

A Review of Heat Dissipation and Absorption Technologies for Enhancing Performance in Photovoltaic–Thermal Systems

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Abstract: With the growing demand for photovoltaic (PV) systems as a source of energy generation that produces no greenhouse gas emissions, effective strategies are needed to address the inherent inefficiencies of PV systems. These systems typically absorb only approximately 15% of solar energy and experience performance degradation due to temperature increases during operation. To address these issues, PV–thermal (PVT) technology, which combines PV with a thermal absorber to dissipate excess heat and convert it into additional thermal energy, is being rapidly developed. This review presents an overview of various PVT technologies designed to prevent overheating in operational systems and to enhance heat transfer from the solar cells to the absorber. The methods explored include innovative absorber designs that focus on increasing the heat transfer contact surface, using mini/microchannels for improved heat transfer contiguity, and substituting traditional metal materials with polymers to reduce construction costs while utilizing polymer flexibility. The review also discusses incorporating phase change materials for latent heat absorption and using nanofluids as coolant mediums, which offer higher thermal conductivity than pure water. This review highlights significant observations and challenges associated with absorber design, mini/microchannels, polymer materials, phase change materials, and nanofluids in terms of PV waste heat dissipation. It includes a summary of relevant numerical and experimental studies to facilitate comparisons of each development approach.



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1. Introduction

Over recent decades, the escalating energy demands have paralleled technological and industrial advancements [1]. This surge has led to an increased reliance on fossil fuels as the primary energy source across various industries [2]. Besides their finite availability, fossil fuels have significantly contributed to carbon emissions, totaling 37.5 GtCO₂ in 2022, thereby exacerbating global warming [3]. In response, ongoing research efforts aim to identify renewable energy alternatives to replace traditional commercial fuels.

Among the several renewable energy sources, including hydropower, bioenergy, geothermal, and wind energy, solar energy, harnessed through photovoltaic (PV) technology, has emerged as a leading solution in renewable energy development [4]. Annually, the solar energy potential is approximately four million exajoules, positioning it as a superior energy alternative due to its abundance and reduced greenhouse gas emissions [5]. According to the International Renewable Energy Agency [6], photovoltaics rank as the second most installed renewable energy source, trailing only hydropower (excluding pumped storage). In 2022, the installed PV capacity reached 31.2%, marking a 3% increase from the previous year [6]. As depicted in Figure 1, electricity production via PV technology

has been on an upward trajectory in every region, highlighting the growing public interest and the anticipated continual rise in demand. The versatility of PV technology, evident in its applications ranging from personal wearable devices to transportation and building systems, further fuels its demand [7].

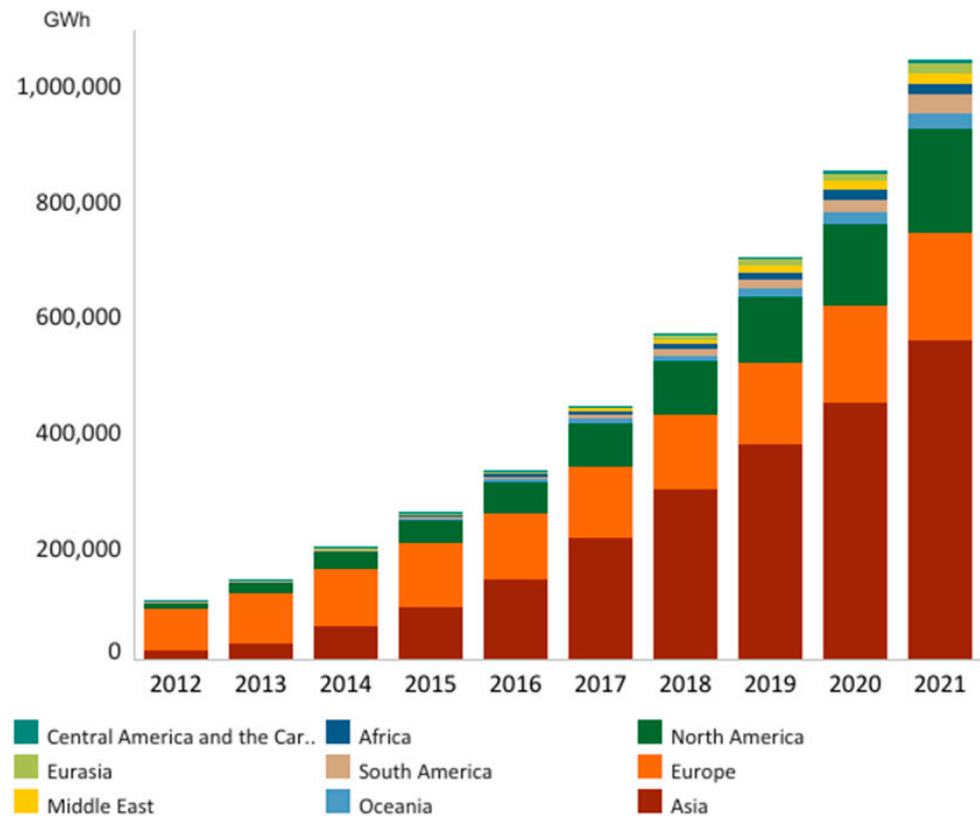


Figure 1. Rising global electricity generation by photovoltaic technology [6].

As shown in Figure 2a, PV technology operates by capturing sunlight photons on solar cell surfaces, initiating electron movement, and creating electron–hole pairs within the material [8]. These electrons and holes migrate towards their respective material ends, influencing the internal electric field and generating a current. Given the relatively low power output of individual solar cells, an assembly of multiple cells is necessary for adequate power generation. However, solar cell arrays remain delicate and susceptible to damage over prolonged outdoor exposure [9]. Figure 2b illustrates the use of materials such as Tedlar polyester Tedlar (TPT) and ethylene vinyl acetate (EVA)—a polymer compound for sealing, insulating, and waterproofing—in constructing PV systems. The system’s top layer is typically glass-covered to prevent surface damage from external elements. Recent studies have explored polymer materials for PV covers to optimize photon absorption and leverage polymer construction benefits [10–14].

As advancements continue, experts are refining PV technologies to optimize their performance. These developments include adjustments to the cells themselves, such as crystalline silicon solar cells in the first generation and thin-film, copper indium gallium di-selenide, amorphous silicon, and single-junction gallium arsenide cells in the second generation [15]. While crystalline silicon PV cells are predominantly used commercially because of their ease of manufacture, other types remain under research. Additionally, enhancing PV performance has involved the implementation of solar trackers, which can harvest more sunlight throughout the day regardless of the inclination angle [16], and hybrid systems that combine PV with other renewable energy sources to generate increased power [17].

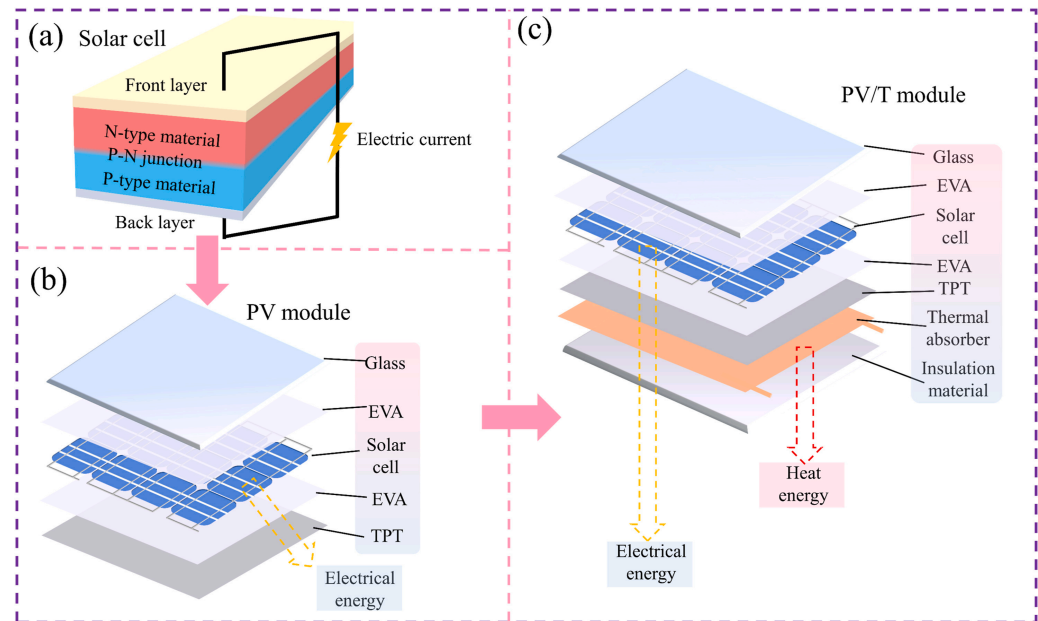


Figure 2. Typical structure of (a) solar cell, (b) photovoltaic module, and (c) photovoltaic–thermal module [8].

Despite these advancements, PV systems typically achieve a maximum efficiency of only 15%, implying that 85% of solar energy remains unutilized in the conversion process [18]. A primary challenge in PV efficiency is the overheating caused by outdoor exposure. PV system efficiency decreases by approximately 0.4–0.5% for every 1 °C increase in temperature due to increased solar irradiance [19]. Furthermore, solar cell temperature can also rise due to dust accumulation on the surface [20]. Although regular dust cleaning is essential maintenance, it does not entirely prevent performance degradation due to shading [21]. The use of materials such as EVA in photovoltaics can lead to performance and lifespan degradation when temperatures rise to 85 °C [22,23]. Additional ambient conditions impacting PV performance are discussed in detail in a previously published article [24].

Consequently, numerous studies have been conducted to address the temperature challenges in PV systems [25–28]. One approach involves integrating PV systems in floating plants and solar tracking systems [29]. This design allows water beneath the PV installation to reduce heat, while the solar tracker enhances solar energy harvesting by adjusting the PV surface to follow the sun’s direction. However, this approach represents a large-scale application of water immersion cooling techniques [30]. Surface temperature reduction in PVs has been attempted using pulsed-spray cooling water [31]. This method, while conserving water compared to continuous spraying, does not match its electrical power output efficiency. A passive cooling method that achieved a 12% reduction in PV module temperature involved the use of fabricated aluminum heat spreaders, cotton wicks, and headers [32]. Additionally, evaporative cooling utilizing a system made of copper and covered with synthetic clay has been explored [33]. The findings indicate that the thickest clay layer was most effective in heat rejection, with a maximum output voltage enhancement of 19.4%.

Beyond the previously mentioned PV cooling system technologies, innovative methods for reducing PV temperatures include employing a thermal absorber, known as PV-thermal (PVT) [34]. Essentially, this involves improving a standard PV system with thermal absorber equipment, which transfers excess heat to a working fluid that can be harnessed as thermal energy, as depicted in Figure 2c. Incorporating a thermal absorber into a PV system can result in greater power generation compared to a standalone PV system [35]. Elevated temperatures in PV systems increase the fill factor of currents and decrease open-circuit voltage, leading to a decline in electrical performance [36]. Hence, the integration of thermal absorbers is vital to prevent such performance degradation. The aim of this paper is to examine review articles on PVT technology, categorizing them based on employed methods to provide a reference for future research in this field. This review will focus on five key areas of PVT development—redesign of absorbers, mini/microchannels, polymer materials, phase change materials (PCMs), and nanofluids—enabling a comparison of each study's achievements. Additionally, considering the thermal change phenomena central to this discussion, related articles on solar collectors, which operate similarly to PVT thermal absorbers, will also be included.

2. Fundamentals of PVT Systems

2.1. Principle of PVT Systems

As discussed earlier, PVT technology aims to harvest excess waste heat from solar cells and mitigate overheating issues that diminish the electrical performance of PV systems. The evolution and research in PVT technology have led to a diverse range of solutions tailored to meet market demands and optimize performance. Noro et al. [37] categorized PVT systems based on the heat extraction medium, including air-, liquid-, heat pipe-, PCMs-, and thermoelectric-based systems. They noted that liquid-based PVT collectors are more efficient in terms of thermal performance, facilitating more uniform temperature distribution owing to the higher heat capacity and heat transfer coefficient of liquids compared to gases. Further expanding on classifications, Oh et al. [38] provided a broader categorization encompassing various systems based on the medium of heat extraction, type of heat extraction, solar input, system configuration, and the use of spectrum filters. Additionally, Figure 3 describes both conventional and novel PVT system techniques, along with their integration into various application areas [39–46].

Several factors, known as key performance indicators, can influence PV performance. These indicators may be affected by variables such as weather conditions, cable issues, shading, linking, and circuitry [47]. However, the parameters typically used to evaluate PVT performance include solar cell temperature, thermal efficiency, electrical efficiency, and overall efficiency [48,49]. These parameters can be influenced by factors such as solar irradiance, the mass flow of the working fluid, and the amount of dust accumulation. Given that PVT systems are used in open space installations, surrounding conditions, particularly solar irradiance, play a crucial role [50]. Higher solar irradiance intensity leads to decreased overall system efficiency [51]. PVT performance can decline due to dust accumulation if regular cleaning is not performed [52]. The accumulation of dust can also be mitigated by adjusting the inclination angle. However, the optimum tilt angle should be determined based on the installation area to maximize solar radiation capture while simultaneously reducing dust buildup [53]. Therefore, both the tilt angle and dust management strategies must be carefully balanced to optimize solar radiation absorption and minimize dust accumulation.

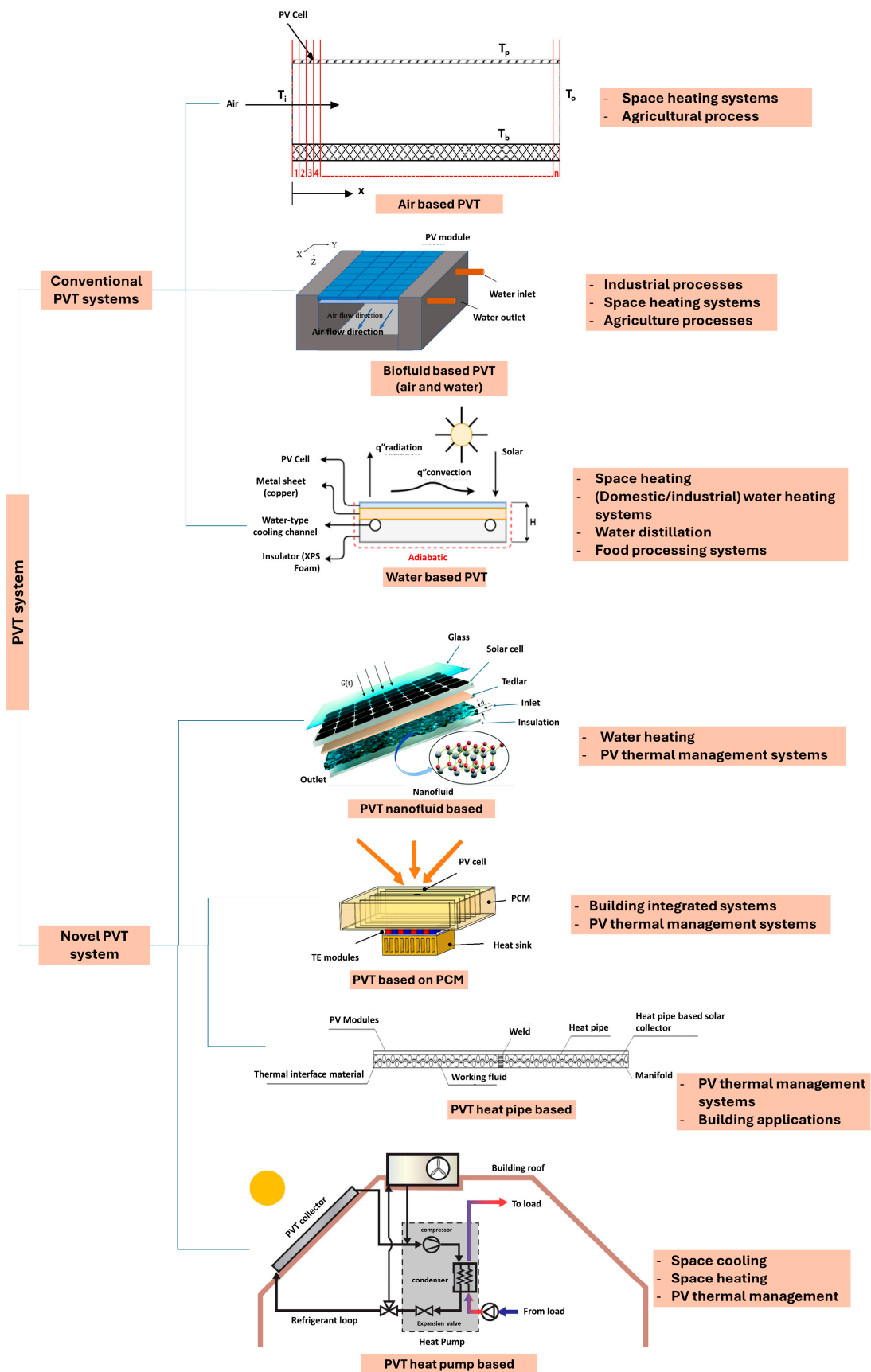


Figure 3. Comparison of conventional photovoltaic–thermal and novel photovoltaic–thermal systems [39–46].

2.2. Critical Factors Affecting PVT Systems

The heat absorption process is central to PVT systems, as rising temperatures in solar cells lead to increased current and, consequently, greater power generation. However, PV systems have specific temperature limitations. An increase in sunlight irradiance can elevate the outlet temperature by enhancing heat transfer between the solar cells and the fluid flowing within the absorber, subsequently increasing thermal energy [54]. Hassan et al. [55] observed in their experiments that an increase in solar radiation raises the temperature of PV cells, thereby reducing electrical efficiency. The temperature dependence of PV performance can be expressed by the following equations [56,57]:

$$P_{T_c} = \eta_s P_{in} K_f [1 + \alpha(T_c - 25)], \quad (1)$$

$$\eta_T = \eta_{ref} - \mu(T_c - T_{ref}), \quad (2)$$

where P_{T_c} is the output energy (W), η_s is the conversion efficiency under the standard test condition (STC), P_{in} is irradiation (W/m^2), K_f is the correction coefficient for factors other than temperature, α is the temperature coefficient (rad/s^2), and T_c is the module temperature (K), while η_T is PV efficiency, η_{ref} is the cell efficiency evaluated at the reference temperature (T_{ref} ; K), and μ is overall cell temperature coefficient (STC is defined at 25 °C).

During daily operation, power output continues to increase, peaking around noon due to rising solar radiation, before beginning to decline [58]. While solar radiation decreases after 1 PM, ambient temperature often continues to rise, which is a primary cause of performance degradation [59]. Although this degradation cannot be entirely eliminated, it can be mitigated by maximizing heat rejection from the cells. Gholampour et al. [60] conducted an experimental study on unglazed transpired solar collectors, finding that the air mass flow rate significantly influences the cooling efficiency. Greater air mass flow rates were associated with higher system efficiency, particularly when comparing electrical to thermal ratio numbers of 1 and 4 based on first-law efficiency. Haddad et al. [61] reported similar findings in their study of a water-cooled PVT hybrid system, emphasizing that the amount of coolant medium directly affects thermal performance.

According to the second law of thermodynamics, exergy loss can be minimized by reducing entropy generation. Leong et al. [62] noted that an increase in nanofluid mass fraction and the use of minimal mass flow can decrease entropy generation. They also found that TiO_2 nanofluids exhibit lower total dimensionless entropy generation than Al_2O_3 due to TiO_2 's higher thermal conductivity, which enhances heat transfer. In another study, H.B. et al. [63] compared hybrid nanofluids ($\text{Al}_2\text{O}_3\text{--CuO}$) with standalone Al_2O_3 nanofluids, revealing that hybrid nanofluids achieved lower total entropy generation values at various temperatures compared to Al_2O_3 . Liu et al. [64] analyzed PVT systems with and without needle fin configurations in the absorber tube. They determined that incorporating needle fins led to an entropy generation increase of 49–54% over the other configuration, attributed to increased flow mixing and velocity gradients.

The thermal performance of PVT systems is influenced not only by operational conditions but also by the design of the absorber, which plays a crucial role in the heat rejection process from the solar cells [65]. The primary focus here is the heat rejection phenomenon, particularly involving the absorber surface in direct contact with the coolant medium. Therefore, the dimensions and shape of the absorber are significant factors in this process. Bahrehmand and Ameri [66] conducted a numerical study comparing single-glass-cover and two-glass-cover solar collectors with varying designs of tin metal sheets. Their findings showed that increasing the channel length from 1 to 4 m achieved the highest energy efficiency. Ibrahim et al. [67] compared two different collectors: a spiral flow absorber and a single-pass rectangular tunnel absorber, both aimed at generating hot water and electricity. They found that the spiral flow absorber had a higher maximum power output of 25.35 W compared to 22.45 W for the single-pass rectangular tunnel absorber. In a separate study on heat sink technology, Ghale et al. [68] examined the thermal performance of a straight

rectangular microchannel versus one integrated with a rib. The addition of a rib, effectively expanding the contact area and enhancing flow turbulence, led to improved heat transfer performance; the associated changes in flow direction and increase in cross-velocity enhanced the heat transfer. However, modifications to the rib's dimensions had varying effects; while an increase in rib width of 28% enhanced heat transfer by 31%, a 66% increase in rib height only resulted in a 15% improvement in heat transfer.

3. Developments in Heat Dissipation and Absorption Technologies for Improving Overall Performance of PVT Systems

To address performance deficiencies, a substantial body of research has been dedicated to enhancing the overall efficiency of PVT systems through internal modifications [69]. These methods include redesigning the absorber, using mini/microchannels, employing polymer materials, integrating PCMs, utilizing nanofluids as working fluids, reducing heat loss, and implementing enhancement devices [70].

3.1. Absorber Design

As mentioned previously, the absorber is a critical component in addressing overheating issues in PV systems. Its dimensions and shapes significantly influence the amount of heat rejected from solar cells. Vengadesan and Senthil [71] note that numerous studies aim to enhance the heat transfer surface area, induce turbulence in the fluid, and extend the fluid's distribution time through the absorber. However, these modification efforts often result in undesirable outcomes, such as increased pressure drop or friction loss, posing challenges for future research. Table 1 summarizes some key studies focused on analyzing the impact of PVT absorber design on thermal performance [72–79].

Table 1. Summary of studies concerning redesigned absorbers in PVT systems.

Refs.	Types	Electrical Efficiency	Thermal Efficiency	Remarks
Koech et al. [72]	Varying collector length while keeping the number of PV cells constant	31%		Extending collector length reduces the packing factor and enhances heat loss.
Ali et al. [73]	Single and double serpentine	15.22%	43%	Double serpentine increases the heat transfer coefficient.
Ibrahim et al. [74]	Direct, oscillatory, serpentine, web, spiral, parallel-serpentine, modified serpentine-parallel		50.12%	Heat absorption increases with a tighter spacing between tubes.
Ekramian et al. [75]	Five positions and four different shapes of riser			Riser tubes with sharp corners in cross-section weaken convective heat transfer.
Kumar and Rosen [76]	With and without fin			Extending heat transfer by utilizing fins excessively reduce cell temperature.
Cetina-Quinones et al. [77]	Linear fins, zig-zag fins, wavy fins			Wavy fins create turbulent flow, enhancing convective heat transfer.
Kazem et al. [78]	Direct flow, web flow, spiral flow	9.17%	26%	The spiral flow tube in the absorber demonstrates superior performance in thermal evaluations.
Missirlis et al. [79]	3 different inlet and outlet pipe manifold			The different manifold of inlet and outlet produces different temperature distribution.

Koech et al. [72] conducted a study on various factors affecting the performance of PVT air solar collectors. They found that with a constant number of PV cells, thermal efficiency increases while electrical efficiency decreases as the collector length is extended. This trend is attributed to more solar radiation being absorbed through the inter-cell spaces in the TPT. By increasing the collector length, heat loss was reduced, thus maximizing the system's efficiency. Additionally, they observed that altering Tedlar thermal conductivity from $0.0005 \text{ W/m}\cdot\text{K}$ to $0.1 \text{ W/m}\cdot\text{K}$ improved both thermal and electrical performance as it facilitated more significant heat removal to the air. Missirlis et al. [79] explored the impact of incorporating a manifold of inlet and outlet pipes in three different orientations in a polymer solar collector with a honeycomb hydraulic structure and a black-absorbing fluid. The study concluded that the most efficient configuration, in terms of reduced heat loss, was achieved when the pipes were aligned with the honeycomb collector's direction. This setup allowed for smoother flow and more uniform fluid distribution within the collector.

In a comparative analysis of seven different absorber collector designs, Ibrahim et al. [74] determined that a spiral flow design achieved the highest total efficiency of 68%, while a serpentine design showed the lowest at 45%. This efficiency correlated with the fluid temperature at the outlet, where the spiral design recorded the highest temperature of 31°C . Among the designs tested, spiral, modified serpentine-parallel, parallel serpentine, and direct flow, which were characterized by tight spacing between tubes, were more effective in heat rejection, resulting in higher PV efficiency compared to the other designs. Ali et al. [73] examined the performance of a PVT system using an $\text{Al}_2\text{O}_3\text{-Cu}$ /water hybrid nanofluid flowing inside a serpentine absorber channel. Their findings indicated that a double-serpentine absorber enhanced the heat transfer coefficient more effectively than a single serpentine, owing to a larger contact surface area between the channel walls and the working fluid. Additionally, the electrical efficiency of the double serpentine was found to be 2.37% higher than that of the single serpentine across various Reynolds numbers (Re) and nanofluid concentrations. However, at a Re of 2000, they noted that increasing nanofluid concentrations had no significant effect on overall efficiency due to increased pumping power requirements.

Ekramian et al. [75] conducted a study comparing the thermal performance of absorber risers in five different positions, as illustrated in Figure 4. The highest thermal efficiency was achieved by the model depicted in Figure 4a. The efficiency progressively decreased as the riser was positioned lower (from top to bottom surface of the absorber). This was attributed to the configuration in Figure 4a having a larger absorption surface compared to the other configurations. Additionally, Figure 5 shows four riser shapes—triangular, square, hexagonal, and circular—and their impact on the heat transfer process. Of these, the circular riser yielded the highest thermal efficiency, primarily because heat transfer at sharp corners tends to be weaker. The efficiency of the circular riser was 38.4%, 11.2%, and 6.6% higher than that of the triangular, square, and hexagonal risers, respectively.

Kumar and Rosen [76] investigated a solar air collector with a double-pass configuration, comparing its performance with and without fins in the lower channel. Their analysis included thermal efficiency, electrical efficiency, temperature rise, and cell temperature. At an air mass flow rate of 0.06 kg/s and an inlet air temperature of 25°C , using fins to expand the heat transfer area surface decreased the cell temperature and increased both thermal and electrical efficiencies to 15.5% and 10.5%, respectively. Cetina-Quiñones et al. [77] proposed three fin designs, as shown in Figure 6 for PVT and conducted a numerical evaluation with a 9E analysis covering energetic, exergetic, environmental, economic, energy–environmental, exergoenvironmental, enviroeconomic, energoenvironomic, and exergoenvironomic assessments. Among these designs, the wavy fins achieved the highest performance, with a more uniform air temperature at the outlet and an overall efficiency of 62.2%, which is 7.2% greater than conventional PVT. This improvement was due to the wavy fins providing a larger surface area, promoting turbulent flow and thereby enhancing the convection process. Furthermore, the analysis revealed that air channel height plays a more significant role in temperature regulation than the quantity and thickness of fins. Kazem et al. [78]

investigated three configurations of solar collectors. The study focused on evaluating the impact of climate conditions and coolant mass flow rate to determine optimal conditions for Gulf Cooperation Council countries and discussing the optimal solar collector configuration. The PVT system demonstrated superior performance compared to general PV, especially the spiral configuration collector, which achieved an electrical efficiency of 9.1%. In conclusion, both experimental and numerical predictions indicated that the spiral flow configuration is the most efficient, followed by the direct flow and web flow configurations.

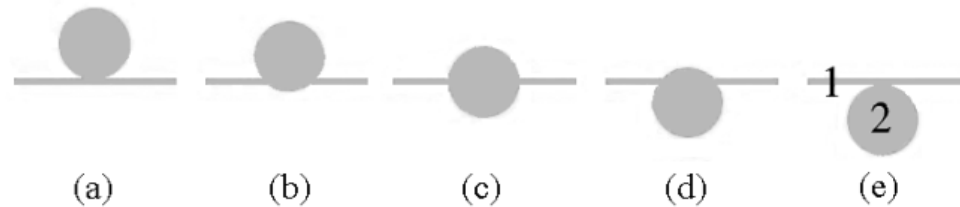


Figure 4. Riser position variation over absorber: (1) absorber; (2) riser tube; (a,b) are attached on the top surface of the absorber, (c) is attached in the middle of absorber, (d,e) are attached in middle of absorber [75].

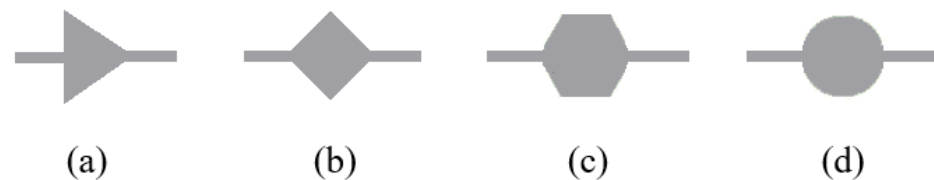


Figure 5. Various riser tube shapes; (a) triangular, (b) square, (c) hexagonal, (d) circular [75].

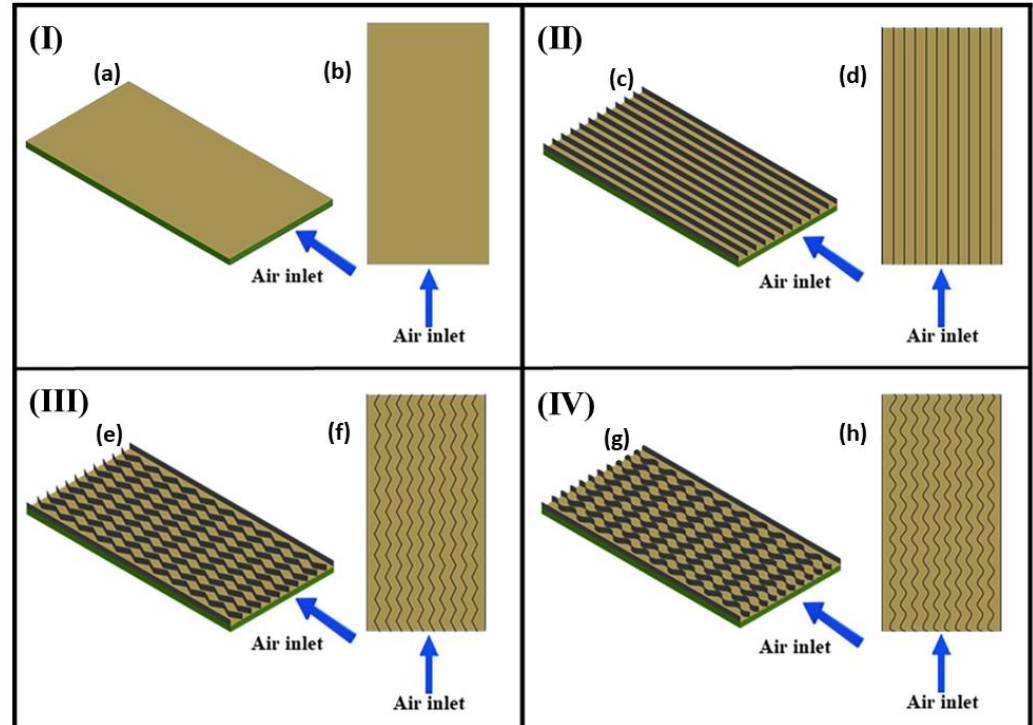


Figure 6. Schematic of photovoltaic–thermal air collector; (I) conventional photovoltaic–thermal; (II) linear fins; (III) zig-zag fins; (IV) wavy fins; (a), (c), (e), (g) isometric view; (b), (d), (f), (h) top view [77].

3.2. Mini/Microchannels

As previously discussed, the PVT system's thermal absorber plays a crucial role in the heat transfer process. The diameter of the pipes in the system is particularly important; larger diameters tend to result in lower efficiency [80]. Consequently, smaller diameters are preferred to maximize the performance of the equipment. Tuckerman and Pease [81] suggested that liquid-cooled heat exchangers with microscopic dimensions could significantly enhance the heat transfer process. This has led to the global development of microchannel technology. Extensive research has been conducted to integrate mini/microchannels into PVT systems, supporting the advancement of renewable energy [82]. Figure 7 shows some of the mini/microchannel geometries that have been developed [83]. Table 2 summarizes notable studies on mini/microchannels [84–91].

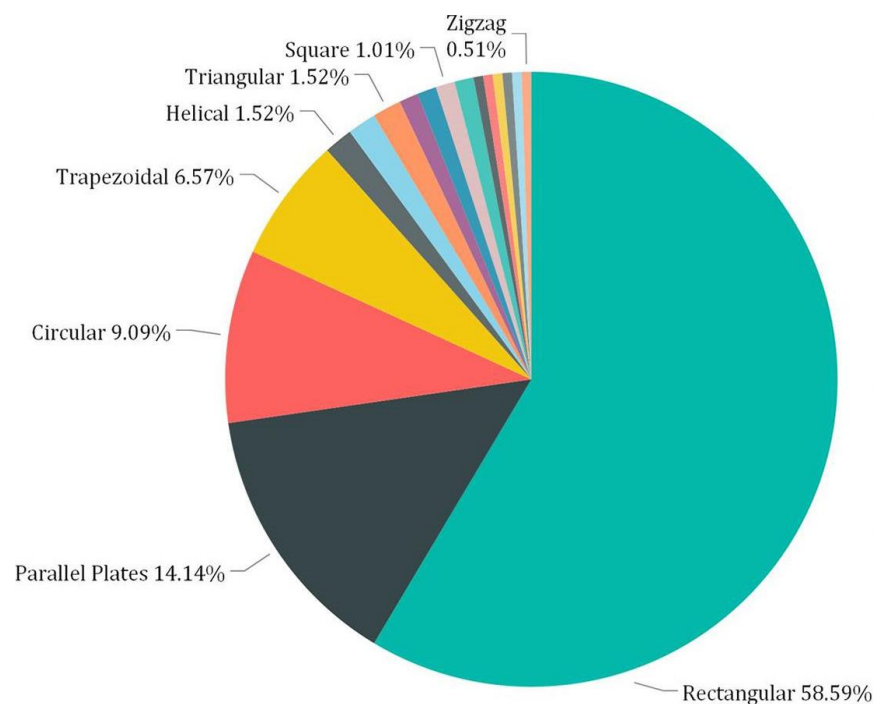


Figure 7. Developed mini/microchannel geometries [83].

Deng et al. [84] demonstrated that integrating a microchannel heat pipe array (MHPA) into a flat-plate solar collector (FPC) tends to result in low heat loss. This system managed to maintain only a 1 °C temperature difference between the evaporator and condenser. However, compared to other systems employing different solutions, MHPA has specific weaknesses in terms of insulation. Despite this, MHPA exhibited superior performance in all instantaneous efficiency tests when compared to other samples. Shahsavari et al. [85] compared three microchannel designs and found that a staggered design, combined with a PVT system using nanofluid flow, achieved superior performance compared to parallel and plain designs. Besides the choice of nanofluid to enhance thermal performance, the staggered design's geometry facilitated enhanced fluid mixing. Their results showed maximum thermal energy outputs of 37, 33.6, and 29.1 W for staggered, parallel, and plain units, respectively, at a mass flow rate of 80 kg/h and a nanofluid concentration of 2.0%.

Table 2. Summary of studies investigating mini/microchannels.

Refs.	Types	Electrical Efficiency	Thermal Efficiency	Remarks
Deng et al. [84]	Microchannel heat pipe array			MHPA–FPC responds to generate temperature difference in less than 2 min.
Shahsavari et al. [85]	Plain, parallel, staggered groove		53.7%	Staggered grooves achieved the best performance than other types in energetic and exergetic terms.
Mansour [86]	Square			Displacing tube to minichannel as heat-reducing tools boosts the heat removal process.
Sharma and Diaz [87]				Minichannel brings better performance; operational condition needs to be considered.
Wei et al. [88]	Integrated heat pipe with 15 vertical pipes, having two horizontal connected pipes at both ends		73%	Vacuum insulation inside solar heat collectors improves thermal performance.
Oyinlola et al. [89]	Sixty microchannels measuring 0.5 mm × 2 mm × 270 mm			Insulation on each side of the plate minimizes heat loss.
Radwan et al. [90]		19%	62%	Employing microchannel in low-concentration photovoltaic was proven can significantly reduce cell temperature.
Agrawal and Tiwar [91]				Microchannel outperforms single-channel in efficiency.

Mansour [86] explored the impact of square minichannels on solar collectors, comparing them to conventional collectors under identical conditions, including geometry. The proposed design outperformed the conventional collector due to reduced overall heat loss, thereby maximizing the heat transfer rate. However, while a higher mass flow rate positively impacts thermal performance, it adversely affects hydraulic performance. An increase in mass flow rate from 0.014 kg/s to 0.02 kg/s led to a 104% increase in solar collector efficiency and a 42.8% increase in pressure drop. Sharma and Diaz [87] investigated the effects of mass flow rate at various inlet temperatures and concluded that increasing the mass flow rate generally enhances efficiency. Increasing the inlet temperature for each specific mass flow rate led to a decrease in efficiency. They also compared their proposed minichannel design to an evacuated tube collector developed by previous researchers, demonstrating improved thermal performance for the minichannel. This was attributed to the minichannel's larger heat transfer area, which increased efficiency across all cases. Similar to other studies, they also observed a higher pressure drop with increasing fluid mass flow rate.

Wei et al. [88] enhanced solar collector design by incorporating an integrated heat pipe with fifteen vertical pipes and two horizontal pipes connected at the ends of the vertical pipes. This configuration, owing to a larger condenser area, improved the heat transfer coefficient of the solar collector's flowing fluid. The efficiency value increased significantly before 10 AM, stabilized between 10 AM and 1 PM, and then gradually declined. Maximum collector efficiency, reaching 73%, was achieved by maintaining a vacuum state within the solar collector. However, in experimental conditions, maintaining such a vacuum was challenging due to air filling the space, resulting in uncontrollable natural convection. Oyinlola [89] studied temperature distribution in an absorber plate featuring sixty microchannels, each with dimensions of 0.5 mm × 2 mm × 270 mm and spaced 1 mm apart (3 mm pitch). Temperature profile variations between the fluid and the plate became less distinct with an increase in mass flow rate. Generally, the temperature

difference between the plate and the fluid remained constant along the length. Heat transfer did not significantly impact the fluid temperature profile but reduced the temperature difference between the plate and the fluid. For axial thermal conduction analysis, notable changes were observed only in the initial and final 10% regions of the plate temperature.

Radwan et al. [90] demonstrated that using a microchannel heat sink is an effective cooling technique, reducing the temperature from 62.1 °C to 33.45 °C under maximum irradiation. Despite challenges such as high-power loss from friction in the small channels, their experiments showed that power loss due to friction was minimal, not exceeding 1% of the output electrical power in both the highest and lowest states of electrical efficiency. They concluded that microchannel heat sinks are a viable alternative in cooling technology with comparatively low power consumption. Agrawal and Tiwari [91] compared the energy and exergy performance of microchannel PVT (MCPVT) systems with single-channel PVT (SCPVT) systems across four different Indian cities (Srinagar, Bangalore, Jodhpur, and New Delhi), each with distinct weather conditions. Their findings indicated that in all locations, MCPVT outperformed SCPVT. Notably, the overall thermal energy gain for SCPVT was only 24.39 kWh, while MCPVT reached 42.96 kWh, almost doubling the performance of SCPVT. Additionally, MCPVT installations achieved a maximum overall annual exergy efficiency of 63.19% in Bangalore, surpassing that of SCPVT.

3.3. Polymer Materials

The exploration of polymer materials, particularly in thermal absorbers, is driven largely by their potential for reduced manufacturing costs, prompting researchers to investigate the feasibility of replacing metals with polymers. The IEA Solar Heating and Cooling Program Task 39 [92] highlights that polymeric materials could be a superior alternative in solar thermal energy systems, offering benefits such as overheating protection and effective surface coatings for collectors. However, despite their advantages as surface coatings and lighter weight compared to conventional glass, polymers have limitations in terms of durability [93]. During installation, especially in outside exposure conditions, the durability of polymer materials is likely to degrade over time. As shown in Table 3, degradation on polymer materials is due to various factors.

Table 3. Various polymer degradation factors.

Degradation	Main Factor
Thermal degradation [94]	Temperature increase
Oxidative degradation [95]	Water and temperature
Chemical degradation [96]	Chemicals
Biodegradation [97]	Microorganism enzyme
Hydrolytic degradation [98]	Water and temperature
Mechanical degradation [96]	Mechanical stress
Photo-oxidative degradation [99]	UV radiation and oxygen

Chow [100] also stated that polymers which play a role of absorber materials in this system have low thermal conductivity, large thermal expansion, and limited service temperature. The typical range of polymer materials' thermal conductivity is from 0.1 to 0.5 W/m·K, which shows a wide gap between polymer and metal materials in terms of heat absorbance. The low capability of transfer heat energy is caused by the complex morphology of polymer chains that are often tangled and disordered [101]. However, some polymers that are classified as thermal transparent polymers cannot absorb heat, so they directly release heat to ultra-cold space, which also brings an efficient cooling effect [102]. Moreover, the flexibility of polymer materials presents opportunities for technological advancement by addressing these weaknesses. Table 4 summarizes the research exploring the use of polymer materials in PVT systems [103–112].

Table 4. Summary of studies employing polymer materials in PVT systems.

Refs.	Types	Electrical Efficiency	Thermal Efficiency	Remarks
Erkata Yandri [103]	Polymethyl methacrylate	7.9%	82.56%	Electrical and thermal efficiency react oppositely to increases in solar temperature.
Filipovi'c et al. [104]	Chlorinated poly, polyamide		76.8%	The number of air gaps and base material thermal conductivity showed opposing effects on thermal efficiency.
Selikhov et al. [105]	Polyethylene			Mass flow rate determines heat flux value.
Nishit and Bekal [106]				Al ₂ O ₃ application significantly enhances system performance to compensate for polymer limitations.
Ariyawiriyanan et al. [107]	Polyvinyl chloride-blue (PVC-B), polybutene (PB), polypropylene random copolymer (PP-R), and polyvinyl chloride-carbon black (PVC-CB)		50%	Thermal conductivity varies among polymer types and surface areas, influencing heat rejection.
Mintsa Do Ango et al. [108]	Polycarbonate			Optimal efficiency is achieved with a 10 mm air-gap thickness.
Chen et al. [109]	Polycarbonate			In thermal efficiency, aluminum solar collectors outperform polymer ones.
Kim et al. [110]	Polycarbonate			Length extension does not affect thermal efficiency or absorber optical properties.
Pugsley et al. [111]	Polycarbonate		32%	Polycarbonate and CNT performance still falls short of conventional collector performance.
Resch-Fauster et al. [112]	Paraffin wax			At peak irradiation, PCM-polymer maintains the surface temperature below the threshold.

Yandri [103] conducted a study analyzing the thermal energy produced by a current passing through conduction materials in a PVT system, utilizing a combination of polymethyl methacrylate (PMMA) and a copper sheet to construct the absorber. In a scenario with an absorber but without water flow, the electrical efficiency decreased more slowly relative to the increasing surface temperature over time. Even in the absence of a coolant medium, the copper sheet was able to absorb and store heat in the PMMA. When water flow was introduced through the absorber, the collector temperature remained between 40 and 50 °C, which is below the critical temperature of polymer materials. With fixed radiation and a mass flow rate of 300 g/min, the system achieved a thermal efficiency of 82.5%. Filipović et al. [104] developed a polymer solar collector composed of polyvinyl chloride for a single section and polyamide for external water connections. Their research focused on preventing overheating during stagnation periods while measuring thermal efficiency. They evaluated the impact of variables such as air gap, conductivity, and emission on thermal efficiency, comparing these values to a reference. Increasing the air gap from 10 mm to 30 mm resulted in a 2% efficiency gain at higher water temperatures, while increasing thermal conductivity from 0.14 W/m·K to 10 W/m·K led to a noticeable efficiency decrease, particularly in the 10 mm and 30 mm air gap scenarios. However, they noted that the location of the absorber coating did not significantly impact system performance.

Selikhov et al. [105] investigated the use of polymer materials as absorber elements in solar collectors. By varying the water flow rate from $0.5 \text{ m}^3/\text{h}$ to $3.0 \text{ m}^3/\text{h}$, they observed the variation in the specific heat value with water temperature, which, in turn, was influenced by solar radiation. The specific heat flux affected the solar collector's efficiency profile, with maximum efficiency achieved at a specific heat flux above $0.6 \text{ kW}/\text{m}^2$ and a water flow rate of $3.0 \text{ m}^3/\text{h}$. Compared to studies using copper and aluminum absorbers, this approach showed a lower ability to maximize solar plate efficiency. Nevertheless, polymer-based collectors remain a preferable alternative to conventional solar collectors. Nishit and Bekal [106] pointed out that polymer-based solar collectors typically underperform compared to conventional flat-plate solar collectors. To address this, they developed a polymer PVT system using Al_2O_3 nanofluid as the primary working fluid. Considering nanofluid stability, they proposed adding surfactant in various concentrations. This resulted in a maximum instantaneous efficiency increase of approximately 27.7% compared to polymer solar collectors. Al_2O_3 's higher thermal conductivity than water contributes to improved heat absorption during exposure.

Ariyawiriyanan et al. [107] proposed the substitution of metal collectors with thermoplastic-based solar collectors, considering the advantageous mechanical and physical properties of thermoplastics. Their comparison of thermal performance over the same surface area involving PVC-B, PB, and PP-R revealed that thermal efficiency increases with higher thermal conductivity, reflecting the material's heat transfer capacity. Additionally, they noted that the aperture area also plays a significant role in influencing the system's thermal performance. For instance, expanding the area to 0.2 m^2 could enhance thermal efficiency from 36.3% to 50% in PVC-CB. Mintsa Do Ango et al. [108] aimed to improve flat-plate solar collectors by using polymers instead of traditional materials such as copper or aluminum for absorbers and glazing. They observed that extending the length of the collector does not impact the system due to the linear correlation between polymer length and coolant mass flow rate. As the length increased, the heat captured increased; simultaneously, the increase in coolant mass flow rate resulted in enhanced heat rejection. However, other factors such as mass flow rate, air gap thickness, and inlet coolant temperature influenced the heat rejection process, thereby affecting system efficiency.

Chen et al. [109] conducted an experimental study using a flat-plate solar collector with a honeycomb-shaped multichannel absorber made of polymer materials. Modifying the absorber shape aimed to maximize heat transfer despite polycarbonate's low thermal conductivity. Their findings indicated that the thermal efficiency of conventional solar collectors was 7–14% higher than that of the proposed polymer solar collector. Comparisons with other studies utilizing different polymer materials revealed similar findings. Kim et al. [110] modified absorber materials to polycarbonate to reduce costs while optimizing heat transfer by adding filler to the polymer layer. Their initial design, which included carbon nanotubes (CNTs) as filler, effectively improved the solar collector's thermal performance. However, recognizing the drawbacks in the first design, they developed a second design with an elongated length and a redesigned mounting part to prevent air trapping. The second design achieved higher efficiency and lower efficiency degradation compared to the first, aligning more closely with the expected performance standards.

Pugsley et al. [111] evaluated two prototypes, an asphalt CNT (ACNT) collector and a polycarbonate CNT (PCNT) collector, comparing them to conventional collectors. The ACNT collector demonstrated a maximum efficiency of 45%, significantly below that of the benchmark collector, whereas the PCNT collector achieved a maximum efficiency of 62%. Furthermore, the ACNT collector exhibited a typical efficiency of only 5% and a heat loss of $8.1 \text{ W}/\text{m}^2\text{K}$, while the PCNT collector's typical efficiency was 32% with a heat loss of $6.0 \text{ W}/\text{m}^2\text{K}$ under solar thermal conditions of $0.05 \text{ m}^2\cdot\text{K}/\text{W}$. Despite its lower performance compared to conventional collectors, the PCNT collector demonstrated promising results. Economically, the use of polymer materials in solar collector systems is advantageous because of their flexibility and adequate performance. Resch-Fauster et al. [112] explored the integration of solar thermal collectors on façades with latent heat storage, using a

combination of polymers and PCMs to protect against overheating. The addition of latent heat storage positively impacted the system by preventing the inner wall temperature from exceeding 35 °C; a wall temperature below 30 °C was required to maintain an indoor temperature of 20 °C. Concerning insulation temperature, the reference study without latent heat storage revealed a maximum value of 140 °C, while the proposed design with PCMs integration exhibited maximum temperatures of 100 and 85 °C for the front and back parts, respectively. This indicates the effectiveness of incorporating latent heat storage in controlling temperature extremes.

3.4. Phase Change Materials

PCMs have been recognized as efficient latent energy storage materials since their introduction by Telkes and Raymond [113] in the 1940s. PCMs are highly effective in absorbing and releasing large amounts of heat within constant or narrow temperature ranges, making them suitable for various applications, including smart housing, waste heat recovery, and solar collectors. Various types of PCMs are classified as depicted in Figure 8 [114]. PCMs absorb sensible heat until they reach their melting/solidification temperature; at this point, they begin to absorb latent heat and continue melting, as illustrated in Figure 9 [115]. The mechanism of PCMs itself does not require any flowing medium to reject heat, it also means that in the PCMs system, external energy such as pumping power is not needed [116–119]. In recent years, researchers have focused on utilizing the unique heat rejection capabilities of PCMs in PVT systems, as summarized in Table 5 [120–131].

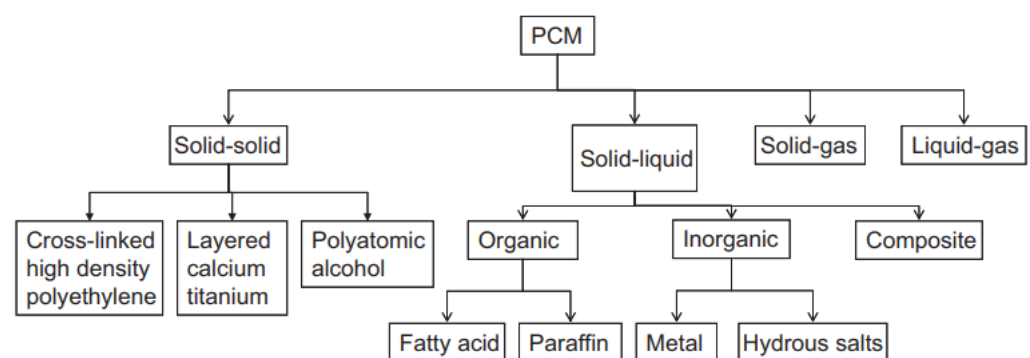


Figure 8. Classification of phase change material [114].

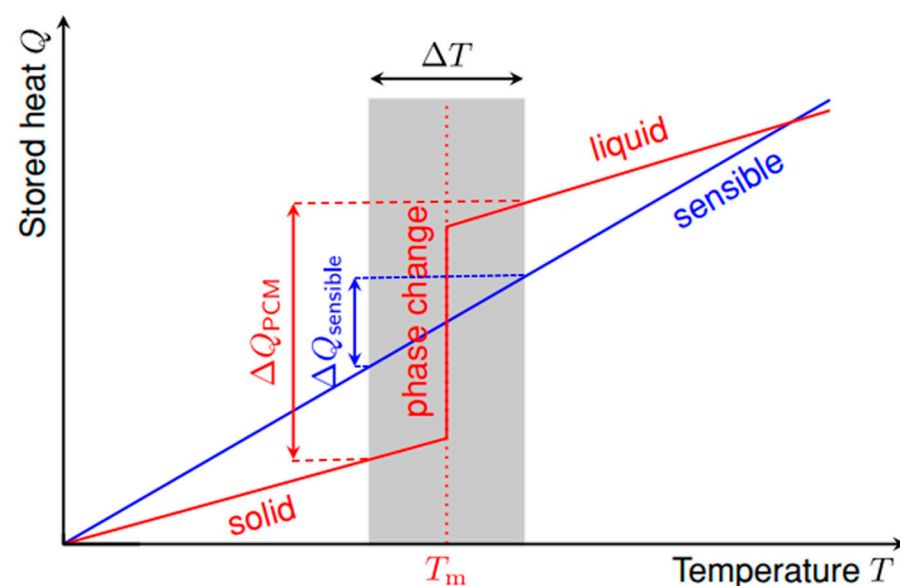


Figure 9. Stored heat in phase change material to increasing temperature [115].

Table 5. Summary of studies investigating phase change materials in PVT systems.

Refs.	Types	Electrical Efficiency	Thermal Efficiency	Remarks
Alsaqoor et al. [120]	Lauric acid	13.5%	71.7%%	Inclusion of PCM on PVT and storage tanks leads the better temperature degradation.
Sardarabadi et al. [121]	Paraffin wax			PCM application outperforms nanofluid application.
Yazdanifard, et al. [122]	RT25 (paraffin) and S27	14.5%	46.5%	Higher melting point PCM facilitates faster heat transfer, leading to quicker system stabilization to a steady state.
Elsheniti, et al. [123]	RT25HC			PCM usage in cold weather proved to be less effective. PCM usage in cold weather proved to be less effective.
Chaabane et al. [124]	RT42-graphite and myristic acid			Myristic acid with a higher melting temperature performs better in daily operation.
Diallo et al. [125]		12.2%	55.6%	Increasing water inlet temperature results in heat loss and reduced useful heat.
Fayaz et al. [126]	Paraffin (A44)	13.98%	76.1%	Utilizing PCM can boost PVT system in overall evaluated performance values.
Simón-Allué, et al. [127]	RT50, C48			PCM does not significantly change thermal performance but improves heat production distribution.
Ren et al. [128]	SP24E & SP26E			Thermal energy storage performance strongly depends on design variables.
Su et al. [129]				Different melting points of PCM respond variably over time under various operational conditions.
Yang et al. [130]	Capric acid	8.16%		PCM absorbs both sensible and latent heat, distributing it when solar radiation is absent.
Hasan et al. [131]	Eutectic of capric–palmitic acid and calcium chloride hexahydrate			PCM demonstrates significant benefits in hotter environments.

Alsaqoor et al. [120] explored the impact of integrating PCMs into PVT systems on their thermal and electrical performance. The incorporation of PCMs can reduce thermal efficiency because of their capacity to absorb latent heat, storing this energy within its layers for potential alternate use. However, the study found that although PVT systems with PCM (PVT–PCM) exhibited lower solar temperatures than PVT systems alone, PVT–PCM managed to generate higher power output and more effectively resisted the decline in electrical efficiency caused by gradual increases in cell temperature. Sardarabadi et al. [121] conducted an experimental study on a PVT system with a PCM (paraffin wax) layer on the absorber and ZnO as a nanofluid, comparing it to conventional PV systems. Their results indicated a more stable surface temperature change during day operation and a cooler system temperature with a 6 °C drop. While the use of ZnO nanofluid achieved a thermal efficiency of 42%, the addition of PCMs to the absorber enhanced performance, reaching 48% in thermal efficiency owing to the significant increase in the specific heat of the PVT system.

Yazdanifard et al. [122] conducted a numerical study on concentrated PVT systems using two different PCMs (RT25 and S27) and a nanofluid (Ag/water) to optimize performance. They also experimented with different placements of PCM above and below a

liquid absorptive optical filter. The study revealed the superior performance of S27 compared to RT25 owing to its optical properties essential for heat absorption. The electrical efficiency of each PCMs type increased during the phase change process. S27 exhibited higher electrical efficiency in the solid state compared to RT25, but following phase change, their efficiencies were approximately equal due to RT25's higher transmittance in the liquid state and the lower PV temperature of S27. Placing PCM below the nanofluids resulted in an increase in total energy and exergy efficiency by over 11% and 7%, respectively. Elsheniti et al. [123] developed a one-dimensional enhanced conduction model to accurately predict the temperature interface of PVT/PCM systems. They noted that PCM typically yields enhanced electrical performance except during mid-summer, which is attributed to the sun's position nearing zenith at noon in summer, differing from its position in other seasons. Furthermore, they identified optimal inclinations for PVT/PCM systems as 18°, 17°, 48°, and 41°, depending on the season.

Chaabane et al. [124] conducted a numerical study on an integrated collector storage solar water heater (ICS-SWH) using two types of PCM (RT42-graphite and myristic acid) to analyze performance during day and night operations. During the day, water temperature in ICS-SWH without PCM decreased after reaching a peak, whereas ICS-SWH with PCM demonstrated a consistent increase. Notably, myristic acid achieved higher water temperatures than RT42-graphite due to its higher melting point. Additionally, smaller PCM radii resulted in higher water temperatures, though the difference did not exceed 1 °C. During night operations, the latent heat storage unit's temperature decline was slower than that of the sensible heat storage unit. In the RT42-graphite case, the temperature continued to rise until 7 PM before gradually decreasing, while the myristic acid case experienced a more significant temperature decrease, varying between 17.3 and 29.5 °C. Diallo et al. [125] carried out a numerical study on a PVT system incorporating a microchannel heat pipe at the evaporator and triple PCM heat exchangers at the condenser, as shown in Figure 10. The study assessed the impact of environmental factors, structural parameters, and circulating fluid variables on the system's energy performance. The results compared the performance of the integrated model with conventional PVT systems, revealing that electrical efficiency could be enhanced under conditions such as lower solar radiation, lower ambient temperature, higher packing factor, lower coolant medium inlet temperature, and fewer covers. Electrical and thermal efficiencies improved with a higher mass flow rate and more microchannels. The model achieved a maximum electrical efficiency of 12.2%.

Fayaz et al. [126] conducted a three-dimensional numerical and experimental analysis of a PVT system using paraffin A44 as PCM, considering its safety profile and suitable thermal characteristics. The study discovered that increasing solar irradiation caused cell temperatures to rise in PV, PVT, and PVT-PCM systems, both numerically and experimentally. However, paraffin A44 effectively mitigated these temperature increases and enhanced power output and electrical efficiency. The PVT system achieved the maximum thermal efficiency of 76.1% numerically and 75.1% experimentally, with overall efficiency also being highest under the same conditions. Simón-Allué et al. [127] investigated the impact of incorporating PCMs into a PVT system with two different absorber materials. The presence of PCMs did not significantly alter thermal performance when comparing different absorber materials. However, the impact of PCMs became more apparent when solar exposure was reduced, showing that PCMs could more effectively prevent a drastic decline in heat power compared to configurations without PCMs.

Ren et al. [128] utilized the Taguchi method to evaluate PVT-PCM, aiming to maximize the information obtained from a minimal number of simulations. Their findings indicated that the air flow rate was the most influential factor, contributing 69.77% towards enhancing thermal performance. Other factors, such as PCM brick thickness, unit length, and air gap size, had minor impacts and were considered negligible. Su et al. [129] assessed a PVT-PCM system and concluded that optimal overall energy efficiency was achieved with a 3.4 cm-thick PCM layer with a melting point of 40 °C. Their analysis of cell temperature over time suggested that incorporating a PCM layer could lower cell temperatures compared to

systems without PCMs. Additionally, they noted a more significant temperature decrease with higher PCM melting points, owing to the temperature difference between the PCM and flowing water facilitating easier thermal energy transfer.

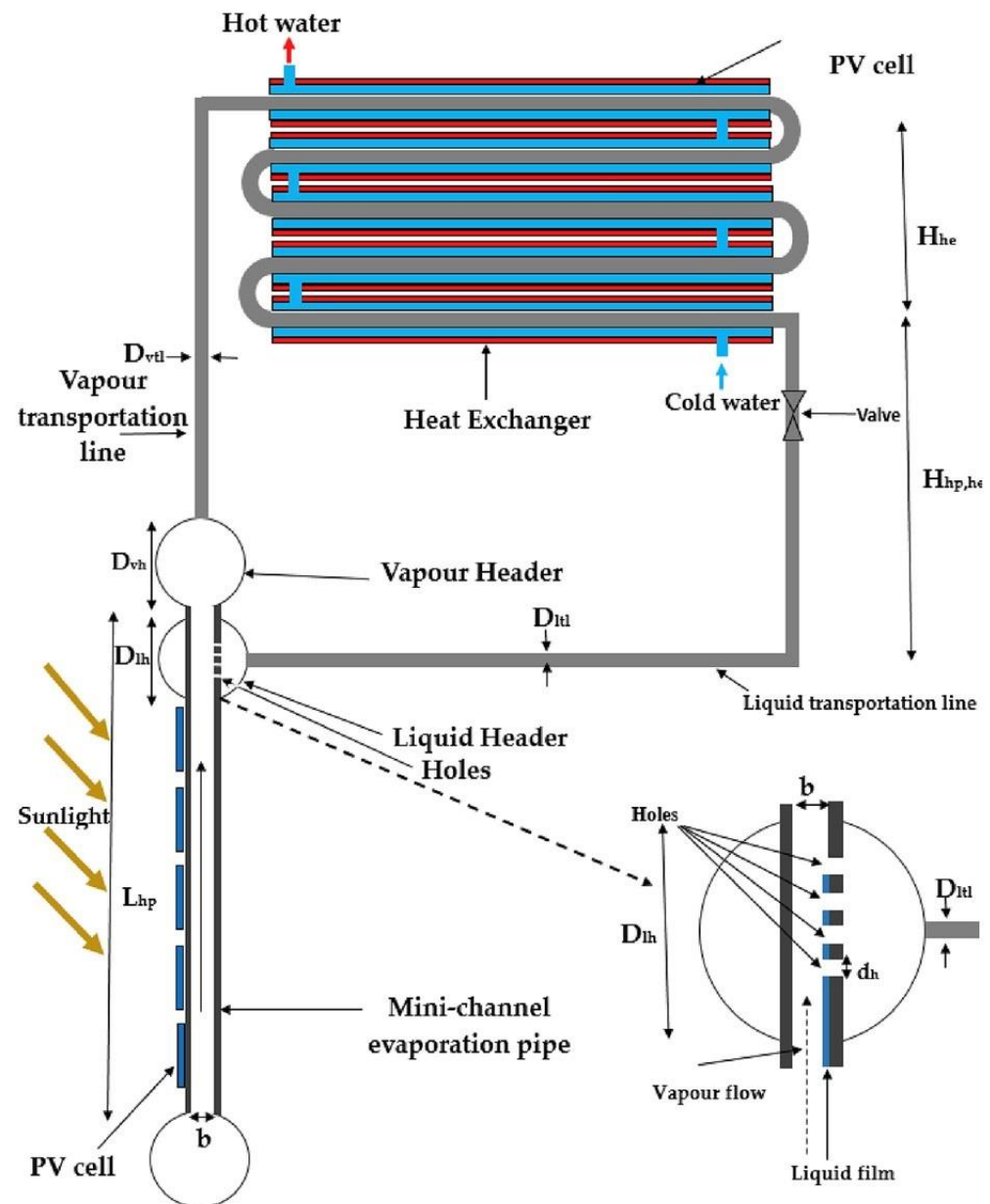


Figure 10. Schematic photovoltaic–thermal system incorporating microchannel heat pipes at the evaporator and triple-phase-change-material heat exchangers at the condenser [125].

Yang et al. [130] demonstrated that integrating a PVT system with PCMs effectively lowers the backplane temperature. Furthermore, in the absence of solar radiation, PCM transfers absorbed heat to water, enhancing the overall efficiency of the PVT–PCM system compared to standard PVT systems. The solar thermal efficiency, electrical efficiency, and total conversion efficiency of the PVT–PCM system were 70.34%, 8.16%, and 76.87%, respectively. As illustrated in Figure 11, Hasan et al. [131] extended PVT–PCM research by installing systems in different locations to compare performance under varying weather conditions. They hypothesized that in cooler conditions, such as in Ireland, PCMs solidification would occur more rapidly, whereas in warmer conditions, such as in Pakistan, PCM would absorb larger heat loads but solidify at a slower rate. The simulation and experimental results demonstrated that calcium chloride hexahydrate exhibited superior

performance, achieving temperatures 3–4 °C higher than capric–palmitic acid in Pakistan. Consistent with expectations, systems in warmer climates generated more power savings due to higher and more stable radiation intensity. This suggests that PCM systems are particularly effective in hot-climate areas.

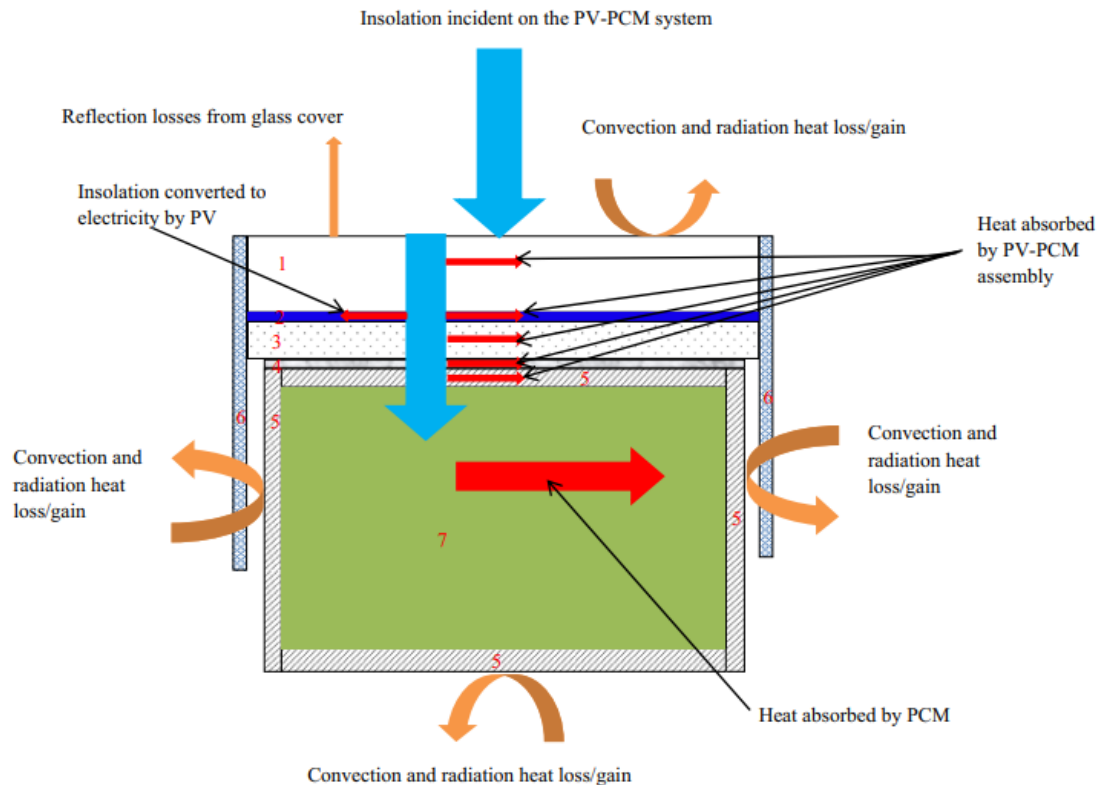


Figure 11. Schematic of combination photovoltaic–thermal and phase change material system: (1) glass cover; (2) photovoltaic cell; (3) photovoltaic back sheet; (4) layer of epoxy glue as an interface between photovoltaic and phase change material container; (5) phase change material container wall; (6) photovoltaic frame; and (7) phase change material layer [131].

3.5. Nanofluids

The use of nanofluids in modern PVT systems has become increasingly common because of their desirable characteristics, such as enhanced thermal conductivity and light absorption [132]. Research has demonstrated that employing nanofluids as coolant media in the thermal absorbers of PVT systems significantly improves performance by managing the high temperatures of solar cells [133–135]. The various types of nanofluids can be seen in Figure 12 [136]. Nanofluids play a crucial role in efficiently transferring heat from solid components to the flowing fluid. Thus, the selection of nanofluid type in a PVT system is vital to ensure compatibility and meet the desired performance criteria. Table 6 summarizes studies involving PVT systems with nanofluids as coolant media, featuring different types and configurations [54,137–147].

However, while nanofluids can enhance heat transfer, their use presents challenges, including lower specific heat, stability issues, increased pressure drop, foam formation, higher viscosity, and elevated costs [148]. Proper preparation is essential to address these challenges. For stabilizing nanofluids, surfactants are commonly used to maintain or improve stability and reduce surface tension. However, surfactants can also adversely affect the thermal conductivity of the nanofluid, leading to reduced performance [149]. Pressure drop issues in nanofluids are often related to increased volume concentration, which correlates with viscosity [150]. Additionally, larger friction factors can lead to higher pressure drops [151]. This can result in increased pumping power requirements to circulate

the working fluid during operation [152], necessitating the need for consistent pumping power to maintain optimal performance.

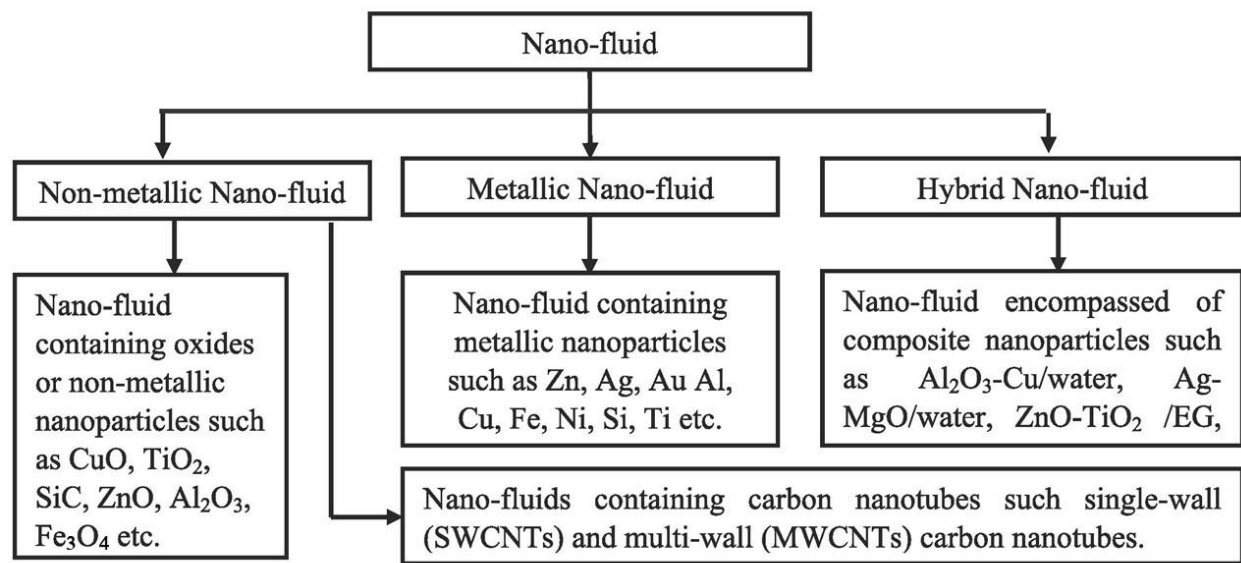


Figure 12. Nanofluid types based on nanoparticle dispersion in base fluid [136].

Table 6. Summary of studies investigating nanofluid application in PVT systems.

Refs.	Types	Electrical Efficiency	Thermal Efficiency	Remarks
Tian et al. [137]	MgO			Higher nanofluid concentration enhances exergy output.
Menon et al. [138]	CuO	35.67%	78.41%	Nanofluid, as a coolant medium, stores sensible heat more efficiently during PVT operation.
Bassam et al. [139]	SiC	9.6%		SiC nanofluid prevents microcracking but does not significantly increase system efficiency.
Ahmadinejad and Moosavi [54]	CuO and CNT	17.85%	64.5%	CNT holds the greatest outcome over CuO and pure water at any different irradiation conditions.
Geovo et al. [140]	MgO			Applying nanofluids as cooling fluids can reduce the size of solar collectors.
Adun et al. [141]	Al ₂ O ₃ -ZnO-Fe ₃ O ₄	13.74%		Ternary nanofluid improves heat transfer, but pumping power considerations are essential.
Fayaz et al. [142]	MWCNT	12.50%	81.24%	Higher mass flow rates maintain temperature gradient, enhancing convective heat transfer.
Hooshmandzade et al. [143]	Hybrid (Al ₂ O ₃ + SiO ₂)		62.50%	Nanofluid lowers temperature due to high thermal capacity and increases open-circuit voltage output.
Shen et al. [144]	ZnO	8.7%	34%	Voltage generation continues to rise over time, even if temperatures decrease after an initial increase.

Table 6. Cont.

Refs.	Types	Electrical Efficiency	Thermal Efficiency	Remarks
Murtadha [145]	Hybrid ($\text{Al}_2\text{O}_3 + \text{TiO}_2$)	17.6%		Al_2O_3 with TiO_2 combination outperforms standalone Al_2O_3 as a working fluid.
Alktranee et al. [146]	$\text{TiO}_2\text{--CuO}$	9.20%	50.2%	Enhanced performance considering system capacity, dimensions, and nanofluid concentrations.
Parsa et al. [147]	Ag	12.28%	65.5%	Nanofluid stability is more influential than volume concentration.

Tian et al. [137] simulated a 250 W PVT system with MgO /water as the coolant medium and studied the impact of fluid flow rate on exergy output and efficiency. They found that as the mass flow rate increased, the fluid temperature near the outlet approached ambient temperature, eventually reaching a state where exergy output was zero. Greater temperature differences between the outlet and ambient temperatures resulted in higher exergy values. Each increase in nanofluid concentration marginally improved exergy output, with the highest exergy efficiency achieved at a flow rate of 0.5 L/min and a nanofluid concentration of 1%, which was less than 13%. Menon et al. [138] highlighted the crucial role of the cooling medium in enhancing both electrical and thermal efficiency in photovoltaics. Their results indicated that using nanofluid as a coolant medium improved the average electrical efficiency of the PVT system by 35.6% and 20.78% compared to uncooled and water-cooled systems, respectively. This improvement is attributed to the greater thermal conductivity of nanofluids compared to water, enhancing heat removal.

Bassam et al. [139] developed a PVT system combined with PCMs and micro-fin tubes to enhance thermal efficiency. Among four configurations, the most effective method for improving PVT performance was using SiC nanofluids in micro-fin tubes with nano PCMs. With an irradiance of 800 W/m^2 , this configuration achieved electrical and thermal efficiencies of 9.21% and 77.57%, respectively. Ahmadinejad and Moosavi [54] assessed the performance of baffled channel PVT systems, as baffled channels can improve heat transfer from solar cells to the working fluid more effectively than simple channels. Their results indicated that CNTs were more effective at resisting the increase in cell temperatures due to rising solar irradiance than CuO and water (increased solar cell temperatures typically reduce the electrical efficiency of the system).

Geovo et al. [140] conducted a numerical study on flat-plate solar collectors using MgO nanofluids, modeled using Matlab software. The maximum thermal efficiency occurred at a 0.75% volume concentration of MgO nanofluid, with higher concentrations leading to diminished efficiency gains. Adun et al. [141] advanced nanofluid technology in PVT systems by combining three types of nanoparticles ($\text{Al}_2\text{O}_3\text{--ZnO--Fe}_3\text{O}_4$) in mixture ratios of 1:1:1 and 2:1:1, without using surfactants. The highest thermal conductivity was achieved at a mixture ratio of 2:1:1 across all temperatures. Furthermore, the maximum thermal and electrical efficiencies were obtained using a mixture ratio of 0.33. This finding aligns with other studies on hybrid nanofluids, indicating that a 1:1 mixture ratio is optimal for the heat transfer process, considering the combined effects of specific heat capacity and viscosity variations. Fayaz et al. [142] focused on the impact of nanofluid flow rate on PVT systems, maintaining solar radiation at 1000 W/m^2 while varying mass flow rates from 30 L/h to 120 L/h. They conducted both numerical and experimental comparisons between water and multi-walled CNT (MWCNT) nanofluids. The PVT surface temperature varied with different mass flow rates. Increasing the nanofluid flow rate resulted in lower temperatures at the outlet, particularly above 60 L/h. The study demonstrated the superiority of MWCNT nanofluids over water in various assessments.

Hooshmandzade et al. [143] installed a PVT system in a greenhouse, creating different environmental conditions inside and outside, which influenced system performance. They tested pure water, Al_2O_3 nanofluid, SiO_2 , and a hybrid nanofluid ($\text{Al}_2\text{O}_3 + \text{SiO}_2$) as coolant mediums. The results indicated that the hybrid nanofluid was more effective than single nanofluids and pure water, particularly in indoor installations. Shen et al. [144] investigated the performance of PVT systems used in hydrogen production through the electrolysis process. They found that enhancing PVT performance with nanofluids could minimize the decline in hydrogen production caused by reduced radiation, especially when increasing the amount of coolant in the system. Overall, the highest performance was achieved using the largest amount of working fluid containing 0.25% ZnO nanofluid. Murthada [145] assessed the effects of using a hybrid nanofluid composed of Al_2O_3 and TiO_2 nanoparticles as a coolant in PVT systems, aiming for optimal efficiency and power output. The evaluation, conducted under three different conditions, demonstrated that the hybrid nanofluid PV system more effectively reduced PV temperatures compared to water-cooled and uncooled PV systems, with the greatest temperature reduction reaching approximately 20.9%. The study also suggested that factors such as turbulent flow, high solar radiation leading to increased surface temperature, and other climatic conditions could contribute to enhanced power output.

Alktranee et al. [146] aimed to improve PVT performance by integrating TiO_2 and CuO nanofluids into the system to achieve lower temperatures. Their results confirmed that the hybrid nanofluid system outperformed water and single-nanofluid systems from previous studies. This improvement was attributed to the higher thermal conductivity of the hybrid nanofluid, which significantly improved the heat transfer rate, thereby enhancing PVT functionality. Moreover, this approach prevented overheating in PV modules, which can lead to increased exergy loss. The reduction in exergy loss was 32.3% and 37.9% at 0.2 and 0.3% volume concentrations of hybrid nanofluids, respectively. Parsa et al. [147] analyzed the impact of nanofluid preparation methods on PVT performance. Their study revealed a notable trend of instability when using a two-step method for nanofluid preparation. In every evaluation parameter, 3 wt.% nanofluid in turbulent flow performed better than 5 wt.% nanofluid in laminar flow. In the one-step method, higher concentrations and turbulent flow consistently led to improved performance. Therefore, they recommended developing a one-step method that ensures long-term stability to enhance PVT efficiency.

3.6. Comparison between Various Cooling Technologies

As mentioned earlier, this paper presents five different methods by which to overcome the overheating phenomenon of photovoltaic systems and simultaneously improve performance. Although the five technologies have the same development goals, each technology has unique potential and obstacles. Table 7 highlights the strengths and weaknesses of each technology, providing a convenient comparison of alternative methods to improve photovoltaic performance. This can help increase awareness of promising options and serve as a basis for future development. Optimizing the system by redesigning the absorber part has superiority in terms of flexibility in manufacture since the collector design can be modified in various ways. This system can be made more efficient if the issue of high fabrication cost can be solved. Challenging issues in absorber design concerning the need for larger space may be solved by mini-microchannel technology, which offers a solution by enhancing heat transfer area without enlarging the space. Still, however, carrying small hydraulic diameter pipes leads to an increment of pumping power. Adjusting the diameter must be seriously considered to achieve maximum performance with as low pumping power as possible. Further, the utilization of polymer materials as collector materials can make a big difference in terms of cost compared to metal materials. Despite the achieved performance being relatively low, combining polymer materials with other techniques still looks like a promising next step. Another option is utilizing PCMs, which absorb a greater amount of heat, but the challenge for this solution is the dependency of PCMs' performance on the melting point; exposure installation causes performance degradation over time.

Among the five methods, the nanofluid method is the one which obtains the highest electrical efficiency. This method is also easily applied, bringing significant enhancement with simple preparation and low cost. The important obstacle to be solved in this case is simply reducing the pumping power which keeps increasing with higher nanofluid concentration.

Table 7. Strengths and weaknesses of various photovoltaic–thermal systems.

PVT System	Strength	Weakness
Absorber design	-Easily install in conventional PV system	-High cost
	-High efficiency	-Consume external power for using liquid cooling
	-Absorbed heat can be reused	-Non-uniform cooling effect
	-Variative modification	-Need larger space
Mini/microchannels	-Uniform temperature distribution	-Increasing pumping power
	-Effective space	-Mostly applied in concentrated PV
	-High efficiency	-High cost
Polymers	-Low cost	-Less performance enhancement
	-Easy fabrication	-Should be combined with other techniques
	-Corrosion resistance	-Absorbed heat is wasted
	-Light-weight	
PCMs	-No need to circulate fluid	-Physical contact with PV material can cause damage
	-Easily attach	-Risk damage by leakage
	-Low cost	-Degradation performance for outdoor exposure
	-Able to absorb more heat	
Nanofluids	-Significant efficiency enhancement	-Increase pumping power
	-Low cost	-Need additional heat exchanger
	-Can be applied and integrated with other cooling techniques	-Challenge of nanofluid stability and conglomeration

4. Conclusions

To mitigate overheating in PV systems, PVT systems have been developed over several decades, incorporating various technologies to meet market and user requirements. This article has focused on five key approaches based on redesigned absorbers, mini/microchannels, polymer materials, PCMs, and nanofluids. These methods primarily aim to reduce solar cell temperatures by maximizing the absorption of excess heat from the solar cells into the absorber using various media. The impact on thermal or electrical performance is assessed. Key conclusions are as follows:

- Absorber design: Optimal PVT performance can be achieved by increasing the heat transfer contact area. This can be realized through longer collectors, strategic riser tube placement, homogenizing fluid flow with fins, and arranging pipes to minimize flow distance between each other.
- Mini/microchannels: While mini/microchannels, owing to their small dimensions, can enhance heat transfer from solid materials to the flowing fluid, they also present a higher risk of power loss. Modifications have primarily focused on channel pipe arrays, utilizing plain or grooved external channels and diameter adjustments.
- Polymer materials: Considering the high cost of conventional metal-based PVT systems, polymers have been explored as an alternative. Despite their lower thermal conductivity compared to metals, polymers offer flexibility in design to maximize

heat transfer through increased contact area. Polymers are useful not only as absorber materials but also to replace the glass cover. While polymer-based PVTs have not yet surpassed conventional PVT systems in performance, their cost-effectiveness and versatility make them a promising option for future development.

- **PCMs:** PCMs can absorb significant amounts of heat through latent heat storage. The efficiency of PCMs integration depends on factors such as thickness, type, and placement within the system. Considering latent heat utilization, PCM can be a more effective solution than changing absorber materials.
- **Nanofluids:** As coolants, nanofluids demonstrate superior performance compared to pure water owing to their higher thermal conductivity. Various nanofluid types and combinations thereof have been explored to increase thermal conductivity. Generally, higher volume concentrations lead to greater heat rejection and improved electrical efficiency. However, the preparation of nanofluids is crucial as it affects stability and heat absorption capabilities.

These conclusions offer insights into the current state of PVT system development and highlight potential areas for further research and innovation. Overall, among the five novel cooling systems offered, absorber design, mini/microchannel, and polymer materials provide solutions for optimizing performance by enhancing the heat transfer area or even manipulating the heat transfer process that occurs between the coolant medium and collector, while fabrication cost and level of improvement show a contrary relation in these solutions. Moreover, PCMs and nanofluids promise significant and economical refinement. In boosting the heat rejection process without additional complex manufacturing, one must nonetheless consider means by which to make up for each system's shortcomings. Furthermore, a life cycle assessment analysis needs to be conducted, considering how these techniques influence the process in terms of economics, manufacture, or even the environment. The most important branches, namely, energy payback time, solid waste, and carbon reduction, must be solidly analyzed to understand the sustainability of each product.

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