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Review Paper

Recent Advances in Phase Change Material-Assisted Photovoltaic Systems: A Review of Thermal Management and Energy Performance

M.H. Alturaihi, R.H. Alkhayat

Mechanical Engineering Department, Faculty of Engineering, University of Kufa, Al Najaf 54001, Iraq

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Corresponding author: M.H. Alturaihi (muna.alturaihi@stu.nit.ac.ir & monah.alturaihi@uokufa.edu.iq)

Abstract. Photovoltaic (PV) and photovoltaic thermal (PVT) systems are increasingly employed for sustainable energy conversion; however, elevated operating temperatures remain a major limitation because they decrease electrical efficiency, accelerate material degradation, and restrict long-term system performance. Phase change materials (PCMs) have attracted substantial attention as a passive solution for thermal regulation because they can temporarily store excess heat during melting. The paper discusses the current advances in PCM-integrated PV and PVT technologies with a focus on material selection, system configuration, heat-transfer enhancement approaches, environmental effects and sophisticated hybrid thermal management systems. Literature findings reveal that PCM-based thermal regulation can decrease PV module temperatures by around 5–25°C across different operating scenarios. Moreover, reported studies have achieved electrical-efficiency improvements of as high as 15% and annual energy-generation increases above 5% in suitable climatic environments. In PCM-assisted PVT systems, experimental investigations have demonstrated back-surface temperature reductions of up to 15.8°C and improvements in total solar-energy conversion efficiency of approximately 12.94% compared with conventional PVT configurations. The reviewed evidence further shows that system performance depends not only on the PCM temperature and latent heat of the PCM but also strongly on thermal conductivity, PCM thickness, module geometry, environmental conditions, and heat-transfer enhancement methods such as fins, conductive additives, nanoparticles, and hybrid heat-exchanger structures. Overall, PCM-assisted PV/PVT technologies provide an effective route for simultaneously mitigating thermal losses, improving electrical output, recovering useful thermal energy, and enhancing overall solar-energy utilization. Nevertheless, their broader implementation is still constrained by low PCM thermal conductivity, leakage and phase-segregation issues, long-term stability, limited outdoor validation, and uncertain techno-economic viability. Future work should therefore concentrate on high-conductivity and durable composite PCMs, optimized system-level integration, long-term outdoor testing under different climates, standardized performance assessment, techno-economic and life-cycle analyzes, and intelligent optimization and control strategies to bridge the gap between laboratory-scale concepts and commercially viable PCM-assisted PV/PVT systems.

Keywords: Thermal Energy Storage (TES); Photovoltaic Thermal (PVT); Passive Cooling; Phase Change Materials (PCMs); Thermal Management; Heat Transfer Enhancement.

1. Introduction

Rising environmental pressures, climate change concerns, and the diminishing availability of conventional energy resources have accelerated worldwide efforts toward sustainable energy development. As such, the need for rapid movement to renewable energy (RE) technology has never been more urgent. The environmental impact of consumption habits of RE sources is far less than fossil fuels. Among these sources, solar energy is known to be able to assume an important role in the modernization of the energy industry. Reducing greenhouse gas emissions while ensuring energy security and economic development has become a major driver of the global shift toward RE. The reliance on fossil fuels not only causes serious environmental problems, but also geopolitical tensions and economic instability. In contrast, RE sources like solar energy provide clean, abundant and endless sources of energy without negative impacts on the environment [1]. Energy is at the core of human life and the development of society. With the population growth and the increase in the living standards, the need for fossil fuels is ever increasing, which result in higher environmental degradation and limit the sustainable economic development. The continued reliance on fossil fuels contributes significantly to persistent environmental problems, including greenhouse gas emissions and acid rain. The consequences of atmospheric CO_2 on the global temperature have been studied correlatively as well as causally. This flow of information gets stronger over time as can be seen in Fig. 1 where the statistically significant values appear from around 1960. These results further highlight the crucial role of anthropogenic CO_2 forcing in recent global warming and stress the need to speed the transition toward low-carbon and renewable energy technologies [2].

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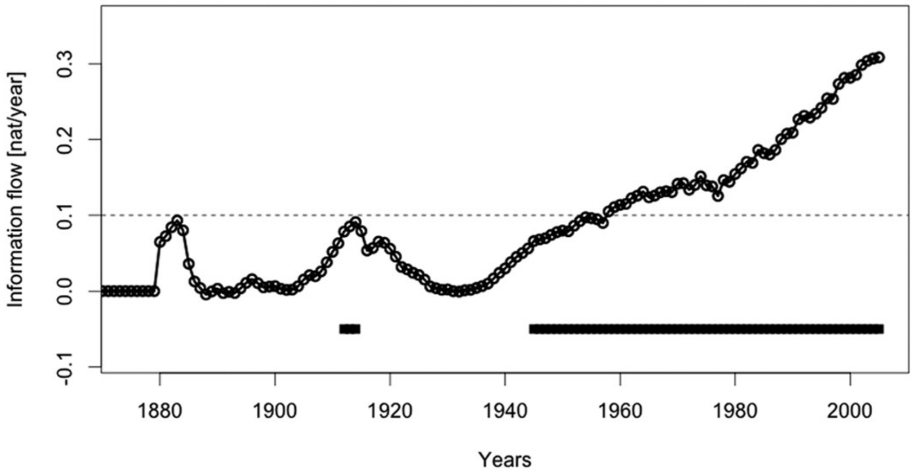

Fig. 1. Temporal evolution of information flow from CO_2 forcing to global temperature anomalies [2].

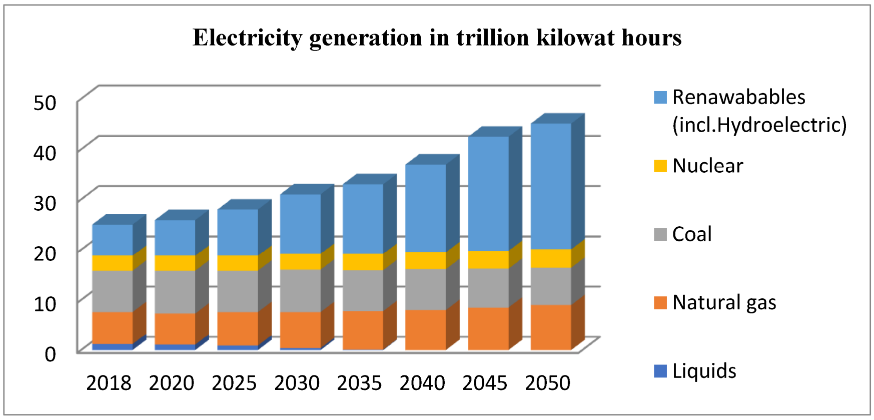

Fig. 2. Schematics showing difficulties with overheated PV cells [4].

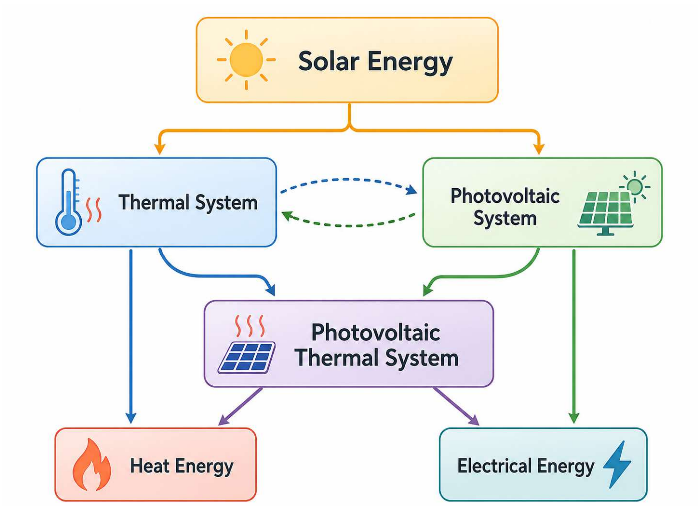

Fig. 3. Schematics representing various solar technologies.

Sun energy is one of the basic forms of RE with great potential for a sustainable future. It is obtained from sun radiation. In just one hour, the amount of solar radiation received by the Earth is sufficient to surpass the world’s total annual energy consumption. The vast availability of solar energy underscores its potential to become one of the principal sources of clean energy in future energy systems. PVT systems use solar panels to harvest sun photons for thermal energy or electricity generation [3].

However, the IEA expects a large increase in the share of sustainable energy in the global energy mix (Fig. 2). By 2027, the cumulative installed capacity of PV power plants will exceed 2350 GW, and PV power generation will become the world's main electricity source [4]. Solar energy applications are now present in many industries, offering solutions in the home, commercial and industrial areas. Solar energy addresses the needs of domestic electricity in the residential sector through rooftop solar panels, thereby reducing reliance on the traditional grid and thus, reducing energy prices. In the commercial sector, solar energy supplies power to businesses, offices and commercial facilities, leading to lower operating costs and a smaller carbon impact [5].

One example of an industrial application of solar energy is the concentrated solar power plant. In this case, sunlight is concentrated and focused on a receiver, creating high-temperature heat. The resulting thermal energy is subsequently converted into electricity by driving turbines. Solar energy is also used in agriculture. Solar powered irrigation systems can provide solutions to improve efficiency and sustainability in food production. PV panels have become widely used because to the dramatic improvement in their efficiency and economics over the past decades. PV panels are important for energy generation and provide energy independence and resilience for energy systems. Therefore, the deployment of RE, especially solar energy, is one of the main foundations of the worldwide effort towards a sustainable and green future. Its versatility, scalability and eco-friendly nature position it as a leading candidate in the energy industry's revolution. Advances in PV technology and the growing deployment of solar energy could reshape conventional energy production and consumption patterns, contributing to a broader transition toward clean and and RE [6]. Compared with fossil fuels, solar energy represents a far more effective alternative for human development because it does not emit carbon, sulfur, or other pollutants that damage the environment. Both now and in the future, energy development is expected to focus on the large reserves and broad availability of solar energy in China. Figure 3 presents the main approaches for solar energy utilization, including photothermal technology for current heat production, as well as PV electricity generation, solar thermal power generation, and photochemical conversion for electricity production. PV conversion represents one of the most prominent applications of solar energy for electricity generation. Under typical operating conditions, approximately 20% of the incident solar radiation is converted into electrical power, whereas most of the remaining absorbed energy is released as heat. The excess heat elevates T_{PV}, which adversely affects electrical efficiency and can, under extreme conditions, lead to overheating and permanent damage [7].

1.1. PV panels

PV generate electricity by converting incident solar radiation into electrical energy through semiconductor materials that exhibit PV effect. When photons in sunlight hit a PV cell, they can transfer their energy to electrons in the semiconductor material, knocking them loose from their atomic bonds and thereby creating an electric current. PV panels, commonly called solar panels, generate power from the above-described PV effect. This happens when photons particles of light impact the solar cells integrated in the PV panel. The incident photons, once reaching the solar cells, possess enough energy to free up electrons in the silicon-phosphorus layer, allowing them to travel. These free electrons are directed by the electric field to the silicon-boron layer, producing an electric current. This process produces Direct Current (DC) power, which can be used directly, stored in energy systems [8]. Conversion efficiency of these cells has been a main focus of study leading to a range of materials and designs. Apart from residential and commercial rooftop systems, PV technology is extensively used in utility-scale power plants and in space applications to power satellites. The integration of PV systems has also evolved from traditional panel installations to Building-Integrated PVs (BIPV) where solar parts are integrated into the building envelope, for instance windows or facades. The continuous development of PV technology and materials science is the fundamental driver for the improvement of conversion efficiencies and for the extension of the applicability of solar-based solutions and, in this way, to strengthen the role of PVs in the transition to RE [9,10].

Studies have revealed that over a certain limit, the performance of solar PV panels drops with increase in operation temperature. For traditional Si-based PV modules, the power loss is typically roughly 0.4–0.5 % per 1 °C above the standard working temperature of 25 °C [11]. In practice, this translates to a drop of roughly 15-20% in power production compared to its rated value at 25°C for a panel working at 60°C, which is a typical condition under intense tropical sun radiation [12]. The bandgap of the semiconductor decreases with increasing temperature and the recombination of thermally generated charge carriers (i.e., electrons and holes) is enhanced at high temperatures which reduces the cell voltage and overall efficiency. This is the cause of this degradation. In addition to the short-term effect on the power output, the high temperature of the module also accelerates the mechanisms of long-term degradation of PV components [13]. Long lasting temperature stress can cause difficulties such as discolouration of the encapsulant, hydrolysis, photodegradation, corrosion and cell microcracking, all of which reduce the service life of the modules (Fig. 4) [14]. Elevated module temperatures can accelerate material degradation and shorten the service life of photovoltaic panels. Accordingly, various cooling techniques have been investigated to limit thermal exposure and improve module durability.

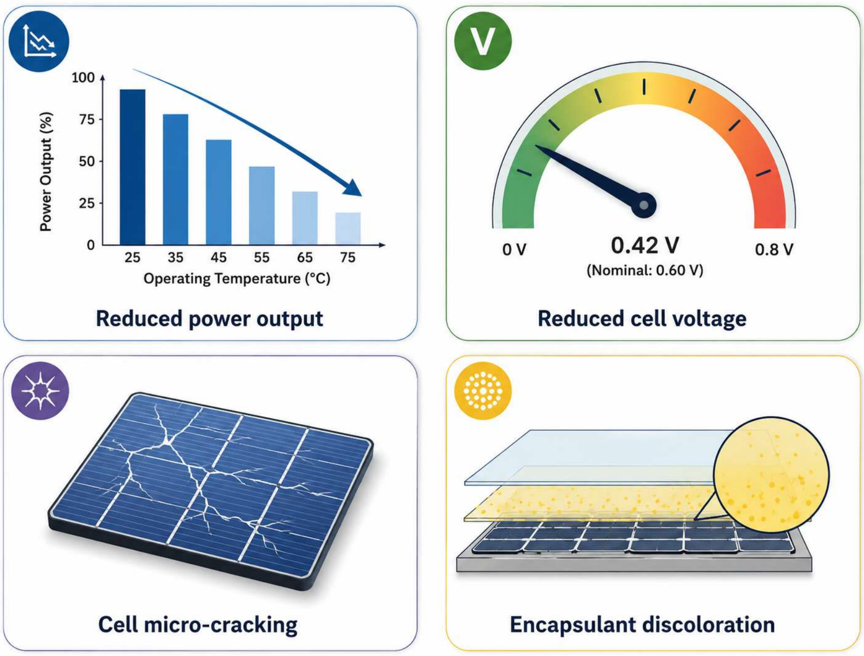

Fig. 4. Schematic of problems of overheated PV cells.

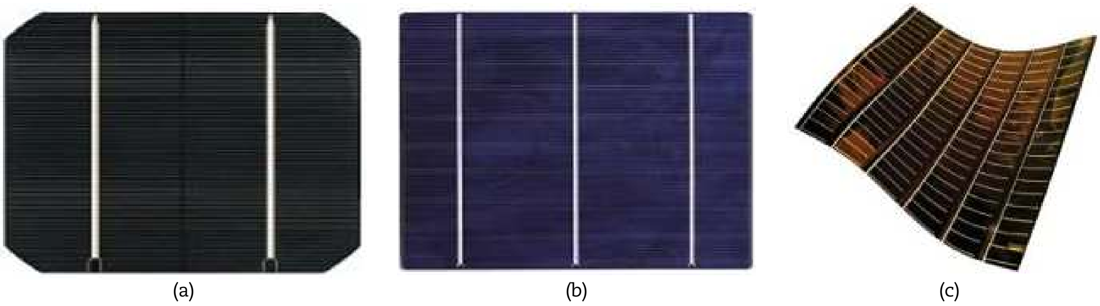

Fig. 5. Types of PV panels based on cell material, (a) Monocrystalline silicon solar cell, (b) Polycrystalline silicon solar cell, (c) CdTe thin-film solar cell [5].

Previous research has suggested that appropriate thermal management can substantially extend the operational lifetime of PV modules, with reported estimates indicating an increase from approximately 25 years to 30 years and, under certain conditions, potentially up to 48 years [15]. Many solar power systems in underdeveloped countries are working under harsh weather conditions and poor maintenance standards. Therefore, it is vital to be maintained to maximize power generation by limiting losses due to overheating and mechanical wear. More critically, PV overheating is a serious worry [14] as global warming is increasing the severity of heatwaves and resulting to the soaring of temperatures to the high level in most countries of Africa and South Asia.

1.2. Types of PV panels

PV panels are grouped into several types depending on the cell material (Fig. 5):

- **Monocrystalline solar panels**

Monocrystalline solar panels are easy to identify because of their consistent look and dark black color. Each monocrystalline panel has solar cells that are built from a single crystalline structure of silicon so the passage of electrons can happen with less resistance. Best to work them here, they work best here and are best at converting sunlight to power/energy. Efficiency of monocrystalline panels is usually about 20% up to 24% in some cases, which is one of the highest value obtained for solar panels. This efficiency level shows their better ability to convert solar energy into electricity. This makes them especially attractive to consumers in places with high electricity prices [16].

- **Polycrystalline solar panels**

You may also identify polycrystalline solar panels by their specific blue color and square form of the cells. While they may not be quite as efficient as monocrystalline cells, they nevertheless have a major role to play in the solar energy market because they are cheaper to produce and perform well. Polycrystalline panels are made by joining together several pieces of silicon. This method of manufacturing decreases production costs greatly, however it leads to a matrix of different crystal forms in each cell which might impede the passage of electrons and somewhat reduce efficiency. This modest drop in efficiency, typically in the 15%-16% range, still leaves polycrystalline panels as a cost-effective and appealing choice for many individuals and businesses. They are particularly suited to applications when the absolute greatest efficiency per unit area is not required, or for those looking for a cheaper solar energy alternative [17].

- **Thin-film solar panels**

Solar PV technology comes in thin film solar panels. The design flexibility, ease of manufacturing, and cheap material requirements offer new opportunities to PV applications. Unlike conventional wafer-based technologies, thin-film PV cells are formed by coating a substrate with extremely thin photovoltaic semiconductor layers. These layers are very thin (usually in the nanometer range) and make such panels light-weight and flexible. This property can sometimes make them more suitable for some applications than rigid monocrystalline or polycrystalline panels. The efficiency of thin-film panels is usually lower than that of silicon panels, typically ranging from 10% to 12%. They may also need a bigger installation space to produce the same amount of power as monocrystalline or polycrystalline panels. In addition, their ability to function effectively in high-temperature and low-irradiance settings makes them even more attractive. Thin-film panels are also usually less suitable for small-scale residential or commercial use because of lower efficiency and greater space requirements, but they have a proper place in larger commercial operations and other specialized applications where unique characteristics such as flexibility and low weight become distinct advantages [18].

1.3. PVT systems

PVT systems are devices that combine PV and thermal technologies into a single module that converts solar radiation to both electricity and thermal energy. In these systems the solar cells generate energy, but the heat that is left over is caught by a thermal system rather than being wasted. This combination can considerably improve the total energy efficiency of solar installations. Traditional solar panels only convert a percentage of the solar energy absorbed into electrical energy, the rest of the solar energy absorbed is lost as heat which can cause a decrease in efficiency of the PV cells. This problem can be solved by PVT systems which make an effective use of this extra thermal energy. This heat can be used for immediate uses like domestic hot water (DHW) and space heating, or saved for future use. Some PVT systems circulate fluids (usually water or anti-freeze solutions) below or below the solar cells to reclaim the extra heat. Consequently, this approach simultaneously lowers the operating temperature of PV cells, thereby improving their electrical performance and service life, while enabling the recovery of useful thermal energy at temperatures exceeding those typically achieved by conventional solar thermal technologies [19]. PVT systems have many advantages, especially in residential or commercial buildings with a constant demand for both energy and hot water. The combination of these functions allows PVT systems to lower the spatial and capital expenses of separate PV and solar thermal installations. Current research in this area is directed toward increasing the efficiency and cost-effectiveness of these systems, making them more attractive to consumers and major players in RE portfolios [20]. Buildings are major consumers of the world's energy and require electrical and thermal energy to function. Building-integrated PVT (BIPVT) systems provide an effective approach for addressing these simultaneous demands by combining electricity generation with useful heat recovery within the building envelope. In these systems, circulation of a heat-transfer fluid removes excess heat from the photovoltaic surface, which can improve electrical performance while providing recoverable thermal energy for building applications.

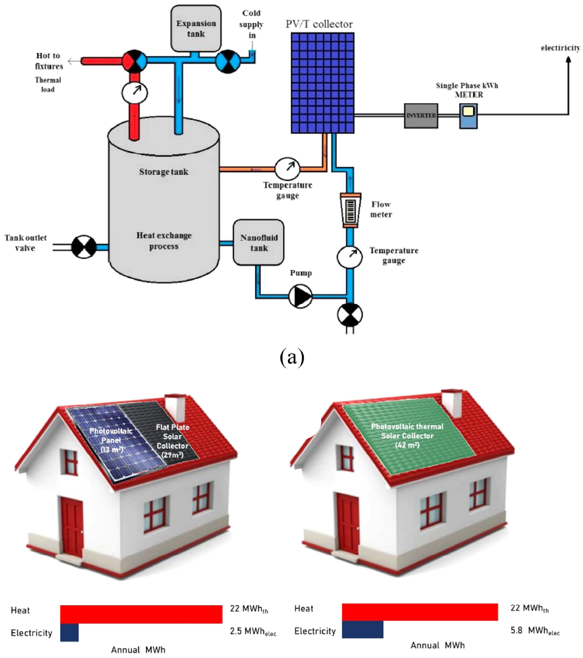

Fig. 6. Schematic of PV/T system and comparing PV and PV/T energy [21].

Integration of PVT collectors into façades or other building surfaces also offers an attractive solution in urban environments where the available installation area is limited. Figure 6 illustrates representative configurations and integration approaches of BIPVT systems [21, 22]. Solar PVT collectors are an interesting technique for the simultaneous use of PV conversion and heat absorption. These collectors use the cooling media for heat extraction from the PV cells which in turn increases the rate of the photoelectric conversion and improves the overall efficiency of solar energy. By producing electricity and thermal energy simultaneously, PVT collectors offer an effective means of maximizing solar-energy utilization in buildings. Air and water are the most commonly used heat-transfer fluids in these systems.

1.4. Types and applications of PCMs

PCMs are materials of high heat of fusion that melt at specific temperatures and may store and release significant quantities of energy. As these materials change from solid to liquid states, or from liquid to solid states, thermal energy is absorbed or released. Thus, PCMs are defined as Latent Heat Storage (LHS) devices. The effectiveness of a PCM in thermal management applications is critically dependent on its TES density and its rates of heat absorption and release. PCMs are classified to be organic, inorganic and eutectic. Organic materials such as paraffin waxes and fatty acids are used due to their consistent melting, low sub-cooling (supercooling) and great cyclic stability. Salt hydrates offer the advantages of relatively high melting temperatures and enhanced thermal conductivity, although phase separation and significant subcooling can compromise their long-term thermal performance. The advantage of eutectics is that their melting points and latent heats can be tailor made. PCMs are selected based on characteristics such as stability, thermal conductivity, latent heat capacity, cost and suitability for the application. PCMs have several applications in thermal management, ranging from passive thermal protection of buildings and fabrics to active thermal control of solar energy systems and cooling of electronic devices. Utilization of PCMs for energy storage has been very useful in several industries. During construction, PCMs are used for energy storage and insulation, while in heat sinks, they are used to increase temperature uniformity. PCM's one of the most important application areas is the solar energy industry. Integrating the PCMs can increase the operation hours of these systems to solve the intermittency of solar energy. PCMs are used in solar PVT panels to control the temperature of the solar cells and to help the thermal system to work for a longer period of time [23].

The application of PCMs in solar systems offers a wide range of uses and functions that contribute to the optimization of solar energy systems' performance. Some typical uses for these materials in solar systems are:

• **Temperature control and energy storage:** PCMs are employed as TES. They can store heat when solar energy is available and release it when needed.

• **Temperature regulation of solar cells:** The temperature of solar cells can considerably affect their efficiency in PV systems. The operating temperature of these cells can be controlled using PCMs to increase their performance.

• **PCM heating and cooling systems:** PCMs can be used in heating and cooling systems. In cold seasons they can store heat, in warm seasons they can let it go.

• **Applications in electricity generation:** PCMs can be used to improve the performance of solar-based power generation systems such as PV panels by regulating the temperature and reducing efficiency losses at high temperatures.

These applications are just a few examples of the use of PCMs in solar systems. Overall, the use of these materials may increase the performance and efficiency of solar systems leading to better utilization of energy and decreased costs (Fig. 7) [24, 25].

The widespread adoption of renewable energy technologies, including solar PV systems, is essential for decreasing dependence on finite fossil-fuel resources and limiting the environmental consequences associated with their use. Solar and PV systems that either use solar radiation directly or convert it to electrical energy provide a reasonably clean and renewable source of energy. Environmentally, the usage of solar and PV systems is a sustainable and ecological option. The main source of energy in these systems is sunshine, and they do not create greenhouse gases without the burning or mixing of materials. PV systems are a fast-growing technology and offer flexibility in installation and operation. They may be installed on many scales from tiny residential to huge industrial scale. To summarize, the design and implementation of solar and PV systems is a significant step towards mitigating the negative environmental impacts of energy generation and creating a sustainable energy infrastructure [26, 27].

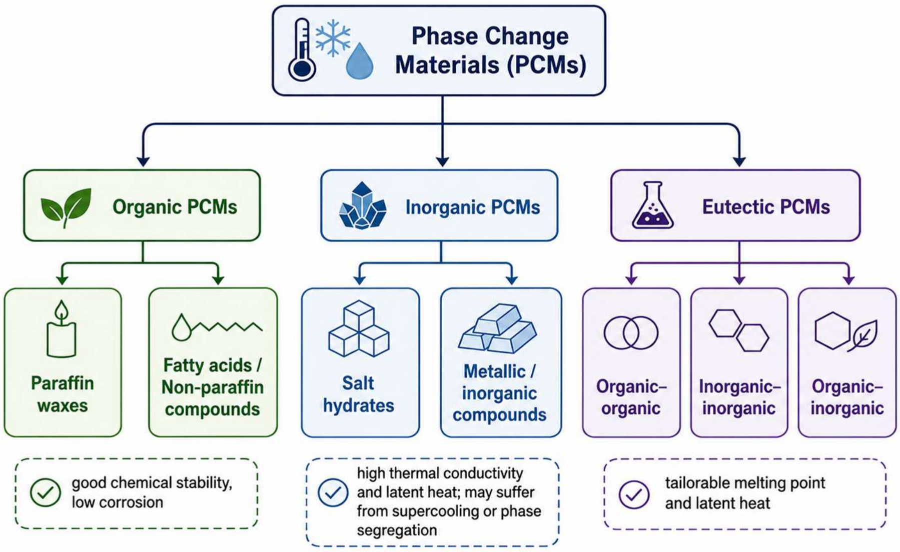

Fig. 7. General classification of PCMs.

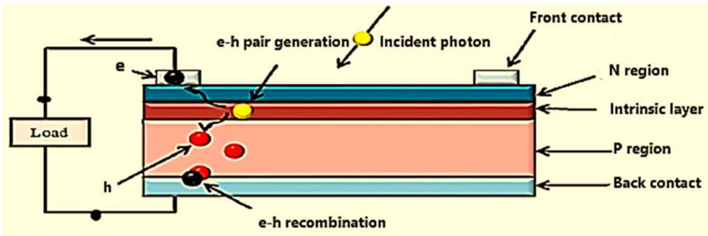

Fig. 8. Schematic representation of the operating principle of a p–n junction photovoltaic cell [28].

The PVT system is a renewable system that produces heat and generates power from the sun. "They are designed to increase efficiency and make the best use of solar energy." In the following, the need for engineering evaluations of PVT systems as well as some of the progress in the area of renewable solar systems is covered.

Engineering Considerations for PVT Systems:

• **Efficiency improvement:** Engineering evaluations in the area of PVT system performance allow optimizing various components, such as solar cells and the thermal subsystem. Improvements in cooling system and heat transmission can improve the overall system efficiency.

• **Stability and performance in varied situations:** PVT systems must work well across a range of climatic conditions. Engineering assessments can reveal flaws under particular operating conditions and offer repair methods.

• **Cost reduction:** Cost-benefit studies and improvements in manufacturing and installation procedures can help lower the installation and operating costs of these systems.

With the progress of engineering analysis and ongoing research in the area of PVT systems and solar technologies, the opportunity to improve efficiency and optimize the use of solar energy has expanded dramatically. A review of the work done on renewable solar systems and PVT systems is offered in the following.

2. PCM-Assisted Thermal Management of PV Systems

PV cells are primarily fabricated from semiconductor materials, most commonly silicon. When photons from incident sunlight are absorbed by the semiconductor, their energy promotes electrons to higher energy states, generating electron–hole pairs. The resulting charge carriers can then be separated and transported through the device, producing an electrical current. This excitation generates electron-hole pairs. Put simply, it causes some of the electrons in the material to be moved from their normal positions, leaving behind 'holes'. The excited electrons can now move around within the semiconductor and create an electric current. A photovoltaic cell converts the incident sun radiation directly to electrical energy by the photovoltaic effect. Incident photons with energies exceeding the semiconductor bandgap produce electron–hole pairs within the PV material. The built-in electric field at the p–n junction then facilitates the separation of the generated carriers, forming the basis for photovoltaic electricity generation. Electrons go toward the n-type region and holes drift toward the p-type region. Figure 8 is a schematic illustration of the basic operation of a p-n junction photovoltaic cell, including absorption of photons, generation of carriers, separation of charges and flow of current. The PV cells are interconnected in series and parallel to form an array so as to generate more power. There are four types of PV panels: i) Monocrystalline solar panels. ii) PV modules of polycrystalline silicon iii) Thin film solar cell iv) Flexible solar panels [28].

Li et al. [27] improved a PV power plant model by include the sensible heat flux computed below the surface. The model was validated against experimental data from the Red Rock PV plant in Arizona, United States. Results showed that the PV installation induced localized daytime urban heat island effects. The evaluation of microclimatic changes before and after construction of plants, taking into account the effect of PV coverage, showed increased temperatures throughout the day and a decrease in ground temperature up to 5°C. Additionally, a 15% increase in PV coverage led to an increase of 0.55°C in the daytime air temperature difference at 3 m height and a decrease of 3.6°C in the ground temperature during the day and 1.1°C at night. Thermal stress is a key limitation of PV technology because increasing cell temperature generally decreases electrical efficiency and accelerates long-term module degradation.

Recent studies have demonstrated the feasibility of using natural convection cooling loops for the temperature control of floating PV installations. The efficacy of such natural convection cooling loops strongly depends on the elevation of the cooling reservoir, as established by Sutanto et al. [29] using numerical calculations and experimental testing. Consequently, this parameter becomes a crucial design variable that may be exploited to optimize the cooling performance of the PV module, leading to a 17.84% boost in electrical efficiency compared to the uncooled baseline configuration.

In their study, Junior et al. [30] assessed the coupled performance of a grid-connected PV installation and a multi-zone air-conditioning system serving an office building in a tropical climate. Transient simulations were performed in an effort to investigate the relationship between the PV system and the HVAC units. The proposed configurations were assessed in terms of energy and economics. The energy performance was estimated using indicators of self-sufficiency and self-consumption of the air handling units. The economic feasibility was assessed by calculating the net present value (NPV), the internal rate of return (IRR) and the payback period. The demand side energy management application lowered the peak hour electricity demand dramatically with 96 % reduction in the reference instance. The simulation results also reaffirmed the energy viability of all studied scenarios. In terms of economy, the retrofit of the conventional split air-conditioning system and the use of a centralized variable refrigerant flow (VRF) system resulted in the most positive financial performance with payback periods of around 6–7 years and internal rates of return of 22% and 21%, respectively.

Higher temperature accelerates the deterioration of materials and reduces the conversion efficiency [31]. Therefore, effective thermal management is an important research trend. In recent years, many cooling solutions have been presented, among which passive cooling based on PCMs has received much interest due to its simplicity, reliability and low energy consumption. PCMs manage the operational temperature of PV modules by absorbing excess heat throughout the day through melting and subsequently releasing the heat to the environment when they solidify when the sun sets [32]. The thermal regulation mechanism of PCMs is mainly controlled by the latent heat storage. During times of high solar radiation, the absorbed heat is diverted to induce the phase transition rather than increasing the temperature of the module, which enables the PV panel to operate near to its optimal condition. Once the thermal load is lowered, which happens after sunset or throughout the night, the PCM releases the stored thermal energy, returns to its solid state and regains its heat storage capacity for the next operational cycle.

This temperature stabilization has many practical advantages over mere cooling. PCMs control excessive thermal fluctuations, which alleviates the thermal strains in solar modules, improves their operating stability and prolongs their lifetime. More importantly, the lower cell temperature immediately benefits the electrical performance as the power output of traditional PV modules usually drops by about 0.4–0.5% each 1°C increase over the optimum operational temperature [33]. Previous studies have demonstrated peak temperature reductions in the range of about 5 to 25°C, and can lead to up to 5% gains in electrical efficiency under optimal operating conditions [34] depending on the PCM properties and module arrangement. PV cells are generally inefficient in the high irradiation and high temperatures seen in the Global South. We introduce a self-regulating thermal buffer, a novel passive-cooling invention using a phase transition material. Therefore, PCMs absorb the extra heat as latent heat during the daytime and release it at night, improving the power production.

The application of PCMs in solar systems has shown significant promise to improve thermal control and electrical efficiency. Studies have reported temperature reductions of approximately 6–20°C for PCM-assisted PV modules, with corresponding electrical-efficiency gains of up to 15%, depending on the configuration and operating conditions [36]. Moreover, large-scale climate simulations showed that the correct use of PCM could increase the annual electricity generation of PV systems by more than 5% in many regions of Africa, Latin America and South Asia, highlighting the wide applicability of this passive cooling method in warm climatic conditions [37]. The studies have shown repeatedly that PCMs can considerably affect the thermal response of solar systems through the reduction of temperature variations and the delay of excessive heat build-up. The good results have made the PV-PCM technology an interesting thermal management method. The first studies focused on assessing the capability of PCMs to lower the operating temperature of PV modules, and consequently enhance their electrical performance under strong solar irradiation [38].

The numerical investigation of PCM based PV cooling with geometrically optimized fins was done by El Ouassidi et al. [39]. The panel temperature was reduced to 41.5 °C using PCM and 33.9 °C with fins, which is 22.8 °C lower than the uncooled case. The best performance was obtained by T-shaped fins that achieved the minimum surface temperature of 29.60 °C. Likewise, Japs et al. [40] studied the use of PCMs as a passive cooling solution for solar panels, indicating a temperature drop of about 7 °C and better temperature uniformity on the module surface. Their investigation also revealed that the presence of fins in the PCM container promotes the heat transfer between the PV module and the storage material, therefore enhancing the overall cooling performance. A key disadvantage of the typical PCMs is the comparatively low thermal conductivity. Therefore, the authors also highlighted the significance of developing composite PCMs by mixing phase change materials with highly conductive additives such as graphite, aluminum, or copper particles. These composite materials provide a better diffusion of heat and improve the general thermal responsiveness of the cooling system.

Using location-specific meteorological data, Smith et al. [41] performed an assessment of how the phase-change temperature of the PCM affects the overall performance of a PV system. Their analysis showed that even if the PCM melting temperature was not perfectly tuned, substantial improvements in annual energy production might still be gained. A part of the incoming solar radiation is converted to electrical energy and the rest of thermal energy is collected by the PCM mounted behind the PV module and stored as latent heat. This technique inhibits the increase in temperature of the solar panel during the operation of the day. Beyond passive cooling, the PV-PCM system exchanges heat with the ambient environment continually through convective and radiative mechanisms, which leads to a more stable and almost isothermal operating temperature.

Channouf et al. [42] numerically optimized a passive PV heat sink integrating multiple PCMs and fin structures. Increasing fin thickness from 1 to 3 mm reduced the maximum T_{PV} by about 5.5 °C. The optimum configuration with seven fins and a 10 mm RT-35/30 mm RT-25HC arrangement reduced T_{PV} by 16.29 °C. Likewise, Mahamudul et al. [43] scrutinized the viability of RT35 as a heat regulation medium for PV modules. In the computational models, the use of a 2 cm PCM layer reduced the module temperature by roughly 35°C, while in the experiments, the reduction was approximately 10°C as shown in Fig. 9.

Qu et al. [44] studied the effect of ambient temperature variation on temperature, output power and efficiency of PV panels combined with PCM The results show that the cooling effect decreases with the increase of ambient temperature, which indicates that PCM cooling and performance improvement effect is more significant at lower ambient temperature on PV panels. Technology advances, and the next research began increase its uses. The window system with the PV-PCM technology has produced a multipurpose building component that produces electricity and regulates the internal thermal climate at the same time. PCM integration can enhance the energy conversion performance of PV modules while contributing to the simultaneous management of daylighting, solar shading, and thermal conditions within buildings [45].

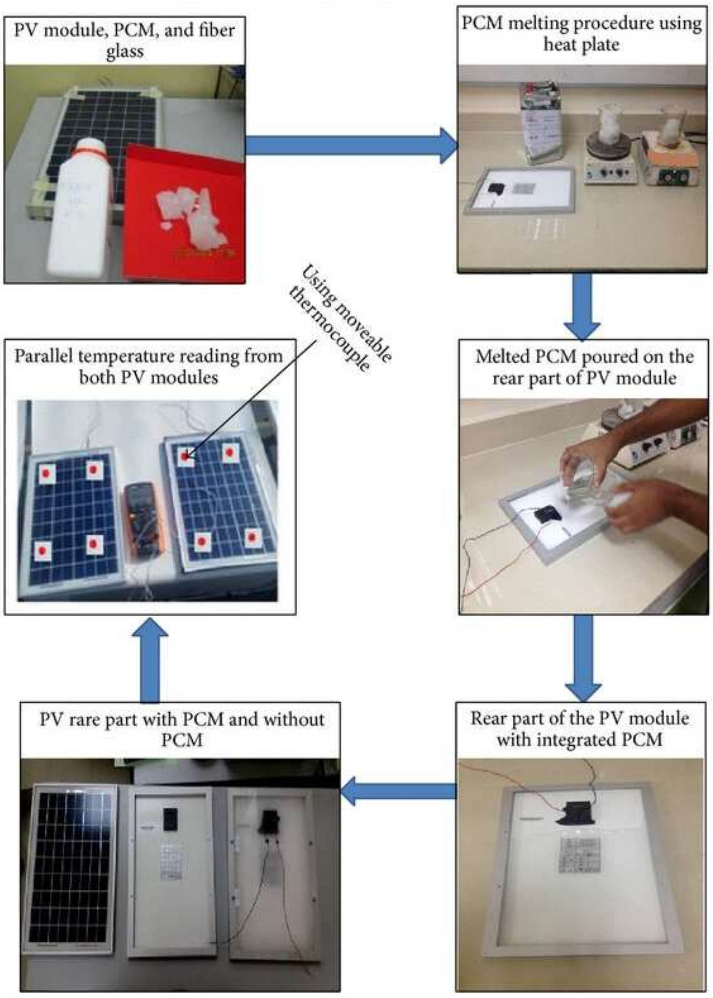

Fig. 9. Experimental setup related to thermal photovoltaic panel with PCM in the work of Mahamudul et al. [43].

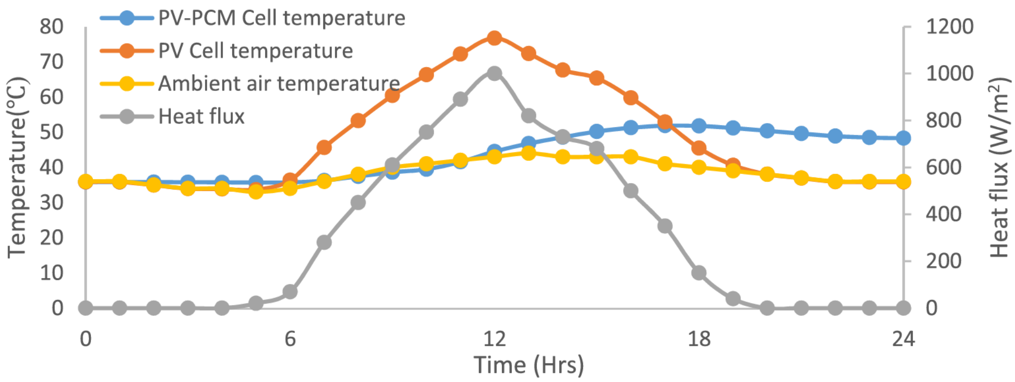

Fig. 10. Variations in ambient-air, PV-cell, and PV–PCM temperatures and heat flux over a 24-h period [49]

The experimental results have proved that PCMs have a positive impact in diverse climatic situations and system configurations. Stritih et al. [46] installed RT28HC behind PV panels and found a maximum temperature drop of 35.6 °C. Cuce et al. [47] designed and tested a passive PV cooling system, by combining a coral-inspired aluminum heat sink with nanoparticle-enhanced PCM. The hybrid arrangement was shown to lower the module temperature variation by 8-15 °C and to provide a maximum efficiency gain of 9.2% over the uncooled panel. An average efficiency gain of 5.6% was achieved under outdoor conditions, indicating a large potential for enhanced annual energy yield. Using RT25 as the PCM, Khanna et al. [48] numerically examined how variations in meteorological conditions, module orientation, and PCM melting temperature collectively influence PV system performance. Under the optimized operating conditions, the module temperature decreased by as much as 19 °C.

Besides choosing appropriate phase change materials, researchers have increasingly concentrated on refining the structural design of PV-PCM systems for improving heat transfer. Amalu et al. [49] statistically studied the usage of paraffin-based PCM and found that the improvement in thermal control may improve the PV conversion efficiency by 10.88% and reduce the PV cell temperature by 72.4%. The temperature behaviour of each individual system component during a full 24-h operation cycle is shown in Fig. 10. A solar chimney configuration equipped with a double-glass PV module was numerically examined by Sheikholeslami and Al-Behadili [50]. A 30°–60° increase in chimney inclination resulted in an approximately 15% rise in intake mass flow rate, while the use of porous foam increased the TES liquid fraction by 47% at 60°.

Foteinis et al. [51] assessed the long-term implications of using RT27 as a PCM for cooling of solar panels under the climatic conditions of Greece. They anticipated that the total electricity generation of PV modules with PCM-assisted cooling may be increased by about 9.4% over a service life of 25 years. It was expected that the thermal stress reduction will extend the operating lifetime of PV panels by at least five years in addition to enhancing energy generation. Using a solar simulator, Xu et al. [52] evaluated the thermal behavior of a paraffin-based PCM through indoor experiments performed under controlled conditions. The tests were conducted at an irradiance of 1000 W/m² and an ambient temperature of 7°C, with wind effects excluded from the experimental setup. The PCM reduced the highest module temperature by 36.5°C during a 5-hour working period.

El Kassar et al. [53] investigated that system performance depends not only on the choice of PCM, but also on the effectiveness of the associated heat transfer enhancement approach. Of the configurations reviewed, the heat sinks with integrated PCM performed best overall, yielding an electrical efficiency boost of almost 22%. The improved behavior is related to the combined thermal storage and structured heat transfer mechanisms which offer for an enhanced heat dissipation. Similarly, the hydrate salt HS36 system demonstrated impressive performance, boosting the power output by over 21% and improving the electrical efficiency by around 17%, showcasing its potent capacity to capture and store thermal energy during periods of abundant solar radiation. Commercial RT-series PCMs also exhibited robust performances consistently under practical operating settings with ~17% improvement in efficiency along with about 15% improvement in power output. Graphite nanoparticle loaded composite PCMs exhibited balanced gains of approximately 9% for both efficiency and power production, demonstrating the vital function of improved thermal conductivity in speeding heat transport inside the storage medium. In contrast, organic PCMs and nano-enhanced PCMs showed more moderate performance improvements. The organic PCMs only improved the electrical efficiency by ~4%, but they still obtained ~10% higher power output, indicating that these materials may be more effective under transient operating conditions. Nano-PCMs also gave measurable, but quite minor, improvements for both performance measures. In contrast, configurations using aluminum foam, finned PCM containers or paraffin jelly with expanded perlite showed only minor improvements in performance. In most cases the gain in electrical efficiency was less than 5% and the increases in power production were minimal or nil. These data indicate that the presence of PCM alone is not enough to provide significant thermal regulation unless it is combined with effective heat transfer channels. Taken together, these findings demonstrate that the incorporation of thermally conductive materials, enhanced heat-exchanger designs, or advanced structural configurations can play a crucial role in strengthening heat dissipation and, consequently, improving the electrical output of PV systems [53].

With the advancement of research of PCM-enhanced PV system, there is a growing interest to study the effects of the PCM properties and environmental parameters on the total system performance. Recent research has gone beyond the cooling capacity of PCMs alone, to the combined effects of design parameters, environmental conditions, and operational configurations to determine optimal system performance. Maghrabie et al. [54] placed RT-42 below PV panels to examine the impact of various tilt angles and PCM thicknesses on the temperature distribution, power production, and efficiency of the system (Fig. 11). The cooling effectiveness of PCM-assisted PV systems is strongly influenced by the surrounding thermal conditions. Under a module inclination of 30°, the configuration incorporating a 30-mm-thick PCM layer achieved an approximately 15.8% higher power output than the reference PV module.

Refaey et al. [55] scrutinized the temperature control of PV panels utilizing RT35 and RT42 under solar irradiation levels of 510, 680 and 850 W/m^2. Three fin geometries (semi-cylindrical, triangular and rectangular) were investigated to grow the heat transfer between the PV module and the PCM. The best cooling performance was obtained by the RT42 with the trihedral fins decreasing the temperature of the panel by 24% at the lowest irradiation level.

The literature also shows that the PV performance can be further enhanced by the improvement of the thermal conductivity of PCMs by composite materials. Govindasamy and Kumar [56] examined four distinct PV module layouts using paraffin jelly with different porous supporting materials. The systems studied were expanded graphite, expanded perlite and expanded vermiculite, besides a conventional PV module, utilized as reference case. The best thermal performance was seen in the configuration with expanded perlite and paraffin jelly (Module 2) which reduced the temperature of the module surface from 57.5°C to 48°C. The rise in electricity efficiency from 11.97% to 14.10% during the midday operation period paralleled this improvement in thermal control. The observed results further confirm that the choice of suitable supporting materials for composite PCMs is of great importance to improve the heat dissipation and maximize the electrical performance of PV systems.

Numerical and experimental research have thoroughly explored the influence of PCM thickness and melting temperature on the thermal and electrical performance of PV-PCM systems. Using numerical simulations, Zhao et al. [57] evaluated a PV module coupled with a 30-mm-thick layer of RT35 PCM. Their analysis demonstrated that PCM integration lowered the module operating temperature by approximately 24.9°C and resulted in an 11% increase in electrical power generation. The thermal regulation capabilities of the proposed design were promising but the optimization was confined to the thickness of the RT35 container from 10 mm to 30 mm (Fig. 12).

1- PV panel. 2- PV-PCM panel. 3- Infrared camera. 4- Multimeter. 5- Pyranometer.

Fig. 11. Real photo of the experimental set-up of PV and PV-PCM panels. [54].

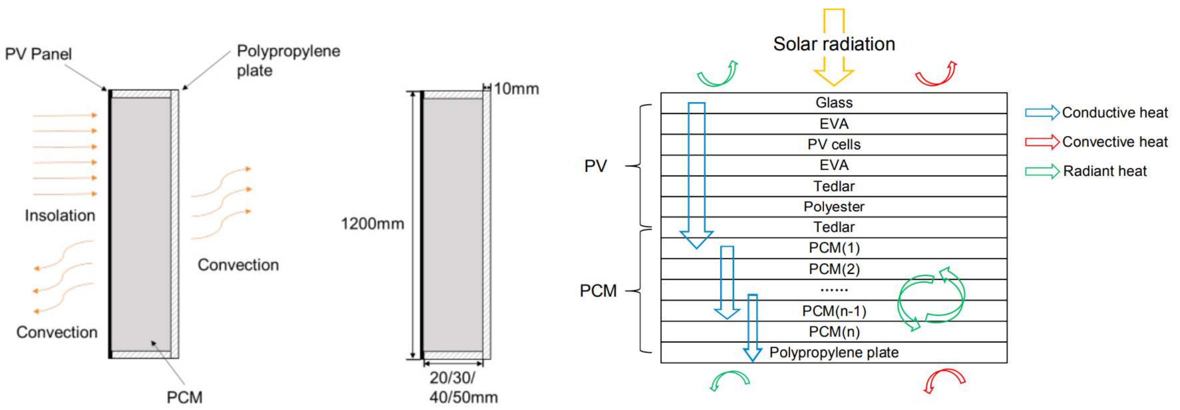

Fig. 12. System configuration of the PV-PCM system [57].

The numerical investigation of CPV cooling utilizing a PCM-based heat sink embedded with 3% and 5% CuO nanoparticles was conducted by Vatandoust et al. [58]. The optimal thermal performance was observed at 5% CuO content, which decreased the PV cell temperature by 11°C. So, the electrical efficiency raised from 2.55% for pure PCM to 3.37% for 5% CuO nanoparticles.

3. Recent Advances in PCM-Assisted PVT Systems

Conventional photovoltaic technology is inherently limited by the relatively small fraction of incident solar radiation that can be converted into electricity. This limitation is primarily associated with the fundamental energy-conversion characteristics of semiconductor materials, particularly their bandgap. As a result, commercially available PV modules generally exhibit electrical conversion efficiencies of approximately 12–18%, while more than 80% of the incoming solar energy is either reflected or ultimately dissipated within the cell as thermal energy. For the production of electric power, a great part of the incident solar energy is wasted, and contributes to heat build-up in the PV cells. However, the rising cell temperature continuously damages PV performance. The warmest cell in a series-connected module will typically control the electrical output of the string. This is because as the temperature increases the conversion efficiency of individual cells decreases, the current generated is limited and the overall power output is reduced. Therefore, keeping the operating temperature low is important not only for boosting electrical efficiency but also for reliable module functioning. To reduce such thermal losses, different cooling approaches have been developed. Liquid- and air-based cooling systems are the most used among them. These methods enhance the electrical performance by extracting surplus heat from the PV module and simultaneously render the reclaimed thermal energy available for practical purposes. This principle forms the basis of PVT, in which photovoltaic and solar-thermal conversions are integrated within a single collector. By utilizing the available solar radiation for simultaneous heat recovery and electricity generation, PVT systems can achieve a higher overall solar-energy conversion per unit collector area than either conventional PV modules or separate solar-thermal collectors [3].

The use of PCMs in PVT systems is mainly targeted to achieve effective TES and regulated heat release by the phase transition process. When the solar irradiation is high, they can absorb the extra thermal energy and release it when the operating temperature is low, reducing the temperature swings in the PV modules and improving the overall photoelectric and photothermal performances of the system. Therefore, the effective use of PCM assisted PVT systems essentially depends on the choice of materials having thermal properties appropriate with the operational needs of the system. The selection of a suitable PCM in general must satisfy two major design requirements. First, solar modules are most effective at a relatively low temperature range, generally between 25° and 40°C. If the cell temperature is above or below this range, the electrical conversion efficiency can drop by around 10-20%, depending on the solar technology used. The second is that the recovered thermal energy must be provided at temperatures suitable for low- and medium-temperature applications, such as household hot water production and space heating, where the heat transfer fluid in general is required to function in the range of 35–60°C. These operating restrictions define the basic requirements for the selection of PCM materials for PVT applications. Other thermophysical features, such as latent heat storage capacity, thermal conductivity, charging and discharging characteristics, and long-term thermal stability are of equal importance for reliable system operation. Besides, the climatic conditions prevailing at the place of installation should be considered while selecting. For regions characterized by intense solar irradiation and substantial day–night temperature fluctuations, PCMs with high latent heat capacity and enhanced thermal conductivity are particularly suitable, as they facilitate rapid heat uptake during daylight hours while enabling controlled thermal discharge during the subsequent nighttime period. Conversely, PCMs with substantially higher phase transition temperatures and good stable performance at low temperatures are more preferable for colder locations to ensure reliable thermal storage performance and avoid the degradation of phase change process at low ambient temperatures [58,59].

Maarof et al. [60] proposed a novel PVT configuration using PCMs with wavy fins (PVT-PCMWF) and compared the performance with a typical PVT-PCM system. The undulating fin structure increased the heat flow between the PV module and the PCM, leading to a more effective thermal management mechanism. The suggested PVT-PCMWF system decreased the average PV cell temperature by 5.8%. The thermal performance showed substantially more enhancement with an increase of thermal efficiency of around 685% demonstrating the major role of modified fin shape in heat recovery.

Sheikholeslami and Mustafa [61] numerically studied a PVT system cooled by RT-35HC paraffin enhanced with Al_2O_3 nanoparticles, sinusoidal fins, and copper foam under realistic weather conditions. The optimized configuration reduced T_{PV} by 3.11% and increased LF by 114.56%. It achieved an overall efficiency of 98.36% compared with 66.47% for the baseline system and improved electrical efficiency by 15.43% relative to an uncooled PV panel.

Tashtoush and Al Ghadi [62] numerically investigated two PVT-PCM configurations with water tubes positioned above or below a stearic acid–MOF composite PCM layer under 24-h real weather conditions in desert and non-desert regions (Fig. 13). System A achieved a maximum cumulative electrical output of 3095.81 W/day in Ma'an with a 3-cm PCM layer, whereas System B provided superior nighttime thermal performance and latent heat retention. Higher flow rates reduced the heat storage by the PCM and the outlet-water temperature. This shows the considerable influence of system configuration and climatic conditions on continuous energy production.

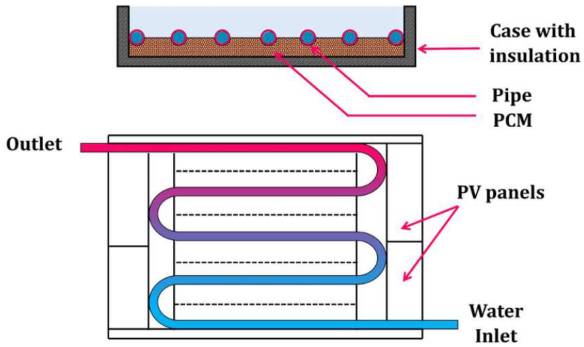

Fig. 13. PVT-PCM unit utilized in Mondal et al. [71].

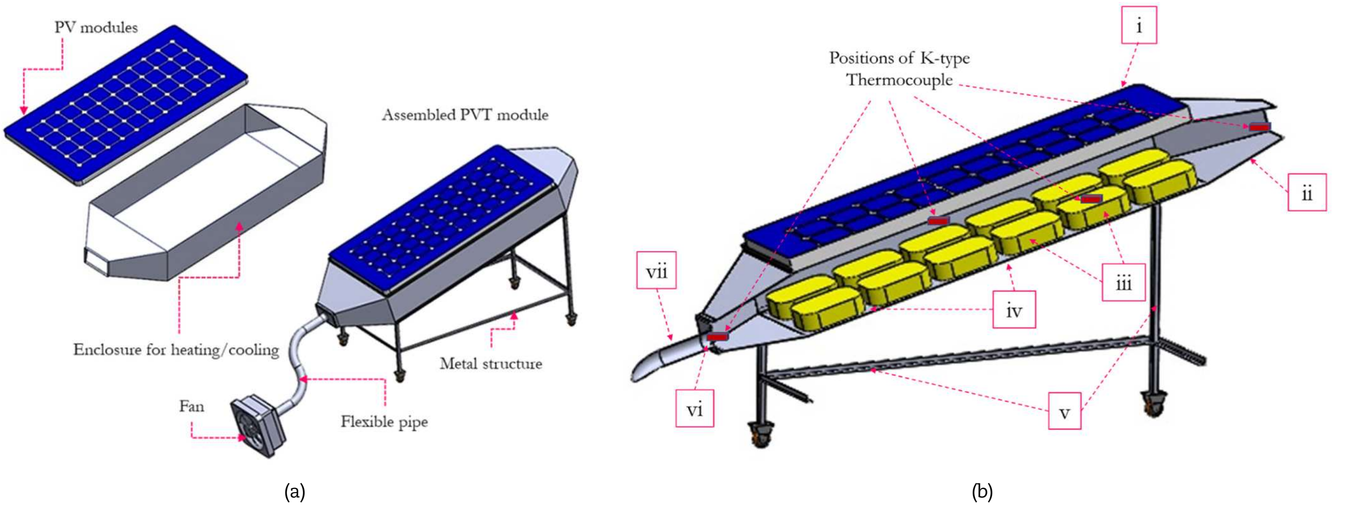

Fig. 14. Configuration of the dual-purpose PVT module for heating and cooling; (a) schematic representation of the system and, (b) cross-sectional view showing the embedded thermocouples and PCM-filled main enclosure [66].

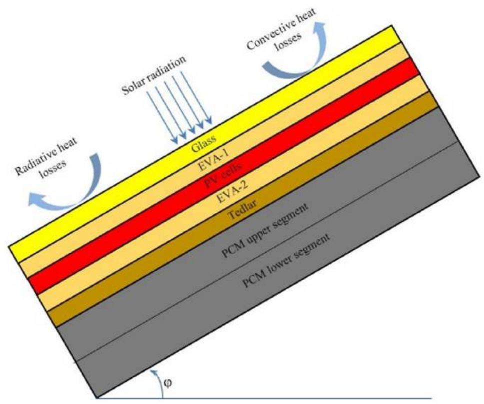

Fig. 15. Schematic diagram of the PVT-PCM assembly components [67].

Abdelgaied et al. [63] studied an integrated sun drying and desiccant air-conditioning system with a PVT collector, PCM storage, solar concentrator and waste-heat recovery. The system succeeded in maintaining the indoor temperature at roughly 14.5 °C with a regeneration airflow rate of 400 m³/h, a cooling load of 10.6 kW and a COP of 1.8. Waste-heat recovery increased the dryer inlet temperature by 50.6% and shortened the drying time by 50.3%. Sheikholeslami [64] numerically investigated a concentrated PVT system employing paraffin, MWCNT nanoparticles, nanofluid cooling, and different fin geometries under various Reynolds numbers. The short-base arrow fin configuration provided the highest useful heat and electrical efficiency. Adding MWCNT nanoparticles increased useful heat by about 9.58% at the highest flow rate, while increasing Reynolds number enhanced electrical efficiency by approximately 3.72%. Gad et al. [65] presented a PVT system with a concentration, employing indirect PCM pre-cooling, to boost the electrical, thermal and hydrogen generation performance. The PCM integration improved the generated power by 1.2% for summer operation, while the increase of concentration ratio from 1 to 4 improved the power output by 200.8%. The PVT/PCM setup was projected to have a hydrogen production cost of $7.88/kg. Fakhraei et al. [66] designed a dual-purpose PVT-PCM collector using CaCl2.6H2O for passive heating and cooling, and experimentally validated it using CFD simulations in ANSYS Fluent (Fig. 14). The proposed system increased the cooling efficiency by 11.28%, the power-generation efficiency by 4.23% and the heating efficiency by 18.86%. The measured PCM solidification period was approximately 130 min, compared with about 120 min predicted by the numerical model.

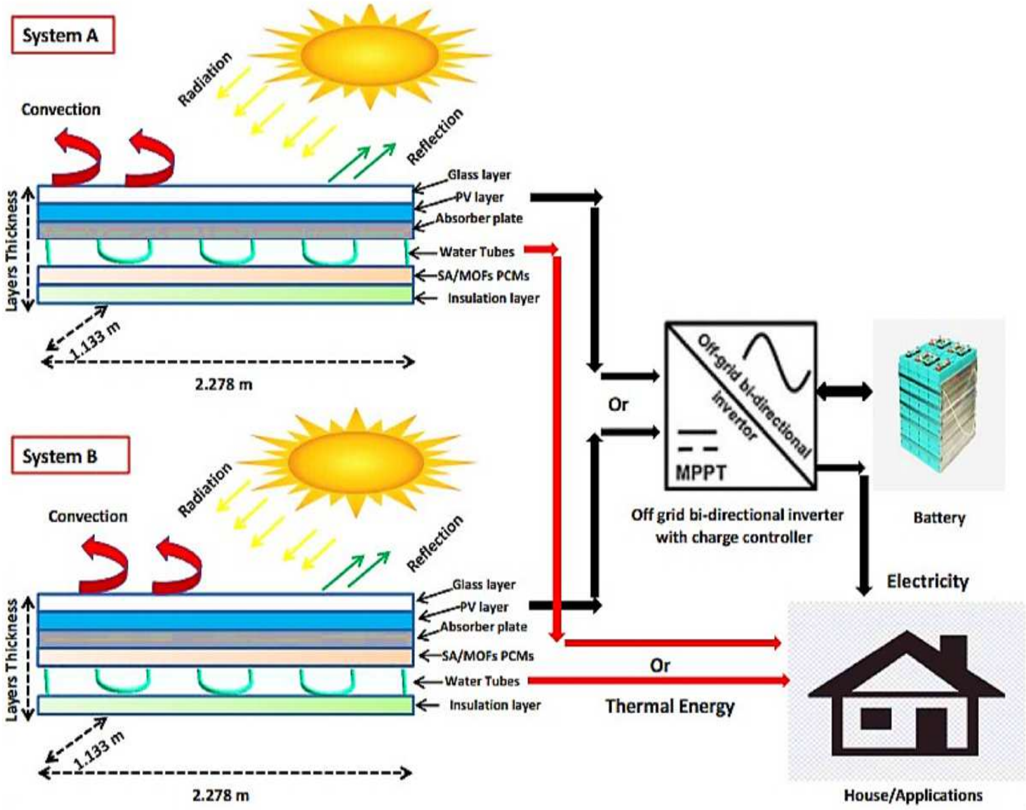

Fig. 16. Diagram of the current systems Tashtoush and Al Ghadi [62].

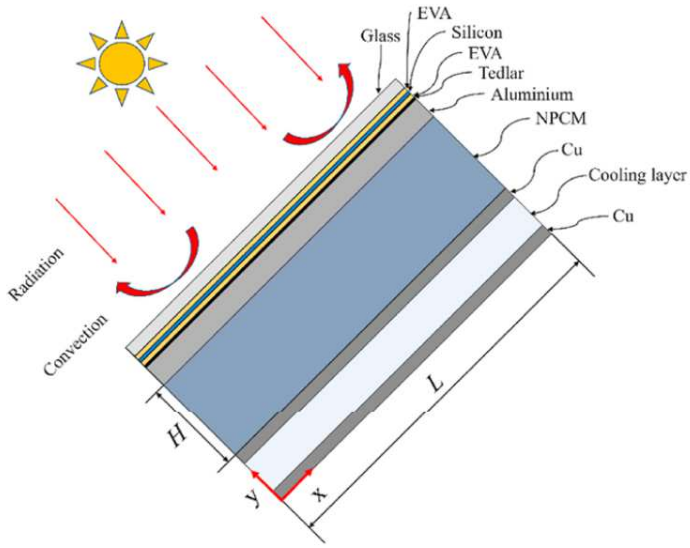

Fig. 17. PVT system integrated with NPCM [72].

Al-Najjar et al. [67] established a numerical thermodynamic model based on Nu correlations to study energy and exergy performance of PCM-integrated PVT collectors under various operating and environmental circumstances (Fig. 15). Thermal exergy reduced dramatically from 10.1 to 0.34 W with the increase of ambient temperature from 0 to 35 °C, which indicates the high sensitivity of thermal performance to the ambient conditions.

Li et al. [68] provided a hybrid PVT-PCM solar collector to satisfy the varying energy demands of building-integrated applications. The proposed system combined air- and water-based operating modes to provide building heating under different seasonal conditions, while the incorporated PCM stored the excess thermal energy that could not be removed by the heat transfer fluid. Seasonal performance evaluation demonstrated that the system achieved an overall perfomance of 39.4%.

Fu et al. [69] devised and experimentally tested a PVT system using microencapsulated PCM (MPCM) slurry as the cooling fluid. The electrical and thermal performances of the proposed system are compared with those obtained by using tap water under different operating circumstances. Increasing the flow rate of the MPCM slurry enhanced heat removal from the PV cell, thereby lowering its operating temperature. The MPCM slurry demonstrated better overall performance than both pure tap water and the conventional water–PCM configuration. In particular, the average electrical efficiency and maximum thermal efficiency increased by approximately 0.8% and 13.5%, respectively.

Fig. 18. Schematic representation and photograph of the experimental setup used to evaluate photovoltaic panel performance, (a) Schematic diagram of experimental setup, (b) Photo of experimental setup, (c) Lamps, (d) Integrated PV panel thermal storage container, (e) Copper plate, (f) 12-channel thermometer, (g) 4-channel thermometer, (h) Solar meter [74].

Kilkis [70] introduced a PV system featuring a composite configuration and described several application examples. Once the auxiliary elements are incorporated, the composite PVT module is finalized by placing a flat-plate collector layer above it. A built-in network of pulse-controlled heat pipes regulates the heat flux so that the overall exergy yield, including both electrical power and thermal energy, remains at its optimum level. This PVT panel arrangement removes the need for external thermal storage, coolant circulation pumping, and the parasitic losses associated with such components. During a representative summer month, the combined exergy output (power and heat) was twice that of a standard PVT unit. These findings were further interpreted in relation to evolutionary recommendations. The study also stressed the significance of the exergy-levelized panel cost as the basis for the development of a fundamental, dedicated, widely acknowledged and independent approach for the rating of PVT system performance.

Mondal et al. [71] experimentally evaluated a heliostat-field-assisted PVT collector incorporating stearic acid as the PCM, both in its pristine form and with carbon-black enhancement, while varying the water flow rate (Fig. 16). The PV efficiency was 10%–13% and the greatest thermal efficiency was 46.56% with carbon-black-enhanced PCM as compared to 45.45% with pure stearic acid at 0.0035 kg/s. Carbon black boosted the average thermal efficiency by 6.83%.

Chen et al. [72] developed a transient two-dimensional heat-transfer model to investigate a PVT system incorporating NEPCM and intermittent nanofluid cooling, with the objective of enhancing the photovoltaic conversion efficiency (Fig. 17). Intermittent cooling reduced the pumping demand associated with circulating 2,220 L of nanofluid over a 7-h operating period, while the system achieved an average electrical efficiency of about 19.7%. Moreover, this approach exhibited a similar performance with the continuous cooling with a maximum variation of 0.0348%.

Tashtoush et al. [73] constructed a hybrid PVT-PCM-FO-MD system for brackish water desalination. The system can produce freshwater continuously for 24 h using solar energy. Owing to thermal storage by PCM and electrical storage by batteries, the system maintained stable nighttime operation as well. The results showed that a PCM thickness of 2 cm provided the highest water production, reaching 213.25 L over 24 hours, while the membrane distillation (MD) efficiency was 83.78% during the day and 37.07% at 3:00 a.m. In addition, the initial salinity of the feed water and the concentration of the draw solution had only a negligible effect on the freshwater production rate.

Bai et al. [74] scrutinized a passive PV cooling system using a combination of serrated fins and shape-stabilized PCM with walnut-shell charcoal and graphene nanoplatelet (Fig. 18). The optimized design, incorporating eight fins and a 10 wt% hybrid filler, achieved a 24.82°C reduction in PV temperature and increased the η_{PV} by 1.45 percentage points.

Sheikholeslami and Alinia [75] performed the simulation of a CPVT system which comprises RT-28HC paraffin, a thermoelectric module, water-based cooling, reflectors and finned thermal storage. The highest heat storage and electrical power generation were achieved in the investigated configurations of a parabolic reflector with seven fins. The maximum overall system efficiency attained for this setup was 68.37%. Yang et al. [76] studied the effect of five heat-sink fin designs on the enhancement of convective heat transfer and the overall performance of a double-pass PVT system. The optimum design gave an overall efficiency of 49.02% to 66.58%, with a PV efficiency of 13.3% and thermal efficiency more than 53% at the maximum airflow rate. Hamed et al. [77] experimentally assessed a passive cooling approach for PV modules that combined PCM with alumina nanoparticles and semicircular rod-shaped fins. The best SCR configuration resulted in a 62.3% relative temperature reduction of the module end temperature, from 89.0 °C to 51.0 °C. With the addition of 1.0 wt% Al_2O_3, the reduction was further improved to 65.9%, the final temperature decreased to 48.8 °C, and the operation at below 45 °C was extended by 35 min. Arifin et al. [78] performed a systematic review and meta-analysis encompassing 50 experimental and numerical studies to evaluate the application of hybrid nanofluid–PCM cooling strategies in PVT systems. The hybrid setups give average gains of 3.10% in electrical efficiency and 5.50% in thermal efficiency. The investigation by them revealed that the combination of nanofluids and PCM was generally better than the single-mode cooling techniques.

Khan et al. [79] conducted experimental studies on spatially distributed ternary PCM to delay melting and enhance the PV performance during peak sun hours. For their PV-PCM setup, the temperatures stayed quite uniform, with a maximum temperature differential of just 0.64 °C between the PCM-covered portions and the uncovered regions. The system raised the voltage by 0.32 V and a maximum average power gain of 4.16%. Juwana et al. [80] performed a systematic analysis of 42 papers on fin–PCM cooling for solar systems published between 2020 and 2025. Fin–PCM integration increased thermal efficiency by up to 18.7%, reduced peak PV temperature by as much as 15 °C, and provided an average electrical efficiency gain of 2.8%. Economic analysis indicated that reducing additional costs below $250/kW and increasing thermal efficiency beyond 22% could yield an IRR of approximately 28%. Soliman and Cheng [81] conducted a numerical assessment of a concentrated PV–PCM system coupled with an H_2O–LiBr absorption cooling cycle. The incorporation of PCM enabled the absorption system to remain operational for nearly two additional hours after sunset and yielded a thermal output of 198.03 W. At 12:30 p.m., this represented a 162.75% increase in thermal power relative to the configuration without PCM.

Ali and Abdel-Rehim [82] analyzed numerically PCM enclosures of pyramidal shapes for the improvement of thermal performance of PV modules under realistic weather conditions of Cairo. The optimization of the 15-enclosure arrangement has lowered PCM usage by 23.55% without compromising the PV performance. Abedanzadeh et al. [83] evaluated the techno-economic feasibility of a CPVT designed to supply the thermal requirements of a commercial building in Iran, while directing the excess electricity generated to the electrical grid. The system generated an NPV of $551.55k, an IRR of 150.79%, a benefit to cost ratio of 10.32, and a payback period of about 0.51 years. IRR still stayed at 120.63% with a payback period only extended to 0.63 years, reduced with 20% in generated energy. Sheikholeslami and Alturaihi [84] designed a sophisticated CPVT system with a parabolic concentrator, RT35 paraffin with porous foam and U-turn water channels to improve heat control. The η_{PV} was increased by 16.22% with a maximum value of 13.36% by the cooling design.

Kibria et al. [85] developed a hybrid PVT solar still system using a nano-enhanced PCM consisting of paraffin, graphene, Al_2O_3 nanoparticles, and radial metal mesh. The enhanced PVT module could reach a maximum total energy efficiency of 92.05%. The fresh water production has been improved by 60.22% and the electrical efficiency has been boosted by 24.09% compared with the standard system. Chouchane et al. [86] studied a ribbed PVT solar dryer coupled with PCMs and optimized the performance using the NSGA-II method. The integration of PCM lowered the T_{PV} from 68.4 °C to 55 °C and improved η_{th} by 52.99%. The final moisture content was reduced to 0.216 dry basis than 0.337 without PCM. The optimized system resulted in a payback period as low as 0.21 years and up to 17.99 tons of CO_2 in 25 years avoided. Hao and Tai [87] experimentally studied seven PVT configurations with PCM, water, TiO2, and ZnO nanofluids and used machine-learning models to predict performance. The maximum η_{PV} of the PVT-PCM-TiO2 system was 19.02% compared to 11.46% for the standard PVT while the total and exergy efficiencies were 47.13% and 17.83%, respectively. The maximum hydrogen generation was 99 .2 mL/min. The R2 values of the ML models were higher than 0.96.

4. Conclusions and Future Perspectives

The fast growth of PV technologies has consolidated their place as one of the most essential RE alternatives to meet the growing global need for sustainable electricity. However, the working temperature of PV modules still greatly affects their efficiency, therefore thermal management is a key issue for increasing both short-term performance and long-term durability. This study presents recent progress in PV and PVT technologies, focusing on the use of PCMs as passive temperature management and energy storage medium. A survey of the literature shows that the use of PCM technology in PV and PVT systems has evolved from a simple cooling concept to an integrated strategy to improve the electrical performances, to recover the thermal energy and to improve the overall solar radiation utilization at the same time.

The studies evaluated all indicate that adding PCMs in PV systems is an efficient way of suppressing excessive temperature rise under high solar irradiation. This results in solar modules operating closer to their optimum temperature range, resulting in higher electrical efficiency while decreasing thermal stresses responsible for material degradation and long-term performance losses. However, the stated gains are very variable from one experiment to another, emphasizing the fact that the effectiveness of PCM-based cooling cannot be simply attributed to the PCM selection. Rather, the system performance is governed by the interaction of PCM properties, module arrangement, thermal augmentation techniques, ambient circumstances and operating settings. Thus, the optimum selection of a PCM is dependent on a detailed understanding of the target application, and not merely the melting temperature as the only design parameter.

The review also reveals that significant advances have been made to overcome the intrinsic constraints of conventional PCMs. Many researchers have boosted the heat transfer with the addition of fins, heat pipes, metallic structures, nanoparticles, graphite-based additives and optimal encapsulation designs. These trends suggest that future progress is more likely to be achieved through integrated thermal management solutions rather than solely through advancements in PCM materials. Beyond typical PV applications, the combination of PCMs with PVT collectors offers other possibilities to maximize the whole usage of solar energy. Unlike stand-alone PV modules, PVT systems recover a significant fraction of the waste heat created during electricity generation and turn it into useable thermal energy. The reviewed studies reveal that the PCM-assisted PVT systems are not only stabilizing the PV's operating temperatures but also improving the thermal storage capability, making them attractive for application in domestic hot water production, space heating, solar cooling, desalination and other low-temperature thermal processes.

Despite the remarkable advances gained in PCM-assisted PV and PVT systems, there are still significant technological and practical challenges that hinder their transition into large-scale commercial implementation. Major issues include limited thermal conductivity of the traditional PCMs, phase segregation, super cooling, leakage, endurance of the encapsulating system, and uncertainty of the long-term thermal and cyclic stability. Moreover, much of the current literature is based on laboratory scale trials or rather short-term monitoring periods, which hinders the assessment of seasonal performance and long-term reliability under genuine outdoor settings. From the perspective of commercialization, then, more attention should be paid to the durability of the materials, the complexity of the system, the need for maintenance, scalability, and the tradeoff between the higher cost of the PCM integration and the improvements in electrical and thermal performance. Hence, techno-economic analysis, life-cycle assessment and environmental impact analysis are necessary to confirm that the performance enhancements reported at the laboratory scale may be translated into economically feasible large-scale applications.

Emerging research tendencies are toward integrated thermal-management technologies rather than single-component solutions. A particularly crucial direction is the development of composite PCMs with higher thermal conductivity, advanced encapsulation techniques, better fin and heat-exchanger geometries, and hybrid PV/PVT-PCM designs. Further investigations should also be aimed at long-term outside validation under various climatic conditions, consistent performance-assessment techniques and system-level optimization in terms of electrical and thermal outputs. Numerical optimization, machine-learning based techniques and predictive control strategies may further enhance the adaptation of PCM-assisted systems to continuously changing environmental and operating conditions. To summarize, future advancement will rely not only on the improvement of PCM properties, but also on the simultaneous addressing of thermal performance, durability, economic feasibility, environmental effect and system integration. Such a multidisciplinary approach will be critical for taking PCM-assisted PV and PVT technologies from the experimental-demonstration phase to practical and economically viable solar-energy systems.

Author Contributions

Author 1 planned the scheme, initiated the project, and suggested the experiments; Author 2 conducted the experiments and analyzed the empirical results; The manuscript was written through the contribution of all authors. All authors discussed the results, reviewed, and approved the final version of the manuscript.

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Conflict of Interest

The authors declared no potential conflicts of interest concerning the research, authorship, and publication of this article.

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Data Availability Statements

No new datasets were generated or analyzed in this review article.

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ORCID iD

Author 1 https://orcid.org/0000-000x-xxxx-xxxx
Author 2 https://orcid.org/0000-000x-xxxx-xxxx

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