A comprehensive review on recent advancements in cooling of solar photovoltaic systems using phase change materials

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Abstract

Due to the increasing demand for energy worldwide, photovoltaic (PV) cooling systems have become an important field of research in recent years. The most important factor affecting the performance of a solar PV cell is its operating temperature. For harvesting heat from solar PV systems, phase change material (PCM) is regarded as the most effective material. As a result, this study discusses and describes the effect of using PCM and nanoPCM (NPCM) in cooling PV cells. This research reviews the various feasible hybrid photovoltaic thermal (PVT)–PCM and PVT–NPCM methods used for cooling PV. The concept focusing on PV cooling technology is discussed where air, water and nanofluid are used as the working medium in combination with PCM and NPCM. It is observed that when high performance heat transfer and improved cooling rate are needed, active cooling methods are favoured, whereas passive cooling methods rely on themselves and don't require extra power. It is also found that the effectiveness of applying PCM or NPCM for thermal control is heavily influenced by atmospheric air temperatures as well as the precise PCM or NPCM used. It is envisaged that this review will help new researchers better understand the qualities and capabilities of each cooling strategy. They are offered to help investigators quickly identify the basic science that led to the development of the thermal performance system and also improve the overall performance of the PV system.

Keywords: nanoparticle enhanced phase change material (NEPCM); phase change material (PCM); photovoltaic thermal systems (PVT); solar photovoltaic (PV)

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1 INTRODUCTION

Photovoltaic (PV) technology, which directly converts solar radiation and photon energy into electricity through semiconductor band gaps, made great progress in scientific research and commercial applications and is still on track to improve efficiency and to reduce the costs. Firstly, in 1961, Shockley and Queisser suggested a theoretical limit for the AM1.5 solar spectrum of 30% conversion efficiency [1], updated later with a 33.7% more accurate calculation with a 1.34 eV band gap.

According to a recent report, the efficiency of the single crystal silicon (c-Si) transition cell measured in the AM1.5 spectrum reached 26.7%. In fact, compared to small laboratory cells, the efficiency of commercial solar modules is inevitably lower. It is ∼18% for single crystal silicon modules on the market. Also, most of these efficiency results are confirmed under standard test conditions, but in practice PV modules do not work under these conditions. The intensity and spectrum of solar radiation are highly dependent upon time and climate under real environmental conditions. In addition, since most of the solar energy is converted to heat in addition to generating electricity, operating temperatures far exceed 25°C. As the study shows, the coefficient of temperature efficiency is highly material dependent. Sadly, the relatively high efficiency drop rate of c-Si modules is 0.4% to 0.5%/°C, even up to 0.65%/°C [2]. High temperatures also increase the rate of ageing in the PV module.

Among the various applications, c-Si solar cells are the first and most used, in that mainly mono c-Si and poly c-Si pv modules accounting for ∼90% of the market. Thanks to commercial success, worldwide use of solar systems today exceeds 500 GW, and the average selling price continues to decline to 0.26$/W in July 2018. Solar cells absorb 80% of solar energy, but with an efficiency of 24.7%, the current conversion of electricity is only 12% to 18% [3]. The balanced solar energy is converted into heat and the temperature of the solar cell is increased by 40°C higher than the ambient temperature. A thermally controlled solar cell is more efficient than the existing solar cell, which is currently attracting considerable attention in this aspect.

Efforts are being made to decrease the operating temperature of solar cells incorporating passive and active cooling devices. For active cooling, which needs air, water or a nanofluid to be cycled through the circuit, an additional blower or pump is typically needed. Passive cooling of PV cells eliminates the need for additional electricity. Figure 1 depicts an active/passive cooling technology that has witnessed adequate research in an attempt to regulate and foster thermal dissipation. An essential economic aspect is the ability of a hybrid active cooling system to balance electricity usage. It is indeed possible to decrease the power loss of the PV array and boost the module's dependability with sufficient cooling.

According to the aforementioned literature, a research gap exists for phase change material (PCM) embedded photovoltaic thermal (PVT) systems and nanoPCM (NPCM) embedded PVT systems and their related technologies. But perhaps, no one has focused exclusively on them in their related studies. Furthermore, the purpose of this review article is to identify the most significant advances in PCM unified PVT and NEPCM unified PVT findings. This approach concentrates on PCM and NEPCM with several kinds of different cooling methods as well as the performance. Additionally, in order to stand out among the many renowned papers in this field, ultra-modern PVT-related research will be assessed in terms of electrical and thermal performance enhancement.

The most important factor affecting the performance of a solar cell is its operating temperature. This temperature varies depending on ambient temperature, wind speed and insolation. Various thermal control solutions have been proposed to keep the cell temperature as low as possible in order to avoid the loss of efficiency such as an active cooling mechanism based on pumped water or air that requires mechanical or electrical energy to operate, and a passive cooling mechanism that works on the density difference such as PCMs. No matter how many different ways researchers have found to improve the PVT system's thermal performance, it seems the field of PVT systems using PCM and NEPCM is continually developing. This article examines the many ways of cooling PV panels. In the first instance, the active techniques that may be used for PV thermal control are discussed and the second section covers passive strategies. Finally, some recommendations are made in light of the techniques examined and their effect on the efficiency of PV panels, with the goal of further improving their efficiency while simultaneously decreasing their working temperature.

2 ACTIVE COOLING TECHNIQUES

The primary advantage of active cooling systems is their higher capacity to remove heat, despite the fact that they have a more complicated structure as a result of the extra equipment necessary. Since active cooling techniques need additional energy inputs, such as air and water, to drive coolant. After two decades of development, the PVT configuration technology was developed, which can simultaneously collect PV electricity and harmful heat from the PV panel, and is becoming a hot topic with different working fluids for heat extraction. The different working fluids used in active cooling systems are nanofluids, thermal fluids, water and air. The main active methods that are used for PV cell heat dissipation are explained in the following subsections.

2.1 Air cooled PVT system

2.1.1 *Air-based PVT system*

In this type of PVT system, air is used as a medium to extract heat from solar modules. Studies conducted with air in PVT systems include glass, no glass, various air duct arrangements, natural air flow and essential fan air circulation. The final use of heat extracted from the air-based PVT system mainly involves the application of space heating in the integrated building applications (building integrated photovoltaic thermal system [BIPVT]).

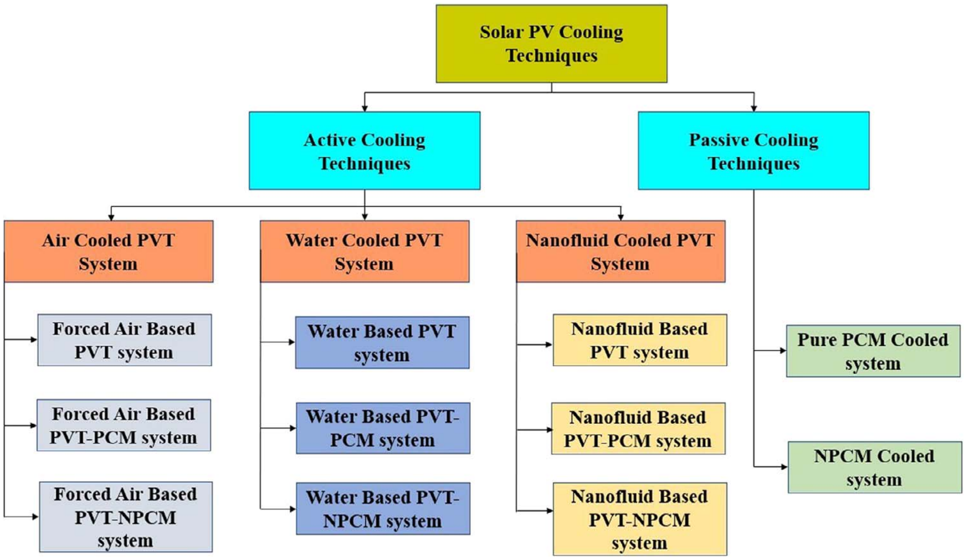

Figure 1. *Solar PV techniques [4].*

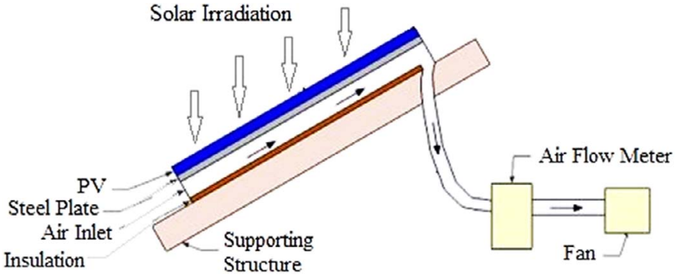

Figure 2. *Air cooled PVT system [12].*

BIPVT systems may be used in a variety of ways inside the building envelope, providing several options for creative designers. Numerous architects have successfully incorporated PV technology into their architecture [5]. Figure 2 depicts the air cooled PVT system. Some of the relevant research on the PVT air-based system is disused further.

Airflow method to cool a PV platform has been built by Rakesh Kumar *et al.* [6]. Different parametric conditions that affect the system efficiency have been explored in their work, including the air flow rate and solar irradiation. The influence of the inserting fin has also been studied to evaluate thermal and electrical efficiency. Their result indicated that the inclusion of fines has improved electrical and thermal efficiency of the system by 10.5% and 15%, respectively. The variation in air flow from 0.03 kg/s to 0.15 kg/s resulted in major improvements in electrical efficiency. Rising solar radiation decreases cell efficiency, mainly due to a higher temperature. The geometric characteristics of the air-cooled system can be used as a part of PVT system performance, in addition to these variables. Their location may influence cooling speed in addition to the geometry of the channel. The cooling channel location effects the PV output has been numerically analysed by Wu *et al.* [7] with forced air flow as the coolant medium. Outdoor tests were conducted in New Delhi over the whole year by Sanjay Agrawal *et al.* [8]. For spatial heating and crop drying, the thermal output was used. The thermal and electrical gains were calculated monthly. The energy recovery time for the device was found to be 1.8 years, based on the tests.

A comparative analysis of BIPV and BIPVT systems was carried out by V.V. Tyagi *et al.* [9]. It was recorded that almost 16% more usable electric energy generated in a medium sized two-story building than the same size BIPV roof. BIPVT systems generate more electricity than BIPV, and as a result of this, break-even costs have often been favourable compared with BIPV systems. M. Farshchimonfared *et al.* [10] describes the optimization of the single pass air style PVT system mounted on a tangled roof. The analyses considered the different channel depth values and mass flow rates. It was determined that 23.4% to 27.2% of the energy needed to operate the fans in the air conduit supply system in the air-based PVT. Basant Agrawal *et al.* [11] discussed about the Indian climatic roof mounted BIPVT system. The study found that series connections are best suited for BIPVT rooftop systems with a steady mass air flow rate. Table 1 presents a summary of air cooled PVT system and performance as well as their most significant results.

2.1.2 *Air-based PVT–PCM system*

PCM is the thermal energy storage equipment, when solar energy is available these PCM materials retain more heat energy. This heat will later be used as the ultimate use. A schematic representation of air cooled PVT–PCM is depicted in Figure 3. A new optimized PVT–PCM system was created by Lin *et al.* [20] to provide thermal indoor comfort during winter and summer seasons. Results indicated that electrical and thermal output, combined electrical and thermal power were 8.31%, 12.5%, 1.35 kW and 17.06 kWh and 8.26%, 13.6%, 1.98 kW and 34.71 kWh,

Table 1. *Air cooled PVT system.*

Author	Application	Method	Electrical efficiency	Thermal efficiency	Inference
Sajjad *et al.* [13]	PVT-air	Experimental method	7.2%	Nan	The findings presented have been compared with uncooled solar panels in this study, where the PV module is incorporated on the air conditioning duct to enhance the performance of PV cells.
Bambrook SM *et al.* [14]	PVT-air	Experimental method	10.6%	55%	The study was conducted on open loop type single pass unglazed PVT system, and found that with increasing air mass rate, increase in thermal efficiencies.
Shahsavar *et al.* [15]	PVT-air	Experimental method	9.8%	Nan	The findings were confirmed by experiments and a balanced thermal model has been established. For a mass cooling air flow rate of 0.1 kg/s, a maximum overall efficiency of 70% was observed.
Syamimi Saadon *et al.* [16]	BIPVT	Numerical method	12%	Nan	The studies take place in three ways. The opaque PV modules are considered at 30% and opaque at 50%. The most power gain is the opaque PV units. The studies also demonstrate that the BIPVT method decreases the ventilation requirements of houses.
Kasaeian *et al.* [17]	PVT-air	Experimental method	12.4%	31%	The channels' depth was diversified to examine their impact on the system's efficiency. Decreased channel depth resulted in improving thermal efficiency according to their results, although it did not have a significant impact on energy efficiency.
Sonveer Singh *et al.* [18]	PVT-air	Numerical method	14.15%	19.48%	The analyses considered the channel length and depth, air fluid velocity flowing into the channel, Tedlar thickness and glass and inlet fluid temperature. For optimization of the PVT method, the Genetic algorithm methodology is recommended.
F. Ghani *et al.* [19]	PVT-air	Numerical method	Nan	Nan	For the performance study of the PVT method, however, the proposed ANN model may be used for the impact of wind and varying irradiance and temperature.
Tingting Yang *et al.* [12]	BIPVT	Experimental method	5%	27.1%	The research concludes that a two-entrance system equal to a frameless PV system will improve thermal efficiency in contrast with a traditional no wire mesh packing in collector system and that higher thermal efficiency is obtained with wire mesh packing in BIPVT collector system.

respectively, in winter and summer. The analysis also reported that the proposed device continuously offered heat convenience with a mean temperature of 23.1°C during the winter season, without the use of air-conditioning. Laura Aelenei *et al.* [21] reported that BIPV–PCM was being applied in winter time on a building in Lisbon. Air from the ventilation system circulated between the PV layer and PCM as prototype was tested. In order to assess the impact on the system enforcement, air flow and gap depth were varied. During the day, the winds stayed free. The total productivity and PV contributed is 20% and 10%. After studies in the concentrated PVT method, Ilhan Ceylan *et al.* [22] identified the importance of using paraffin wax as PCM. Radiations from the primary mirror were concentrated in a region that was surrounded by damaged PV cells and filled with PCM. The stock was dried in a drying chamber by means of heat contained inside the PCM. With PCM cell temperature exceeding 37°C the performance of the panels improved from 5% to 11%.

To put the theoretical research of the air-based PVT–PCM system to the test, Sohel and Cooper [23] utilized MATLAB and TRNSYS tools. As air flow rate rises, energy and thermal quality have increased. The wind speed had a great impact, the thermal efficiency decreases with rise in wind speed. This is because greater wind speeds lead to more heat loss from the PVT surface to the atmosphere. Due to high wind speed, the PV module eliminates the full amount of heat and loses the heat in the area. The electrical and thermal efficiency of the system found was 11% and 29%, respectively. At various wind speeds Khanna *et al.* [24] carried out the energy enhancement in PV system with air cooled PVT–PCM. The findings revealed that at a wind angle of 75° to 0°, an electrical efficiency increase from 7% to 8.60%. Even when wind speeds are changed from 6.0 m/s to 0.2 m/s, power is dropped from to 22.8 W/m^2 to 11.8 W/m^2. The decline in wind speed reduces electrical efficiency, the highest power output obtained is 192 W/m^2 at 6 m/s wind speed. Innovative solar assisted heating, ventilation and air conditioning (HVAC) system has been developed by Fiorentini *et al.* [25] and implemented in a PCM integrated thermal PV device. In China and Australia, tests were carried out. At the flow rate between 160 l/s and 170 l/s the electrical output, thermal output and total performance were 11.2%, 9% and 17.2%, respectively. The author also pointed out that increasing air flow, decreasing temperatures of the PV module and enhancing power, thermal and overall system

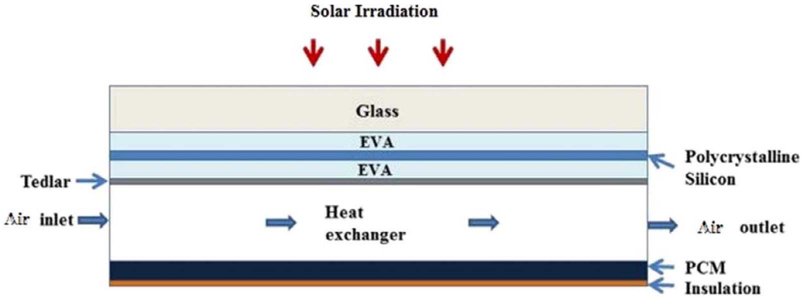

Figure 3. *Air cooled PVT–PCM system [26].*

Table 2. *Air cooled PVT–PCM system.*

Author	Application	PCM	Method	Electrical efficiency	Result
E. Bigaila *et al.* [27]	BIPVT	Paraffin wax	Numerical method	14.5%	The PV module generated electricity during the use of waste heat in warm air supplied to the heat pump and then stored it in the radiant PCM plate. This short-term heat contained in PCM was then used for heating space.
Meriem Nouira *et al.* [28]	PVT	RT25, RT35 and RT44	Numerical method	12.5%	A computational analysis of the interconnected PVT system PCM has been performed. Parameters such as wind speed, direction and dust have been taken into account. Three different forms of organic PCM have been selected. About 8 to 12°C drop in PV panel temperature was noticed.
Negin Choubinesh *et al.* [29]	PVT	Salt hydrate PCM32/280	Experimental method	11.5%	The results concluded that the PV module maximal and average reduction temperature for a low flow and normal flow rate were 3.7°C and 3.4°C and 4.3°C and 3.6°C, respectively.
Haoshan Ren *et al.* [30]	PVT	SP24E/SP26E	Numerical method	Nan	The air-cooled PV panel resulted in improved electrical efficiency when heat was contained in PCM within walls by hot air. The most significant air flow rate, followed by the PCM form used, has been found among numerous control factors.
Shivangi Sharma *et al.* [31]	BIPVT	Paraffin wax (RT42)	Experimental method	7.7%	The hybrid refrigeration device PVT–PCM was demonstrated to be better than PVT system. The panel temperature decrease was also observed with the use of PCM at 3.8°C.

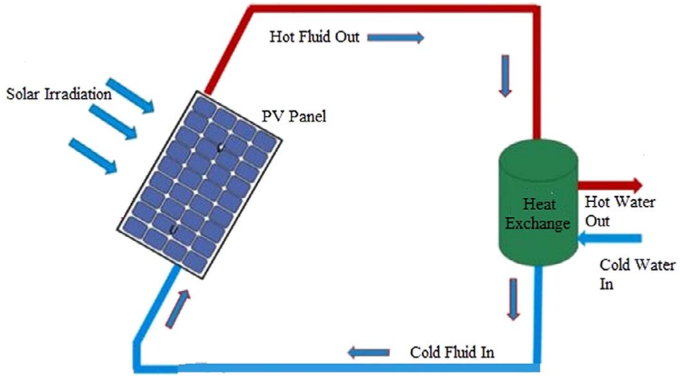

Figure 4. *Water cooled PVT system [37].*

performance. Table 2 presents a summary of air cooled PVT–PCM system and performance as well as their most significant results.

2.1.3 *Air-based PVT–NPCM system*

PCM has a lower thermal conductivity as its key concern. Researchers then proposed that infusing them with nanoparticles can improve device performance. This segment has been used in the PVT method for air-based NPCM. The construction of an integrated PV device by NPCM with a finned plate setup was defined by Sharma *et al.* [32]. In the integrated PV device, paraffin wax was used as a PCM material and copper oxide as a nano material. It was observed that temperature of integrated PV device with finned PCM and finned NEPCM was decreased by 15.9% and 18.5%, respectively. It has been observed that the panel temperature has been lowered to 12.5°C. Ma *et al.* [33] reviewed NPCM in building. Demonstrated that using NPCM in air-cooled ceiling ventilation systems has drawn growing interest to solve one of the fundamental challenges (i.e. low thermal conductivity) to the widespread adoption of PCM in many industrial applications. The result was that the NPCM and PCM consumed gross heat deposited at 23.85 and 22.03 kWh, respectively.

Table 3. *Water cooled PVT system.*

Author	Application	Method	Electrical efficiency	Thermal efficiency	Result
A E. Kabeel *et al.* [40]	PVT water	Experimental method	16.41%	Nan	Three separate cooling methods have been taken into account, including water cooling, forced air and forced water cooling. The experimental results indicate that water cooling is the most effective way of cooling a photovoltaic module in Egyptian climatic conditions.
R. Santbergen *et al.* [41]	PVT water	Numerical method	15.52%	24.3%	Use of counter reflective coating on PV cell with low coefficients temperature is recommended to improve electrical and thermal efficiency.
Wei He *et al.* [42]	PVT water	Experimental method	10%	40%	PV modules have been placed on a base and water tubes have been installed under the plate. However, between 75% and 60% of thermal efficiency increment was observed, which was considerably higher than the traditional PV system's performance.
Patrick Dupeyrat *et al.* [43]	PVT water	Numerical method	8.8%	79%	The prototype was tested and optimized by means of a 2D modelling technique. The researcher proposed that the thermal resistance would be reduced by a single, packed lamination of the glass, PV cell and absorber layer.
Sujala Bhattarai *et al.* [44]	PVT water	Numerical method	13.69%	71.5%	Using one-glazing plates and copper tubes, the heat from the absorber plate will be stored in the tubes. Compared to the traditional thermal collector, the PVT device has poorer thermal efficiency. However, the combination of electric and heat outputs is important.
Niccolo Aste *et al.* [45]	PVT water	Numerical method	13.2%	Nan	The simulation study was considered with spectral efficiency, temperature-related loss of efficiency, the true solar radiation incidence angle of the surface as well as device thermal inertia.

2.2 Water cooled PVT system

2.2.1 *Water-based PVT system*

In general, a high temperature application that uses air cooled PVT systems may be performed well because of their thermal properties, such as low density, reduced thermal energy, less thermal conductivity and so on. Water has, however, greater temperature properties than air and a better thermal conductivity than air. The useful means of cooling forced convective active cooling systems caused by fluid flow within the channels inserted at the rear of PV modules. The literature available primarily covers theoretical and experimental water Based PVT systems research. The study contains PVT glazed systems, without glazed systems, water channels, PV modules fully covered and partly covered collector coating, semi-transparent PV modules, selective coating, multi-fluid systems and PCM collector systems are also available. The PVT system's hot water is used in the majority of cases for domestic uses. Figure 4 represents the circuit of water cooled PVT system.

In order to minimize traditional PVT systems prices, Charalambous *et al.* [34] have proposed a mathematical model. For the performance analysis of this absorber and for its ideal design with EES code a steady state model has been created. A prototype of 6.35 mm copper plating was used in risers and header of a serpentine damping platform. Compared to the template Serpentine introduced by others, this recommended version includes 50% to 40% less material and mass volume. The unglazed flat plate PVT device been experimentally studied by Huang *et al.* [35]. In the analysis, the copper plate was fastened by means of an adhesive material to a 240 W poly c-Si PV module with water tubes. The report concluded that 12.77% and 35.33% rise in electrical and thermal efficiency of PVT system, respectively. The temperature of the water increased between 26.2°C and 40.02°C. In four separate cities in India, Mishra *et al.* [36] examined the efficiency of two PVT schemes. In the first case, the absorber plate of 2 m^2 was 3% partly covered and in the second case, the absorber plate was completely encircled. The maximum electrical and thermal output increase was 5500 and 6000 kWh, respectively, for the totally protected system. These figures were 4800 kWh and 5800 kWh, respectively, for partly covering grid.

The efficiency of a single glassed PVT device has been experimentally tested in Bangkok; Thipjak Nualboonrueng *et al.* [38] investigated in the analysed water-based PVT systems. Solar cells have been placed on a frame and water tubes have been mounted under the cooling layer. Investigators say that the annual output of PVT collectors amounts to 1.1 to 103 kWh/m^2 and 55 to 83 kWh/m^2 of electricity. The integrated PVT system, which includes polycrystalline PV modules and corrugated PV panel heat sinks, has been used by Huang *et al.* [39]. The PV panels were mounted on the flat plate absorber plate. Between the module and the absorber layer, thermal graft was used for improved coordination. In contrast to different PV and thermal systems, the study report increases system efficiency. Investigators demonstrate that glazed collectors can boost efficiency. Overall maximum productivity encountered is 53%. Table 3 presents a summary of

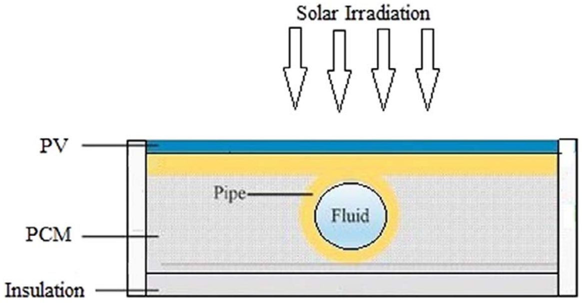

Figure 5. *Water cooled PVT–PCM system [52].*

water cooled PVT system and performance as well as their most significant results.

2.2.2 *Water-based PVT–PCM system*

The collector thermal capacitance is also an efficient means of cooling the cell temperature. Integrated PCM content helps reduce PV cells temperature in a PV module, because of its high latent thermal capability, by absorbing heat as they are melting. Indeed, not only does the PCM layer retain a suitable temperature in the PV cells, but it also serves for a subsequent function as a heat sink for storing waste heat. The use of solar energy in a PVT collector is considered to be intermittent, so the thermal energy storage will improve this issue by storing the heat in the day and discharge it at night. A schematic representation of water cooled PVT–PCM is depicted in Figure 5.

The experimental test of PVT–PCM and PVT water-based system was examined by Yang *et al.* [46] at 0.15 m^3/h. The results showed that electrical efficiency, power output and thermal efficiency of PVT system is 6.98%, 956.45 kJ and 58.35% and PVT–PCM system is 8.16%, 1117.8 kJ and 70.34%, respectively. In addition, overall thermal efficiency conversion for PVT–PCM and PVT were 76.87% and 63.93%, respectively. Su *et al.* [47] conducted performance of the PV thermal system with PCM. The aim of the research was to analyse the effect of the melting temperature on the PCM sheet, as well as optimum PCM thickness in the PVT–PCM method dependent on water. It was established that a 40°C melting point and PCM of 3.4 cm thickness had the highest overall performance and 30°C melting point had the maximum electrical effectiveness. The effects of different layer thickness of PCM such as 2 cm, 3 cm and 4 cm and the fluid rate of 32 dm^3/h and 80 dm^3/h were performed by Klugmann-Radziemska *et al.* [48] on water-based PVT/PCM systems. Best results show with a thickness of 2 cm PCM and at a volume of water of 32 dm^3/h. However, the best alternative was found for PVT–PCM without water cooling, as it lowered the PV temperature by 7°C and was maintained for 5 h. Malvi *et al.* [49] have optimized different parameters such as the flow rate, intakes and thickness of PCM to create a balance of efficiency between PV and PVT–PCM system output improved, whereas PVT system efficiency decreased with increasing of thickness of PCM, water flow rate and lower water supply temperature. PV power output improved by 9% at 50 mm PCM thickness and at 2 dm^3/h water flow rate. Following an experiment with PVT water running down a copper tube within a finned PCM at three different flow speeds was performed by Preet *et al.* [50] and found notable improvements in PV performance. The increased flow rate of water led to a further reduction in PV temperature and a further improvement in PV quality. The PVT–PCM system showed a 53% decrease in temperature and a 3-fold increase in PV performance. Gaur *et al.* [51] in summer and winter conditions performed a water-based computational analysis of PVT method without and with PCM. Introducing the PCM into the PVT scheme led to a greater fall in cell temperature, increased capacity and productivity in the summer than in winter. Moreover, the impact on PVT–PCM efficiency of both PCM mass and thickness and water flow rates showed optimal values of 30 kg, 15 mm and 0.04 kg/s, respectively. Table 4 presents a summary of water cooled PVT–PCM system and performance as well as their most significant results.

2.2.3 *Water-based PVT–NPCM system*

The researchers have focused on using PCM for the energy storage device in the PVT. The use of PCM would increase thermal and electrical efficiency without power addition. In comparison, its lower thermal conductivity is the key drawback of PCM. Therefore, researchers proposed that the overall efficiency of the systems improves by insertion of highly conductive nanoparticles. This segment addressed the water-based NPCM used in the PVT method as depicted in Figure 6. Table 5 presents a summary of water cooled PVT–NPCM system and performance as well as their most significant results.

2.3 NANOFLUID cooled PVT system

2.3.1 *Nanofluids-based PVT system*

Due to their improved thermal conductivity, nanofluids have very high heat absorption properties relative to their simple fluids. They can also be used to minimize the PV surface temperature considerably and are able to consume a substantial volume of excess heat as effective coolants for PV goods closer to an optimal operating temperature. This leads to an increased output of electricity. In addition, nanofluid heat absorption can be used to improve the general performance of the hybrid PVT device than the base fluid. In the following subsections, the work of the various researchers describes both the heat absorption and the spectral filtering properties of PV nanofluids.

SiC (Silicon carbide) nanofluid has been used in a PVT device in research work performed by Al-Waeli *et al.* (2017) [62]. In the initial stage of the analysis, the thermal properties of nanofluids were calculated in various concentrations, including 4%, 3%, 2%, 1.5% and 1%. The increase in thermal conductivities of nanofluid is 2.5%, 2.9%, 4.5%, 8.3% and 8.4%, respectively, at the above-mentioned concentrations. For tests on the device, 3 wt.% were pick based on these values because the thermal conductivity was increased to a small degree in higher mass fraction. The findings of this study show that using nanofluid improves the

Table 4. *Water cooled PVT–PCM system.*

Author	PCM	Application	Method	Electrical efficiency	Thermal efficiency	Result
H. Fayaz *et al.* [53]	A44-PCM (paraffin)	PVT–water–PCM	Numerical and experimental method	12.4%	71%	Experimental and computational studies looked at the electrical performance of the PVT–PCM system, and the findings were found to be quite close with deviation of <2%.
M.F.I Al-Imam *et al.* [54]	Paraffin wax with fatty acid	PVT–water–PCM	Experimental method	Nan	50%	The composite PCM thermally conductive including water in the tubes absorb additional heat from the panel. In PVT–PCM hybrid system the PV temperature has decreased by 20°C compared with reference PV. Increased total system reliability due to improved heat control.
Ahmad Hasan *et al.* [55]	RT42	PVT–water–PCM	Experimental method	6%	41%	The average cell temperature drops by 5°C in comparison with traditional PVT, and the PV efficiency increased by six percent in PVT–PCM. For heating applications, thermal energy stored with PCM water was used.
Taher Maatallah *et al.* [56]	Paraffin wax	PVT–water–PCM	Experimental method	17.33%	26.87%	The findings showed that, based on the total energy need, the PVT–PCM water based payback time was six years, 11.6% shorter than the traditional PV scheme.
Yuekuan Zhou *et al.* [57]	Paraffin wax	BIPVT–water–PCM	Numerical method	12.01%	Nan	The increased flow rate and reduced temperature of the induction resulted in a reduction of the cell temperature and an improvement in PV performance. In addition, the effect on PVT output was more influenced by water inlet temperature than by its flow rate.
Soroush Mousavi *et al.* [58]	Sodium phosphate salt, palmitic/ capric acid paraffin C22, C18 and C15	PVT–water–PCM	Numerical method	18.36%	83%	The result showed that the increase in copper foam in the PCM increases electrical energy and thermal efficiency by 2.3% and 1.0%, respectively. The findings of the model were also validated with experimental results, and both results were well supported.

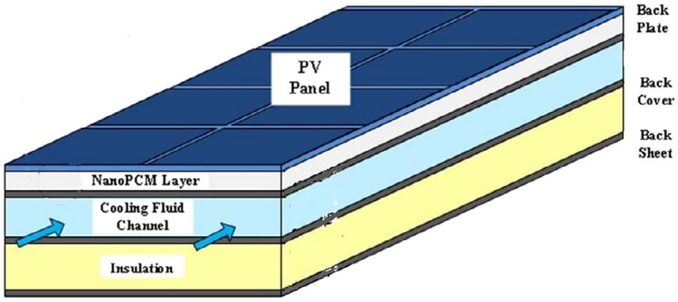

Figure 6. *Water cooled PVT–NPCM system [59].*

electrical efficiency by up to 24.1% as compared to PV without cooling system. The power produced by nanofluid in contrast to the alone PV and water-cooled PV system was 25.6% and 57%, respectively. Besides electric efficiency, nanofluid-cooled systems had a thermal efficiency of 100.19% higher than that of water-cooled one. Ragab *et al.* [63] carried out numerical simulations on PV cooled by Boehmite nanofluid at various frequencies (0.01, 0.1 and 0. 5 wt.%). At a concentration of 0.1 wt.% the overall temperature drop was reached to 24°C and the electrical power rise by 21.87%. At flow rate <200 ml/min, the flow from laminar to turbulent was achieved. Radwan *et al.* [64] have determined impacts on the efficiency of a nano cooled PVT device, its volume fraction, Reynolds no. and concentration ratio. Increased volume fraction up to 4%, a decrease in Reynolds no. and concentration leads to drop in temperature and rise in PV electricity. SiC has been found to be more efficient than Al_2O_3 because of its improved thermal conductivity. Rejeb *et al.* [65] compared nanofluid-based PVT device output and base fluid. Four separate nanofluids have been checked with 0.1, 0.2 and 0.4 wt.% (Cu-Water, Al2O3 Water, Cu-EG, Al2O3-EG). The performance of PV in water-based nanofluids has increased more than in EG. More performance than Al2O3 was improved by Cu-nanoparticle. In comparison, output improved from 0.1 to 0.4 wt.% with rising concentration. Table 6 presents a summary of nanofluid cooled PVT system and performance as well as their most significant results.

2.3.2 *Pvt system with combined nanofluid and PCM*

The use of PVs cooling in combination PCM and nanofluid is more efficient than a single use of PVs. Thus, two heat absorbing systems, i.e. nanofluid and PCM, remove additional heat from the

Table 5. *Water cooled PVT–NPCM system.*

Author	PCM	Nano-material	Application	Method	Electrical efficiency	Thermal efficiency	Result
M.R. Salem *et al.* [60]	Calcium chloride hexahydrate	Al_2O_3 (Alumina)	PVT–water–NPCM	Experimental method	22.7%	48.6%	The findings revealed that the optimal concentration and flow rate of nanoparticle values are 1 wt.% and 5.31 kg/s. The authors have found that the electrical, thermal and complete exergy efficiencies of Al_2O_3 NPCM increases as the concentration ratio increases.
Nasrin Abdollahi *et al.* [61]	Coconut oil and sunflower oil with 82 wt.% and 18 wt.%, respectively	Boehmite	PVT–water–NPCM	Experimental method	29.24%	Nan	In comparison with traditional PV, the PVT–NPCM module temperature reduction was 25°C, 22.6°C and 20.8°C at solar radiation of 690, 530 and 410 W/m^2, respectively.

Table 6. *Nanofluid cooled PVT system.*

Author	Nano-material	Application	Method	Electrical efficiency	Result
Samir Hassani *et al.* [66]	Al_2O_3	PVT–nanofluid	Experimental method	Nan	Thermal efficiency improves by 0.5% and PV efficiency improved at 0.3% concentration owing to a PV temperature decrease by 36.9°C in contrast with water setting.
Mohammad Sardarabadi *et al.* (2016) [67]	TiO_2, ZnO, Al_2O_3	PVT–nanofluid	Experimental and numerical method	6.54%	The peak gain in the PV efficiency using nanofluids TiO_2, ZnO and Al_2O_3 compared with PV was 6.54%, 6.46% and 6.36%. The ZnO water nanofluid has achieved the highest thermal performance of the PVT system.
Mohammad Sardarabadi *et al.* (2014) [68]	SiO_2	PVT–nanofluid	Experimental method	24.31%	The PV panels increased their temperature to 68°C without cooling, but the insertion of nanoparticles drops PV temperature to 50°C, increased the efficiency of PV with increasing the concentration from 1 to 3 wt.%.
Munzer.S.Y. Ebaid *et al.* [69]	TiO_2, Al_2O_3	PVT–nanofluid	Experimental method	50%	The peak PV temperature was lowered by nanofluids of Al_2O_3 and TiO_2 at flow rate of 3000 ml/min is 57.5°C to 40.5°C. Output improved with increasing concentration and flow rates, while Al_2O_3 was more efficient for both concentration and flow rates comparatively than TiO_2.
Y. Khanjari *et al.* [70]	Al_2O_3	PVT–nanofluid	Numerical method	Nan	The PV/T PV performance of the nanotubes system fell from 11.4% to 10.3% by increasing solar irradiation temperature from 293 K to 323 K while the inlet temperature dropped from 11.2% to 9.6%.

PV panel. Nanofluid has higher heat transfer properties because of its higher thermal conductivity, the mixture of nanofluid and PCM does not only lower the PV temperature but also raises the temperature evenness because of approximately uniform rear panel interaction. Inclusion of nanoparticles increases their thermal conductivity in PCM, resulting in improved heat absorption. Many new PVT technologies have evolved in recent years, other than air, water and biofluid with a favourable performance. In this regard, there has been a lot of development in recent years. The effect of heat transfer is completely dependent on the cooling medium thermal conductivity. The homogenous mixture of nanoparticles into the cooling medium will improve the temperature of the cooling fluid and intern increase the heat transfer rate. PCM integrated with nanofluid is discussed in this section.

The experimental work of the PVT–PCM system was evaluated by Sardarabadi *et al.* (2017) [71] with different types of cooling fluids and configuration in the PVT system. The findings showed that the thermal, electrical and general performance of NPVT–PCM is greater and the temperature of the PV panel is decreased further. The result is that, relative to the typical PV system without extra energy usage, the electrical and the overall efficiencies were 13% and 23%, increasing as much thermal energy as the NPVT system. In addition, the PVT system's temperature decreases by 10°C was observed, while NPVT–PCM system increased to

Table 7. *Nanofluid cooled PVT–PCM system.*

Author	Nanofluid material	PCM	Application	Method	Electrical efficiency	Thermal efficiency	Result
Mohammad Hosseinzadeh *et al.* [52]	ZnO	Paraffin wax	PVT–nanofluid–PCM	Numerical method	13.61%	29.60%	The overall PV, NPVT and NPVT–PCM exergy efficiencies were 10.73%, 13.61% and 12.37%, respectively. In addition, there was a 1.59% and 3.19% decrease of entropy generation of NPVT and NPVT–PCM, respectively.
Muhammad O. Lari *et al.* [73]	Ag	Octadecane	PVT–nanofluid–PCM	Experimental method	11.7%	27.3%	The daily and annual performance is compared to a nanofluid-cooled PVT system without thermal storage and an uncooled PV system, and its economics are assessed using engineering equation solver.

16°C by the utilization of water cooling in PVT system. Hassan *et al.* [72] have been tested with various flux values and nanoparticle concentrations at 40, 30 and 20 LPM and 0.15, 0.1 and 0.05 wt.%, respectively, on experimental work of PVT–PCM using nanofluids, for thermal control and uniform temperatures. Different configurations were developed in this research, such as a traditional PV, water-based PVT–PCM system and NPVT–PCM system. It was confirmed that NPVT–PCM system performs better at 0.1% concentrations and 40LPM at 45.8%, 44% and 60.3% respectively, with thermal, electrical and total efficiency. Table 7 presents a summary of nanofluid cooled PVT–PCM system and performance as well as their most significant results.

2.3.3 *NANOFLUID-BASED PVT(NPVT)-NPCM system*

The PCM basis can be equipped with strongly conductive nanosized metallic particles in order to overcome the characteristics of low thermal conductivity. The very tiny nanoscopic properties increase the surface area and thus generate immense potential for applications of nanoparticles. In this segment the PCM and the cooling fluid are distributed with nanoparticles, which are used for thermal energy conservation in the PVT device. Not only does it enhance the output of electricity, but it also has the potential for water heating or space heating. However, there are still some obstacles to practical applications, such as how to increase the rate of heat transfer and how to remove and use heat efficiently. Therefore, PVT systems usually become more complex or require additional electricity to operate cost effectively. Table 8 presents a summary of nanofluid cooled PVT–NPCM system and performance as well as their most significant results.

3 PASSIVE COOLING TECHNIQUES

Some researchers have turned their attention to PCM in recent years, which can absorb large amounts of latent heat with a slight increase in temperature during the phase transition process. The main advantages of passive cooling are simple design, no additional devices or equipment required and lower maintenance costs than operation. By connecting the PCM to the back of the solar panel, it is expected that these PV–PCM will keep the solar cell's low temperature to ensure higher conversion efficiency. With passive cooling, no additional drivers or electricity are required, so PV–PCM systems require little maintenance with comparison to most conventional available PVT technology [79]. In addition, PCM is considered an effective solution for the use of thermal energy from non-conventional energy sources. Extensive studies on solar energy and energy preservation provides a solid foundation for solar heat generation and electricity in PV–PCM systems.

Passive approaches are important for PV cooling projects in addition to the above active methods. No mechanical equipment is required for these methods. However, the key benefit of passive methods is that they need not drive the cooling mechanism from an external power source. The structure was easier and maintenance costs were reduced. The following subsection shows some of the passive methods and their effect on the PV cell efficiency.

3.1 PV with pure PCM

The use of PCM for thermal control is a passive method that is applicable for preventing PV panel temperature increases. In constant, temperature PCM consumes the excess thermal energy from the cell. A schematic view of PCM cooled PV system is depicted in Figure 7.

Lo Brano *et al.* [80] developed a basic PV–PCM computational model using a finite difference method and compared it with an obtained data from *in situ* at a test facility. As experimentally measured and numerically calculated c-Si cell temperature was in the range of ±5%, the proposed model found good agreement with experimental results. From the CFD analyses, Kant *et al.* [81] clarified that heat transfer was improved during the melting process of PCM with convective mode. For convection and conduction heat transfer, the cell temperature fell by 6°C and 3°C, respectively, with convection supremacy. Increased convection angles within the PCM and increased wind speed improve convective heat losses while enhancing PV effectiveness. The efficiency of pork

Table 8. *Nanofluid cooled PVT–NPCM system.*

Author	Nanofluid material	Nano PCM material	Application	Method	Electrical efficiency	Thermal efficiency	Result
Ali H.A. Al-Waeli *et al.* (2017) [74]	SiC–water	SiC–paraffin wax	NPVT–PCM	Experimental method	13.7%	72%	The findings indicated that the voltage, electricity and electric performance improved from 13 V to 21 V, 61.1 W to 120.7 W and 7.1% to 13.7%. In addition, during optimum solar irradiation time, the PV panel temperature decreased to 30°C.
Ali H.A. Al-Waeli *et al.* (2018) [75]	SiC–water	SiC–paraffin wax	NPVT–PCM	Numerical method	13.32%	Nan	In this system, electric current is improved from 3.69 A to 4.04 A, with the electrical efficiency improving by 8.07% to 13.32% compared to traditional PV, with NPCM and nanofluid.
M.M. Sarafraz *et al.* [76]	MWCNT	MWCNT–paraffin wax	NPVT–PCM	Experimental method	20%	44%	The findings reveal that increasing the coolant mass fraction increased electricity and power output while increasing the nano-fluids mass concentration increased pumping power and decreased thermoelectric equivalent power.
Ali H.A. Al-Waeli *et al.* (2020) [77]	SiC–water	SiC–paraffin wax	NPVT–PCM	Numerical method	Nan	Nan	The study proposed linear projection models help reduce the error of furcating potential outcomes and easily and quickly evaluate the optimum conditions for every solar system.
Ali H.A. Al-Waeli *et al.* (2019) [78]	SiC–water	SiC–paraffin wax	NPVT–PCM	Numerical method	13.32%	72%	The different PVT systems were tested, e.g. conventional PV, PVT water-assisted, NPVT and NPVT–PCM. Moreover, with the experimental importance of recent and earlier published works, the ANN model findings were reliable.

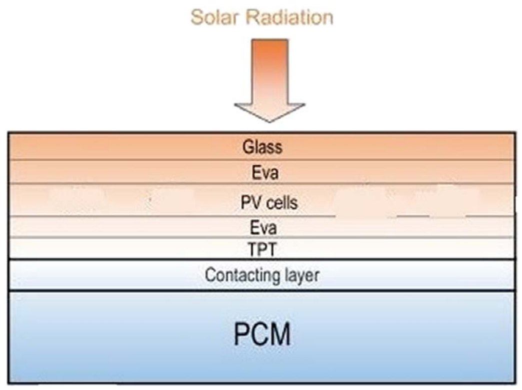

Figure 7. *PCM cooled PV System [59].*

fat as PCM by the comparison to conventional organic PCM for PV cooling has been assessed by Nizetic *et al.* [82]. The simulation of both systems in Croatia for a year was seen to be marginal due to identical physical characteristics. Pork fat was environmentally sustainable and cost less initially, but commercially feasible as thermo-physical properties degraded over the long term.

Hachem *et al.* [83] used PV passive cooling white petroleum jelly by adding it to the PV back plate. Improved performance by 3% and decreased PV temperature by the average of 2.7°C. J. Park *et al.* [84] have collected one month data in Song-do, South Korea, in order to compare PV–PCM system performance with the conventional PV. PCM was achieved with a maximum 5°C drop in the PV temperature. Power output rise from 1.9 W to 1.96 W and PV output increased from 8.06% to 8.34%. By increasing its PCM thickness from 30 to 50 mm, efficiency increased very little while the optimum PCM melting point was 25°C. Kibrias *et al.* [85] has tested BIPV performance numerically by incorporating three PCM for performance comparison separately (RT20HC, RT25HC, RT28HC). Due to its highest latent heat, RT28HC showed optimum performance, with the cell temperature lowered by 18°C and the efficiency improved by 5%. Table 9 presents a summary of PCM cooled system and performance as well as their most significant results.

3.2 PV with NANO-PCM

Many methods are taken to increase PCM efficiency while retaining a lower PV cell temperature. In recent years, nanotechnology

Table 9. *PCM cooled PV system.*

Author	PCM	Application	Method	Electrical efficiency	Result
A. Hasan *et al.* (2017) [86]	Paraffin wax	BIPVT	Experimental method	5.9%	It is found that in April and June, the PCM reached its peak temperature decrease of 13 and 8°C. PCM thus obtained a higher average decrease in temperature in April by 6°C in accordance with that in June by 2.3°C.
Ahmad Hasan *et al.* (2014) [87]	Eutectic capric–plasma acid and calcium chloride hexahydrate	PVT–PCM	Experimental method	10%	In two climates, PV–PCM systems are studied for electrical and thermal efficiency. Finally, expenditures spent owing to PCM integration in PV systems are reviewed and found that this method is more economically favourable for cases of elevated solar radiation and temperatures.
Rok Stropnik *et al.* [88]	RT28HC	PVT–PCM	Experimental and numerical method	7.3%	The overall annual rise in electricity production using the PCM for thermal regulation of the panel was 7.3% relative to the PV, without cooling power, based on the simulated performance, carried out with the application of TRNSYS for environment condition in Ljubljana, Slovenia. In their analysis, additional fins were proposed in order to enhance the heat transfer between PCM and PV cell in order to achieve greater efficiency.
Zacharias Gkouskos *et al.* [89]	Rubitherm RT27	PVT–PCM	Experimental method	Nan	In the study PCM retained a cell temperature close to 25°C when integrated with PV module, which is suitable for PV.
A. Hasan *et al.* (2014) [90]	Paraffin waxes, salt hydrates and mixtures of fatty acids	PVT–PCM	Numerical method	Nan	A study has performed on the effect of the main thermophysical properties of PCM on PV temperature control. A prominent influence on PV temperature control was high latent heat, high thermal conductivity, less cooling, fair melting and solidification range, etc.
Sourav Khanna *et al.* [91]	RT25HC	PVT–PCM	Numerical method	19%	PV panel tilt angle was varied from 0º to 90° and studied the effect of tilt angle on the PV system. PV temperature peak drop of 43.3°C to 34.5°C was accomplished using PCM and 18.1% and 19% better power and performance.
Pascal Henry Biwole *et al.* [92]	RT25	PVT–PCM	Numerical method	Nan	Research work describing the heat and mass transfer to PV panel with intrusion of finned PCM. After just 5 min PV temperature without PCM reached 40°C and started to rise. Using PCM kept the temperature of the panel constant at 40°C for 80 min to regulate the temperature increase, using the latent heat.
Lippong Tan *et al.* [93]	RT27	PVT–PCM	Experimental Method	5.39%	Performance of power and efficiency in PCM is testing for four different configurations were studied and analysed in actual outdoor conditions. In PV–PCM with fins, a maximum decrease of 15°C was observed with 5.39% improved PV efficiency.
Taieb Nehari *et al.* [94]	RT25	PVT–PCM	Numerical method	Nan	The presence of fins has helped to disperse the heat equally within PCM, thereby increasing PV cooling. The most powerful fine lengths were 25, 30 and 35 mm, which are useful in preventing an increase in PV temperature.
Ramkiran B *et al.* [95]	Paraffin wax	PVT–PCM	Experimental method	11.34%	Additionally, the findings demonstrated that temperature decrease does not necessarily result in a gain in power, as seen in the instance of greenhouse net and plant cooling with greenhouse. The largest temperature drop seen when plants are cooled in a greenhouse was 14°C.

has gradually been proposed to boost the capabilities of PCM for heat transfer. Maiti *et al.* [38] used paraffin wax as a composite PCM on the rear of the panel with metal turners. For contrast, indoor and outdoor measurements have been carried out. V-trough was put in front of the panel for an outdoor evaluation, improving solar exposure until 1.55 times. Composite PCM lowered the temperature of PV more than pure PCM. During indoor and outside tests, this value was 65 and 62°C. RT55 paraffin wax was used for the thermal control of PV cells in research performed by Nada *et al.* [96]. Alumina nanoparticulate matter in addition to pure PCM in 2% concentration was used as the second thermal control approach. The findings showed that using a pure PCM containing nano-parts, in contrast to the reference PV panels without a cooling device, decreased the temperature of 8.1 and 10.6°C, respectively. Both temperature reductions have increased the performance of the above-mentioned cooling system by 5.7%

and 13.2%, respectively. The increase in heat transfer by the use of the nanoparticles in the PCM is due to the increase in thermal conductivity. Luo *et al.* [97] have proposed a PCM low thermal conductivity solution contained in the PV cooling process. In RT28, graphite was applied, resulting in a NPCM with thermally conductive of 7.571 W/mK. For a long time, the PV temperature drops by 25°C in PV–NPCM plates, the highest power output increase was 11.5%. For similar works pertinent to PCM and solar energy utilization, readers are advised to refer to [98–112]. PCM and solar energy combination works are found to be very common in effective utilization.

4 SUMMARY OF SOLAR PV COOLING TECHNIQUES

According to the literature, in active cooling PVT system, thermal energy may be used for space heating, HVAC, crop drying, etc. PCM in an active cooling system absorbs excess heat from PV panels that is not converted to electricity. The latent heat of PCM helps reduce the panel temperature, keeping it near to ambient during peak sunlight hours. As PCM's thermal conductivity rises in proportion to the concentration of nanoparticles, PVT-NEPCM achieves higher overall efficiency than air-based PVT or PVT–PCM systems. The water-based PVT–PCM system is more efficient over the long run than PV alone. Thermal and electrical performance of nanoparticles modified with water-based PVT–PCM was shown to be significantly improved. Additionally, the weight percentage of nanoparticles and thermal conductivity of NEPCM increased. Additionally, it was discovered that the effects of temperature on the thermal conductivity of NEPCM are similar to those of pure PCM. Active cooling of PVs is strongly suggested when using nanofluids. However, even though nanofluids need extra power consumption to flow, this may be readily compensated for by efficiency increase and extra thermal power generated by heat absorption in the nanofluid itself. Compared to the most typical PVT systems, the passive cooled PV–PCM system is sluggish and inadequate when it comes to cooling down. However, this system relies on itself and requires less maintenance since there is no flow of fluid or additional power required.

5 CONCLUSIONS

Different factors, such as environmental conditions, material and operating temperatures, influence the efficacy of solar PV cell. The temperature plays a key role in the cell's electrical and thermal efficiency and is preferably kept low as possible. These parameters included during research of numerous active and passive methods in the literature are thoroughly analysed because of the necessity of using an appropriate thermal control solution. When the high performance of heat transfer and improved cooling rate are necessary, active methods are favoured. Air and water are the most widely used fluids in successful methods for cooling PV cell. The model of the cooling channels, their mass flow speed and type coolant used have the greatest influence on the efficiency of active cooling methods. Using nanofluids in active cooling cases improves heat removal rates from PV cell even further. The advantage of passive cooling methods is that they rely on themselves and don't require extra power while retaining a simplified structure. NPCMs are successfully used as passive thermal control strategies for PV cell. The melting temperature of NPCM has a significant influence on cell temperature. The effectiveness of applying NPCM for thermal control is heavily influenced by atmospheric air temperatures as well as the precise NPCM used. The methods used in thermal engineering for heat transfer augmentation, such as incorporating various forms of nanoparticles, are applicable for improving the thermal control of PV cells.

- The configuration of the cooling channels, their flow rates and the coolant type are the primary determinants of the performance of active cooling techniques.
- The use of nanofluids and NPCM in active cooling significantly improves heat removal rate.
- The viscosity, thermal diffusivity, thermal conductivity and convective heat transfer coefficient of the system are all improved when NPCM is used in PVT. Due to the improved heat transfer qualities, convective and radiant losses have been proven to be minimized.
- The thermal conductivity of NPCM was determined by the size of the nanoparticles.
- There is a tremendous increase in using NEPCM to regulate and improve the thermal performance of PV panels in order to increase their energy output.
- In nanofluid PVT–PCM systems, when the mass concentration of nanoparticles in the base fluid rises, viscosity and pressure decrease. As a consequence, the cost of energy rises as the pumping power per unit length rises.
- The payback term for a PVT system could be reduced by increasing the system's overall performance.

6 FUTURE PROSPECT IN PV COOLING

Based on the prior literature study and discussions, various problems and future research possibilities for cooling of PV systems are offered below to assist further develop this technology.

- In order to have a better understanding of how various PCM and nanoparticles behave, further experiments and simulations are needed.
- In spite of promising short-term results, long-term outdoor research is limited. The experimental module may be unreliable over time. New PV–PCM module design and manufacturing technologies are needed to develop.
- Although improving PCM thermal conductivity is vital and extensively used in many researches, the characteristic analyses of PCM thermal conductivity has gotten little attention in

the past. Future study might benefit from theoretical advice on thermal conductivity values.

- In experimental or numerical work, the solidification process should be addressed as well as melting. Sub-cooling may cause inadequate solidification of PCM, reducing their performance on the subsequent day.
- Although incredibly efficient, nanofluid PVT systems have many obstacles, including high active equipment costs and stability concerns owing to clumping, which need critical intervention.

SUPPLEMENTARY DATA

Supplementary material is available at *International Journal of Low-Carbon Technologies* online.

CONFLICTS OF INTEREST

The authors declared that they have no conflict of interest.

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