between three different nanoparticles (Al_2O_3, SiC, and CuO) in a base fluid water with 5 vol concentration (0.5, 1, 2, 3, and 4). This experiment analyzed the thermophysical property of nanofluid and showed that nanoparticles in water can increase thermal conductivity and results suggest that 4 vol % of SiC showed better thermal conductivity and stability than the other two nanofluids. The effectiveness of silica and Fe_2O_3 nanofluid in a hybrid PV/TE system and a naturally cooled-PV panel was compared by

Table 4
Nano particles dispersed with PCM in PVT application.

Nanoparticles	Field of application	Melting/ solidification	Status	Ref.
CuO	PVT-Building	Melting/ solidification	Numerical/ Experimental	[140]
Cu	PVT-Building	Melting/ solidification	Numerical/ Experimental	[28]
Al_2O_3	PVT-Building	Melting/ solidification	Experimental	[175]
$TiO_2 - CuO$	PVT	–	Experimental	[131]
Boehmite	PVT	Melting	Experimental	[176]
SiC	PVT	Melting	Numerical	[177]
SiC	PVT	Melting	Experimental	[178]
SiC	PVT	Melting	Experimental	[179]
SiC	PVT	Melting	Numerical/ Experimental	[180]
SiC	PVT	Melting	Numerical/ Experimental	[172]

Soltani et al. [161]. The result exhibited the highest contribution of SiO_2/water nanofluid cooling system for the maximum power and efficiency performance, exhibiting 54.29 % and 3.35 % improvement than Fe_3O_4/water nanofluid due to its higher thermal conductivity attribute. Al_2O_3 in water-polyethylene glycol mixture and TiO_2 in water-cetyltrimethylammonium with the composition 0.01 wt%, 0.05 wt%, and 0.1 wt% for varied flow rates were used by Ebaid et al. [162] to cool the PV panel. At 0.01 % concentration and 3000 mL/min flow rate, the temperature decreased from 57.5 °C to 39.5 °C for Al_2O_3-water nanofluid and from 40.5 °C to 57.5 °C for TiO_2-water nanofluid. The result also showed that Al_2O_3-water nanofluid was more efficient than TiO_2-water nanofluid for every composition and flowrates. Hasan et al. [163] investigated the usage of jet impingement of three types of nanofluids (SiC, TiO_2, SiO_2/water) with flow rates varying from 0 to 0.167 kg/s and figured out the highest power for SiC-water nanofluid around 62.5 % followed by TiO_2 nanofluid, SiO_2 nanofluid, and pure water. Elmir et al. [164] installed Al_2O_3-water nanofluid back of the PV panel to obtain the maximum cooling effect and showed that the insertion of nanoparticle in base fluid improved the thermal conductivity and increased the rate of heat extraction. Khanjari et al. [165] presented the variation of electrical efficiency with the variation of solar irradiation as well as inlet temperature of nanofluid and estimated that increasing the solar irradiation from 200 to 800 W/m^2 declined the efficiency from 11.4 % to 10.3 %, whereas incrementing inlet temperature from 293 K to 323 K declined the efficiency from 11.2 % to 9.6 %. Rejeb et al. [166] compared the performance of PVT systems at different nanofluid and base fluids. The authors used the nanoparticles Cu and Al_2O_3 in the concentrations 0.1 wt%, 0.2 wt%, and 0.4 wt% and the base fluid was used water and ethylene glycol. The experimental result provided the information that the performance of the PV panel increased in the higher concentration of nanoparticles (0.4 wt%) and the water-based nanofluid showed better performance in the case of electrical as well as thermal output. Cu/water nanofluid provided the maximum electrical and thermal efficiency in comparison to Cu/ethylene glycol, Al_2O_3/water, and Al_2O_3/ethylene glycol. Lelea et al. [167] presented the paper using highly conductive nanoparticle Al_2O_3 as nanofluid and compared the performance with pure water. The result showed that nanofluid at lower *Re* obtained a lowering temperature than water. Using various types of nanofluid (SiO_2, TiO_2, and SiC) with 1 wt% concentration at flow rates ranging

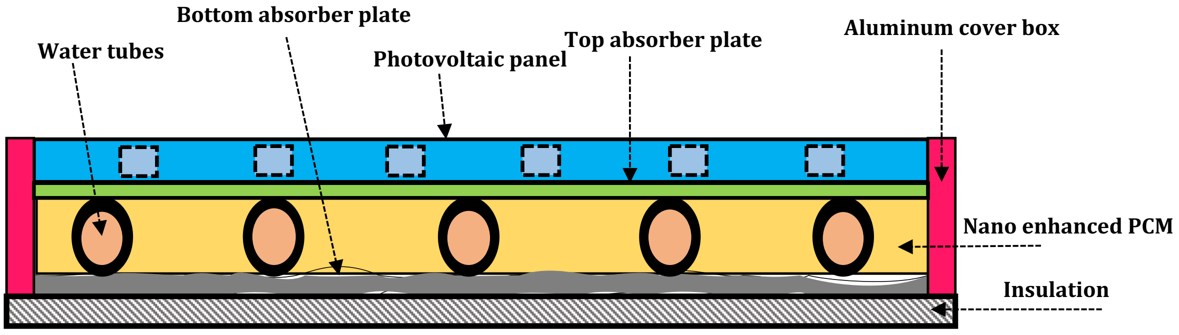


Fig. 14. Water-based hybrid PVT/nano-PCM system.

Table 5
Performance observation of nanofluid-based PVT/PCM and PVT/NEPCM.

PCM	Nanoparticles immersed in water	Improved electrical efficiency	Improved thermal efficiency	Findings	Ref.
Paraffin (49 °C)	SiC	13.7 %	72 %	The recently developed PVT system demonstrated enhanced overall, electrical, and thermal efficiency, resulting in a reduction of the PV panel's temperature to 30 °C.	[172]
Paraffin	SiC	13.2 %	–	Analyzed and contrasted multiple cooling methods, and experimental findings were juxtaposed against artificial neural network (ANN) software. The results indicate a high level of concurrence between the neural network and the experimental findings.	[181]
Paraffin (40 °C)	SiC	13.7 %	71.2 %	The comparison between simulated values and experimental data demonstrated a high degree of consistency and proximity. The overall system performance for the designed system achieved a score of 85.7 %.	[178]
RT 35HC (35 °C)	Graphene	14 %	45.8 %	PVT-PCM system based on nanofluid performs better at 0.1 vol% and 40 LPM. The temperature drop on the PV panels was 23.9 °C.	[182]
Paraffin (42 °C)	ZnO	13 % improved	46 % improved	The thermal, electrical, and overall efficiency of the PVT-PCM-ZnO nanofluid cooling system is higher, and the temperature of the PV panels is reduced more.	[154]
Octadecane (28 °C)	Ag	11.7 % improved	27.3 % coved the residential demand	System is capable of meeting home energy needs by 27.3 % thermal power and 77 % electrical power, respectively.	[183]
Paraffin (46–48 °C)	ZnO	14.05 %	51.66 %	In comparison to PV and Nano-enhanced PVT (NPVT) systems, NPVT-PCM has higher exergy, overall, and thermal efficiency.	[184]

from 0.068 kg/s to 0.170 kg/s, Al-Shamani et al. [168] experimentally tested the PVT system. The result exhibited the highest performance of SiC nanofluid and the highest electrical as well as thermal efficiency was recorded at 13.52 % and 81.73 % respectively at flow rates 0.170 kg/s with the solar irradiation 1000 W/m^2. Hussien et al. [169] designed a PVT system using (Al_2O_3-water) nanofluid at a different concentration ranging from 0.1 wt% to 0.5 wt% at constant flowrates 0.2l kg/s and circulated nanofluid in a pipe situated at the rear of the PV panel. The reduction in temperature was recorded at around 42.2 °C at 0.3 wt% concentration and led to an increase in solar efficiency by about 12.1 %. Xu and Kleinstreuer [170] performed a CFD analysis for the cooling of PV cells by using (Al_2O_3-water) nanofluid considering different parameters including Reynolds number, channel height, the inlet temperature of nanofluid, and mass fraction of nanofluid. The numerical result investigated that optimum efficiency was obtained with a channel of 10 mm height and the Reynolds number up to 20,000. The inlet temperature of fluid had an adverse effect on the performance of the PV panel.

4.5. Combination of nanofluid and PCM

Integration of nanofluid with PCM has been the fascinating cooling method of PV panels for researchers in recent years. Many researchers have already conducted numerous experimental as well as numerical observations on this method and they have figured out a positive impact on PV panels. Nanoparticles in different composition in base fluid enhances the thermal conductivity and PCM has a good heat-storing capacity. These attributes have added unique features for cooling purposes. PCM is integrated with nanofluid to overcome the low heat transfer coefficient and to increase the rate of heat extraction from the PV panel. Salem et al. [171] conducted an experimental investigation of a cooling effect on PV panels by using Al_2O_3/ PCM mixture with a concentration of nanoparticles from 0 to 1 % and mass fluxes from 0 to 5.31 kg/sm^2. The Al_2O_3/PCM combination and/or water were circulated by the authors through conduits made of straight aluminum beneath the PV panel. The results of the experiment demonstrated that compound cooling methods (Al_2O_3/ PCM mixture + water) produced a better cooling impact than simple cooling with water. An experimental investigation was performed and compared among three different systems i.e. conventional PV, PVT with nanofluid, and PVT/PCM with nanofluid by Sardarabadi et al. [154] in Mashhad, Iran. ZnO nanoparticle with 0.2 wt% concentration was dispersed in base fluid water and passed through the tube situated at the back of the PV panel. The experimental result indicated better performance in the case of PVT/ PCM with a nanofluid system compared with the other two systems. In comparison to a normal PV panel, the electrical efficiency of PVT/PCM using a nanofluid system was found to be improved by nearly 13 %. Maximum reduction in cell temperature was obtained at 16 °C for PVT/ PCM with a nanofluid system whereas 7 °C temperature reduction was observed for PVT with a nanofluid system. Al-Waeli et al. [172] tested a system consisting of a PV panel with nano-PCM and nanofluid. SiC nanoparticle was dispersed in PCM (paraffin wax) as well as in a working fluid. The cell temperature was lowered by this upgraded system by around 17 °C. With a flow rate of 0.17 kg/s of nanofluid, the suggested PVT-nano-PCM-nanofluid system increased electrical efficiency from 7.1 % to 13.7 %. For this altered system, the thermal energy was 72 %.

4.6. Hybrid nanofluid combination

Hybrid nanofluids are the additional technique in order to cool the PV panel. This cooling technique is obtained by dispersing the hybrid nanoparticles in the base fluid. In many cases, the dispersion of hybrid nanoparticles enhances thermal conductivity and increases the system's efficiency. Many researchers have recently worked on this technique which will be discussed in the following section. Younis et al. [173] used Al_2O_3-ZnO-H_2O nanofluid in the PVT system with Ethylene Glycol as a surfactant. 0.05 wt% mass fraction of Al_2O_3 and ZnO nanoparticles were used for this application. The average increment in total efficiency was detected around 4.1 % and maximum exergy efficiency was found at 4.6 % for 0.05 wt% mass fraction of nanoparticles. Hjerrild et al. [174] tested a system by nanofluid with multi-nanoparticles including Ag-SiO_2 nano-discs and CNTs. CNTs with higher absorptivity enhanced the rate of heating in nanofluid which indicated the adverse effect on electrical efficiency but increasing the mass fraction of Ag-SiO_2 impacted a positive effect on the electrical efficiency resulting in the higher combined efficiency.

5. Numerical investigation of nano-enhanced PCM

The nano-enhanced PCM is categorized as a nanofluid once it has completely melted. The primary distinction is that while liquid nano PCM typically experiences laminar flow driven by buoyancy, nanofluid experiences both laminar and turbulent flow. The NEPCM performs both solid and liquid activities, and when its temperature varies, it displays a variety of rheological and thermal characteristics. The physical model used for the liquid NEPCM incorporates both single-phase and two-phase methods to accurately consider the nanoparticle size within the base PCM. Thermodynamic dispersion and homogeneous models are two categories for single-phase models. The fluid is uniformly dispersed with ultra-fine nano-sized particles of the homogeneous kind. By preventing any slippage between the nanosized particles and base fluid, which were also in thermal equilibrium, the particles swiftly fluidized. The homogeneous technique is a “static” model that is straightforward and highly computationally efficient. The effective thermophysical characteristics of the nanofluids, however, affect the simulation findings. There have been many developments in thermal dispersion techniques to improve the heat transfer of nanofluids. Table 6 showcases some expressions regarding numerical analysis methods in PVT system.

6. Numerical and experimental approaches of NEPCM in TES

Different types of PCM including paraffin wax, hydrated salts, and organic/inorganic compounds can be employed for the charging and discharging phenomena of TES system. Nevertheless, it possesses limitations due to its low thermal conductivity, which hampers the speed of both charging and discharging. The insertion of conductive nanoparticles, metal foam, metal fins, and porous material into the PCM can enhance the thermal conductivity of the PCM [23]. The addition of the nanoparticles in different weight percentages can make the sedimentation into PCM which can degrade the heat transfer rate [195,196]. The sedimentation of nanoparticles can be reduced by employing better dispersion techniques like a magnetic stirring machine, ultrasonic vibrator [196], and different surfactants [196,197]. However, many researchers have incorporated nanoparticles into PCM for TES applications for higher charging and discharging rates. The melting process of Cu/paraffin nano-PCM was examined both experimentally and numerically by Shuying et al. [198]. The results demonstrated that the addition of 1 wt% of Cu into the PCM reduced the melting time by 13.1 %. The result also shows that the addition of Cu nanoparticles can be effective in increasing the TES latent heat transfer rate. The solidification rate of NEPCM was numerically investigated using Cu nanoparticles with varying mass fractions of 0 %, 2 %, and 8 % by Elbahjaoui et al. [199] and showed that the latent and sensible heat discharged rate increased with increasing the mass fraction of Cu nanoparticles into PCM. The influence of CuO nanoparticles on the melting process into bio-based PCM (coconut oil) with different mass fractions of 0 %, 3 %, and 5 % was investigated numerically and experimentally by Alomair et al. [200]. The experimental findings unequivocally demonstrated that augmenting the mass fraction of nanoparticles lead to enhanced melting efficiency and charging speed in comparison to pure PCM. Colla et al. [77] performed an experiment using commercial paraffin waxes (RT20 and RT25) with 1 % of Al_2O_3 and carbon black and found higher latent heat and lower thermal conductivity in case of Al_2O_3 than carbon black

Table 6
Expressions regarding numerical analysis methods in PVT systems.

Simulation type	Method/parameters	Numerical expressions	Ref.
Macroscale	Effective heat capacity	$\rho C_{eff}\frac{\partial T}{\partial t} = \nabla.(k\nabla T)$ k = Thermal conductivity of NEPCM ρ = Density of NEPCM C_{eff} = Effective heat capacity $C_{eff} = \begin{cases} C_{p,s}\ T_1 < T_s\ (Solid\ state) \\ \frac{C_{p,s}+C_{p,l}}{2} + \frac{L}{T_1 - T_s} T_s \le T < T_1\ (Mushy\ state) \\ C_{p,l} T \ge T_1\ (Liquid\ state) \end{cases}$ $C_{p,l}$ $C_{p,s}$ are specific heat of liquid and solid NEPCM. $C_{eff} = \frac{dH}{dt} \Big/ \left(m\frac{dT}{dt}\right)$ m = mass of NEPCM H = Total enthalpy $\frac{dH}{dt}$ = heat flow rate, $\frac{dT}{dt}$ = DSC test scanning rate	[185] [186,187]
	Enthalpy	$\rho\frac{\partial H}{\partial t} = \nabla.(k\nabla t)$ $H = \begin{cases} \int_{T_0}^{T} C_{p,s} dT\ T_1 < T_s\ (Solid\ state) \\ \int_{T_0}^{T} C_{p,s} dT + L\frac{T - T_s}{T_1 - T_s}\ T_s \le T < T_1\ (Mushy\ state) \\ \int_{T_0}^{T} C_{p,s} dT + L + \int_{T_0}^{T} C_{p,l} dT\ T \ge T_1\ (Liquid\ state) \end{cases}$	[188,189]
	Heat source term	$\rho C_p\frac{\partial T}{\partial t} = \nabla.(k\nabla T) - \rho L\frac{\partial f}{\partial t}$ f = liquid fraction of NEPCM $f = \begin{cases} 0\ T_1 < T_s\ (Solid\ state) \\ \frac{T - T_s}{T_1 - T_s}\ T_s \le T < T_1\ (Mushy\ state) \\ 1\ T \ge T_1\ (Liquid\ state) \end{cases}$	[190–192]
Molecular scale	Effective thermal conductivity	$k_{np} = \frac{k_n + 2k_p - 2\varnothing(k_p - k_n)}{k_n + 2k_p + \varnothing(k_p - k_n)}k_p + \dot{C}(\rho C_p)_{np}\lvert u\rvert\varnothing dn$ u = fluid velocity and $\dot{C}$ = empirical constant evaluated by Wakao and Kaguei. Vajjha's model: $k_{np} = \frac{k_n + 2k_p - 2\varnothing(k_p - k_n)}{k_n + 2k_p + \varnothing(k_p - k_n)}k_p + 5 \times 10^4 \gamma\varnothing(\rho C_p)_p\frac{\sqrt{BT}}{\sqrt{\rho_n d_n}}f(T,\varnothing)$ B = Boltzmann constant (1.3807×10^{-23}), γ = fraction of the liquid volume travelling with the nanoparticle. $\gamma = 9.881\ (100\ \varnothing)^{-0.9446}$, $0.01 \le \varnothing \le 0.06$ (CuO nanofluid) $\gamma = 8.4407\ (100\ \varnothing)^{-1.07304}$, $0.01 \le \varnothing \le 0.1$ (Al_2O_3 nanofluid) $f\ (T, \varnothing) = (2.8217 \times 10^{-2}\ \varnothing + 3.917 \times 10^{-3})\ \frac{T}{T_{ref}} + (-\ 3.0669 \times 10^{-2}\ \varnothing - 3.9112 \times 10^{-3})$	[193]
	Density	$\rho_{np} = (1 - \varnothing)\ \rho_p + \varnothing\ \rho_n$	[110]
	Specific heat	$(\rho C_p)_{np} = (1 - \varnothing)\ (\rho C_p)_p + \varnothing\ (\rho C_p)_p$	[110]
	Latent heat	$(\rho L)_{np} = (1 - \varnothing)\ (\rho L)_p$	[110]
	Dynamic viscosity	$\mu_{np} = \frac{\mu_p}{(1 - \varnothing)^{2.5}}$	[194]
	Thermal expansion	$(\rho\beta)_{np} = (1 - \varnothing)\ (\rho\beta)_p + \varnothing\ (\rho\beta)_n$	[110]

nanoparticles. Another investigation was conducted where Al_2O_3 -Go nanoparticles were dispersed into the PCM with a mass fraction of 2.5 % and 5 % by Hosseinzadeh et al. [201] and it was observed that the solidification process was 1.744 and 2.698 times more rapid compared to the pure PCM.

Singh et al. [202] numerically conducted a study utilizing the combination of various mass fraction (1 %, 3 %, and 5 %) of graphene nanoparticle with the fin and figured out the maximum 68 % reduction of melting time for 5 % graphene with fin. Qu et al. [203] conducted an experiment using Expanded Graphite-Multi-walled Carbon Nano-tube (EG-MWCNT) and Expanded Graphite-Carbon Nano-fiber (EG-CNF) in Paraffin-HDPE 20 SSPCM. The results showed that the EG-MWCNT-based composite PCM had a higher thermal conductivity compared to the EG-CNF-based composite PCM. Table 7 elucidates some of nanoparticles dispersion with PCM in TES application from a number of literatures. Fig. 15 shows the summary of future trends in PCMs.

7. Environmental perspective

The renewable energy demand is now increasing for clean, sustainable, and energy security in the world. The consumption of renewable energy is growing with the increasing population. Solar energy comes first when talking about renewable energy. It is a radiant energy that is harnessed to generate electricity and thermal energy. According to the International Energy Agency (IEA), solar energy can be considered an inexhaustible, affordable, and clean source of energy for a high level of sustainability and energy security in a country through reliability. 35 % of this energy is consumed in the heating system and the remaining 65 % is used for manufacturing, industrial purposes, and electrical appliances. However, the thermal processes emit huge amounts of CO_2 which is a

Table 7
Nano particles dispersed with PCM in TES application.

Nanoparticles	Melting/ solidification	Status	Proposed applications	Ref.
Cu	Melting	Numerical	Residential buildings	[198]
Cu	Solidification	Numerical	Rectangular slabs	[199]
CuO	Melting	Experimental/ Numerical	Energy efficient building, battery thermal management, smart food processing, high-density electronic cooling	[200]
CuO	Melting	Experimental	Heating and cooling applications	[204]
CuO	Melting	Experimental/ Numerical	Building thermal management, solar power plants	[205]
CuO	Solidification	Numerical	–	[128]
Al_2O_3-Carbon Black	Melting/ solidification	Experimental	Building operations, refrigerating machines, heat pipes	[77]
Al_2O_3-Go	Solidification	Numerical	Solar cooling systems, electronic cooling, heat pipes	[201]
Al_2O_3	Melting	Numerical	Buildings, storage containers, solar energy Equipment	[206]
Al_2O_3	Melting/ solidification	Experimental	Heating, cooling, power applications	[207]
Graphene	Melting	Experimental/ Numerical	Medium temperature applications (160–200 °C)	[202]
Graphene	Melting	Numerical	Buildings, space heating, textiles	[117]
Exfoliated graphene nano-platelets	Melting	Experimental	Buildings, solar energy storage	[208]
Expanded graphite-MWCNT	Melting/ solidification	Experimental	Building thermal management, solar energy	[203]
SiO_2	Melting/ solidification	Experimental	Air-conditioning, waste heat recovery	[209]

global concern to mitigate in order to keep the environment clean and improve the efficiency of thermal processes. Many research studies focus on manufacturing novel materials and incorporating them into the system to obtain clean energy, productivity, and sustainability. It is mandatory to decrease the cost of nano-materials and incorporate them to make the system more efficient and for sustainable development [210].

Utilization of sun energy can mitigate global warming and keep the environment clean. Solar energy is going to be a promising technology due to its abundance and integrating this technology into thermal applications for its higher efficiency. Solar collectors and PV panels are effective devices to produce sustainable energy e.g., power and thermal energy. Nowadays, researchers are incorporating nanofluid and nano-enhanced PCM with solar devices for the optimization of the system and minimizing environmental pollution. When graphene nanofluid was used in an FPSC system, Qiu et al. [211] explored that there was about a 9 % decrease in embodied energy when compared to traditional solar collectors. Otanicar and Golden [212] numerically investigated the solar collector system using water-based nanofluid and observed a lower embodied energy of around 9 % than conventional solar collectors. Many researchers have also explored the environmental impact based on life cycle assessment (LCA) of using nano-technology and PCM. The experimental result exhibited a lower emission of CO_2, SO_x, and NO_x for nanofluid and PCM-based solar collectors than conventional solar collectors. LCA refers to the process of evaluating and investigating the environmental consequences of products or services throughout their entire life cycle. Faizal et al. [213] conducted an empirical investigation on the environmental consequences of utilizing a water-based nanofluid containing CuO, TiO_2, SiO_2, and Al_2O_3. The results demonstrated a decrease in the amount of energy consumed by approximately 220 MJ, a payback period of 2.4 years, and a reduction of approximately 170 kg in CO_2 emissions compared to conventional solar collectors. Sahota et al. [214] performed an analysis of energy matrices, enviroeconomic factors, and exergoeconomic factors by introducing Al_2O_3, TiO_2, and CuO water-based nanofluid into the double slope solar still (DSSS). The use of Al_2O_3-water nanofluid resulted in the highest level of CO_2 reduction, reaching approximately 38 % compared to the base fluid. Hassani et al. [215] evaluated environmental and exergy analysis through utilization of CNT/water-based nanofluid and exhibited that the nanofluid PVT system can restrain the emission of CO_2 about 448 kg/m^2.yr. The majority of scientific work on the environmental impact of nano-based technology has concerned of reducing the emission of CO_2. The usage of PCM has been the emerging technology in the field of energy. PCM can absorb the solar energy and store it but during the night time, it gives up heat to the environment and solidify. Additionally, the usage of PCM has also the positive impact to the environment. The usage of

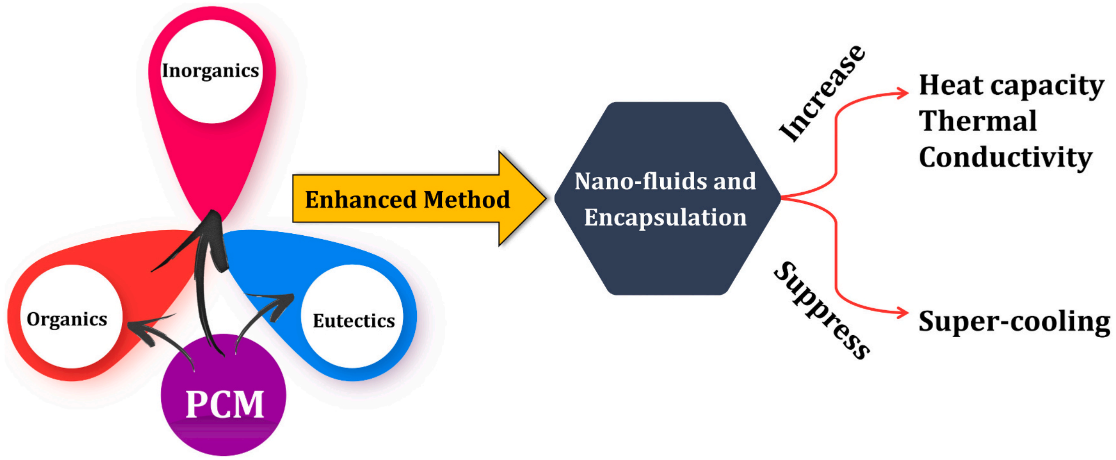


Fig. 15. Summary of future trends in PCMs.

hydrated salt has positive manufacturing effect over paraffin which is decreasing 75 % of manufacturing effect and lowering the global impact, experimented by Gracia et al. [216]. Colarossi et al. [217] conducted an experiment on PV-PCM system and exhibited the carbon footprint around 105 kg CO_2 equivalent for entire setup in which PCM contributed the impact of CO_2 around 4.76 kg and 56.29 kg in the production and disposal phases, respectively.

Nano-based technology is being widely used nowadays and it holds the maximum application field ranging from medical to solar application. It has also negative impact to the environment due to its extensive applications. From fabrication the nano-material in laboratory to disposal into the environment, it consists of several stages and high cost. It can make toxicity and destroy the ecosystem by disposing them to the environment. So, the extensive research works are being carried out for recycling the used nanoparticles rather than disposes to the environment. Overall, the usage of nano-based technology has the majority potential filled with benefits than hazard. The danger effect of nano-based technology can be mitigated by extensive research.

8. Economical perspective

The unique attribute and potentiality of NEPCM and nanofluid is to enhance the heat transfer characteristic. This nano-based technology is widely used in PVT system for improving its efficiency and performance. It improves the heat transfer rate and conductivity compared to conventional PVT system. Nano-based technology is the most effective and efficient for its higher heat transfer ability [213,218]. The economic flexibility of this technology depends on the following criteria:

- The incorporated nanoparticles and the PCM are fabricated or purchased from the market. The cost of integrated nanoparticles and PCM should be evaluated. It can be expensive. However, the ultimate economic analysis must be performed by considering the energy savings and the efficiency of the system [219].
- An inorganic-based waste salt from salt industry landfills can be potentially employed in TES system as PCM to store heat at low cost. Bischofite ($MgCl_2.6H_2O$ as the main ingredient) is one of the most prominent low-cost inorganic salt-based thermal energy storage material which can act as LHS and SHS material. The estimated cost of storing 1 MJ of energy with bischofite was around US$ 1.28 compared with those of synthesis $Mn(NO_3)_2.6H_2O$ and $MnSO_4.7H_2O$ (US$ 15.0 and US$ 12.4, respectively) [220]. This waste salt as PCM can be the most economical for storing the energy.
- The integrated nano-enhanced PCM and nanofluid technology should ensure the long-term performance. The long-term performance and durability ensure the utmost reliability of the system. It should retain its quality of absorbing and transferring heat without any deterioration of the system indicating the maximum usage of cost [214,221].
- The purpose of incorporating nano-enhanced PCM and nanofluid technologies in PV panels is to improve heat transfer properties and store thermal energy. This leads to increased thermal efficiency and reduced energy consumption. Therefore, it is important to take into account the energy savings when conducting the cost analysis [212,222].
- The economical flexibility of nano-enhanced PCM and nanofluid technology depends on the returns of capital investment. Energy savings, greater reliability, and longer lifetimes should be considered. The positive return of capital investment indicates economical sustainability of the system [223].
- The economical flexibility depends on the availability of the nanoparticles in the market. The availability influences the price of the materials. If the availability of the materials on market is rich, then the price will be less indicating higher economical sustainability and to adopt the technology for obtaining higher reliability.

9. Challenges of using NEPCM and nanofluid

- There should have appropriate concentration of nanoparticles in which the thermal conductivity of the material will be high. Sometimes, the higher amount of nanoparticles tend to agglomerate which adversely affect the thermal conductivity properties of nanofluid and NEPCM.
- In the disposal phase of NEPCM after the utilization in PVT and TES systems can adversely affect the environment for the disposing into the landfills due to the emissions resulting from the incineration.
- Utilization of nanoparticles into the solar system enhance the electrical and thermal efficiency but it has the limited used due to its high purchasing cost.
- Since the nanoparticles shows agglomeration attribute, the adoption of new technology like selection and using of perfect surfactant must take in order to prevent from clogging. It will obstruct the normal flow of nanofluid causing the declination of thermal performance of PVT system.
- Due to the clogging tendency of nanofluid, it needs higher pumping power to retain the normal flow of nanofluid. It raises the overall cost of the system and simultaneously reduces the thermal efficiency of the PVT system.
- The utilization of nanofluid into the solar application shows high cohesive force causing the elevation of viscosity, pressure drop, and frictional losses. All the attributes adversely affect the thermal performance.
- Disposal of nanoparticles into the environment exhibits the negative impact and make toxicity for human health. It also destroys the ecosystem and disposal of heavy metals into the environment can damage the lungs, brain, liver, kidney, and other important organs. Hence, the researchers should figure out the way of recycling of nanoparticles.

10. Conclusions and future recommendations

To resolve the issues of efficiency declination of the PV panel due to its surface temperature rise, many researchers have proposed different cooling techniques for PV panels e.g. using PCM with or without nanoparticles, nanofluids, and a combination of PCM and nanofluids. Additionally, the utilization of NEPCM and nanofluid has turned out the promising method for reducing the duration of charging and discharging of TES system. A comprehensive review has been highlighted based on the utilization of NEPCM and nanofluid for different cooling techniques for PV panels to enhance efficiency as well as their application in TES and the major conclusions are revealed as follows:

- Different types of PCMs including organic, inorganic, and eutectic along with their thermophysical properties have been presented and identified their limitations of having lower thermal conductivity attribute which can be enhanced by employing metal and carbon-based nanoparticles for making their suitability to effectively apply in the PV panels and TES applications.
- The presence of nanoparticles has exhibited the excellent result on the enhancement of thermal conductivity of PCM. Most studies showed that the increment reached up to 100 %. But, in some studies showed that the increment reached over 1000 % and carbon-based nanoparticle triumph over the performance of metal-based nanoparticle. The usage of graphite-based nanoparticle with 7.5 % and 10 % by weight increased the thermal conductivity by around 620 % and 1100 % respectively.
- Some studies showed that the addition of nanoparticles increase the latent heat of enthalpy whereas in some cases, it exhibited the declining trend, especially the incorporation of carbon-based nanoparticles. The addition of 10 wt% of graphene platelets reduced the latent heat of enthalpy from 177.9 J/g to 165.6 J/g.

- The engagement of nanoparticles to PCM improves its thermal conductivity, speeding the cooling process of PV panels. A study reported that the nano-PCM reduced the cell temperature by about 11.2 °C compared to 9.6 °C reduction for only PCM. Due to nanoparticle agglomeration, PCM viscosity increases over thermal conductivity and can damage the PCM. During the preparation of NEPCM, authors perspective to use the two-step process which is cost effective along with the addition of surfactant, magnetic stirring, ultrasonication, and high-pressure homogenization to reduce the sedimentation issue.
- The inclusion of nanoparticles in different compositions to water increases thermal conductivity as well as the rate of heat extraction from PV panels. The nanofluid-based PVT system improves PV panel performance over base fluid. At 0.3 wt% of Al_2O_3 concentration in water, cell temperature observed to be decreased to 42.2 °C. Additionally, the addition of Ferrofluid (Fe_2O_3-water) at 3 wt% boosted the system efficiency by 79 %.
- Most studies demonstrated that the addition of nanoparticles into PCM enhances the charging and discharging rate in TES systems. The effect of Cu, CuO, Graphene, Al_2O_3, Al_2O_3-carbon black, Al_2O_3-Go, Expanded Graphite-MWCNT, and SiO_2 nanoparticles into PCM for charging and discharging rate has been presented in this study. The outcomes demonstrated that the addition of carbon-based nanoparticle GNP exhibits maximum 68 % reduction of melting time compared to only 13.1 % reduction for using Cu nanoparticle.
- The reduction of CO_2 emission was found by around 448 kg/m^2.yr for using CNT/water-based nanofluid.
- Overall, numerical expression and the mathematical model of thermal conductivity for NEPCM on the application of PVT system has been highlighted in this study.

The utilization of nanofluid and NEPCM have turned into the promising methods to enhance the performance and efficiency of hybrid PVT and TES systems. However, the engagement of nanoparticles gives birth to several obstacles that must be addressed and overcome for the suitable application of nanofluid and NEPCM in the field of hybrid PVT and TES system. One of the most problem of using NEPCM is their highly cost of preparation, synthesis procedure. From the authors perspective, this problem can be minimized by adopting the widely used and less expensive procedure namely two-step process in which the available dry nanoparticles are dispersed into the PCM and base-fluid. However, this procedure faces the issue of the sedimentation difficulty which can be resolved by using the techniques such as surfactant addition, magnetic stirring, ultrasonication, and high-pressure homogenization associated with the two-step process. There is another issue which is related to environmental impact of using nanoparticles that can be resolved by adopting recycling process. Hence, this issue is major and more study is required to comprehend the danger of using nanofluid and NEPCM. Mitigation technique needs to be adopted to ensure the environmental sustainability before applying them in hybrid PVT and TES system. The utilization of nanofluid and NEPCM seems to be the amazing method for the enhancement of the performance of hybrid PVT and TES system for future. However, the issue of long-term stability of these materials restricts their potentiality to use in those field. Hence, more studies are required to ensure their long-term stability to effectively apply in the hybrid PVT and TES system. Furthermore, it is found from the research outcomes that the addition of nanoparticles enhances the thermal conductivity of PCM and few cases with higher concentration of nanoparticles, it decreases the latent heat of enthalpy. Intensive research is required to ensure the optimum concentration of nanoparticles so that the positive effects (enhancement of thermal conductivity) will triumph over the negative effects (reduction of latent heat of enthalpy). Additionally, since the diameter of nanoparticles effects on the thermophysical properties of nanofluid and NEPCM, the effect of diameter should be scrutinized by the further research in this field. Finally, continuous research and development to increase the stability and lower environmental impact in this field can bring about new era to effectively implementing of nanofluid and NEPCM in hybrid PVT and TES system.

CRediT authorship contribution statement

Utpol K. Paul: Writing – original draft, Visualization, Methodology, Investigation, Conceptualization. **Md. Shahriar Mohtasim:** Writing – original draft, Visualization, Validation, Investigation, Conceptualization. **Md. Golam Kibria:** Writing – review & editing, Visualization, Supervision, Conceptualization. **Barun K. Das:** Writing – review & editing, Supervision.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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