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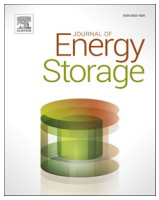

Review Article

Methodology and results of phase change material integration in photovoltaic-thermal systems for enhanced energy production in domestic settings: A review

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ABSTRACT

This review explores the use of phase change materials (PCMs) in photovoltaic/thermal (PV/T) systems to improve temperature control and energy storage. It provides a comprehensive overview of current PV/T systems integrated with PCMs, highlighting their potential to increase domestic energy production. The paper covers fundamental principles, benefits, and limitations of PVT technology, the role of PCM applications, and methods of integration. It also examines efficiency gains in power and thermal output, discusses challenges, and suggests future research directions for sustainable energy. Incorporating PCMs into PV/T systems marks notable progress in balancing electrical and thermal efficiencies. Finned serpentine heat exchangers improve heat transfer to PCMs, with more fins increasing surface area and cooling efficiency, while optimised flow rates balance electrical gains against thermal losses. Encapsulation prevents leakage and enhances thermal conductivity. Design factors such as a 25° inclination, insulation, and using dual PCMs in cold regions further improve performance. Economically, PV-T/PCM systems can have shorter payback periods than conventional PV panels if they are used for dual energy and in regions with high solar radiation. However, their viability depends on solar radiation, energy prices, and system costs, which vary by location.

1. Introduction

The Si-PV system experienced decreased performance due to increased PV cell temperature, which lowers both the efficiency and lifespan of the panels. Solar radiation raises the temperature of Silicon solar cells, and as the temperature increases, the semiconductor's bandgap decreases, leading to reduced panel voltage. In contrast, a hybrid PV/T system that combines a PV panel with a thermal plate offers dual outputs—electrical and thermal—by helping to lower the cell temperature.

The cooling process involving a heat exchanger mounted at the back of the PV panel, along with the working fluid flowing through pipes, causes uneven temperature regulation of the PV cell, resulting in some hot spots uncooled. To address this, phase change materials (PCMs) are used due to their thermophysical properties.

PCMs are installed with the heat exchanger behind the PV panel to mitigate the problem of uneven cooling in PV-T systems and to store heat during the day. The PV panel temperature can be managed with or without mechanical power, known as active or passive cooling, respectively. Active cooling involves mechanical movement, such as a pump, to circulate fluid, and is the focus of this review. When combined with a heat exchanger at the back of the PV panel, PCMS improve temperature regulation more effectively in active mode than passive cooling. This study emphasises the active cooling of photovoltaic–thermal systems integrated with PCMs, using both numerical and experimental methods, to achieve more uniform PV cell temperatures and enhance electrical and thermal performance. Fig. 1 illustrates the cooling techniques found in current literature.

The PV-T system is a hybrid setup that merges PV panels with thermal collectors and a working fluid to cool the panels. It produces both electricity and thermal energy from sunlight, providing a dual-function energy solution. The thermal collector's heat transfer can be air-based or liquid-based. This system comprises a PV panel, a thermal absorber connected to a heat exchanger, and storage units such as a water tank and a battery.

The literature reviewed studies on PVT systems, including

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investigations of PVT under different irradiation levels, where PV temperature rises with solar irradiation, reaching 83 °C without cooling and decreasing to 45 °C with water cooling at 960 W/m^2 [1]. They noted that varying the flow rate improved the electrical efficiency of the PVT system from 12 % to 14 %. Elbreki et al. [2] explored design conditions in their review, noting that the length and depth of the duct, channel, or collector influence both thermal and electrical efficiencies. Longer channels enhance thermal efficiency but may lower electrical efficiency. They also discuss the effects of glazed PV panels and glass thickness, noting that glazed PV panels improve thermal efficiency, whereas unglazed PV panels enhance electrical efficiency. In the same work, [2] explore various fin configurations like perforated, lateral, displaced, triangular, wavy, and foam-metal fins, each providing distinct benefits for better heat dissipation and PV module efficiency. They noted that combining PCM with fins can greatly enhance heat transfer in both passive and active cooling systems. The choice of fin design influences the thermal performance of PV modules, potentially boosting electrical efficiency by 8 % to 10 %.

Abdullah et al. [3] presented a water- and air-cooled PV/T system with a daily thermal efficiency of 39.81 % for water-cooling. The electrical efficiency was 11.69 % for both air- and water-cooling systems. The water-cooled system achieved the highest overall efficiency, reaching 51.40 %. Similarly, Tiwari et al. [4] mention that water-based PV/T systems provide higher thermal efficiency compared to air-based systems.

PV-T systems can achieve electrical efficiencies of 20 % and thermal efficiencies of 50 %, yielding an overall efficiency of 70 % or more [5]. It can be applied with heat pumps or absorption refrigeration systems to provide heating, cooling, and power, to cover significant portions of household energy demands.

Hazami et al. [6] demonstrated that the active cooling system had a thermal and electrical efficiency of 50 % and 15 %, respectively. This cooling enhanced electric efficiency and exergy by 3 % and 2.5 %. The PV/T systems satisfied the energy needs of Tunisian households, with annual average efficiencies of 14.6 % for hot water and 5.33 % for electricity. Additionally, the study identified optimal design parameters: a 7.2 m^2 area, a 540 L hot water tank, and a flow rate of 0.028 kg/s.

Al Tarabsheh et al. [7] pointed out that the inlet temperature of fluid through the pipes varies with flow direction in heat exchange. These temperature gradient differences occur because the inlet temperature starts relatively low. As the flow progresses through the heat exchanger, the inlet temperature rises toward the outlet, causing PV cells near the outlet to stay hotter. One drawback of PVT systems is the uneven cooling of PV cells, which can be addressed by using PCM.

1.1. Objectives of the review

This review aims to thoroughly analyse the current state of PVT systems combined with PCMs. It will examine the fundamental principles, benefits, and limitations of PVT/PCM technology, the applications of various PCMs in energy generation, and the mechanisms of integration. The review will evaluate improvements in power and hot water output, highlight challenges, and discuss prospects for new PCMs and the viability of PV-T/PCM technology.

2. Methodology

The Systematic review approach was chosen to identify and select the relevant literature to examine configurations and materials employed in PV-T/PCM to improve performance. The step was to generate a Boolean expression covering a range of articles without bias. Web of Science and Scopus was used to cover articles from 2015 to 2025 sourced from ScienceDirect, MDPI, AIP Advances, Frontiers, the Journal of Thermal Analysis and Calorimetry, and Energy Science and Engineering. After applying inclusions and exclusions, the review article number was determined. The review is organised as follows: Section 1 introduces the impact of elevated temperatures on PV cells, discusses the two cooling methods for PV panels, states the review's objectives, and provides an overview of PV-T systems along with case studies. Section 2 is the methodology, which outlines the scope of the review. Section 3 covers PCMs fundamentals and classifications, emphasising their importance in PV systems, their classifications, heat transfer mechanisms, selection criteria, applications in PV systems, methods to enhance their thermal conductivity, and the challenges faced. Section 4 examines PV-T/PCM integration mechanisms. Section 5discusses the performance enhancement techniques. Section 6 focuses on economic and environmental perspectives. Section 7 addresses research gaps and future outlook.

3. PCM fundamentals and classifications

PCMs play a crucial role in thermal management by absorbing heat during the day and releasing it at night. This process enables substantial energy storage in a compact form, making PCMs superior to sensible heat storage materials. They help maintain a consistent supply and demand for renewable energy sources, especially in standalone and off-

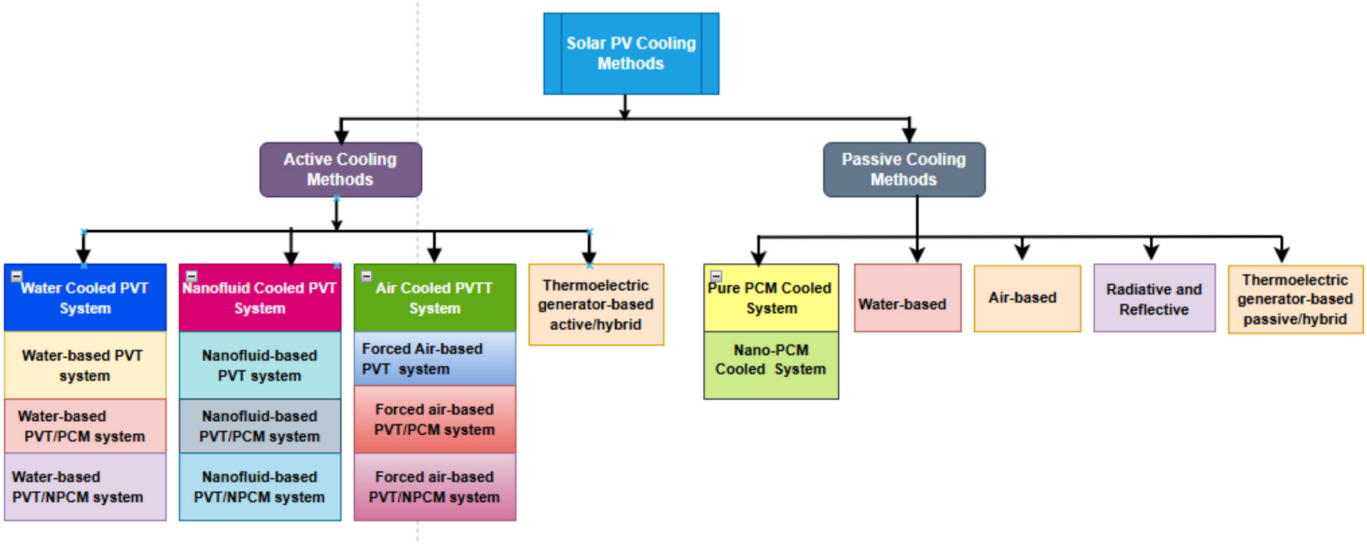


Fig. 1. Photovoltaic cooling techniques.

grid systems. PCMs offer flexibility by providing seasonal energy storage, such as during summer when the sun is strong and winter when radiation is weaker. Additionally, they help balance energy supply and demand between high-radiation daytime and low-radiation nighttime.

3.1. Importance of integrating PCMs in PV systems

Integrating PCMs with PV systems can greatly improve heat transfer by converting excess heat from the PV panels- normally wasted- into useful thermal energy. This integration boosts overall efficiency and ensures a more stable, reliable energy supply, especially for applications needing electricity and hot water. Using PCMS in PV system cooling provides uniform cooling of the PV cells, unlike PV-T systems, where uneven cooling can reduce efficiency.

3.2. Classes of PCMs

There are four types of PCMs: organic, inorganic, composite, and eutectic, as shown in Fig. 2. Each type has distinctive properties and serves different roles in sectors like solar thermal systems and electric vehicles. For PCMS to be suitable for PV applications, they should have appropriate heat capacity, density, and minimal volume change within the operating temperature range.

3.2.1. Organic PCMs

Organic PCMs are derived from hydrocarbons composed of long chains of carbon and hydrogen. They are classified into paraffin and non-paraffin PCMs; paraffins are alkanes, and non-paraffins are fatty acids from plants and animals. Paraffin is the most common and widely used, with a melting temperature of 10 to 80 °C [8]. Non-paraffin wax is more expensive than paraffin but has a higher melting temperature. They possess high latent heat, are non-corrosive and non-toxic, melt congruently, are low in cost, and do not require supercooling.

3.2.2. Inorganic PCM

Salt hydrates, metals, and alloys serve as examples of inorganic PCMs. They possess environmental properties similar to paraffin but are non-combustible and contain high latent heat. Inorganic PCMs offer benefits such as high latent heat, non-flammability, high thermal conductivity, elevated melting points, and cost-effectiveness. They are suitable for large thermal energy storage (TES) systems operating at higher temperature ranges, such as in power plants [9]

3.2.3. Eutectic PCM

Eutectic PCMs consist of a mixture of either two organic, two inorganic, or organic-inorganic phases. They are formulated to have unique melting temperatures that are lower than those of the individual components [8]. This allows for easy customisation to meet specific temperature and energy storage needs. Compared to single PCM systems, eutectic PCMS offer superior thermal energy storage (TES) capabilities. They also help mitigate common PCM issues such as supercooling and phase segregation.

Composite PCMs are chemical modifications or additives of other substances, such as metals, to organic or inorganic PCMs to overcome their disadvantages, such as low thermal conductivity, supercooling, leakage, and thermal cycling [10,11].

The choice of PCM depends on its intended application and the required thermal energy. Table 1 details the characteristics of materials considered for PCM use.

3.3. Heat transfer process in PCM

The heat transfer process during phase change includes conduction and convection. Natural convection can occur during phase change due to variations in liquid density with temperature. During solidification, natural convection is low, except during rapid cooling of an overheated part. [11].

In latent heat thermal energy systems (TESs), PCM stores heat as latent heat during melting and releases it during solidification [11]. The phase transition process is shown in Fig. 3.

The region where melting or solidification happens is called the 'mushy zone' [11]. It plays a crucial role during the phase change between solid and liquid. Gaining insights into the changes within the mushy zone is essential for effective thermal energy storage and the design of heat exchangers.

Eqs. (1) to (5) present the charging of the PCM [13,14].

If $Q_{pcm} < Q_{sol,}$

$$T_{pcm} = T_{mt} - \frac{Q_{sol} - Q_{pcm}}{c_{pcm,sol}}, \lambda_{pcm} = \lambda_{pcm,sol} \tag{1}$$

If $Q_{sol} < Q_{pcm} < Q_{liq,}$

$$T_{pcm} = T_{mt}, \lambda_{pcm} = \lambda_{pcm,sol}\frac{Q_{liq} - Q_{pcm}}{Q_{liq} - Q_{sol}} + \lambda_{pcm,liq}\frac{Q_{pcm} - Q_{sol}}{Q_{liq} - Q_{sol}} \tag{2}$$

If $Q_{liq} < Q_{pcm,}$

$$T_{pcm} = T_{mt} - \frac{Q_{pcm} - Q_{liq}}{c_{pcm,liq}}, \lambda_{pcm} = \lambda_{pcm,liq} \tag{3}$$

Table 1
Characteristics of material considered for use as PCM.

Physical properties	Chemical properties	Eco-friendly	Economics and availability
Large latent heat	Prolong stability	Non-toxic	Cheap and available
High density	High flash point	Low carbon footprint	Easy to obtain
Low vapour	Non-reactive	Recyclable	Commercially available
Minimum volume change during phase change			Practical to implement.
High-thermal conductivity			
The phase change temperature must be adequate for the application.			
Reliability/durability			

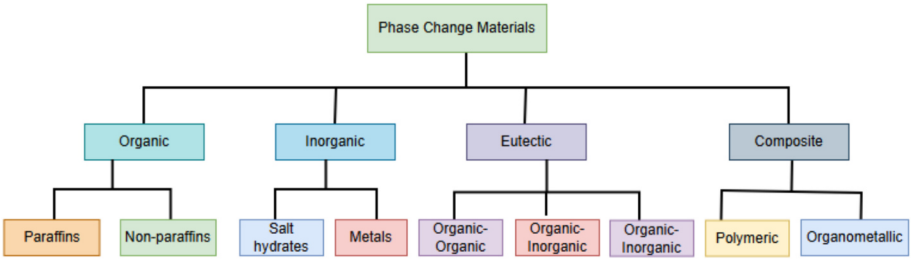


Fig. 2. Classification of PCMs.

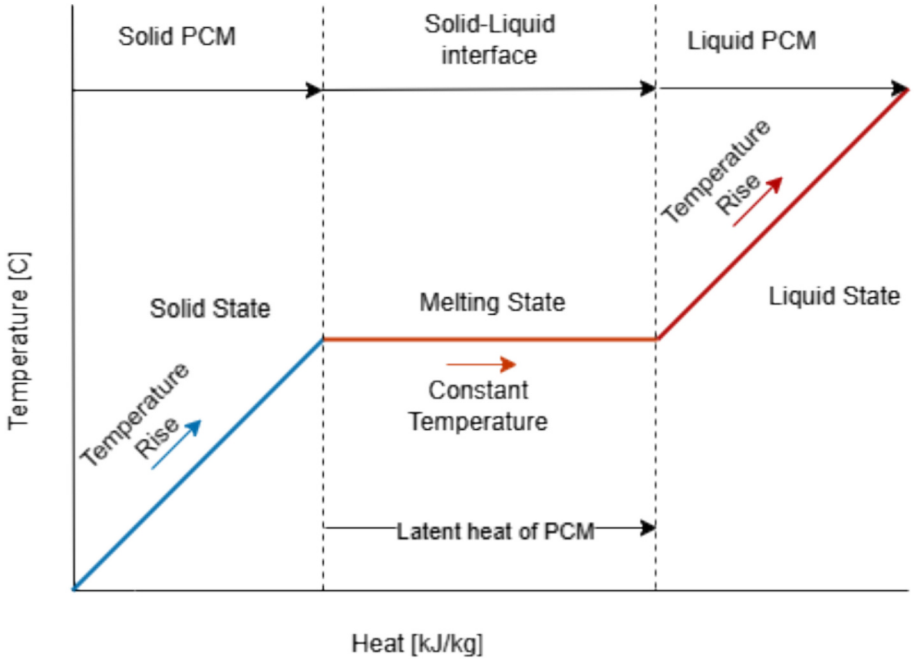


Fig. 3. Schematic diagram of the phase transition process of PCM [12]. [Reproduced with permission from the publisher.]

$$Q_{PCM,cha} = m_{PCM} \times \left[C_{p,s}\left(T_{PCM,2} - T_{PCM,1}\right) + (L_m) + C_{p,l}\left(T_{PCM,2} - T_{PCM,1}\right)\right] \quad (4)$$

$$Q_{PCM,dis} = m_{PCM} \times \left[C_{p,l}\left(T_{PCM,1} - T_{PCM,2}\right) + (L_m) + C_{p,s}\left(T_{PCM,1} - T_{PCM,2}\right)\right] \quad (5)$$

where Q_{pcm}: quantity of heat in the PCM layer; Q_{sol}, Q_{liq}: quantity of heat inside the PCM at the solid and liquid states, respectively; T_{pcm}: PCM layer temperature; T_{mt}: PCM melting temperature.

By assigning enthalpies of the liquid phase (hl) and the solid phase (hs) as functions of temperature, the energy conservation equations are then presented in Eqs. (1) and (2), with temperature as the primary dependent variable [15]. This process is depicted in Fig. 4, and the mushy zone corresponds to the area hsl.

Definitions by Chakraborty [15], illustrated in Fig. 4, provide enthalpies for both the solid and liquid phases as:

$$h_s = C_{ps}T \quad (6)$$

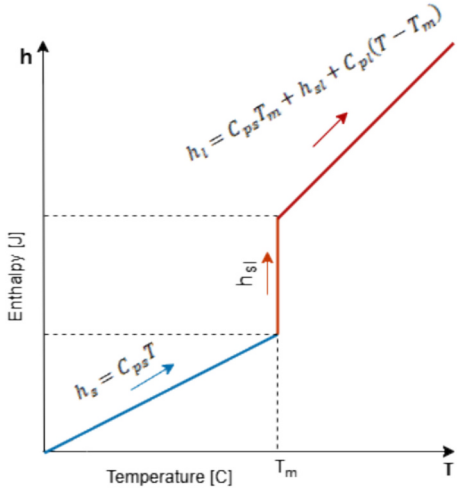


Fig. 4. Enthalpy of solid and liquid phases with respect to temperature [15].

$$h_l = C_{ps}T_m + h_{sl} + C_{pl}(T - T_m) \quad (7)$$

where h_s and h_l are solid and liquid enthalpies, respectively, and h_{sl} is the latent heat of the solid-liquid phase change (mushy zone). T_m denotes the melting point temperature, and C_{ps} and C_{pl} represent the heat capacity of the solid and liquid phases, respectively.

3.4. Criteria for selecting PCM

Integrating PCMs in PV systems is a promising approach to enhancing thermal management and improving electrical conversion efficiency. Selection criteria for PCMs are their melting point, latent heat, and thermal conductivity, which are crucial for effective thermal regulation in PV applications [16]. Also, the specific heat capacity, density/volumetric storage capacity, supercooling, phase stability, cycling, compatibility, corrosion, toxicity, environmental impact, cost, and commercial availability are all crucial properties to consider for domestic applications.

PCMs are chosen based on weather conditions. Research suggests that the ideal melting point for PCMs used in PV cooling ranges from 25 to 35 °C, with higher temperatures preferred in hotter climates. Solidifying at night allows PCMs to effectively regulate temperature during the day [16]. High latent heat capacity is crucial for sustaining a stable surface temperature of PV systems over long periods. Studies indicate that PCMs with greater latent heat better control PV surface temperatures compared to those with lower thermal capacity, especially when using passive cooling techniques.

3.5. PCMs used in the application of the photovoltaic systems

Organic PCMs are frequently employed in the thermal regulation of PV panels due to their thermophysical properties suitable for PV applications. They feature high latent heat, are non-corrosive, non-toxic, compatible with melting, exhibit no supercooling, and are cost-effective. Table 2 displays some examples of the PCMs used along with their thermophysical properties.

Table 2 shows that the melting point of commonly used PCMs in PV panel cooling is above 35 °C. However, studies indicate that the optimal melting point for PCMs in PV cooling is between 25 and 35 °C when the

Table 2
Examples of PCMs used in photovoltaic panels and their thermophysical properties.

Organic PCMs	Melting temperature [°C]	Specific heat [kJ/kg·K]	Latent heat [kJ/kg]	Thermal conductivity [W/m·K]	Density [kg/m^3]	Reference
Paraffin wax	45	2.2	210	0.21	930	[24]
Nano-paraffin wax	Slightly modified pure paraffin wax	2.5	220	0.3	950	[80]
Non-paraffin						
Lauric acid	44	2.0	151	0.44	900	[17]
Stearic acid	69.3	2.3	198	0.17	847	[81]
Eutectic	53	–	208	0.21–2.51	380	[81]
Composite (paraffin/diatomite/CNTs)	27.12				89.40	[10]

electrical aspect is prioritised, with higher values for hotter climates [16].

3.6. Improving the thermal conductivity of PCMs

PCMs have low thermal conductivity, but improvements can be made by adding fins or nanoparticles. Nano-enhanced PCMs are particularly important for enhancing thermal conductivity, which improves thermal regulation and efficiency in PV systems. Nóbrega et al. [18] examine ways to boost thermal conductivity by using nanoparticles and tube fins. Their research investigates approaches like increasing the heat transfer area with tube fins and incorporating metallic nanoparticles, such as Al_2O_3, to develop nano-PCMs. These modifications aim to address the limitations of traditional PCMs.

Another study examined the thermal behaviour of both finned and non-finned tubes using pure PCM and a nano-PCM mixture. The findings showed that adding nanoparticles to PCM significantly boosted thermal performance, notably increasing the contact area and the speed needed for complete phase change [18]. The same study found that finless tubes with 10 % $Al2O_3$ nanoparticles increased contact position by 25 % compared to pure PCM. Additionally, finned tubes with the same nanoparticle concentration reduced solidification time by 9.1 %. These results highlight the combined benefits of fins and nanoparticles for improving thermal efficiency.

3.7. Challenges of PCMs in cooling applications and remedies

Applications of PCMs in solar energy face challenges of reacting with the materials in contact and degradation due to repeated phase changes. The critical issue of corrosion affects container materials used for PCMs, including carbon steel, copper, aluminium, and stainless steel. Stainless steel exhibits the highest corrosion resistance, while carbon steel and copper are more prone to degradation when exposed to different PCMs. PCMs' chemical stability is vital, as changes in their composition can lead to the formation of corrosive substances that degrade the container materials. Thermal cycling can significantly impact the chemical composition of PCMs, potentially introducing new corrosive substances [19]. Therefore, enhancing the compatibility between PCMs and their containers includes incorporating nanoparticles and other additives to improve thermal conductivity and reduce corrosiveness. Z. Li et al. [20] present a novel high-thermal-conductivity composite phase change material to overcome the poor thermal conductivity and crystalline rigidity at room temperature.

3.8. Benefits of combining PV-T with PCM

The use of PCMs with PV-T systems provides advantages, including greater energy efficiency, improved thermal management, and increased reliability of the energy supply. PCMs enable the storage of thermal energy that can be utilised during periods of low solar irradiance to maintain the hot water supply.

Sivashankar et al. [16] demonstrated the effectiveness of PCMs in reducing PV surface temperatures, thereby enhancing electrical efficiency. Glauber salt as a PCM in building-integrated photovoltaics reduced the temperature by 12 %, while 8 % electrical efficiency was recorded. Integrating nano-phase change materials also improved thermal efficiency by 6 % and temperature reduction by 20 °C [21]. The research by Yuan et al. [22] investigates PV-T combined with PCM to address the challenges of high-temperature dissipation and winter freezing that affect PV panels. The PCM absorbed heat on sunny days, reducing the PV panel's surface temperature, and kept it warm at night to prevent freezing.

4. PV-T/PCM integration mechanisms

Using PCMs with PV-T controls PV cell temperature by utilising PCM's latent heat to absorb heat during sunny peak days and transfer it to the working fluid for hot water. Integrating phase change materials with PV-T improves efficiency and temperature management.

4.1. Mechanisms of integrating PCM into PV-T system

PCMs can be integrated with PV-T systems through various methods, such as embedding them within the thermal collector or using them as a separate thermal storage unit. The choice of application depends on the desired performance outcomes. The two aspects of applying paraffin-based PCMs—active and passive cooling methods—and metal oxide nanoparticles are shown in Fig. 5.

Using paraffin-based PCMs can notably lower PV module temperatures by 3 to 26.6 °C, boosting electrical efficiency by 1 % to 56 % [12]. Such improvements are vital since elevated temperatures can impair PV module performance, causing efficiency losses of 0.3 % to 0.65 % per temperature increase. The schematic of the cooling methods is illustrated in Fig. 5.

Effective thermal management is essential, particularly in hot climates where PV systems are more susceptible to overheating. PCMs can absorb excess heat and store it as latent heat, releasing it when temperatures fall, thus maintaining optimal operating conditions for the PV modules. Due to the low thermal conductivity of PCM, adding a metal foam PCM container can improve heat transfer from the PV panel to the heat transfer fluid.

4.2. Organic PCMs

4.2.1. Paraffin wax

Ali Bhutto et al. [23] suggest a PV-T system that incorporates water cooling and PCMs to regulate thermal energy and enhance electrical efficiency. The PCM (RT42), with a melting point of 42 °C, was utilised. The study includes experimental analysis using a solar simulator and TRNSYS simulation software to compare PV, PVT, and PVT-PCM systems under controlled conditions. Fig. 6 shows the PV-T/PCM setup and the TRNSYS model.

The findings show that PV-T/PCM outperforms PV-T and PV panels in cell temperature regulation and overall efficiency. The maximum cell

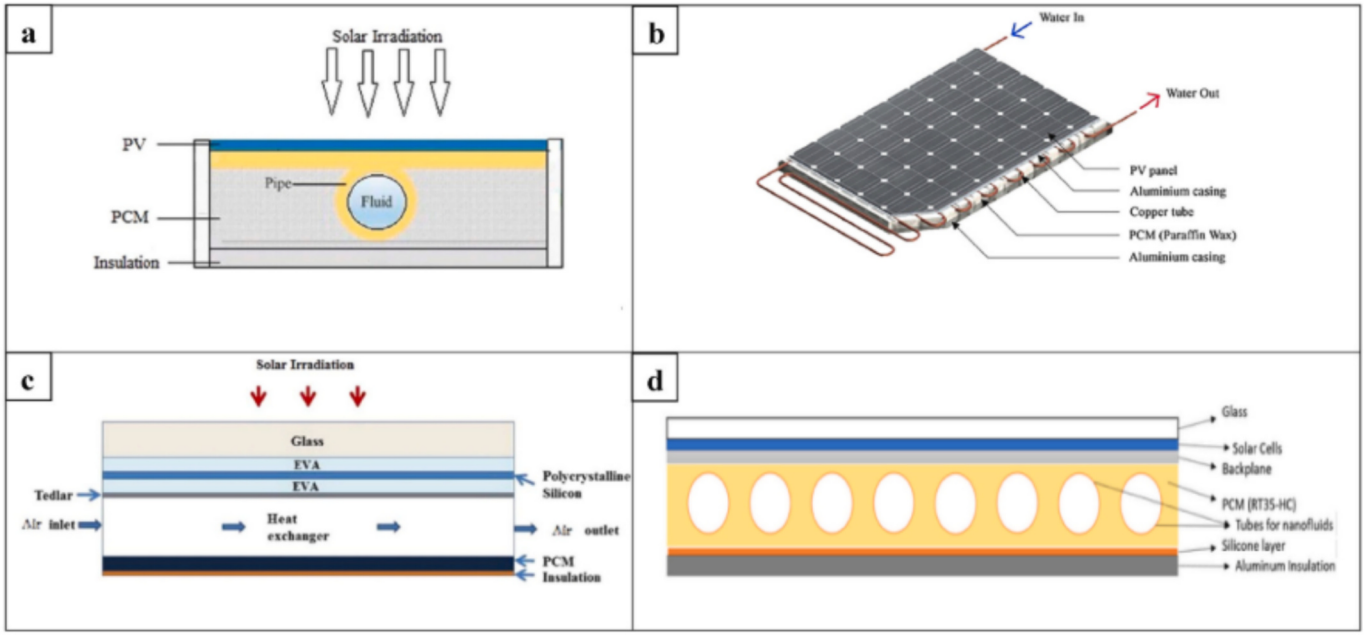


Fig. 5. (a) Passive cooling of PV-PCM; (b) water-cooled PVT-PCM; (c) air-cooled PVT-PCM; (d) nanofluid-cooled PVT-PCM [12]. [Reprint with permission from the publisher.]

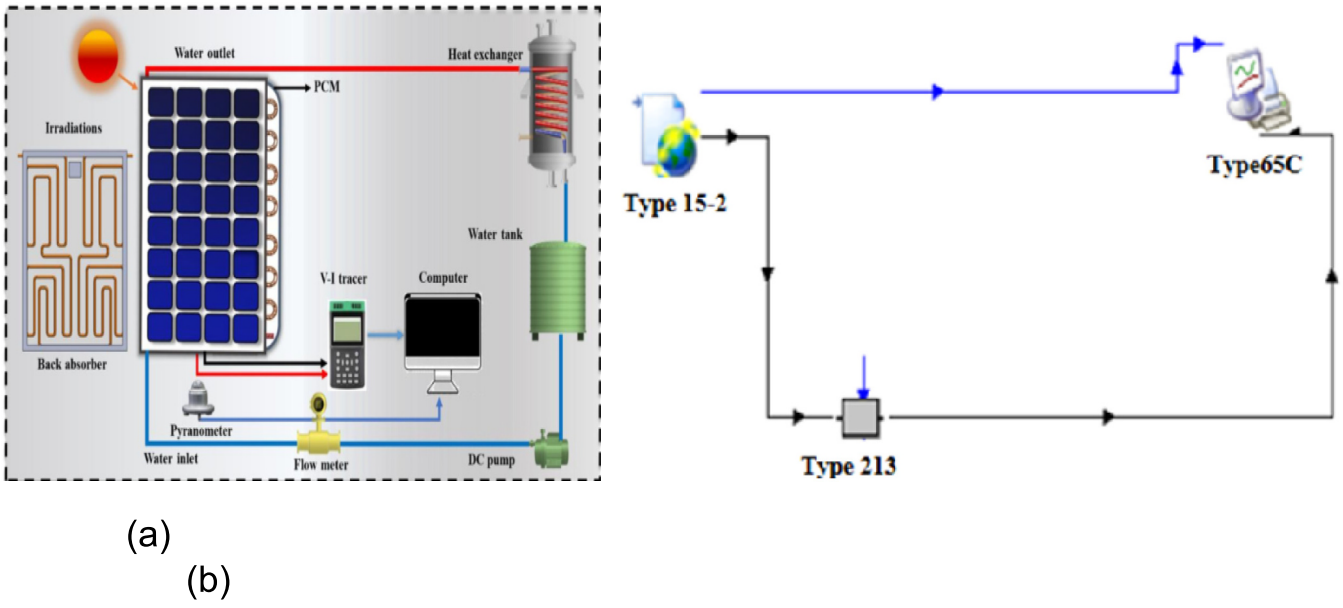


Fig. 6. (a) Diagram of the photovoltaic thermal system; (b) developed TRNSYS model of the PVT-PCM [23]. [Reprint with permission from the publisher.]

temperature for the PV panel was 59 °C, then decreased to 49 °C in PV-T, and further to 36 °C in PV-T/PCM. Additionally, electrical efficiencies for PV, PV-T, and PV-T/PCM were 6.1 %, 7 %, and 9.5 %, respectively. The PV-T/PCM system also achieved 73 % to 72 % thermal efficiency compared to the PV-T system.

Chaichan et al. [24] combine paraffin wax and Vaseline (petroleum jelly) to lower the paraffin wax's melting temperature in the hybrid PV-T/PCM system. The paraffin wax melting point was 45 °C and the Vaseline melting point was 25 °C, all mixed in a proportion of 25 %, 50 %, and 75 %. It was found that the 50 % paraffin +50 % Vaseline mixture gives an electrical efficiency of 13.70 % and a maximum thermal efficiency of 39 %. The mixture of paraffin and Vaseline lowered the pure paraffin wax's melting point to meet the requirements and improve productivity.

Another study aims to enhance solar energy utilisation by tackling the issue of low-grade heat dissipation from PV cells. The proposed PV-T/PCM system is designed to store waste heat as usable thermal energy. M. Li et al. [13] examine the effects of flow rate, cell temperature, and PCM thickness on the system's performance. The model includes a plate and serpentine design optimised for PVT-PCM collectors. The PCM used was paraffin wax with stable thermal cycling. It was found that the PVT-PCM system outperforms traditional PV and PV-T systems in both power and efficiency. Specifically, the system shows a reduction in cell temperature of 12.54 °C and 42.28 °C for PV-T and PV systems, respectively. Additionally, the PV-T/PCM system demonstrated an increased average power output of 1.13 W and 4.59 W compared to PV-T and PV systems,

respectively. The study also examines an absolute flow rate of 0.02 kg/s and an optimal PCM thickness of 0.03 m. They suggested that the flow rate improved electrical efficiency but reduced outlet temperature and thermal efficiency. When the flow rate is too high, efficiency decreases significantly due to limited heat transfer time. They observed a notable improvement in PV-T/PCM system efficiency, at 0.03 m PCM thickness, by 0.18 % compared to 0.02 m. They concluded that performance gains beyond 0.03 m thickness were not significant and proposed 0.03 m as the optimal PCM thickness.

A transient behaviour of PV-T systems integrated with phase change materials (PCMs), as investigated by Bouzelmad et al. [25]. They explored PCMs' potential to mitigate excess heat to enhance the efficiency of the PV systems. The model considers energy exchange between various system components, such as the glass, PV cell, absorber plate, PCM, and flowing fluid, as shown in Fig. 7. A paraffin (RT30) PCM was selected because of its properties within the PV module's operating temperature range, melting point, and thermal energy storage capabilities.

The model's accuracy was verified through comparisons with existing numerical and experimental studies, showing a maximum temperature discrepancy of less than 1.5 °C. On 4 January 2023, the PV-T/PCM system's cell temperature was reduced by 19 °C and electrical efficiency increased by 1.65 %. The PV-T/PCM system significantly lowered the PV cell's temperature by approximately 21.9 °C and improved electrical efficiency by 1.95 % on 4 August 2022.

The concentrated PV-T system integrated with PCM (PV/T-CPCM), as shown in Fig. 8, by [26] uses paraffin with a melting temperature range of 7.8 to 25.8 °C. The pump was turned OFF, then ON, then OFF again, causing the PV cells' temperature to decrease from 33.2 to 27.1 °C, demonstrating the combined impact of PCM and liquid cooling. The PV/T-CPCM system's energy efficiency was 7.9 % higher than that of the photovoltaic-compound parabolic concentrator (PV-CPC) system and 10.7 % higher than that of the photothermal-compound parabolic concentrator (PT-CPC).

Similarly, A. Hasan et al. [27] investigate the application of PCMs with photovoltaic (PV) panels to enhance energy efficiency by managing thermal energy and recovering it for domestic water heating. The experimental setup in Fig. 9 includes polycrystalline PV panels, a water circulation system for heat extraction, and various sensors to monitor temperature, solar radiation, and PV performance. They observed a 1.3 % increase in electrical conversion efficiency of the PV panels and approximately 41 % heat recovery from incident radiation. They produced 50 L of domestic hot water at 38 °C and generated 521 Wh/day of thermal energy. It was also noted that the electrical and thermal efficiencies improved by about 6 % and 41 %, respectively. They concluded that the system is more effective in hot climates, where rising PV temperatures pose a challenge.

Saxena et al. [28] analysed four PV module setups (A, B, C, and D) to assess cooling performance in Moradabad, India. Module A was a front-surface water-cooled type, B employed back-surface PCM cooling, while C and D alternated water and PCM cooling during the day. Fig. 10 shows different heat sinks used for PV cooling with RT-42HC PCM.

The findings show that:

- The front-surface water-cooled system configuration achieved the greatest average surface temperature reduction of 78.7 %, an average power improvement of 23.2 %, and the highest increase in electrical conversion efficiency at 22.8 %.
- The back-surface PCM-cooled setup results in a modest 25.7 % temperature decrease, an average power increase of 8 %, and an efficiency boost of 7.8The time-dependent setup, which switches between water cooling and PCM cooling depending on the time of day, provides a balanced approach. It achieves a temperature reduction of 41.5 %, an average power increase of 11.7 %, and an efficiency improvement of 10.7 %. The researchers concluded that the third system configuration, C, was the most effective because it does not incur additional pumping costs for cooling.

Su et al. [29] analyse the electrical and thermal performance of PV-T systems integrated with PCMs, focusing on the optimal melting point and PCM layer thickness to enhance energy output. They use a one-dimensional energy balance method to examine variables such as cell temperature, electrical power, and thermal power output. Fig. 11 illustrates the proposed PV-T/PCM.

Key findings from the study show that a PCM layer with a low melting point enhances the electrical performance of the collector. However, its heat storage capacity was limited and not effectively usable. The best configuration for maximising total energy output was identified as a 3.4 cm-thick PCM layer with a melting point of 40 °C. This configuration enables the PV-T collector to deliver the highest energy output. Additionally, using a PCM layer with a melting point of 30 °C can boost the collector's electrical power by 13.6 %.

In another study, Zhou et al. [30] proposed a water-based PV-T/PCM system aimed at reducing PV cell overheating and enhancing efficiency.

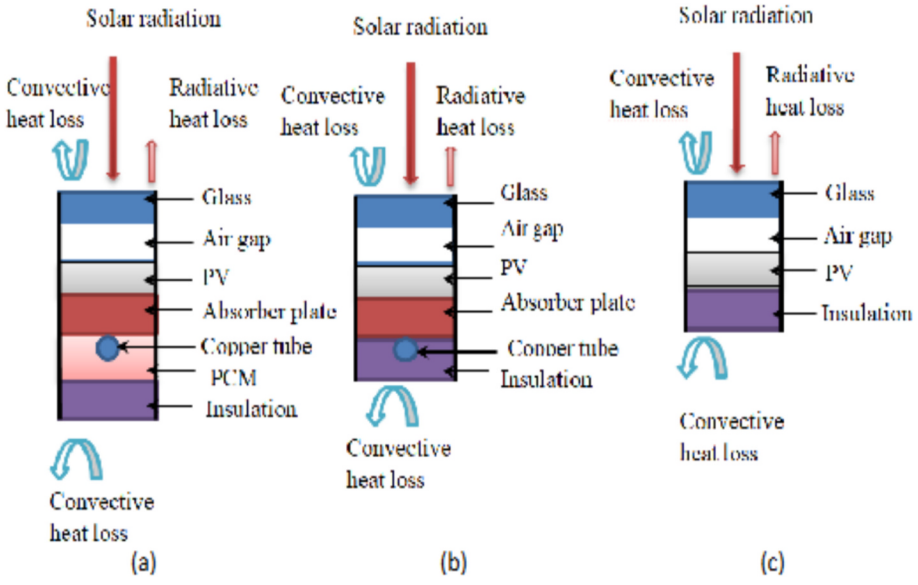


Fig. 7. The design of the (a) PV-T/PCM; (b) PV/T system; and (c) standalone PV system [25]. [Reprint with permission from the publisher.]

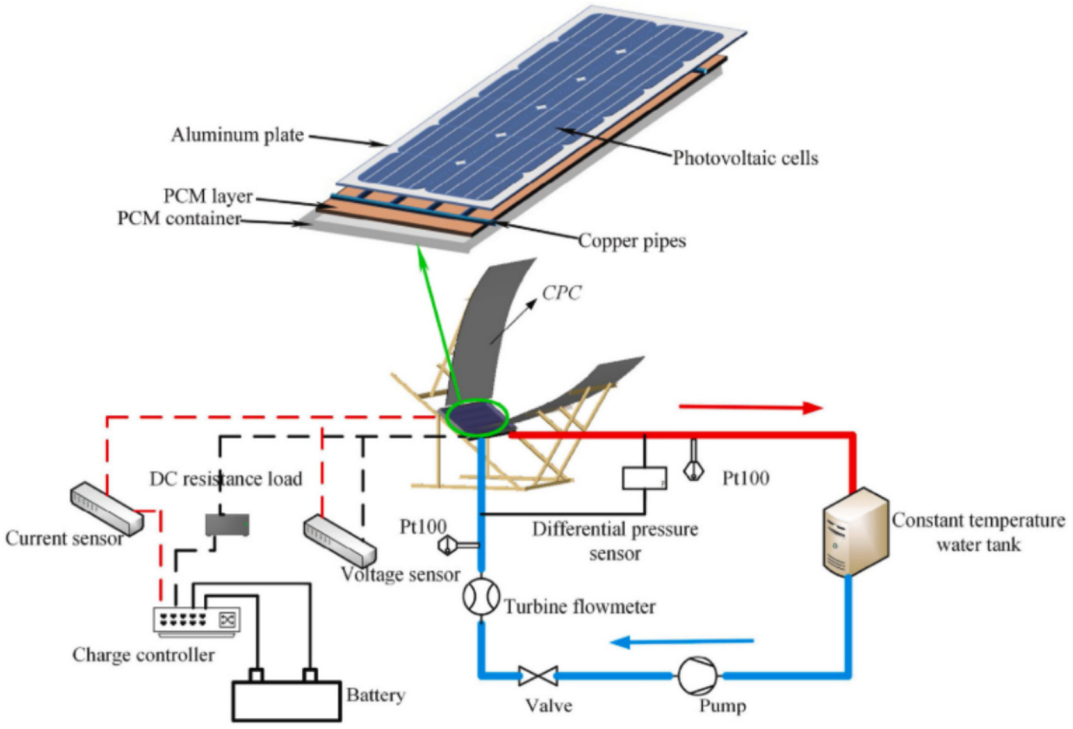


Fig. 8. Schematic diagram of the PVT-PCM system [26]. [Reprint with permission from publisher.]

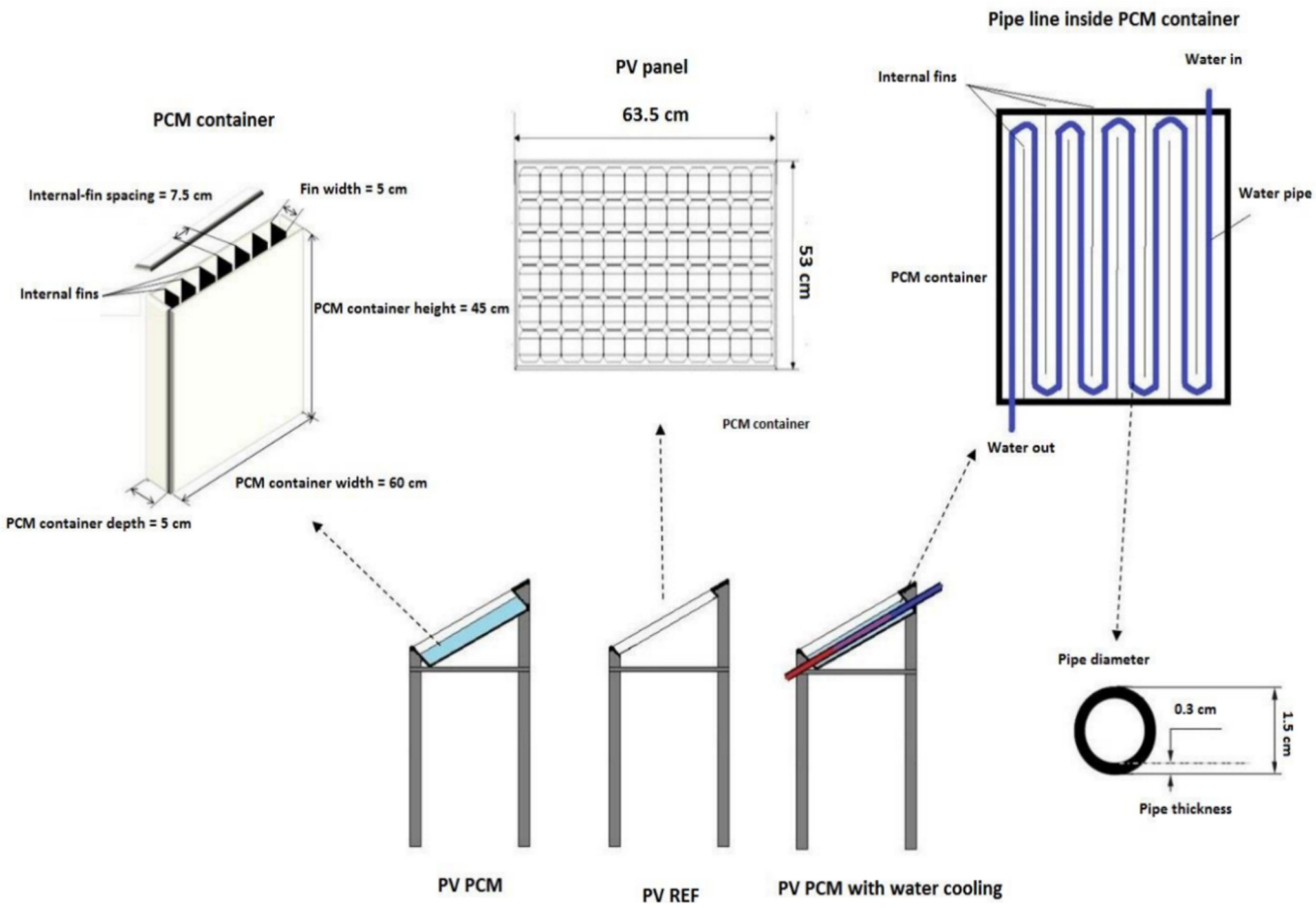


Fig. 9. PV-PCM and metallic pipe heat exchanger immersed in PCM container [27]. [Reprint with permission from the publisher.]

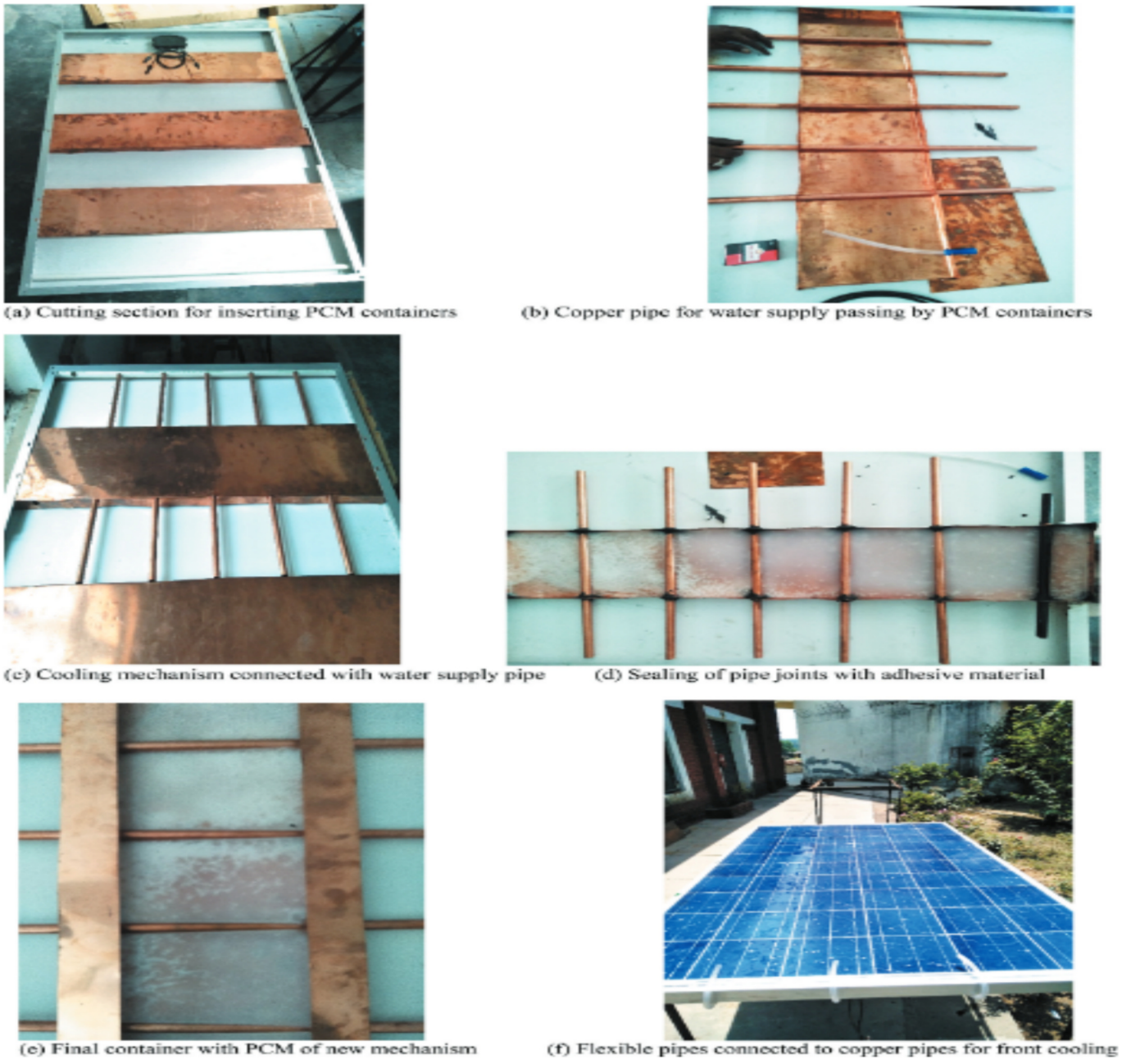


Fig. 10. Various arrangements of novel heat sink for PV cooling [28]. [Reprint with permission from the publisher.]

They examined how cooling water and flow rate affect PV cell temperature and performance. The findings indicate a notable improvement in PV efficiency over traditional panels by increasing the water flow rate and lowering the inlet water temperature. PV efficiency rose from 0.119 % to 0.120 % as the mass flow rate increased from 5 kg/s to 10 kg/s. Meanwhile, the average PV temperature only increased slightly from 0.118 % to 0.118 %, while the inlet water temperature dropped from 25 °C to 15 °C. A further decrease of 5 °C in inlet water temperature, from 15 °C to 10 °C, resulted in PV efficiency climbing from 0.118 % to 0.119 %.

A study by Simón-Allué et al. [31] evaluated the energy performance of various PV-T models, examining the effects of PCM layers and heat-absorber geometries. The research tested PV-T panels under maximum irradiance conditions, comparing glazed and unglazed setups and different absorber materials like copper, aluminium, and polymers. Two PCMs, organic RT50 and inorganic C48, with melting points of 45 °C and 50 °C, were evaluated. Results showed aluminium absorbers performed better in thermal output than polymer types, which, despite lower thermal conductivity, had good electrical properties. The study concluded that increasing PCM layers had little effect on thermal efficiency but helped distribute heat more evenly and maintained up to 30 % of heat after sunlight exposure stopped.

Tashtoush & Al Ghadi [32] proposed two systems, system A was designed with tubes positioned between the lower surface of the absorber and the surface of the PCM, and system B was designed with tubes between the lower surface of the PCM and the upper surface of the insulation layer. At night, the system increased the outlet water temperature by a considerable amount compared to system A, thereby improving thermal output. However, the maximum total electrical power output for system A using 3 cm PCM thickness was 3095.81 W/day.

A numerical study was done by Alnakeeb et al. [33] to analyse the

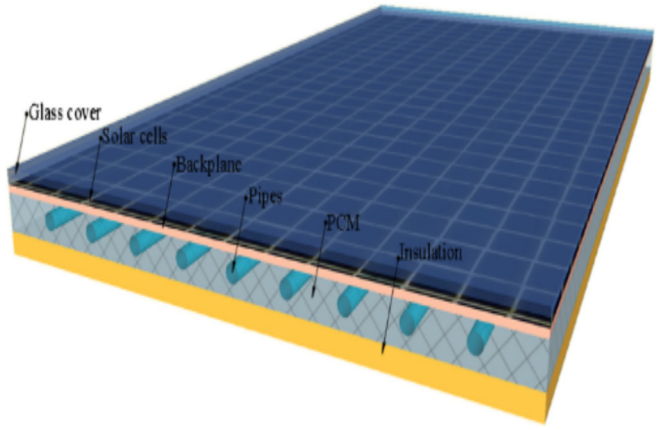


Fig. 11. The proposed PVT-PCM [29]. [Reprint with permission from the publisher.]

influence of a varying half-elliptic inner tube inside the PV-T/PCM system. They examine eight distinct aspect ratios: 0.25, 0.5, 0.75, 1.0, 1,25, 1.5, 1.75, and 2 of the half elliptic inner tube. The overall energy efficiency for the aspect ratios was: 66.28 %, 55.95 %, 52.30 %, 50.86 %, 50.17 %, 49.78 %, 49.65 %, and 49.61 % for 0.25, 0.5, 0.75, 1.0, 1,25, 1.5, 1.75, and 2, respectively. From the energy efficiency results, the inner tube ratio is directly proportional to the energy efficiency of the PV-T/PCM system.

4.2.2. Non-paraffin PCM

Hossain et al. [34] analyse the performance of solar PV-T systems with or without PCMs, utilising a 250-watt p-Si module for the photovoltaic component and copper pipes for the thermal collector. The system's performance was assessed at different water flow rates, focusing on both electrical and thermal efficiencies. The PCM packets are 0.5 mm thick and made from aluminium sheets. PCM packets were filled with 8.72 kg of PCM, as shown in Fig. 12. The peak electrical efficiencies for PV-T and PV-T/PCM were 14.57 % and 15.32 %, respectively, at 3 LPM and 4 LPM. Meanwhile, thermal efficiencies reached 75.29 % and 86.19 % at 2 LPM for PV-T and PV-T/PCM, respectively. The highest electrical power outputs were 148.61 W for PV-T and 160.05 W for PV-T/PCM, both at a flow rate of 4 LPM.

In another work, Hossain et al. [35] introduced a novel approach that uses lauric acid within aluminium foil packets arranged around the flow channel of the PV-T collector, as shown in Fig. 13, to enhance thermal storage capacity. Thermal efficiency reached 87.72 % at a flow rate of 2 L/m, while the PVT-PCM system's electrical efficiency was 11.08 % at 4 LPM. The exergy efficiency was 12.19 % at 0.5 LPM. The maximum power output was 160.29 W, which is 14 % higher than that of a conventional PV module.

Alsaqoor et al. [17] introduced a mathematical model to analyse the performance of PV-T and PV-T/PCM systems under various solar irradiance levels and mass flow rates. The PCM was installed at the rear of the PV panel, in contact with the absorber plate. They used lauric acid PCM, which has a melting point of 43.8 °C and is suitable for thermal energy storage applications within the 20–50 °C range. The researchers developed a MATLAB computational algorithm to simulate system behaviour and validated their results against experimental data from other studies. Fig. 14 illustrates the configuration of the PV-T/PCM system.

The numerical results closely match experimental data, with a maximum temperature deviation of 6.9 %. The PV-T/PCM system achieved a 14 % increase in electrical efficiency compared to the PVT system without PCM. The PV-T/PCM and PV-T systems generated 21 kW and 18 kW, respectively, with the PV-T system outperforming the PV-T/PCM system in thermal energy output and overall efficiency. The PV-T/PCM reduced the cell temperature by 24 % and improved electrical efficiency by 5.9 %. Additionally, the study examined how varying the mass flow rate impacts system performance; higher flow rates boost thermal energy storage and enhance both efficiencies.

Browne et al. [36] conducted a PV-T system with PCM for heat storage in Dublin, Ireland. This PV-T/PCM system was designed to generate electricity and preheat water, and its performance was compared to three other systems: a PV-T without PCM, a PV with an attached container serving as a heat sink, and a standalone PV module shown in Fig. 15. The PV-T/PCM system reached water temperatures 5.5 °C higher than the PV-T system.

Rahimi et al. [37] combine metal-matrix sheets (MMS) with bio-based PCMs to enhance efficiency. Their research examines how changing the number of MMS from 1 to 5 and increasing the bio-based PCM mass from 1.6 to 4 kg influences the PV cell's temperature, output power, and electrical efficiency. The bio-based PCM is a composite of beeswax and oleic acid, selected for its high latent heat of fusion, lower flammability, and cost-effectiveness compared to paraffin PCMs. Fig. 16 illustrates the MMS, which are porous metal sheets used to enhance the PCM's thermal conductivity. Increasing the PCM weight from 1.6 to 4 kg improves PV panel performance, with the best results at 5 MMS layers and 4 kg of PCM, achieving an electrical efficiency of 11.73 % and an output power of 7.04 W. The water flow rate through the PCM-coated copper tube behind the PV panel affects heat transfer and the panel's temperature. It was concluded that the PCM weight should be optimised with the number of MMS to achieve optimal thermal management.

Yang et al. [38] experimented to evaluate PV-T and PV-T/PCM modules, using equipment such as a solar simulator, thermal tanks, pumps, flow meters, I-V trackers, and other accessories. They chose

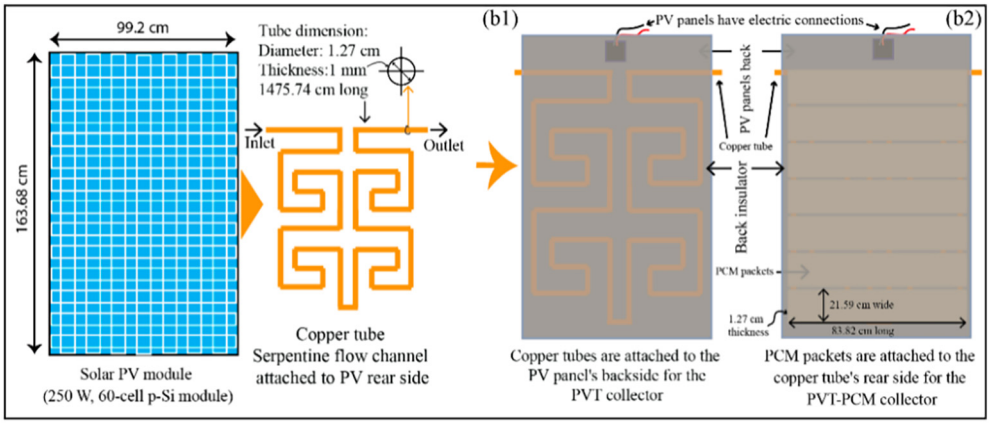


Fig. 12. PV module, double serpentine flow channel to PV rear side and PV-T/PCM thermal collection [34]. [Reprint with permission from the publisher.]

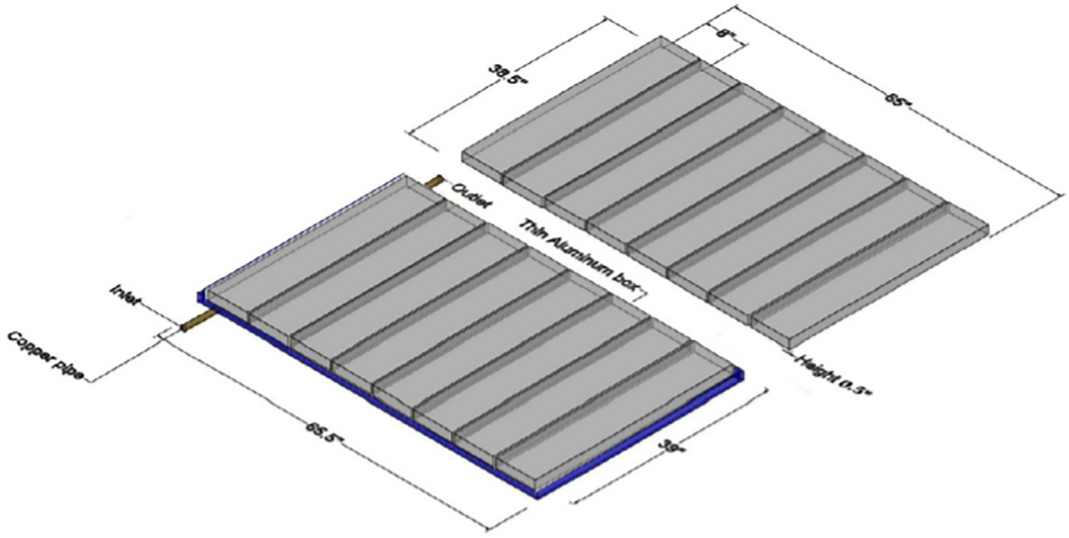


Fig. 13. Flow channels and PCM packets [35]. [Reprint with permission from the publisher.]

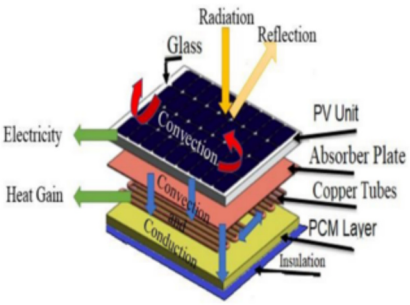
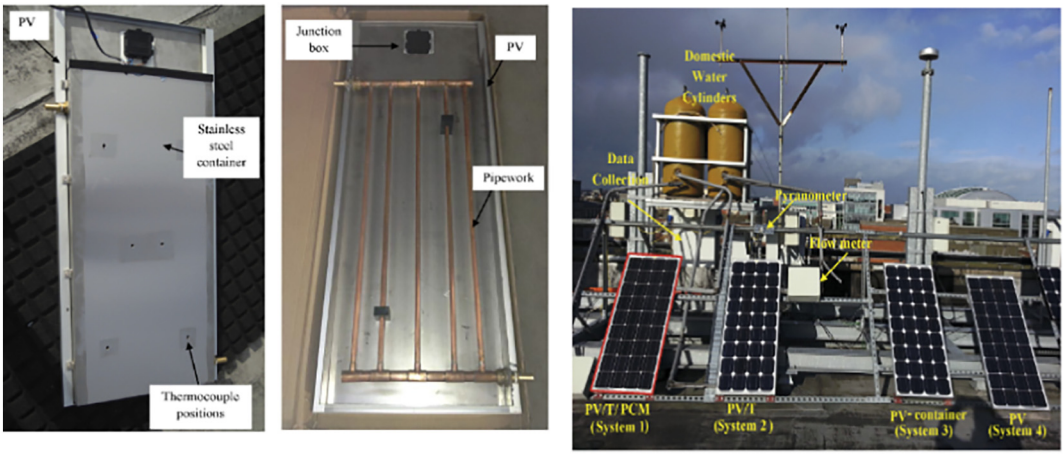


Fig. 14. Methodological configuration of PV-T/PCM [17]. [Reprint with permission from the publisher.]

capric acid as the PCM material because of its transition temperature range and thermophysical properties. The output power of the PV-T/PCM system was 39.65 W, while the PV-T system produced 32.25 W. Correspondingly, their electrical efficiencies were 8.16 % and 6.98 %. The water tank temperatures averaged 42.4 °C for the PV-T/PCM system and 40.3 °C for the PV-T system, with thermal efficiencies of 70.34 % and 58.35 %, respectively. The thermal energy generated was 76.87 % for PV-T/PCM and 63.93 % for PV-T, with energy savings of 87.5 % and 73 %.

Gaur et al. [39] used PCM to improve the thermal and electrical efficiency of PV-T systems in Lyon, France. They determined that an excessive PCM amount increases thermal resistance and hampers energy storage, suggesting an optimal mass of 30 kg of OM37 PCM for optimal performance. The PV-T/PCM cell temperature decreased during summer and winter at 12 and 13 h, reaching approximately 16.04 °C and 5 °C, respectively. The average electrical efficiencies of the two systems in summer were 16.3 % and 15.40 %, while in winter they were 16.87 % and 16.5 %. The highest efficiency occurred in winter, indicating that the PV cell temperature was lowest then.

Mousavi et al. [40] studied how organic and inorganic materials affect system performance, focusing on parameters such as mass flow rate, solar irradiance, inlet water temperature, and inclination angle. They selected paraffin types C15, C18, and C22, a fatty acid mixture of Palmitic acid and Capric acid, and a flow rate of 0.02 kg/s to examine the effects of various PCMs and flow rates. The schematic model used for simulation is shown in Fig. 17. The results show a maximum thermal efficiency of 83 % achieved at a mass flow rate of 0.02 kg/s. Incorporating a porous medium with a porosity of 0.8 improves temperature distribution and thermal performance. The PV-T with metal foam and PCM demonstrates an efficiency of 16.7 %. The analysis indicates an



(a) (b) (c)

Fig. 15. (a) PCM container, (b) pipes in the container, (c) experimental set-up [36]. [Reprint with permission from the publisher.]

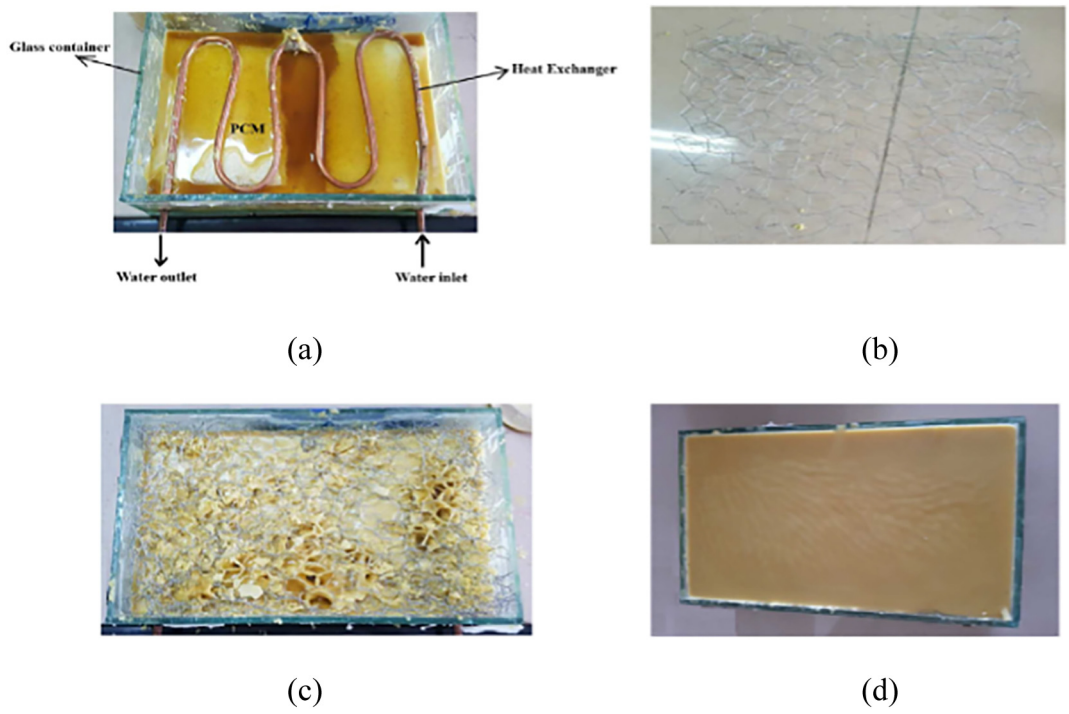


Fig. 16. (a) PCM container equipped with a heat exchanger; (b) metal matrix sheet; (c) placement of an MMS in PCM; and (d)PCM container after placing 5 layers of MMS in it [37]. [Reprint with permission from the publisher.]

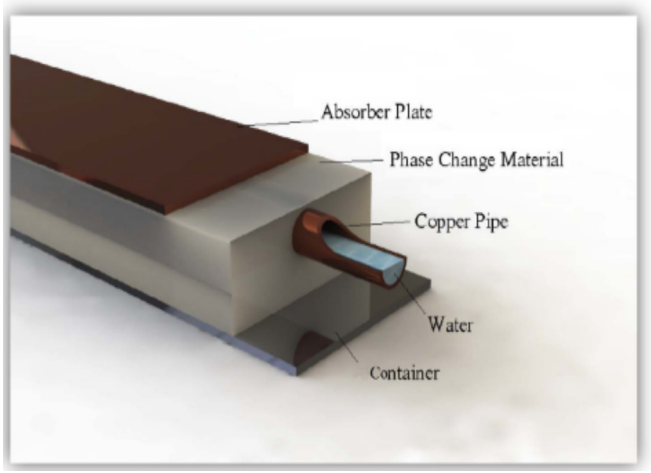


Fig. 17. Schematics of the simulation model [40]. [Reprint with permission from the publisher.]

optimal flow rate of 0.03 kg/s, which balances thermal efficiency and system costs. Table 3 presents the summary of organic PCMs used in the literature.

4.2.3. Inorganic PCM application

Bakir et al. [41] explore the effects of shading, inclination angles, and PCM performance on PV-T systems. They conducted experiments to assess how different shading conditions and tilt angles influence the energy and exergy efficiencies of PV-T collectors. The collector design included filling the gaps between copper pipes with Calcium Chloride Hexahydrate PCM. Fig. 18 shows a diagram of the PV-T/PCM system used in residential homes.

The PV-T/PCM collectors achieved their highest energy efficiencies at various inclination angles, with a 7 °C temperature difference at the water outlet of both PV-T and PV-T/PCM collectors. The peak power occurred at 11:30 am in the collector inclined at 30°, which contained PCM. The highest outlet water temperature was recorded in the collector inclined at 25°. Additionally, the highest panel surface temperatures were observed in the 25° inclined collectors, while the shaded collectors reported the highest exergy efficiencies.

Prakash et al. [42] present a butterfly-shaped serpentine design utilising Hydrated Salt (HS36) PCM to enhance energy and exergy. Fig. 19(a) and (b) illustrates the diagram of this butterfly-shaped serpentine configuration and the fabrication process of PV-T and PV-T/PCM.

The butterfly-shaped serpentine collector and HS36 PCM significantly lowered the PV panel's operating temperature by 35.47 %, enhancing both thermal and electrical performance. The PV-T/PCM system achieved an average efficiency of 94.05 % at a flow rate of 2 L/m, compared to 79.36 % for traditional cooled PV-T systems. Its exergy efficiency was 23.54 % higher than that of conventional PV systems, indicating a more effective use of energy quality—vital for sustainable energy solutions. Both systems perform best at a water flow rate of 2 L/m.

Nižetić et al. [43] studied pork fat as a PCM for passive cooling in PV panels. They analysed its thermal properties and assessed the economic viability of traditional organic PCMs in PV-PCM systems within Mediterranean climate conditions. The simulated annual electricity output remained the same, though pork fat exhibited a marginally lower performance. The cell temperature and power output show minimal differences between the two PCMs. The conventional PCM had an average annual operating cell temperature of 40.8 °C, compared to 41.1 °C for the Pork-PCM. Nevertheless, in terms of thermal management, the traditional PCM outperformed pork fat. Variations in geographical locations and solar radiation levels will lead to notable differences between the two PCMs, especially during periods of peak radiation.

Table 3
Summary of organic PCMs used in the reviewed studies.

S/N	Reference	PCM type	Results
1	Ali Bhutto et al. [23]	Paraffin	59 °C to 36 °C, cell temperature, 9.5 % electrical and 73 % thermal efficiency
2	Chaichan et al. [24]	Paraffin	Electrical efficiency of 13.7 %, thermal efficiency of 39 %
3	Li et al. [13]	Paraffin	12.54 °C reduction, 1.13 and 4.59 W power increase
4	Bouzelmad et al. [25]	Paraffin	21.9 °C reduction, 1.95 % increase in electrical efficiency
5	Kong et al. [26]	Paraffin	27.1 °C cell temperature, energy efficiency of 10.7 %
6	Hasan et al. [27]	Paraffin	1.3 % electrical conversion, 41 % thermal recovery
7	Saxena et al. [28]	Paraffin	41.5 % temperature reduction, 11.7 % power increase, and 10.7 % efficiency increment with less pumping
8	Su et al. [29]	Paraffin	13.6 % electrical
9	Zhou et al. [30]		Increase electrical efficiency from 0.119 % to 0.120 %.
10	Simón-Allué et al. [31]	Paraffin	30 % of the heat is maintained after the sunlight
11	Tashtoush & Al Ghadi. [32]		Power output 3095.81 W/day at 3 cm PCM thickness
12	Alnakeeb et al. [33]		The energy efficiency is inversely proportional to the increase in the elliptic inner tube
13	Hossain et al. [34]		14.57 % for PVT and 15.32 % for PVT-PCM electrical, 75.29 % for PVT and 86.19 % for PVT-PCM thermal, respectively.
14	Hossain et al. [35]	Lauric acid	Electrical efficiency of 11.08 % at 4 LPM and thermal efficiency of 87.72 % at 2 LPM.
15	Alsaqoor et al. [17]	Lauric acid	Increase power from 18 kW to 21 kW, 14 % increased electrical efficiency.
16	Browne et al. [36]		PVT/PCM improved the outlet water temperature by 5.5 °C compared to the PVT system.
17	Rahimi et al. [37]	Bio-base	11.73 % electrical efficiency achievement at 5 metal-matrix sheets and 4 kg of PCM, an output power of 7.04 W.
18	Yang et al. [38]	Capric acid	63.93 and 76.87 % energy conversion for PVT and PVT-PCM, respectively, and 73.5 % and 87.5 % energy-saving for PVT and PVT-PCM, respectively.
19	Gaur et al. [39]	OM37	The temperature drop in summer was 16.04 °C, and in winter, 5 °C. Electrical efficiency is 16.3 % in summer and 16.87 % in winter for system A, and 15.40 % and 16.5 % for system B.
20	Mousavi et al. [40]		83 % thermal and 16.7 % electrical at a flow rate of 0.03kf/s, chosen as the optimal flow rate.

5. Performance enhancement techniques

5.1. Nanofluid

Nanofluid applications in solar energy, particularly for PV-T systems, introduce a new approach to cooling technology. The deionised fluid used in these systems has low thermal conductivity and is less effective at heat transfer. However, incorporating metals such as zinc, copper, and aluminium enhances water's thermal conductivity, improving its heat transfer performance.

Sumayli et al. [44] investigated the effects of metal foams with lower porosities in the collector tube and PCM container. Copper foam with a porosity of 0.94 achieved a thermal efficiency of 56.74 %, but its overall efficiency was only 13.24 %. Meanwhile, copper foam with a porosity of 0.705 demonstrated an electrical efficiency of 12.12 % and a thermal efficiency of 66.70 %. Ultimately, a good balance between electrical and thermal efficiency was observed with aluminium foam at 0.774 porosity and copper foam at 0.704 porosity within the PCM tank, recording 13.11 % and 61.06 % efficiencies, respectively.

Almeshaal & Altohamy, [45] investigated the effect of nanofluid copper oxide water (CuO-water) on the electrical and thermal efficiency of a PV-T/encapsulated PCM balls. They tested with different flow rates (0,5, 1.0, and 1.5 LPM) and added CuO nanoparticles to water with different weight concentrations (0.05, 0.1, 0.2, 0.3, 0.4, and 0.5 %) to form the nanofluid. The nanofluid achieved an overall energy efficiency of 82.1 % with a solar cell temperature decrease of 8.7 % and 3.6 %; the electrical efficiency improved on average by 37.7 % and 13.3 % compared to PV and water-PV-T/PCM systems, respectively. The optimal concentration of copper oxide nanofluid was found to be 0.3 wt %.

The heat transfer ability of the PCM was improved by adding Al_2O_3 and copper fins in both passive and active cooling by Gürbüz et al. [46]. They presented three cases: Case 1, hybrid PV-T/PCM-TEG; Case 2, addition of Al_2O_3 nanoparticles into the PCM; Case 3, by placing copper fins around the copper pipes. The heat stored in the PCM was transferred to the hot side of the thermoelectric generator (TEG). The power improvement was 10.29 %, 12.73 %, and 14.22 % for Case 1, Case 2, and Case 3, respectively. Additionally, maximum PV efficiency was 30 %, while the Cases were 32.8 %, 33.9 %, and 35.2 % for Case 1, Case 2, and Case 3, respectively. Fig. 20 shows the design of the PV-T/PCM with copper fins around the pipes.

Vaziri Rad et al. [47] experiment conventional PVT system integrated with PCM, TEG, and nanofluids. Water-based CPV-T achieved electrical, thermal, and exergy efficiencies of 15.5 %, 37.4 %, and 16.7 %, respectively. However, applying porous media, PCMs, and concentrated plates improved energy generation, leading to an offset of their initial cost to achieve an energy cost of $0.135/kWh. However, TEG with nanofluid integration remain uneconomical because of a 15–35 % increase in energy cost recorded within them.

A comparative analysis of a novel PV-T/NePCM with PV, PV-T, PV-T/PCM systems was developed using multi-walled carbon nanotubes (MWCNTs) by Rajamony et al. [48]. At a flow rate of 0.4 LPM, there was a significant heat gain, resulting in an energy-saving efficiency of 75.67 %. Also, the total efficiencies of the PV-T, PV-T/PCM, and PV-T/NePCM were 81.9 %, 84.5 %, and 85.05 %, respectively. The experimental setup of the four systems is shown in Fig. 21.

J. Jasim et al. [49] investigated the effects of using rectangular, triangular, and circular cross-sections with PCM and hybrid nanofluids in PV-T systems. At different nanofluid concentrations, PCM and PCM composite reduced cell temperature more. Additionally, using carbon-based hybrid nanoparticles improved efficiency, especially at higher concentrations, and reduced cells' temperature, with electrical and thermal efficiencies improving. Also, with 4.5 % Fe_3O_4-MWCNT, PCM, and PCM composite, the exergy efficiency improved by 13.3 % and 16.2 % compared to the no-PCM system.

Sardarabadi et al. [79]constructed and compared two PV-T systems: one with PCM and one without PCM. They examined the combined effects of using ZnO/water nanofluid and PCM in PV-T systems to improve electrical efficiency. A pictorial experimental setup is shown in Fig. 22. The average electrical output rose by 13 % with the PCM/nanofluid-based collector system. The nanofluid's average thermal performance increased by 5 % for PV-T and 9 % for the PV-T/PCM system. Additionally, exergy analysis shows that combining nanofluid and PCM can boost the overall exergy efficiency by more than 23 % compared to traditional PV modules. The PV-T system, using water or a nanofluid as coolant, lowers the cell temperature by 10 °C, while the PV-T/PCM system achieves a 16 °C reduction during the operating hours from 9:30 am to 3:30 pm.

Similarly, Hosseinzadeh et al. [50] studied the energy and exergy efficiencies of PV-T systems using ZnO/water nanofluid and organic

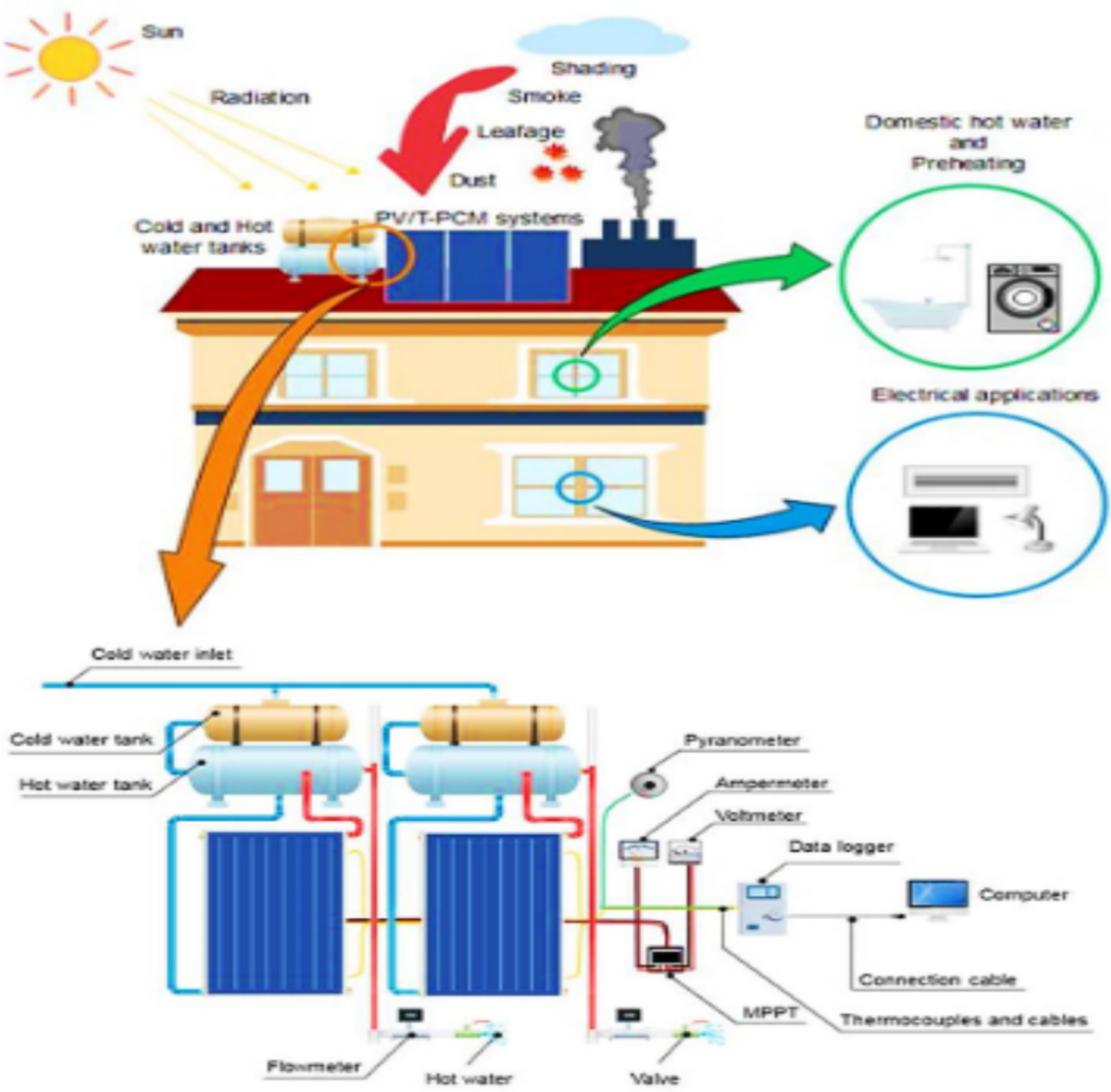
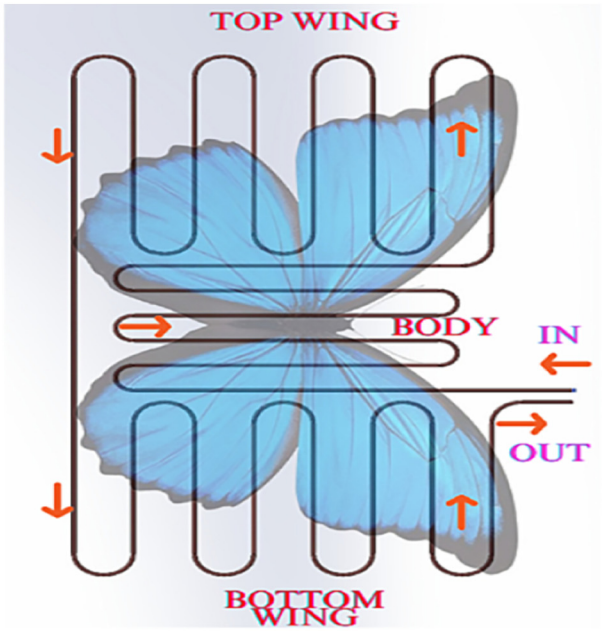


Fig. 18. Schematic diagram of PV-T/PCM application in a residential home [41]. [Reprint with permission from the publisher.]

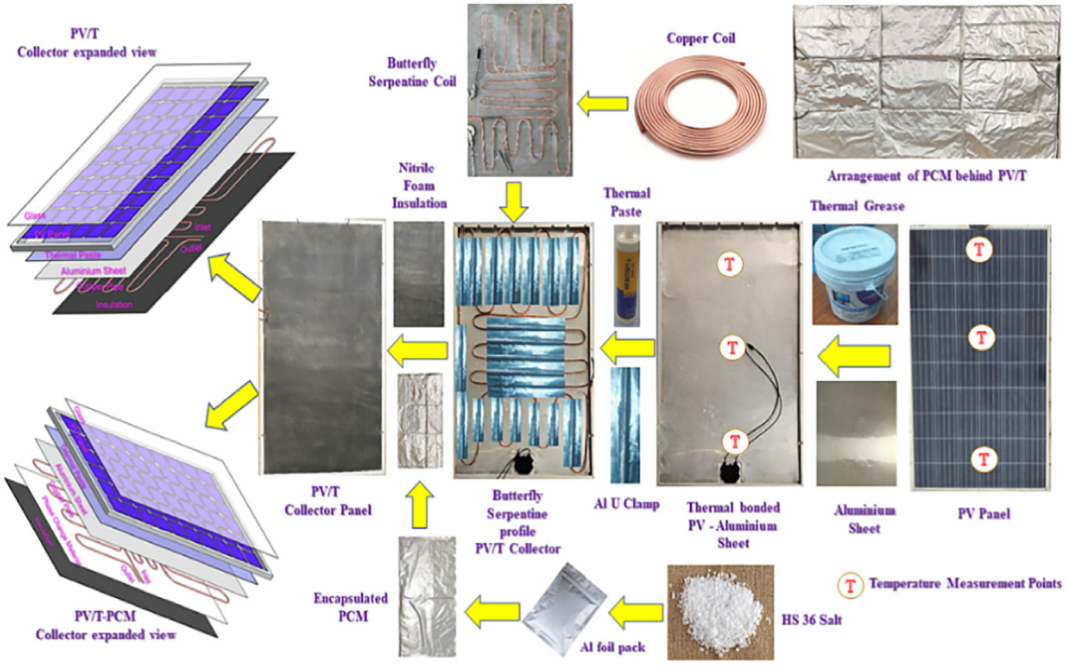
PCM. They compared three configurations: a PV module, a nanofluid-based PV-T, and a nanofluid-based PV-T/PCM. The experimental setup for this study is shown in Fig. 23. The nanofluid PV-T system increases thermal output by 29.60 %. The PV-T/PCM setup achieves an overall exergy output of 114.99 W/m^2 and an electrical efficiency of 13.61 %. Additionally, entropy generation decreases by 1.59 % in the PV-T system and 3.19 % in the PV-T/PCM system. Also, nanofluid-based PV-T and PV-T/PCM systems increase electrical power output by 7.10 % and 11.90 %, respectively, compared with conventional PV systems. When organic PCM is combined with a nanofluid-based PV-T system, thermal exergy improves by 79.36 % compared to a nanofluid-based PV-T system without PCM.

Another study presented by Kazemian et al. [51] investigated the application of ethylene glycol and PCM as coolants in PV-T systems. It compares three setups: a conventional photovoltaic (PV) module, a PV/PCM system, and a PV-T/PCM system. Fig. 24 shows a mixture of 5 wt% water and ethylene glycol, along with pure ethylene glycol, used as the working fluids. The results show that PV/PCM improves electrical exergy by 4.22 % compared to a traditional PV setup. Adding ethylene glycol to water reduces thermal efficiency but boosts thermal exergy efficiency. The entropy decrease was 0.58 % for PV/PCM, 2.42 % for PV-T/PCM-water, 2.51 % for PV-T/PCM-EG 50 %, and 2.84 % for PVT/PCM-EG 100 %. Pure ethylene glycol freezes at 12.5 °C but does not crystallise when mixed with water. The freezing point of ethylene glycol mixed with water by 50 wt% drops to −36.5 °C. In conclusion, ethylene glycol mixed with 50 wt% of water is recommended as a suitable working fluid for cold climate conditions in PVT/PCM applications.

AL-Musawi et al. [52] examined the performance of pure water, SiO_2/water nanofluid, and PCM as coolants in PV-T and PV-T/PCM systems. Incorporating PCM into a PV-T setup significantly lowers the PV cell temperature by 16 °C and enhances electrical and thermal efficiencies by 8 % and 25 %, respectively, compared to a system without



(a)



(b)

Fig. 19. (a) Diagram of butterfly-shaped serpentine flow collector; (b) fabrication methodology of PV-T and PV-T/PCM collector [42]. [Reprinted with permission from the publisher.]

PCM. Additionally, using SiO_2 nanofluids at 1 % and 3 % mass fractions improves thermal efficiency by 3.51 % and 10.40 %, respectively, over the PVT/PCM with pure water. The research indicates that the optimal PCM melting point for maximising electrical efficiency is around 31 °C, and nanofluids like SiO_2/water can further enhance the system's thermal performance.

In a study by Al-Waeli et al. [53] concerning the photovoltaic thermal system, integrating nanofluid and nano-phase change material was developed to enhance electrical and thermal performance. The cell temperature dropped by 30 °C under peak solar radiation. Power output increased from 61.1 W to 120.7 W, while electrical efficiency rose from 7.1 % to 13.7 %. The thermal energy of the PCM nano combined with the nanofluid increased, reaching 72 % efficiency in the PV-T/PCM with nano-water, compared to 50.5 % in the PV-T/PCM with water. They

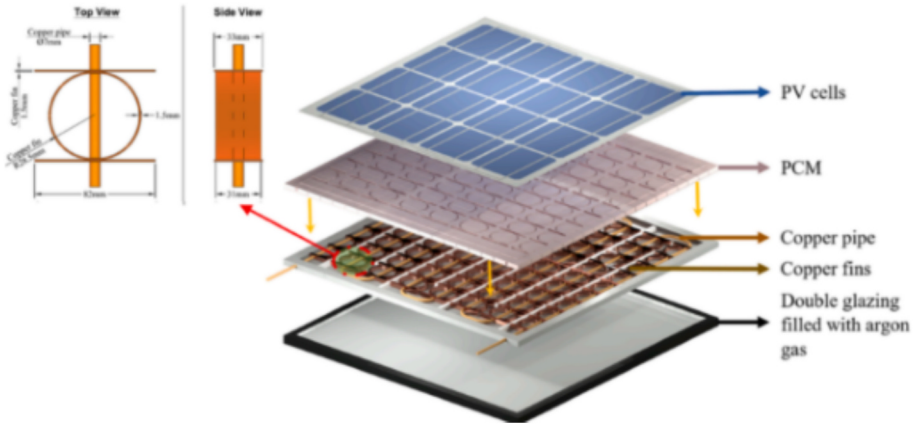


Fig. 20. Design of PV-T/PCM with copper fins around the pipes [46]. [Reprint with permission from the publisher.]

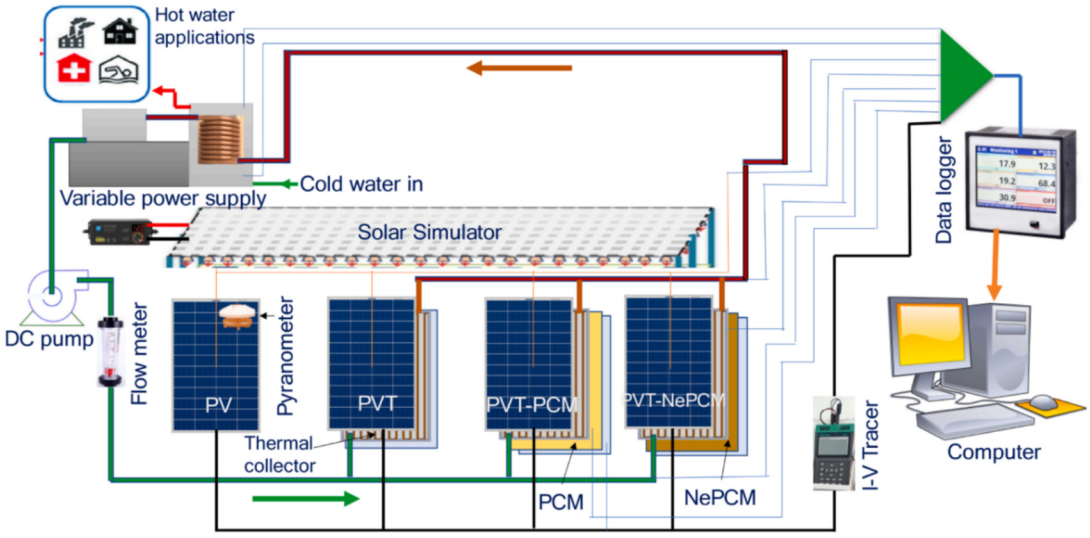


Fig. 21. The experimental setup of the PV, PV-T, PV-T/PCM, and PV-T/NePCM systems [48]. [Reprint with permission from the publisher.]

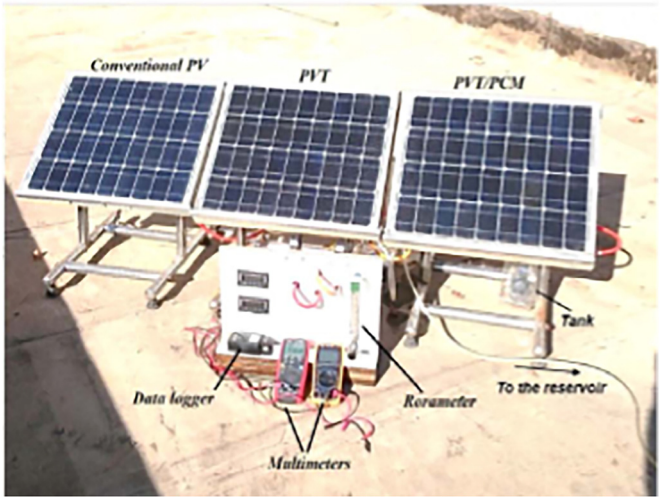


Fig. 22. Pictorial view of experimental set-up [79]. [Reprint with permission from the publisher.]

concluded that utilising a PV-T system with nano-SiC-PCM and nano-fluids improves thermal, electrical, and overall energy performance more than any other PV-T systems examined. Fig. 25 shows the setup of the experiment.

Al-Aasam et al. [54] conducted experiments using nanoparticle-enhanced PCM and twisted tubes. The configurations tested include unenhanced PV panels, PV-T systems with circular and twisted tubes, and PV-T systems combining both tube types with nano-PCM, as shown in Fig. 26. The twisted-PVT-PCM setup exhibits electrical, thermal, and combined efficiencies of 9.46 %, 79.40 %, and 88.86 %. Using twisted tubes and nano-PCM reduced the PV surface temperature by 30 °C relative to a standard PV panel, resulting in a 34.5 % increase in PV efficiency. The system reached a thermal efficiency of 88.86 % at a flow rate of 0.04 kg/s and enhanced electrical power output by 27.74 % compared to conventional PV panels.

Salem et al. [55] in Cairo, Egypt, researchers experimented with a mixture of Al_2O_3/PCM using water-cooling at high solar intensity and energy consumption to develop effective solar energy solutions. They explored active, passive, and combined cooling methods to study how water/PCM and Al_2O_3 nanoparticles affect PV cells. Fig. 27 shows the experimental setup. The results show the best performance with a mixture of 1 % Al_2O_3 nanoparticles, 25 % PCM, and 75 % water. At a flow rate of 1 LPM, the 25 % PCM to 75 % water channel ratio resulted in the lowest cell temperature and the highest electrical and thermal efficiencies.

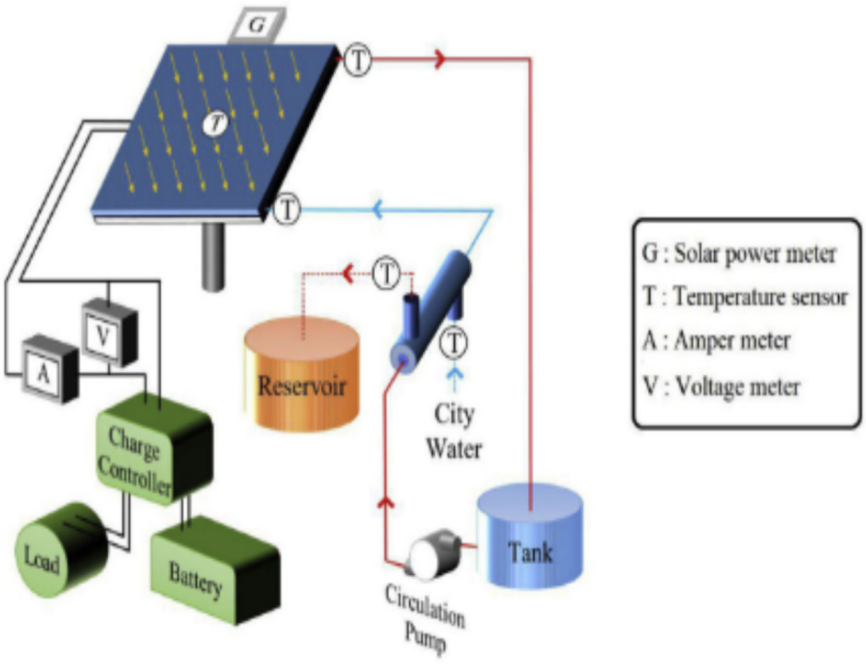


Fig. 23. The experimental setup [50]. [Reprint with permission from the publisher.]

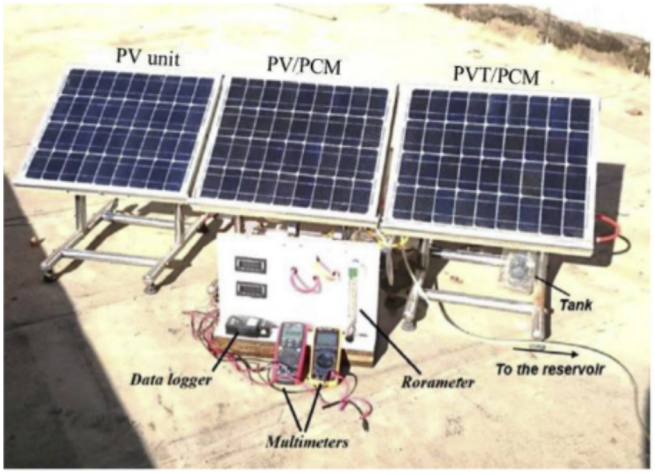


Fig. 24. Pictorial view of the experimental setup [51]. [Reprint with permission from the publisher.]

Chaichan et al. [56] presented a 2 % nano-TiO_2 added to water and paraffin, which significantly improved the thermal conductivity of water by 126 % compared to ordinary water, and paraffin was improved by 170 % in thermal conductivity. During the peak sunny hours, the cell temperature of the PV panel was decreased by 19 °C. In contrast, the electrical efficiency increased by 106 % and 56 % compared to the uncooled PV panel and the water-cooled system. Fig. 28 shows the PV-T/PV-T/nano-paraffin and PV-T/PV-T/water-cooled system.

Sarafraz et al. [57] investigate the electrical and thermal power production of a PV-T/MWCNT-paraffin system. The presence of MWCNT-WEG 50 nanofluid improved the system's thermal efficiency by 130 % and its electrical efficiency by 20 %. The thermal and electrical values at peak sunny hours reached 276.3 W/m^2 and 307.9 W/m^2, respectively. Fig. 29 presents the schematic diagram of the cooling jacket of the PV panel and the PCM container.

5.2. PCM encapsulation

Encapsulating PCM mainly enhances thermal conductivity and prevents leaks in PV-T systems. Hamada et al. [58] conducted an experimental study on a water-based PV-T system using PCM balls for encapsulation. This innovative PV-T/PCM system can operate in both active and passive cooling modes to improve PV-T power output and thermal efficiency. It features a copper duct filled with PCM balls that absorb heat during phase change, thereby lowering the cells' temperature and boosting the panel's overall efficiency. The experimental setup is depicted in Fig. 30.

They applied different water flow rates, and the highest electrical and thermal energy gains occurred at 3 L/min, yielding an overall efficiency of 74.1 % for the actively cooled PV-T/PCM panel. The passively cooled PV-T/PCM panels achieved efficiencies of 34.6 % and 12 % for PV panels. They also investigate how backside insulation affects PV-T/PCM systems, finding that while insulation enhances thermal energy storage, it may slightly reduce power output. The system with active cooling and backside insulation achieved the highest total efficiency.

A PV-T/PCM panel was fabricated using a 250 W PV module to test different mass flow rates. Lauric acid, which melts at 44–46 °C, is suitable for hot-water applications and matches the operating temperature of the PVT panel. The experimental setup is illustrated in Fig. 31. The optimal water flow rate for maximum heat gain was 0.033 kg/s, with an average energy efficiency of 69 %. The PV-T/PCM system showed a 3–5 % improvement in energy delivery, the maximum power and thermal efficiency. Also, at a flow rate of 0.033 kg/s, the average maximum power, performance, overall efficiency, and energy savings were recorded as 3 %, 7 %, 23 %, and 28 %, respectively [59].

A similar rig design incorporates two PV-T/PCM collectors and a conventional PVT system by Yuan et al. [22]. The PCM was glued to an aluminium plate, which was well insulated, and installed at a 32° south-facing angle, with a flow rate of 0.1 L/s. Experiments took place from 9:00 to 16:30 during the day and continued overnight in December 2017 and January 2018. Fig. 32 illustrates the PVT-PCM layout and the arrangement of PCM within the aluminium sheet packets labelled A-F. The PV-T/PCM system achieves daily electrical and thermal efficiencies

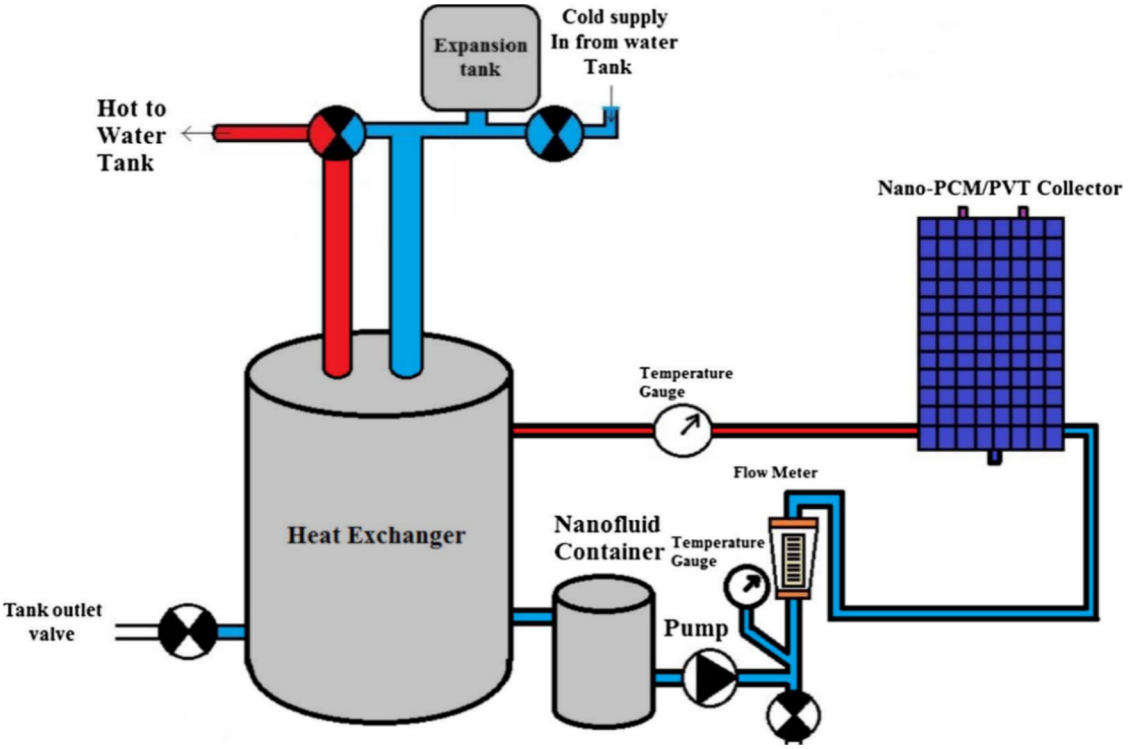


Fig. 25. Experimental setup of PV-T/nano-PCM with nanofluid [53]. [Reprint with permission from the publisher.]

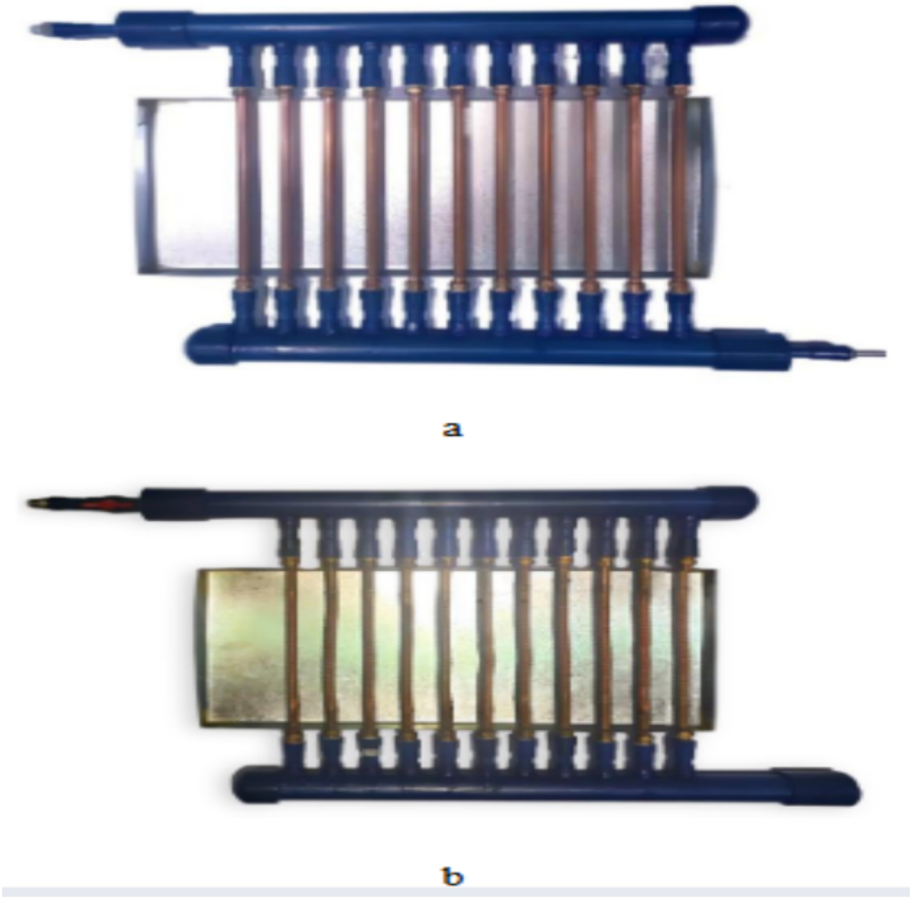


Fig. 26. The nano-PCM container with PVT configuration with (a) circular absorber tubes and (b) twisted absorber tubes [54]. [Reprint with permission from the publisher.]

Fig. 27. The experimental setup [55]. [Reprint with permission from the publisher.]

of 12.1 % and 42.3 %, respectively, compared to 11.9 % and 44.5 % for conventional PV-T. They observed that choosing PCM with a single melting point is unlikely to lower daytime temperatures significantly while avoiding freezing at night. Therefore, using PCM panels with varying melting points can meet the desired efficiency targets for the PV-T/PCM system.

Sudhakar et al. [60] investigated the enhancement of solar PV panels fitted with PCM and water circulation techniques. The setup includes a PCM chamber behind a PV panel and an aluminium water flow channel. The PCM was positioned at the rear of the PV panel in a duct shown in Fig. 33(a) and (b). The continuous water supply cooling technique from top to bottom outperforms the bottom-to-top method. It achieved electrical efficiency, power improvement of 12.4 %, temperature reduction of 13.54 °C, overall exergy output of 26.07 %, and exergy efficiency of 8.08 %.

Another performance assessment of PV-T and PV-T/PCM systems under various operating conditions by Fayaz et al. [61] employed a serpentine shape, which enhanced heat transfer and system performance. Fig. 34 displays the experimental setup, including a detailed description of the components, instrumentation, and fabrication process. The type of PCM used in the study was A44-PCM, a paraffin-based material.

The experimental setup was precisely controlled, utilising a solar simulator that delivered 1000 W/m^2 irradiation. Both ambient and inlet water temperatures were kept steady at 27 °C. The peak electrical efficiencies for the numerical and experimental PV-T were 12.4 % and 12.28 %, respectively, while PV-T/PCM reached 12.75 % and 12.59 %. There was a notable improvement in electrical performance, with PVT-PCM showing the most significant improvement at a flow rate of 3 LPM. The power output increased by 1.124 W and 1.04 W, and the electrical efficiency improved by 0.068 and 0.063 for numerical and experimental results, respectively, with each 1 °C decrease.

Waqas et al. [62] conducted research using encapsulated PCM at 30–32 °C within aluminium tubes attached to the back of the PV module. The setup involved 1.0 kg of PCM spreading over 0.30 m^2. An illustration of this experimental configuration, including the aluminium tube and PV module, is shown in Fig. 35. During sunny hours, the modified PV panel temperature was 2.4–2.8 °C lower than that of the conventional PV module. The PV-PCM system increased electrical efficiency by 3.0 %, with power improvements ranging from 2.8 % to 3.0 %.

5.3. Fins enhancement

Phase change material with charcoal (PCM + C) and PCM and charcoal and metal flakes (PCM + C + M) was developed by Maneechot et al. [63]. It was found that, PV-T/PCM + C + M system reduced the PV cell temperature by 24.82 °C and 4.19 °C compared to the PV and PV-T/PCM + C, respectively. However, PV-T/PCM + C exhibited the highest outlet water temperature difference of 11.62 °C. Fig. 36 presents the experimental setup.

Mao et al. [64] conducted an optimisation of a fan-shaped finned

Fig. 28. presents the PV-T/PV-T/nano-paraffin and PV-T/PV-T/water-cooled system [56]. [Reprint with permission from the publisher.]

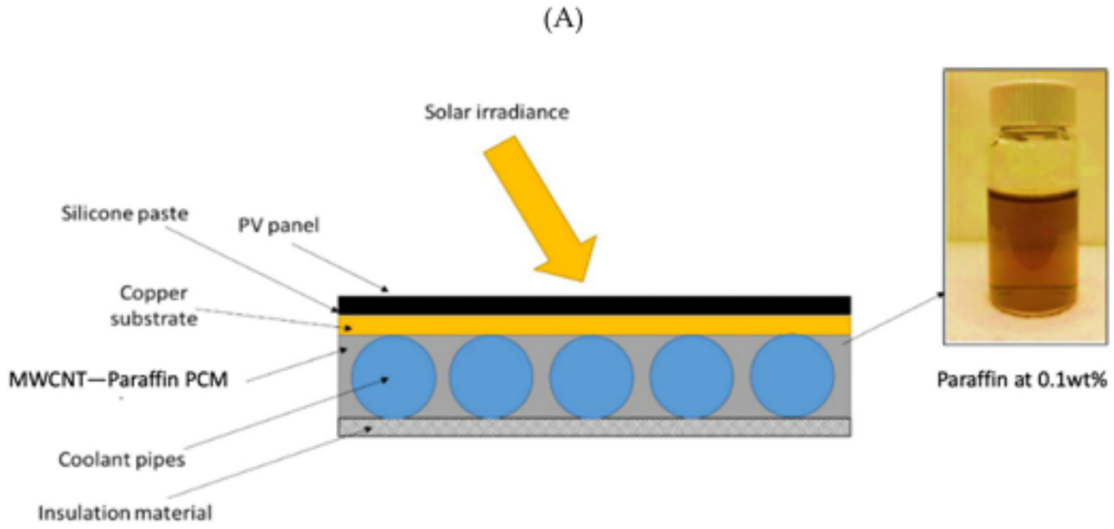


Fig. 29. Schematic diagram of the cooling jacket of the PV panel and the PCM container [57]. [Reprint with permission from the publisher.]

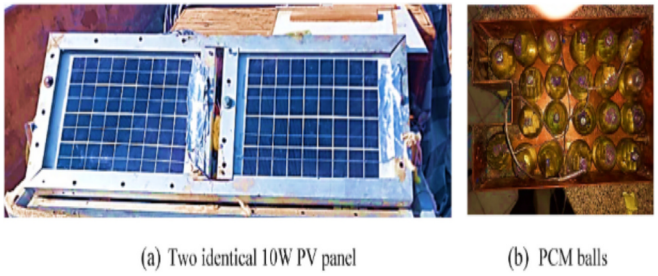


Fig. 30. The experimental test rig [58]. [Reprint with permission from the publisher.]

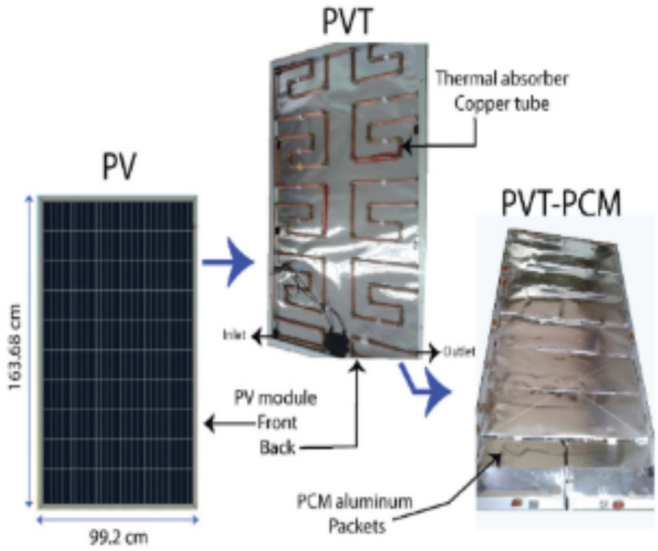


Fig. 31. Experimental set-up of PVT-PCM [59]. [Reprint with permission from the publisher.]

tube heat exchanger, with a particular focus on its application in solar power generation. The study aimed to improve energy utilisation by proposing, in Fig. 37, a fan-shaped fin structure for metal shell-and-tube devices. The findings demonstrated that raising the inlet temperature increases heat storage with energy efficiencies of 13.4 % and 10.2 %, respectively. Similarly, increasing the flow rate reduces the melting time by 33.4 %.

The study also investigates various fin structures derived from the fan-shaped fin to analyse their impact on the heat storage rate. The results show that Fin-A demonstrates the highest melting degree, with a 2.98 % increase in energy efficiency compared to the standard fan fin. The complete melting time of PCM in Fin-A is shorter than in Fin-B and Fin—C. Fin-B enhances the LHS system to achieve maximum heat storage; the PCM's average temperature in Fin-B is the highest, indicating greater heat storage. They concluded that to maintain the efficient energy performance of the latent heat storage (LHS) system and achieve a shorter heat storage duration, the inlet water temperature should not be below 353 K. Additionally, increasing the number of fins raises the surface area, which improves the rate of heat transfer—as observed in Fin-B in Fig. 38.

Colarossi & Principi, [65] analysed the annual performance of the PV-T/PCM system for domestic hot water (DHW). Their experimental setup featured a solar simulator for summer and intermediate months, and outdoor testing for winter conditions. Different water tank sizes, ranging from 50 to 125 L, were tested to identify the optimal storage capacity for energy savings. They used RT35 HC PCM, which has a melting point of 35 °C. Fig. 39 illustrates the PVT-PCM arrangement used in the experiments.

The findings were that the PV-T/PCM system achieved energy savings of 15.39 % and 22.06 % for 50- and 100-litre tanks, respectively. The 50-litre tank reached 25.9 °C as the final temperature, the highest among the tank sizes. During an intermediate month, the energy savings were 10 % for the 100 L tank and 8.25 % for the 50 L tank. No melting of the PCM occurred in winter; the PCM temperature was too low. After several days of monitoring, the PCM temperature reached 28,6 °C, well below the 35 °C melting point of RT 35 HC. The maximum system efficiencies were 38 % and 16 % in summer and winter, respectively, with a 100 L storage capacity identified as the most efficient.

Preet et al. [66] studied a water-based PV-T/PCM system and PV-T without PCM. The study compares a conventional PV panel, a water-based PV-T with a double absorber plate, and a water-based PV-T integrated with RT30 PCM. Experiments were conducted at various mass flow rates (0.013 kg/s, 0.023 kg/s, and 0.031 kg/s). The system includes an aluminium container at the rear of the PV panel that houses PCM copper pipes inserted within the PCM to extract heat, and nine fins embedded in the PCM, as shown in Fig. 40. The peak output was achieved at a flow rate of 0.031 kg/s, resulting in a 53 % reduction in maximum temperature for PV-T/PCM. At this flow rate, the thermal efficiency was 62.37 % for PV-T and 35.4 % for PV-T/PCM. The

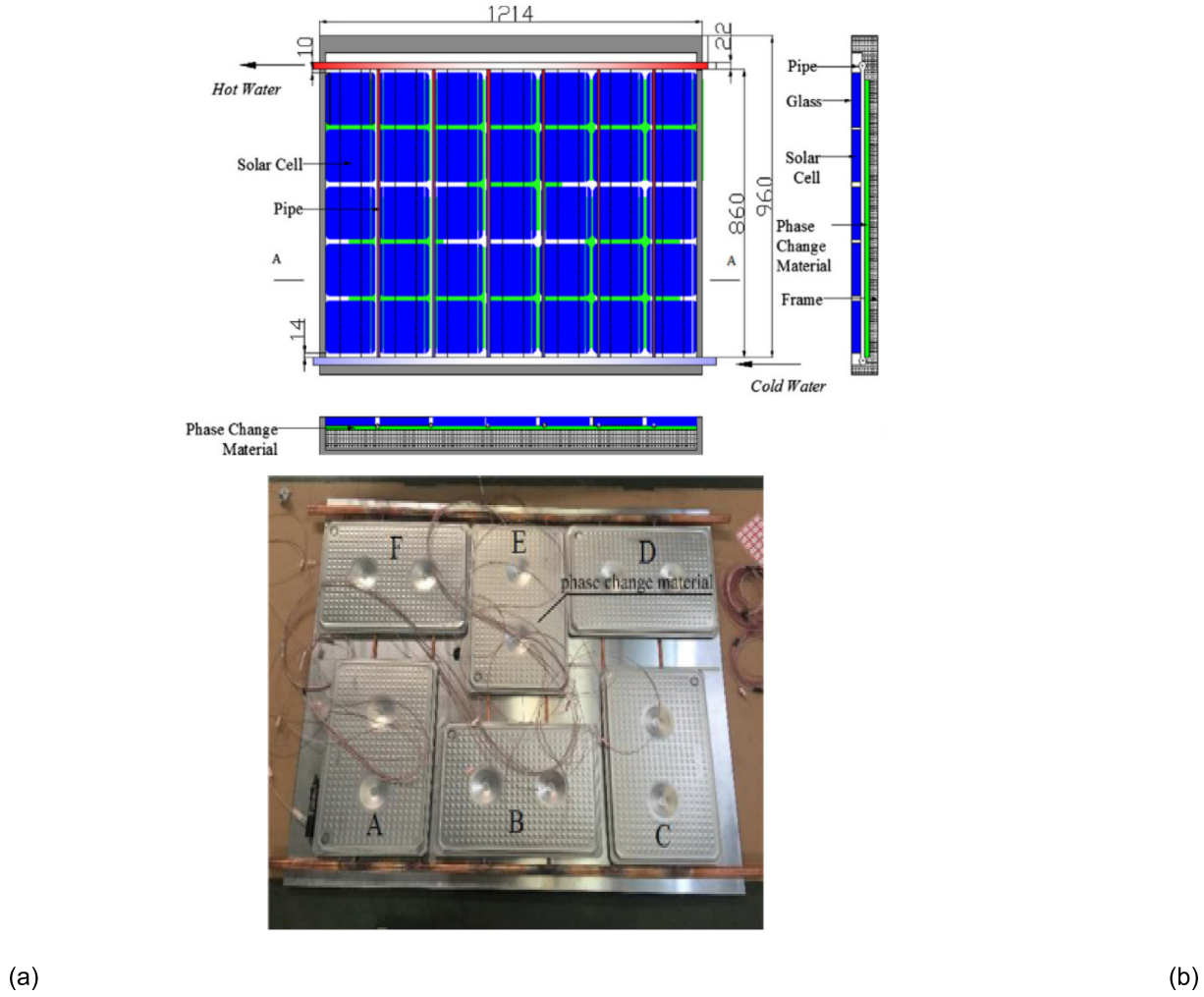


Fig. 32. (a) Layout of PV-T/PCM; (b) PCM incorporated with the PV-T [22]. [Reprint with permission from the publisher.]

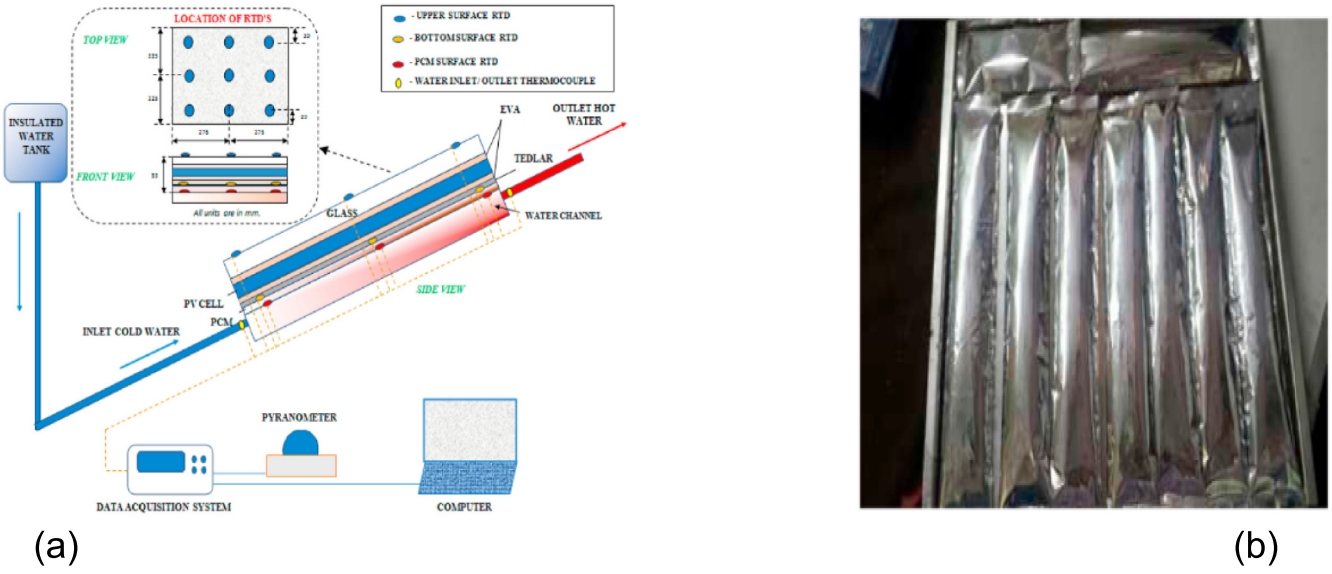


Fig. 33. (a) Diagram of PV-T/PCM with water cooling; (b) PCM chamber loaded [60]. [Reprint with permission from the publisher.]

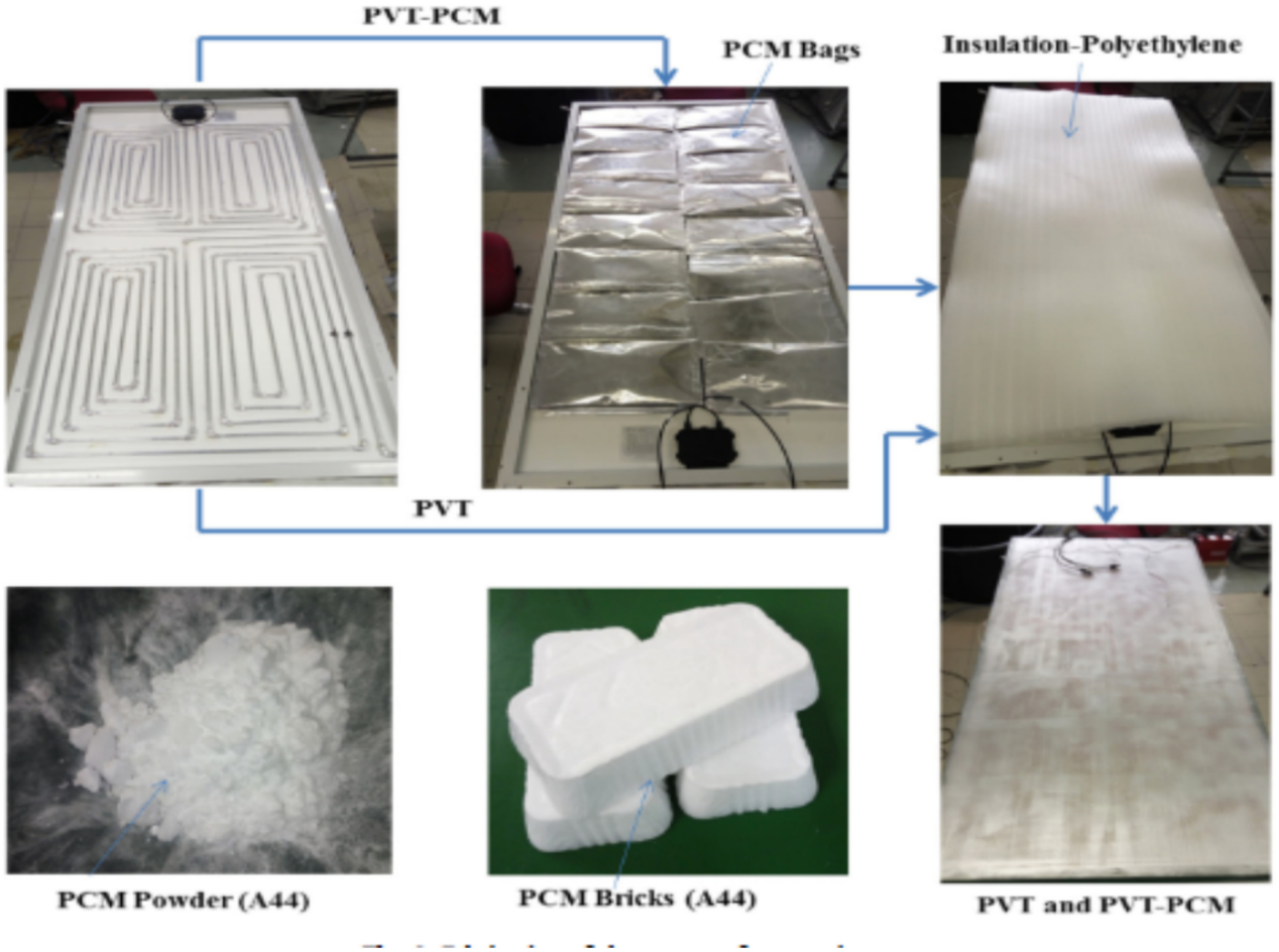


Fig. 34. Fabrication and arrangement of the system for the experiment [61]. [Reprint with permission from the publisher.]

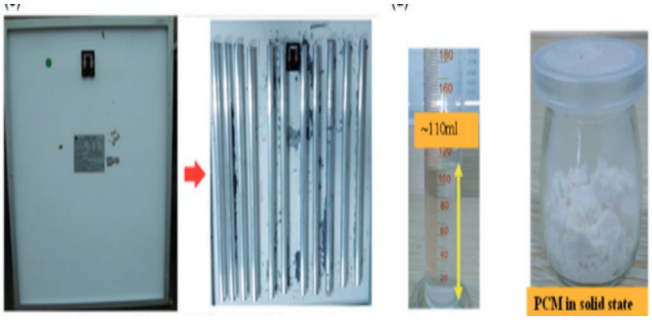


Fig. 35. Conventional PV and PV incorporating a PCM in aluminium pipes [62]. [Reprint with permission from the publisher.]

electrical efficiencies were 10.66 % and 12.6 % for the water-based PV-T and PV-T/PCM systems, respectively. Additionally, the average increase in open circuit voltage (Voc) was 21.27 % for the water-based PV-T and 32.5 % for PV-T/PCM compared to conventional PV at 0.031 kg/s.

Haidy Al-Hamzawi et al. [67] analyse climate conditions in Baghdad and Tehran, focusing on solar radiation, wind patterns, and atmospheric pressure. They examine how wind speed and atmospheric pressure influence system performance, noting that higher altitudes with lower atmospheric pressure receive more direct solar irradiation, which can boost solar energy system performance. The PV-T system with the heat exchanger design shown in Fig. 41 achieves 26 % higher electricity output than conventional systems. The analysis indicates that the system can supply an average of 0.11 m3/h in Baghdad and 0.10 m3/h in Tehran each month. Additionally, it generates 170 kWh and 140 kWh of electricity in Baghdad and Tehran, respectively.

Carmona et al. [68] evaluated the overall performance of solar collectors by integrating PCM into PV panels to maintain lower, more stable temperatures during operation. They developed a finned absorber plate and flexible PCM containers to improve heat transfer and accommodate thermal expansion. The PCM used was RT-35, with a melting point between 29 and 36 °C. Their results showed the daily electrical efficiency of the PV module was 7.43 %, while the hybrid PV-T/PCM module achieved a total efficiency of 31.35 %. The daily electrical efficiency of the PV-T/PCM was 13.12 %, reflecting an overall increase of 20.45 %.

In another study, Zhang et al. [69] conducted a detailed analysis of a switchable PV-T/PCM system, examining how copper fin heights and various thermal regulation strategies influence performance. The 3-D configuration of the system is depicted in Fig. 42. The phase change material (PCM) employed was a fatty acid, TH-SL35, which melts at 37 °C. The electrical efficiency of the PV-T/PCM system improved from 10.83 % to 10.99 %. Its electrical exergy efficiency ranges from 11.10 % to 12.44 %, demonstrating effective thermal management that boosts electrical output. Thermal energy efficiency also reached 86.49 % when water flow was optimised at 2.92 L/min. Additionally, electrical efficiency increased from 2.07 % to 2.95 % as the regulation strategy switched from full-time to intermittent mode, enabling adjustments based on thermal and electrical energy demands.

Similarly, Wongwuttanasatian et al. [70] studied palm wax as a phase change material (PCM) in a finned heat sink to improve photovoltaic (PV) module performance via passive cooling. They designed and

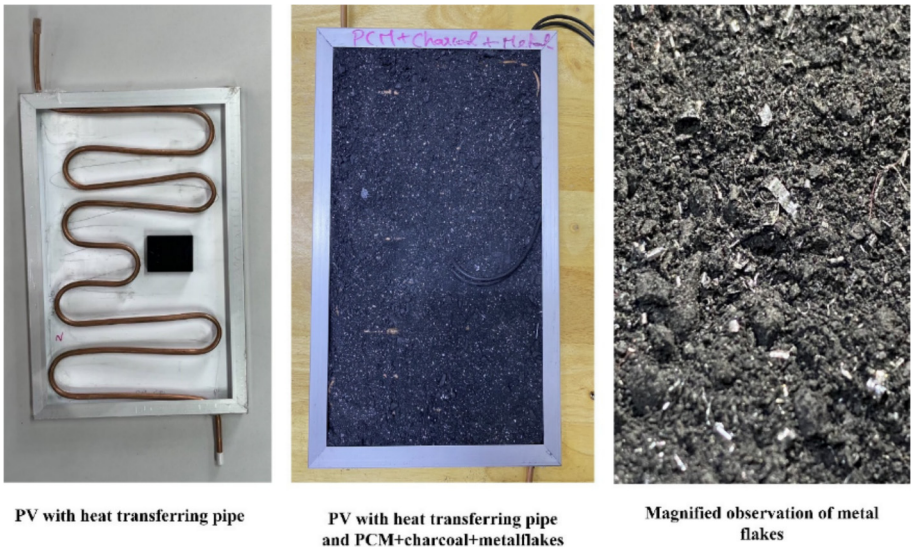


Fig. 36. The experimental setup of PV-T/PCM + C + M system [63]. [Reprint with permission from the publisher.]

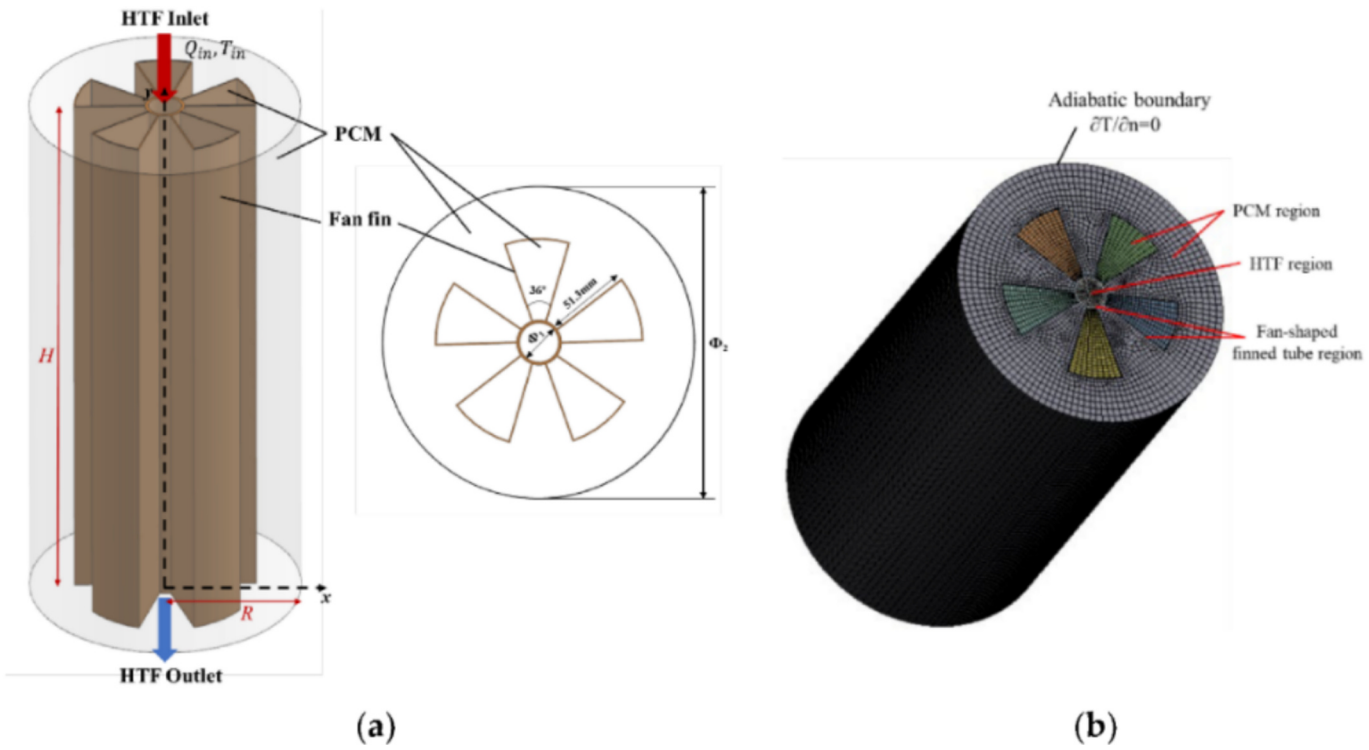


Fig. 37. (a) Physical model of the LHS unit; (b) computational domains [64]. [Reprint with permission from the publisher.]

tested three types of PCM containers—grooved, tubed, and finned—-shown in Fig. 43, to compare their cooling efficiencies. The finned container effectively reduces PV module temperature from 57.9 °C to 51.8 °C to improve the efficiency from 9.33 % to 9.82 %, a 5.3 % improvement, with an average performance of 4.8 %. The study concludes that PCM cooling substantially enhances PV performance only when irradiance exceeds 500 W/m^2. This indicates that passive PCM cooling is particularly beneficial under high solar irradiance conditions and may not be cost-effective in regions with low average irradiance.

Khodadadi & Sheikholeslami, [71] introduced a fin setup for PV-T/PCM systems. Their numerical and experimental studies show that varying fin designs and adding nanoparticles to PCM enhance the thermal and electrical performance of PV-T systems. The study investigates how various fin types—rectangular, trapezoidal, T-shaped, Ψ-shaped, Y-shaped, and ┼-shaped—and fin quantities (0, 6, and 10) influence performance. Fins enhance heat transfer, reducing the fluid's outlet temperature and increasing the liquid fraction of the RT-35HC PCM. This allows more heat to be stored in the PCM, boosting the overall efficiency of the PV-T system. The finned absorber geometry is illustrated in Fig. 44. The system with ten fins experienced a 5.03 % faster melting rate and a 13.31 % decrease in surface temperature compared to systems with six fins or no fins. Incorporating nanoparticles into the PCM further increases the liquid fraction by 2.13 % compared to pure PCM. Table 4 presents the summary of performance enhancement in PV-T/PCM systems used in this review.

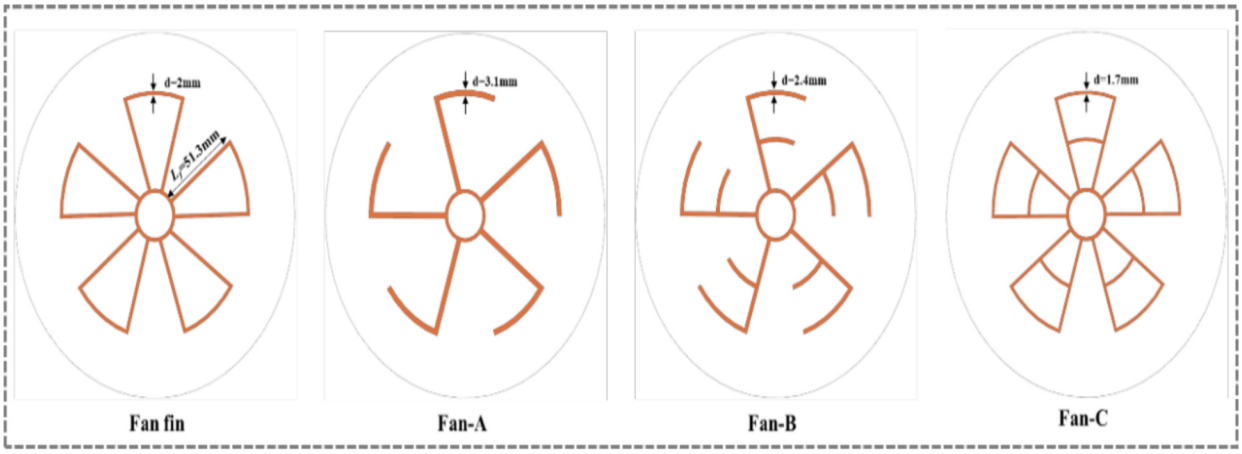


Fig. 38. Schematic diagram of different fin structures [64]. [Reprint with permission from the publisher.]

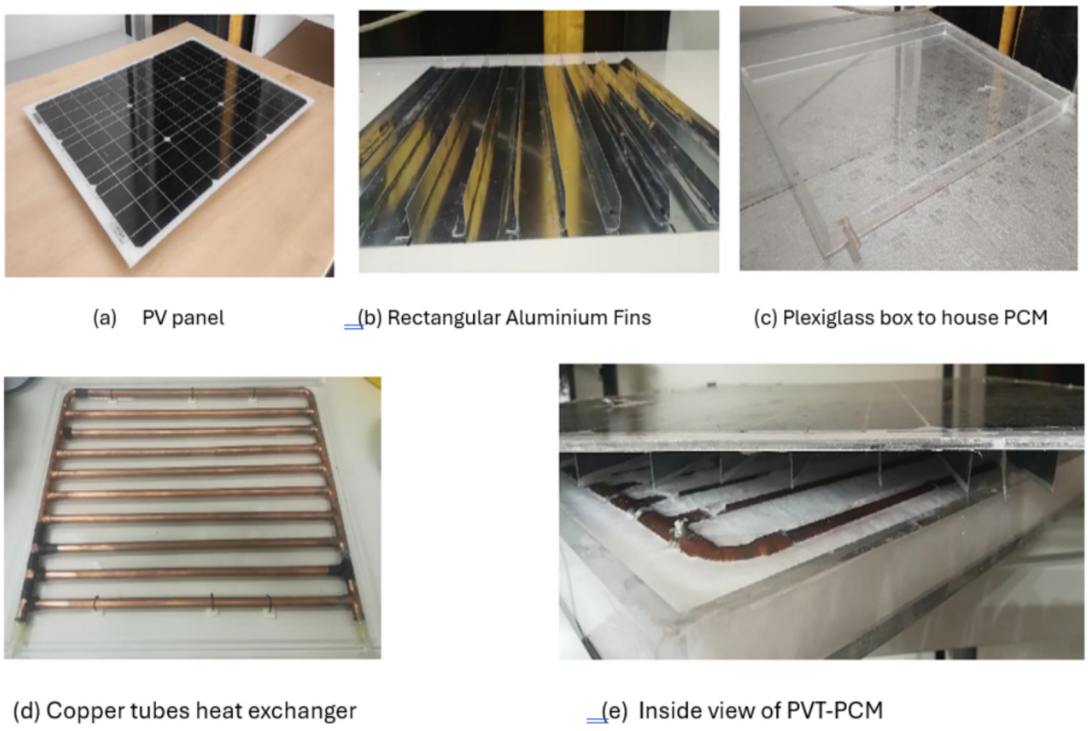


Fig. 39. The experimental set-up of the PVT-PCM [65]. [Reprint with permission from the publisher.]

6. The economic and environmental perspectives

The economic analysis of the PV-T/PCM system, including cost implications and payback period, considered expenses such as PV panels, thermal collectors, PCMs, system installation and maintenance, as well as the economics of long-term operation.

This study examines a new sink constructed with a bifacial PV system using both numerical simulations and experimental methods developed by Soliman [72]. The proposed phase change material (PCM) with 8 rib arrangements reduced the cell temperature and enhanced the system's electrical efficiency. Comparisons were made between the 2PV-PCM-ribs and the 2PV-PCM-smooth configurations. An economic analysis was conducted for the 2PV-PCM-rib system and a bifacial system without cooling. The electrical power generation costs were found to be $ 0.0768, $ 0.0779, and $ 0.0928 per kWh over 10, 15, and 20 years for the 2PV-PCM-ribs, respectively, compared to $ 0.0772, $ 0.0783, and $ 0.0932 per kWh for the bifacial system without cooling.

Emam et al. [73] proposed a 4E (energy, exergy, economic, and environmental) water-based PV-T/PCM system. A cell reduction of 8.3 °C and an electrical efficiency increase of 4.0 to 13.3 %, along with an exergy efficiency peak at 74.64 % in July. Economically, the PV-T/PCM system achieved a 1.58-year payback time and carbon emissions were reduced by 32 %.

Hossain et al. [35] performed an economic assessment of PV and PV-T/PCM systems under typical Malaysian climate conditions. The PV module's breakdown cost was MYR 2000 (US$469.25), considering its long-term usability and minimal maintenance over 5 to 10 years. PCM costs around MYR 560.53 (US$1313.29), representing a significant initial investment but requiring no maintenance for up to 4 years. PCM replacement occurs after 5 to 6 years, including installation. The total system cost was MYR 1900 (US$445.22), based on a 4-year usage period using the annual-worth method. The resulting cost-benefit was MYR 3320.61 (US$779.48), with an annual worth of MYR 1111.61 for the PV-T/PCM system. The analysis indicates that PV-T/PCM systems are more

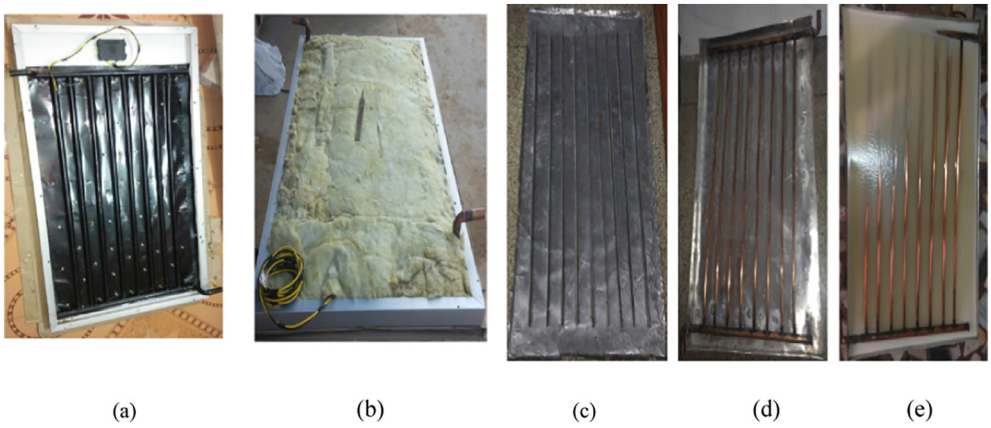


Fig. 40. (a) Thermal absorber at rear of the PV panel; (b) insulation; (c) aluminium absorber plate with fin; (d) copper tubes in aluminium container; and (e) aluminium box filled with PCM [66]. [Reprint with permission from the publisher.]

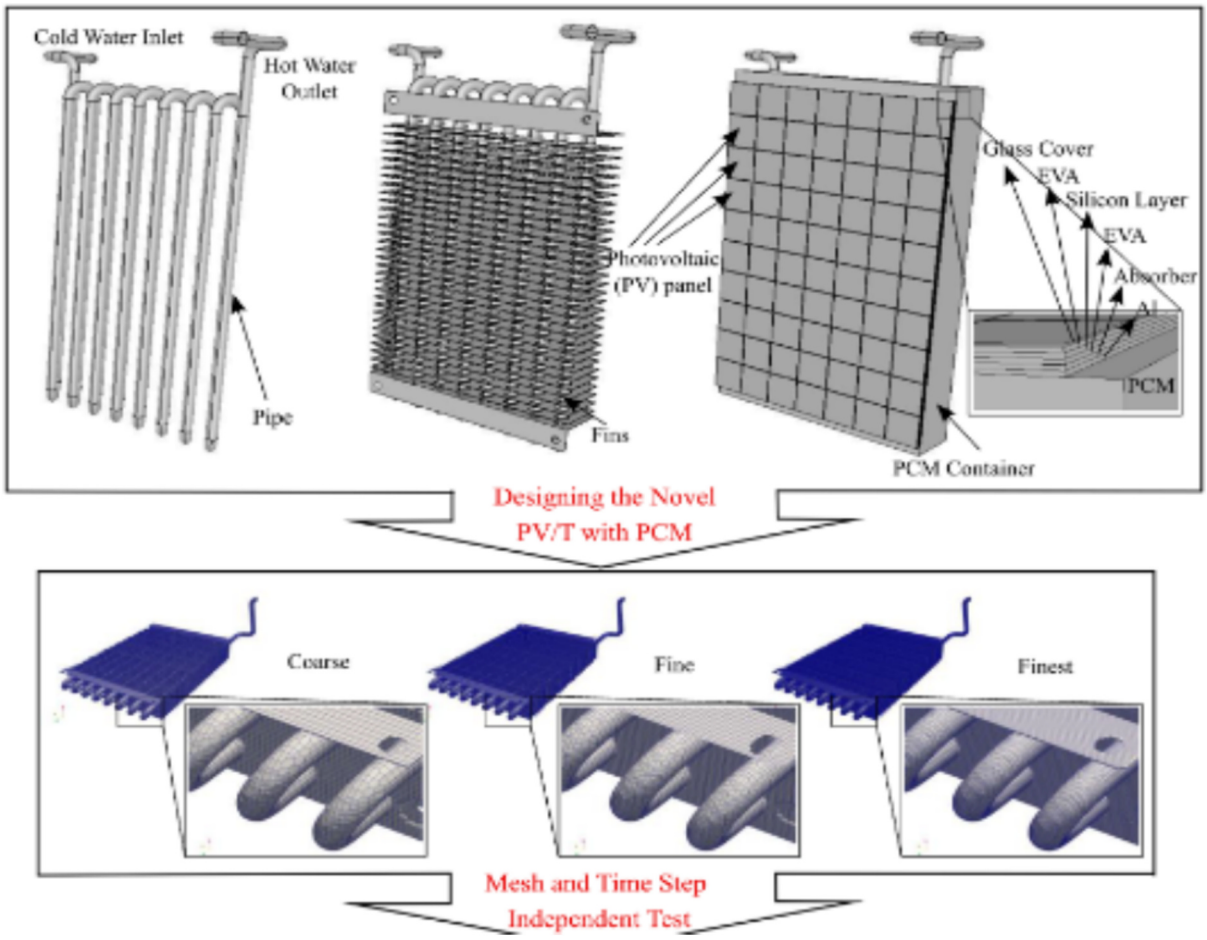


Fig. 41. Finned tube heat exchanger configuration [67]. [Reprint with permission from the publisher.]

cost-effective and appealing than traditional PV systems over the long term. The study concludes that utilising solar water heaters with at least 5 years of lifespan is advantageous for households.

The annual performance of PV, PV-PCM, PV-T, and PV-T-PPCM was presented across five locations in China by Asefi et al. [74]. The levelized cost of energy (LCOE) for PV-T and PV-T/PPCM ranged from 0.02 to 0.04 CNY/kWh, indicating their economic viability. In contrast, the LCOE for the PV and PV-PCM system was between 0.35 and 0.58 CNY/kWh, primarily due to higher investment costs. Additionally, the study compared the LCOE-electrical of PVT in China with that in the UK and Spain, revealing that PV-T in China has a lower LCOE-electrical. This is attributed to China's lower electricity prices and PV-T costs, making the system more financially feasible.

An energy and economic assessment of a water-based PV-T system integrated with RT-30 PCM explores its performance. Experiments were carried out at various water flow rates. Results show that adding PCM greatly enhances the electrical, thermal, and total efficiencies of PV-T/PCM systems by 17.33 %, 26.87 %, and 40.59 %, respectively. The

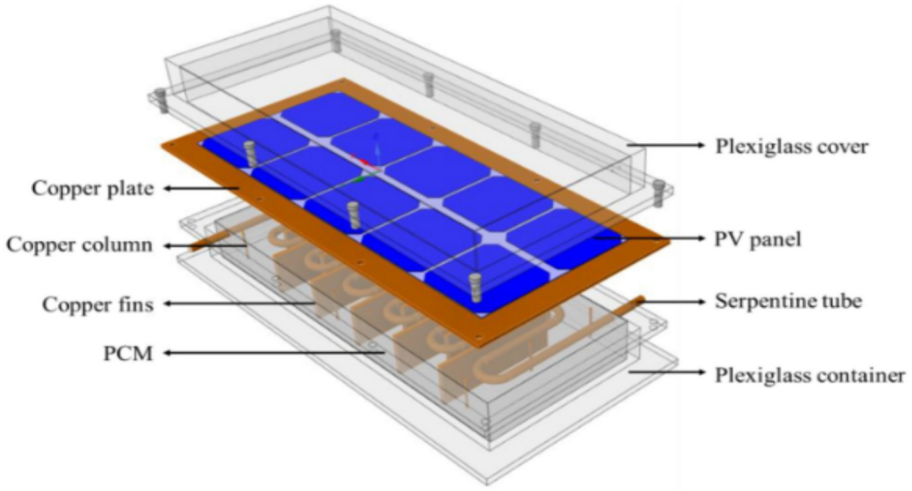


Fig. 42. 3D structure of PV-T/PCM with copper fins [69]. [Reprint with permission from the publisher.]

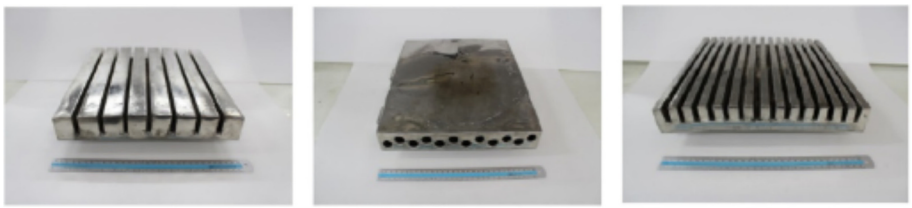


Fig. 43. (a) groove PCM container; (b) tube PCM container; (c) finned PCM container [70]. [Reprint with permission from the publisher.]

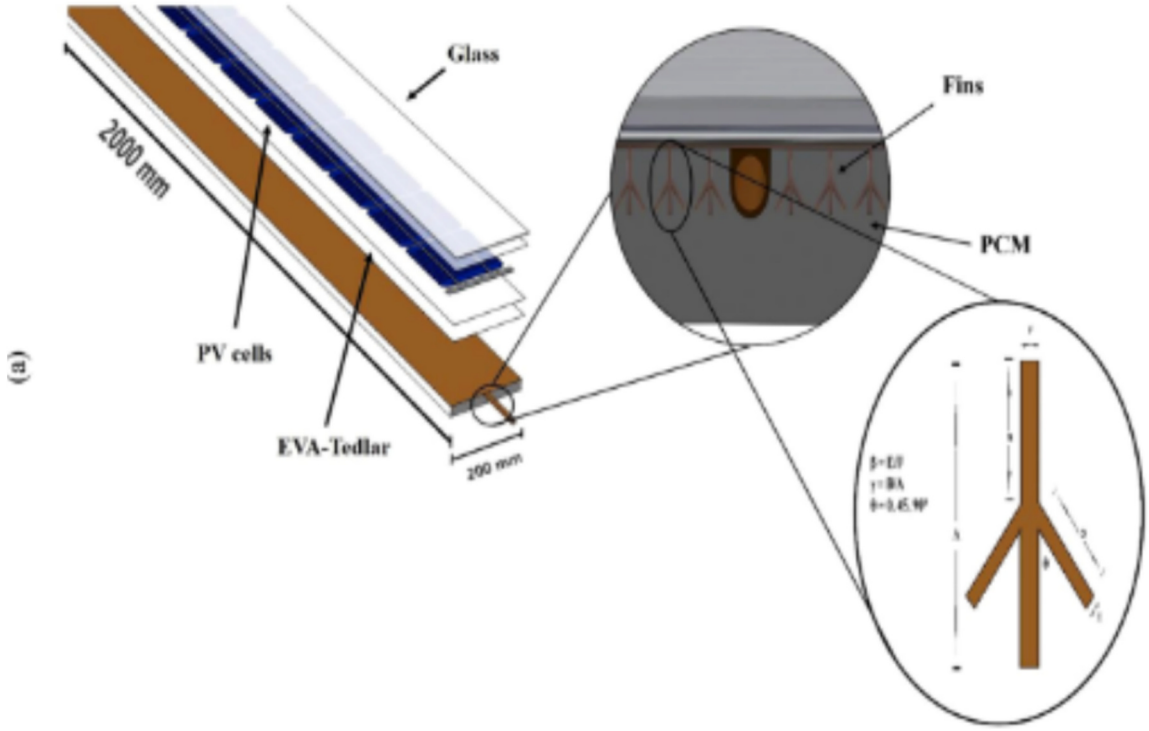


Fig. 44. Collector geometry and fin design configuration [71]. [Reprint with permission from the publisher.]

Table 4
Summary of performance enhancements in PV-T/PCM system studies reviewed.

S/N	Reference	Type of enhancement	Results
1	Sumayli et al. [44]	Metal foams	Aluminium and copper foams of porosity of 0.774 and 0.704, respectively, achieving 13.11 % and 61.06 % of electrical and thermal efficiencies.
2	Almeshaal & Altohamy [45]	CuO-water (nanofluid)	Overall energy efficiency of 82.1 % and electrical improvement average of 37.7 % and 13.3 % compared to PV and PVT/PCM, respectively.
3	Gürbüz et al. [46]	Al_2O_3-PCM/copper fins	Maximising efficiency of 32.8 %, 33.9 %, and 35.2 % for Case 1, Case 2, and Case 3, respectively, compared to 30 % for the PV system.
4	Vaziri Rad et al. [47]	Nanofluid	Electrical, thermal and exergy efficiencies of 15.5 %, 37.4 %, and 16.7 %, respectively, were achieved for CPVT. However, porous metals and PCM applications reduced the initial cost.
5	Rajamony et al. [48]	Carbon nanotubes	Total efficiencies of 81.9 %, 84.5 %, and 85.05 % for the PVT. PVT/PCM and PVT/NePCM, respectively, were achieved.
6	J. Jasim et al., [49]	Nanoparticles/fins	4.5 % of Fe_3O_4-MWCN with PCM, and PCM composite. The exergy efficiency improved by 13.3 % and 16.2 % compared to the no-PCM system.
7	Sardarabadi et al. [79]	ZnO/water nanofluid	The nanofluid's average thermal performance increased by 5 % for PV-T and 9 % for the PV-T/PCM system. Combining nanofluid and PCM can boost the exergy by 23 %
8	Hosseinzadeh et al. [50]	ZnO/water nanofluid	Nanofluid-based pVT and PVT/PCM increase the power output by 7.10 % and 11.90 %, respectively.
9	Kazemian et al. [51]	Ethylene glycol	50 wt% of ethylene glycol added to water drops the freezing point of water, and is recommended in cold climates
10	Al-Musawi et al. [52]	SiO_2/water nanofluid	SiO_2 nanofluids at 1 % and 3 % mass fractions improve thermal efficiency by 3.51 % and 10.40 %, respectively, over the PVT/PCM with pure water.
11	Al-Waeli et al. [53]	Nanofluid/nano-SiC-PCM	Power output increased from 61.1 W to 120.7 W, while electrical efficiency rose from 7.1 % to 13.7 %, and thermal efficiency of 72 %
12	Al-Aasam et al. [54]	Nano-PCM/fins	Twisted tube setup exhibits electrical, thermal, and combined efficiencies of 9.46 %, 79.40 %, and 88.86 %.
13	Salem et al. [55]	Al_2O_3/PCM	1 % Al_2O_3 nanoparticles, 25 % PCM, and 75 % water gave the lowest cell temperature and the highest electrical and thermal efficiency.
14	Chaichan et al. [56]	Nano-TiO_2	An increase in electrical efficiency of 106 % and 56 % compared to the PV panel and pure water-cooled PVT/PCM system.
15	Sarafraz et al. [57]	MWCNT-WEG 50 nanofluid	System's thermal efficiency by 130 % and its electrical efficiency by 20 % were improved, and thermal and electrical values at peak sunny hours reached 276.3 W/m^2 and 307.9 W/m^2, respectively.
16	Hamada et al. [58]	Copper duct with PCM balls	The system achieved an overall efficiency of 74.1 % under active cooling, while a 34.6 % was achieved in passive cooling.
17	[59]	PCM aluminium packets	An average efficiency of 69 % at a 0.033 kg/s flow rate was recorded.
18	Yuan et al. [22]	Aluminium plate	The PVT/PCM system achieved daily electrical and thermal efficiencies of 12.1 % and 42.3 %, respectively, compared to 11.9 % and 44.5 % for conventional PV-T.
19	Sudhakar et al. [60]		Power improvement of 12.4 % was achieved, and the overall exergy output of 26.07 %.
20	Fayaz et al. [61]		The PVT/PCM system reaches an electrical efficiency of 12.75 % and 12.5 %, for numerical and experimental, respectively. While the PVT system attained electrical efficiency of 12.4 % and 12.28 % for numerical and experimental.
21	Waqas et al. [62]	Aluminium tube	The power increase of the system ranges from 2.8 % to 3.0 % and an increased electrical efficiency of 3.0 %
22	Maneechot et al. [63]	Metal flakes	The PVT/PCM + C + M reduced cell temperature by 24.82 °C and 4.19 °C compared to PV and PV/PCM + C.
23	Mao et al. [64]	Fan-shaped fins	Increasing the number of fins raises the surface area, which increases the rate of heat transfer.
24	Colarossi & Principi, [65]	Rectangular fins	The maximum system efficiencies were 38 % and 16 % in summer and winter, respectively, with a 100 L storage capacity identified as the most efficient.
25	Preet et al. [66]	Fins	The thermal efficiency was 62.37 % for PV-T and 35.4 % for PV-T/PCM, and electrical efficiencies were 10.66 % and 12.6 % for the PV-T and PV-T/PCM systems, respectively.
26	Carmona et al. [68]	Fins absorber plate	The daily electrical efficiency of the PV module was 7.43 %, while the hybrid PV-T/PCM module achieved a total efficiency of 31.35 %. The daily electrical efficiency of the PV-T/PCM was 13.12 %, reflecting an overall increase of 20.45 %.
27	Zhang et al. [69]	Copper fins	The electrical efficiency of the PV-T/PCM system improved from 10.83 % to 10.99 %, and the thermal efficiency attained a maximum of 86.49 %.
28	Khodadadi & Sheikholeslami [71]	Fins design	The system with ten fins experienced a 5.03 % faster melting rate and a 13.31 % decrease in surface temperature compared to systems with six fins or no fins. Incorporating nanoparticles into the PCM further increases the liquid fraction by 2.13 % compared to pure PCM.

payback period for the PV-T/PCM system is around 6 years, which is 11.26 % less than that of traditional PV panels. Additionally, the system achieves a 27 % higher long-term lifecycle conversion efficiency. [75].

Numerical analyses of energy, economic, and environmental aspects of PV-T, PV-T/PCM, PV-T/DXHP, and PV-T/PCM-DXHP systems were carried out by Babu et al. [76]. The yearly electrical performance efficiencies of the PV-T, PV-T/PCM, PV-T/DXHP, and PV-T/PCM-DXHP systems are 9.77 %, 10.57 %, 11.83 %, and 12.91 %, respectively. Economic analysis presented based on a discounted payback period of 8, 7, 6, and 5 years and the costs of energy production are ₹4.08 per kW-h, ₹3.67 per kW-h, ₹3.37 per kW-h, and ₹2.87 per kW-h for PV/T-W, PV/T PCM-W, PV/T DXHP, and PV/T PCM-DXHP systems, respectively. Also, the environmental analysis shows that the four systems mitigated the CO2 of 64.72 tons, 90.45 tons, 117.35 tons, and 156.49 tons throughout their lifetimes, and cost savings of ₹75,075, ₹104,925, ₹136,175, and ₹181,525, respectively.

[77] developed PV-T/PCM and PV-T/PCM-Dust systems to compare their performance. The power outputs achieved were 160.29 W and 153.85 W, and the electrical efficiency of 17.52 % and 14.83 %, respectively. The cost analysis shows that PV-T/PCM is more cost-effective in the long term compared to a PV system. The PV-T/PCM system costs approximately MYR 5604.53, which can be reduced after 25 years of use.

A novel PV/T system incorporated with silica aerogel and composite PCM has been proposed by Zheng & Zhou, [78]. Incorporation of aerogel and composite PCM with high thermal conductivity is beneficial to improve electrical and thermal efficiencies. The results also show an improvement in overall energy and exergy efficiencies of 40.2 % and 1.5 % in summer and by 42.4 % and 0.43 % in winter. The annual CO2 mitigation of 104.1 kg/m2 and the return on investment (ROI) of 0.169 were achieved.

7. Research gaps and future outlook

The PCM is a good candidate for reducing the PV cells' temperature and building heating decarbonisation. The research gaps and outlook of

this review for the topic of discussion above are as follows:

- The most investigated PCM is paraffin-based PCM and is commercially available. However, the low thermal conductivity of the organic PCM demands novel approaches to improve the thermal conductivity.
- Organic PCMs like paraffin wax are highly flammable and toxic to the environment. Irrespective of the excellent characteristics of organic PCMs, there is a need for effective containment in the event of fire may be required when utilising such materials in the PV-T. Also, a blend of bio-based and eutectic PCM will make PV-T/PCM system more environmentally friendly and sustainable.
- Supercooling, phase separation, and the corrosive nature of the salt hydrate PCM limit their application in the literature, irrespective of their good thermal conductivity and high energy storage density. More research is needed in this area to develop an effective salt hydrate-based PCM.
- Thermal cycling and stability of PCM are important in the application of the PV-T system. Long-term cycle stability of PCM will reduce maintenance costs since fewer replacements will be needed.
- Cost of nanomaterial, instability, and sedimentation due to density difference are the limiting factors of nano-enhanced PCM.
- Irrespective of the quality of nanoparticles integrated with PCM to enhance the thermal conductivity, the complex preparation methods, associated cost, and leakage of PCM from the shell over many thermal cycles hamper the widespread application of micro and nanoencapsulation of PCM.
- A hybrid of various heat transfer enhancement methods, such as fins/nanoparticles, fins/encapsulation, fins/porous materials, etc., must be investigated further so that shortcomings of using a single method can be avoided.
- Application of PCM/EG or similar composites has high thermal performance in small-scale systems and significantly controls the volume expansion of the PCM. However, the long-term effect of such composites in real-time practical systems is not well studied.
- A large volume of research articles is available on experimental and numerical studies on PCM integration to the PV-T systems; most of the works are limited to laboratory scale, with a few focused on real-life scenarios. Therefore, building integrated systems should be studied in detail under real weather and internal load conditions, over the long term.
- A general numerical model should be developed to optimise the system performance for various operating parameters like flow rate, PCM thickness, PCM melting point, etc.
- Long-term techno-economic feasibility of PCM integrated into the PV-T system operated with HP should be investigated experimentally and numerically.
- Economically, the initial cost of PV-T/PCM is higher than the PV system. However, if the PV-T/PCM is applied in a region of high solar radiation, and its dual output of electrical and thermal outputs is utilised, the payback time is reduced.
- A standard procedure for PCM integration in building components and LHTES units for space heating and hot water production, including the PCM selection, system design, and testing of the system, should be developed to enhance the penetration of these technologies into the global market.
- Finally, there are no papers exploring the PV-T/PCM system application in sub-Saharan Africa, even though the region is known for high solar radiation and long hours of sunlight.

8. Conclusion

This review paper investigates the current state of the art of PV-T integrated with PCM through studies that enable PCMs to cool PV panels and store thermal energy in water-based PV/T systems. Applications that provide cooling by absorbing the heat are necessary to benefit the efficiency of photovoltaic cells and to control the increasing cell temperature. Phase change materials are effective cooling techniques today. However, it is necessary to evaluate with cost management techniques whether the cost of PCM implementations exceeds the amount of savings achieved.

Paraffin wax PCMs are the most used photo-thermal PCMs. However, suffered from low thermal conductivity. Introducing metal particle effects to boost light absorption or change the heat transfer mode of carbon-containing PCMs is a very sensible way to solve their low efficiency.

Economically, PV-T/PCM system is expected to have a longer payback period as additional costs can be attributed to the established system. However, if the energy obtained from PV panels are to be used for hot water, ventilation, heating or electricity generation; economic benefits are expected to increase. Thus, the additional costs of PCM can be ignored. Therefore, life cycle analysis and economic evaluations of PV-T/PCM systems should be made. Research into the creation of multifunctional energy conversion PCMs is still popular and important. More work should be done to improve the properties and efficiencies of energy conversion PCMs, as well as to increase their use.

CRediT authorship contribution statement

Kar R. Awai: Writing – review & editing, Writing – original draft, Resources, Methodology, Investigation, Conceptualization. **Peter King:** Writing – review & editing, Supervision. **Kumar Patchigolla:** 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

No data was used for the research described in the article.

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