Pathways toward high-efficiency solar photovoltaic thermal management for electrical, thermal and combined generation applications: A critical review

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Abstract

Photovoltaic (PV) panels convert a portion of the incident solar radiation into electrical energy and the remaining energy (>70 %) is mostly converted into thermal energy. This thermal energy is trapped within the panel which, in turn, increases the panel temperature and deteriorates the power output as well as electrical efficiency. To obtain high-efficiency solar photovoltaics, effective thermal management systems is of utmost. This article presents a comprehensive review that explores recent research related to thermal management solutions as applied to photovoltaic technology. The study aims at presenting a wide range of proposed solutions and alternatives in terms of design approaches and concepts, operational methods and other techniques for performance enhancement, with commentary on their associated challenges and opportunities. Both active and passive thermal management solutions are presented, which are classified and discussed in detail, along with results from a breadth of experimental efforts into photovoltaic panel performance improvements. Approaches relying on radiative, as well as convective heat transfer principles using air, water, heat pipes, phase change materials and/or nanoparticle suspensions (nanofluids) as heat-exchange media, are discussed while including summaries of their unique features, advantages, disadvantages and possible applications. In particular, hybrid photovoltaic-thermal (PV-T) collectors that use a coolant to capture waste heat from the photovoltaic panels in order to deliver an additional useful thermal output are also reviewed, and it is noted that this technology has a promising potential in terms of delivering high-efficiency solar energy conversion. The article can act as a guide to the research community, developers, manufacturers, industrialists and policymakers in the design, manufacture, application and possible promotion of high-performance photovoltaic-based technologies and systems.

Keywords: active cooling, cooling techniques, efficiency enhancement, nanofluids, passive cooling, phage change materials, photovoltaic, PV-T cooling, thermal management

Contents

Nomenclature

Abbreviations

a-Si	Amorphous silicon
AF	Aluminium foam
ANP	Analytical network process
BIPV	Building-integrated PV systems
CdTe	Cadmium telluride
CFD	Computational fluid mechanics
CIGS	Copper indium gallium selenide
CPV	Concentrated photovoltaic collectors
CPVT	Concentrated hybrid PV and thermal
DC	Direct Current
DPP	Discounted payback period
DSC	Differential scanning calorimetry
GaAs	Gallium arsenide
HTF	Heat transfer fluid
IR	Infrared radiation
LCOE	Levelised cost of energy
MAT	Maximum attainable temperature
MEPCM	Microencapsulated PCM
PCM	Phase change materials
PDMS	Polydimethylsiloxane
PV	Photovoltaic
PV-T	PV-thermal
RT42	Paraffin
Si	Silicon
S-CCHP	Solar combined cooling, heating and power system
SEM	Scanning electron microscope
TEC	Thermoelectric cooler
THM	Temperature history method
TMS	Thin metal sheet

Symbols

A	Solar cell area
E_{g0}	Bandgap
FF	Fill factor
G	Solar irradiance
G_c	Generation rate of carriers
I_0	Reverse saturation current
I_L	Photogenerated current
I_{max}	Maximum value of the current
I_{PV}	Current of PV cells
I_{sc}	Short circuit current
k	Boltzmann constant
L_n	Diffusion lengths of electrons
L_p	Diffusion lengths of holes
n	Ideality factor
P_{max}	Maximum power produced by solar panel
q	Element charge
T	Operating temperature
T_{ref}	Reference temperature
V	Output voltage
V_{max}	Maximum value of the voltage
V_{oc}	Open-circuit voltage

Greek

β	Temperature coefficient of PV cell
γ	Irradiance coefficient
η_{el}	Electrical efficiency
η_{ref}	Electrical efficiency at the reference temperature
λ	Wavelength

1. Introduction

Energy is an indispensable resource, linked closely to human, economic and societal development, and the empowerment of mankind. It is often broadly classified into conventional and alternative (including renewable) forms [1]. At present, the majority of the world's energy demand is fulfilled by non-renewable sources, such as fossil fuels and nuclear energy [2-5], although the deployment of renewables continues to accelerate. Key characteristics of non-renewable resources are that they can be found in finite quantities and that their rate of replenishment is considerably slower than the rate at which they are being utilised or consumed. Their continuous usage at significant rates of consumption poses a serious risk of continued energy security and environmental impact. This has given rise to extensive worldwide efforts by a wide range of diverse stakeholders (e.g., researchers, scientists, companies, organisations, policymakers, governments) to increase renewable energy penetration for meeting the growing global demands for energy in its various forms [6-10]. Arguably, amongst all renewable energy resources, solar energy is the most abundant, widespread and promising in terms of its ability to cater to a global energy demand [11-13].

The two main solar energy technologies are solar thermal collectors and photovoltaic (PV) panels. A solar thermal collector transforms solar radiation into useful thermal energy, typically by using a heat transfer fluid whose temperature (and, therefore, enthalpy) increases as it passes through the collector. On the other hand, a PV panel converts solar radiation falling on its surface directly into electrical energy via the photovoltaic effect. Typically, the efficiency of commercial solar PV panels ranges from about 10 % to 23 % [14,15,16]. The most widely used PV panels are based on silicon (Si) cells and are categorised into three types: mono-crystalline, poly-/multi-crystalline, and amorphous. More recently, silicon heterojunction cells, as well as thin-film technologies (e.g., CdTe, CIGS) have also entered the market [17,18].

In a PV panel, photons with energy greater than the band gap energy support the photovoltaic effect through which electricity is generated, however, the remaining photon energy is mostly converted into heat, causing the cell temperature to increase. This temperature rise, in turn, is deleterious to the open-circuit voltage (V_{oc}), fill factor and output power, thus ultimately decreasing the electrical efficiency of the panel. Common factors that influence the operating temperature of a solar cell, beyond the local solar irradiance include climatic conditions such as wind speed, ambient temperature and relative humidity, as well as factors such as accumulated dust on the panel. In this context, any solution capable of cooling a PV panel by removing some of the unwanted or accumulated thermal energy is of interest as this can reduce cell temperatures, improve electrical efficiency, and prevent the irreversible damage to the panel caused by the cells temperature rise and periodic thermal cycling over the day- and night-time operation.

Various thermal management methods have been proposed, developed and tested over the years specifically aimed at the cooling of PV panels, and some commercial products that implement such solutions are available on the market. These thermal management methods can be classified as active and passive. The former category relies on forced convective heat transfer, whereas approaches that fall into the latter category rely on free convective, conductive and/or radiative heat transfer control.

When surveying studies relevant to this domain in the literature, a number of comprehensive and informative reviews can be identified. Siecker et al. [19], for example, presented an extensive overview of various hybrid cooling techniques, and covered techniques including: (i) floating tracked concentrated cooling systems, (ii) PV-thermoelectric systems cooled by a heat sink, (iii) PV panels with integrated phase change materials (PCMs), (iv) PV panels cooled via immersion cooling, (v) PV panels with transparent coatings, (vi) hybrid PV-thermal (PV-T) systems cooled by water spraying, and (vii) PV-T systems cooled by forced fluid circulation. This review extended to providing insight into these cooling techniques, however, it did not cover all the available techniques, e.g., the potential employment of nanofluids, heat pipe cooling, or radiative methods, along with a presentation of their thermal and electrical performance. Furthermore, Maleki et al. [20] and Hasanuzzaman et al. [21] presented an overview of active and passive cooling techniques available for regulating PV panel temperatures and suggested that passive techniques are more feasible for small-scale implementation with active techniques being more useful in commercial-scale systems given the added costs and additional power requirements.

Velmurugan et al. [22] presented a comprehensive review on PCM types and passive cooling using PCMs, and Muhammad Ali [23] elucidated the recent advancements in PV cooling, especially with PCM systems holistically, while Sargunanathan et al. [24] presented an extensive review on a range of cooling concepts such as heat pipe cooling, liquid immersion cooling, and active cooling by water flowing over the front surface of PV panels or by integrating air/water/fin cooling systems on the rear side of the panels. An analysis was presented of the role of these methods on decreasing PV panel operating temperatures. Kandeal et al. [25] presented a state-of-art review on PV performance enhancement techniques where the authors specifically focus on cooling techniques based on convection, conduction and radiation. Bahaidarah et al. [26] and Hamzat et al. [27] also presented an overview of different thermal management methods, relying on the employment of: (i) heat pipes, (ii) microchannels, (iii) liquid immersion, (iv) heat sinks, (v) impingement jets, and (vi) PCMs.

Together the aforementioned reviews contain very interesting information on such solutions and their development, however, they do not cover more recent research topics, including the use of nano-liquid cooling, radiative thermal management methods and novel designs, or recent developments in the field of combined hybrid PV-T collectors, which also involve thermal energy removal from PV cells. This leaves a gap in the literature for a comprehensive review of PV thermal management methods.

In this context, the present article presents a thorough review of thermal management techniques aimed at increasing the efficiency of PV panels. The main aspects covered in this article include:

- Discussion of the effect of temperature on PV cell/panel performance.
- Summary of thermal management techniques.
- Overview, where relevant, of key implementation, operational and performance characteristics.
- Consideration of the advantages and disadvantages of each approach or solution.
- Discussion of the application of each technology based on its characteristics and limitations.
- Outlook of important research gaps and future research directions.

To perform a comprehensive review, a significant volume of data is required. The information presented and summarised in this review was collected both from the academic literature, i.e., articles from reputed journals or books that have been peer-reviewed by experts, and from the grey literature, which comprises reports (technical or other), information on official websites (e.g., government websites, the private sector and other non-governmental organisations), white papers, and many reputed sources. Initially, a literature survey was performed by keyword search in renowned journal publishing platforms such as Elsevier, IEEE, MDPI, and similar. This yielded more than 3000 articles containing the desired keywords. In a second step, 'title screening' was performed, by considering specifically the titles of the pre-selected articles relevant to the core subject of this review, which accounted for about 1260 studies. By reviewing the abstract, the subject and focus of each study were estimated, and based on requirements such as novelty, clear objectives, methods, high impact, a further screening step was undertaken in the step termed 'abstract screening'. As a result of this step, 388 articles were identified, the content of which was investigated for the methods employed, the key findings, and the quality of the conceptual discussion. This led to the filtering of the most appropriate 236 studies, of which 207 studies were original research articles while the remaining 27 studies were reviews.

2. Motivation for thermal management

The useful electrical output of a solar PV panel mainly relies on the incident radiation and the electrical efficiency of the panel. The electrical efficiency of a PV panel is highly dependent on its temperature.

Specifically, for every degree in temperature rise, the efficiency of a PV panel drops by between 0.2 % and 0.5 % for silicon cells, as confirmed by many researchers [28-31]. Furthermore, the panel's output power varies with other atmospheric conditions such as solar irradiance, wind speed, cloud coverage and relative humidity, as well as material composition [32]. In concentrated PV (CPV) collectors, the operating PV cell temperatures are much higher than in flat PV panel systems, which, in turn, significantly reduces the lifespan of CPV panels. In these systems, cooling is crucial for reducing the cell temperature and enhancing overall performance, irrespective of their type.

During the conversion process of solar energy to electricity, the generation of (waste) heat elevates the temperature of a PV cell. This lowers the gap between the valance and conduction bands of the PV cell, which decreases the open-circuit voltage (V_{oc}) by about 2 mV/°C [33-35] and fill factor, while also causing a slight increase in the short circuit current (I_{sc}). Due to the noticeable decrease in V_{oc} relative to the increase in I_{sc}, the overall output power of the PV panel, which depends on the multiple of both, decreases. Other than decreased efficiency, higher operating temperatures also lead to the degradation of PV cells and, thereby, affecting their effective lifespan.

The accumulation of thermal energy within the PV panels as a consequence of continuous exposure to sunlight is detrimental as it results in a deterioration in electrical performance. An equivalent electrical circuit of a PV cell is shown in Fig. 1, and this can be considered to characterise this deterioration [36].

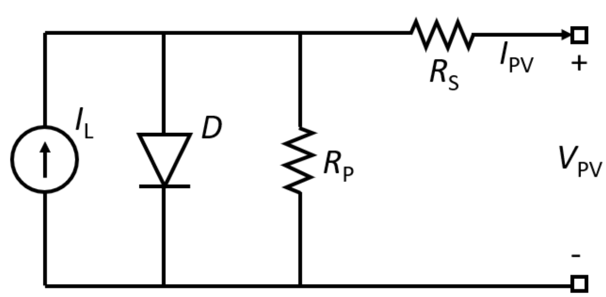

Fig. 1. Equivalent electrical circuit of a PV cell.

With reference to Fig. 1, the current I_{PV} in a single-junction solar cell is given by [37]:

$$I_{PV} = I_L - I_0[\exp\left(\frac{qV_{PV}}{nkT}\right) - 1] \quad (1)$$

where I_0 is the reverse saturation current corresponding to the diode, q is the element charge, V_{PV} is the output voltage of the solar cell, n is the ideality factor, k is the Boltzmann constant, and T is the operating temperature. The photogenerated current is given by $I_L = A \cdot q \cdot G_c \cdot (L_n + L_p)$, where A is the solar cell area, G_c is the generation rate of carriers, and L_n and L_p are the diffusion lengths of electrons and holes, respectively.

Moreover, the open-circuit voltage V_{oc} of the cell is [38]:

$$V_{\text{oc}} = V_{\text{oc}}(T_0) - \left[\frac{E_{\text{g0}}}{q} - V_{\text{oc}}(T_0)\right]\left(\frac{T}{T_0} - 1\right) - \frac{3kT}{q}\ln\left(\frac{T}{T_0}\right) \tag{2}$$

where T_0 is the reference temperature, and E_{g0} is the bandgap where the temperature dependency of the open-circuit voltage is directly evident. The change of V_{oc} with temperature is described by [39]:

$$\frac{\mathrm{d}V_{\text{oc}}}{\mathrm{d}T} = -\frac{\left[\frac{E_{\text{g0}}}{q} - V_{\text{oc}}(T_0)\right]}{T_0} - \frac{3kT}{q} \tag{3}$$

where T_0 = 300 K, E_{g0} = 1.1 eV, and V_{oc} = 0.55 V, typically for silicon cells. The V_{oc} decreases with the cell temperature with a coefficient of $\mathrm{d}V_{oc}/\mathrm{d}T$ of -2.45 mV/K at 25 °C [39].

The fill factor FF of the solar cell is determined from the maximum values of the output voltage and current, V_{max} and I_{max}, the open-circuit voltage V_{oc} and short-circuit current I_{sc} [14]:

$$FF = \frac{V_{\text{max}}I_{\text{max}}}{V_{\text{oc}}I_{\text{sc}}} \tag{4}$$

such that the maximum power P_{max} in the numerator is given by [14]:

$$P_{\text{max}} = V_{\text{max}}I_{\text{max}} = (FF)V_{\text{oc}}I_{\text{sc}} \tag{5}$$

Since the fill factor FF and open-circuit voltage V_{oc} depend on the cell temperature, it follows that the output power is also affected by the temperature. Therefore, the electrical efficiency of a PV cell can be calculated from the expression [40]:

$$\eta_{\text{el}} = \eta_{\text{ref}}[1 + \beta(T - T_{\text{ref}}) + \gamma\ \ln(G/1000)] \tag{6}$$

where β = -0.0045 K^{-1} is the typical temperature coefficient of silicon cells, T_{ref} = 25 °C is the reference temperature at the standard test condition, η_{ref} is the cell reference efficiency at a temperature of 25 °C and solar irradiance of 1000 W/m^2, γ = 0.085 is the irradiance coefficient, and G is the solar irradiance. Typical temperature coefficient ranges for different solar cell technologies are shown in Fig. 2. For most solar panels, with the notable exception of amorphous silicon (a-Si) which has a non-monotonic behaviour, the observed decrease of electrical efficiency is linear with the cell's temperature increase.

Finally, the PV efficiency can also be related to maximum power output P_{max} via:

$$\eta_{\text{el}} = (P_{\text{max}}/G \cdot A)\ . \tag{7}$$

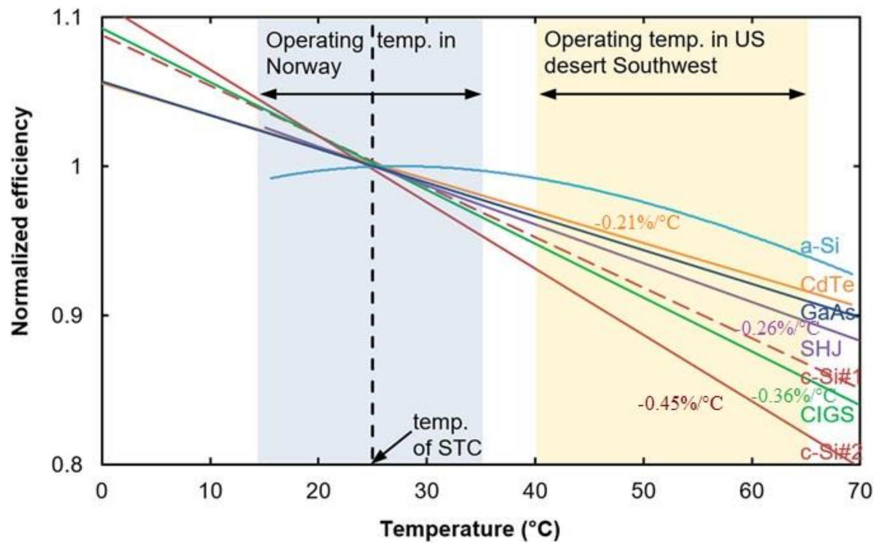

Fig. 2. Variation of normalised efficiency of different PV technologies with temperature [41].

Chander et al. [42] examined the performance of mono-crystalline PV panels by varying the cell temperature from 25 °C to 60 °C and the light intensity from 215 W/m^2 to 515 W/m^2. The results showed that the temperature coefficient has a negative effect on the open-circuit voltage, fill factor and maximum electrical output, whereas it has a positive impact on the short-circuit current. Jiang et al. [43] examined the effects of temperature and irradiation intensity variations on PV performance and found that higher temperatures inherently decrease the output power of PV panels. The *I-V* characteristics of the PV panel measured in this work at various ambient temperatures are shown in Fig. 3. Nevertheless, the PV panel temperature can be controlled by employing thermal management techniques.

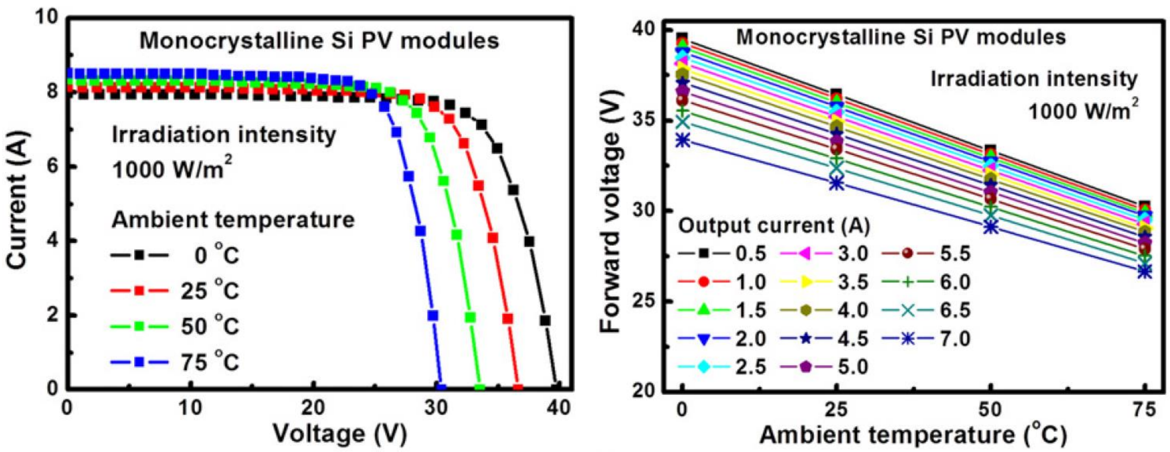

Fig. 3. *I-V* characteristics of a PV panel over a range of ambient temperatures [43].

3. Convective thermal management approaches

Convective thermal management techniques for PV panels can be split into two types: active and passive [44,45]. Active methods consume energy due to the use of pumps and/or fans in order to circulate the heat transfer fluids or coolants which removes heat through (most often) forced convection, whereas passive methods rely primarily on processes such as natural convection, capillary flow, etc., that do not require additional energy in order to achieve the same goal, i.e., to remove heat from the PV panels. In all cases, the benefits of implementing any solution onto conventional PV panels and systems incur added complexity and cost, and it is necessary to ensure that these are significantly outweighed by the performance benefits that they enable. If this cannot be ensured, the practical implementation of a solution cannot be justified. Fig. 4 shows the classification of convective PV cooling methods. The sections below discuss different active convective cooling methods in terms of their effectiveness to improve standalone, solar PV panel efficiency. A summary of the surveys is also provided in the form of tables for ease of access.

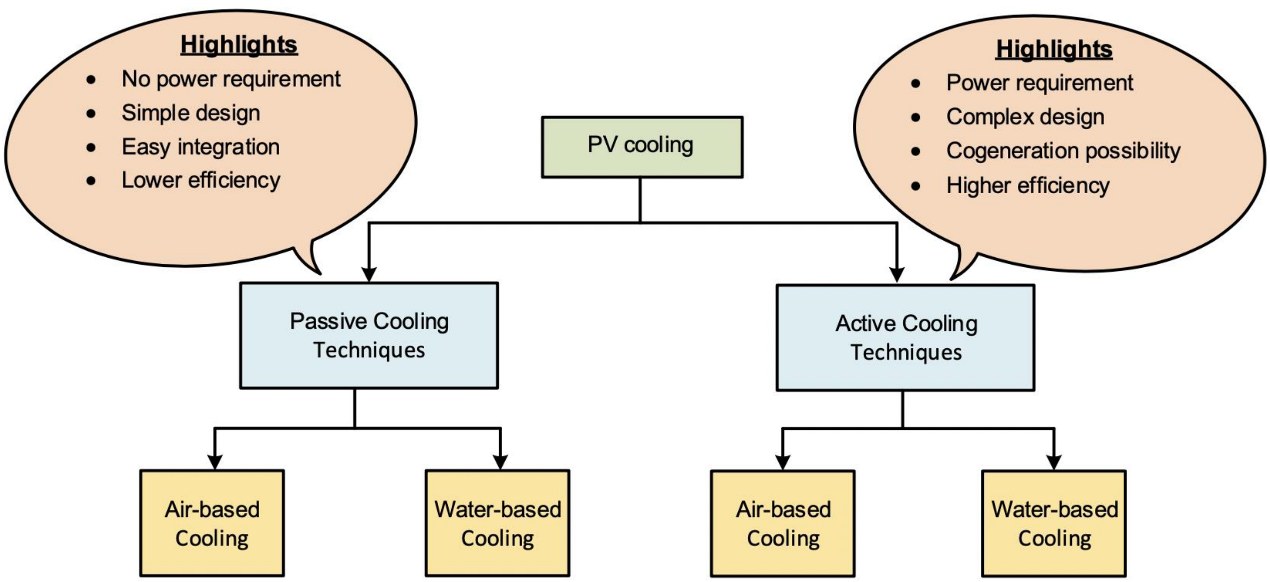

Fig. 4. Classification of convective PV thermal management methods, focussing on cooling.

3.1 Active thermal management

Active thermal management is almost invariably aimed at cooling using pumps/fans to circulate air or water to cool PV panels. Since it consumes power, the cost is high compared to passive cooling, nevertheless, it generally gives better performance than passive cooling techniques.

3.1.1. Air cooling

Air cooling is one of the most straightforward and simple ways for PV panel cooling because of its availability, simplicity and low cost. Teo et al. [46] studied cooling techniques for PV panels in an experimental arrangement that consisted of a parallel array of air ducts connected to the underneath surface of PV panels to actively cool the panels. To enhance the rate of heat transfer, fins were connected to the air ducts and a blower was used to extract air from the surroundings and to control the air flow rate. A second PV panel without cooling was included in the study for comparison purposes. It was found that an air flow rate of 0.055 kg/s was effective in reducing the temperature of the panel. The results revealed a temperature reduction from 68 °C (reference panel without cooling) to 38 °C with air cooling when the solar irradiance was 1000 W/m^2. It was also observed that the efficiencies of the panels improved significantly (by ~50 %) from 8-9 % without cooling to 12-14 % with cooling. Farhana et al. [47] used a brushless DC fan in experiments with an inlet/outlet manifold design for a constant flow of air. This cooling system consisted of aluminium fitted under a PV panel and the DC brushless fan attached to the heat sink. Air flow from the fan removed heat from the PV panel and transferred this to the heat sink, which promoted heat transfer to the surroundings. With this approach, the authors were able to demonstrate a reduction in the panel temperature by 40 % compared to a panel without cooling.

Syafiqah et al. [48] computationally studied PV panel cooling by using a DC brushless fan at the rear surface with six different speeds The results revealed that the PV power output, along with the parasitic input power to the fan, both increased with an increase in the fan speed. A fan speed of 3.1 m/s was chosen as the optimum speed for cooling since it had the highest net power output compared to other speeds. Boulfaf et al. [49] examined the thermal behaviour of a hybrid PV-T solar air collector using a finite element method. A diagrammatic representation of this collector is shown in Fig. 5. Their simulation results showed that the solar cell temperature decreased from 78 °C to 62 °C as the air flow rate increased from 0.05 kg/s to 1 kg/s with a solar irradiance of 1000 W/m^2. These results showed that at high fluid flow rates, and therefore speeds, the PV temperature and fluid outlet temperature both decreased more effectively, as expected. Further insights on solar PV-T air collectors for cogenerated heat and power are provided in detail in Section 7. Dehghan et al. [50] assessed the techno-economic perspectives of PV air cooling in two scenarios in the northwest of Iran where the difference between the scenarios lies with the use of 3 and 6 low-energy fans. The energy balance analysis indicated the production of more electrical output in the scenario where 3 fans were utilised. Net specific energy improvements amounting to 4.4 % and 4.1 % for Scenarios 1 and 2 were reported, respectively. The techno-economic analysis highlighted that the proposed thermal management can be easily justifiable only at high feed-in-tariff rates.

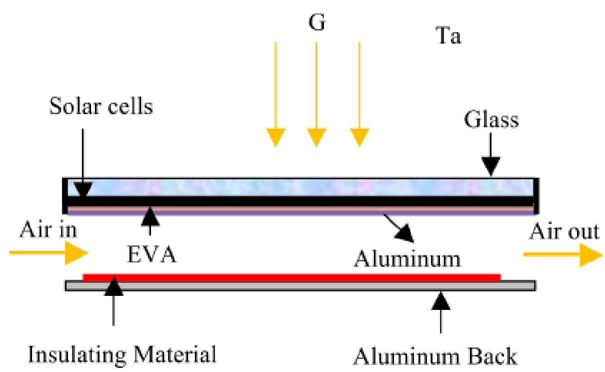

Fig. 5. Diagrammatic representation of a hybrid PV-T air collector [49].

Almuwailhi and Zeitoun [51] investigated the effects of cooling on the performance of poly-crystalline PV panels by using three different techniques namely: (i) natural convection, (ii) forced convection, and (iii) evaporative cooling with natural and forced convection in Riyadh, Saudi Arabia. From the experiments, it was deduced that natural convection cooling (with a 120 mm air gap) enhanced the daily energy generation and efficiency of the panels by 1.7 % and 1.2 %, respectively, whereas forced convection (with an airspeed of 3 m/s) enhanced the daily energy generation and efficiency by 4.4 % and 4.0 %. The greater enhancement with forced convection was attributed to a higher convective heat transfer coefficient underpinned by the velocity of air flow. On the other hand, forced convection evaporative cooling (using a speed of 2 m/s) enhanced both the daily energy generation and efficiency of PV panels by 3.8 %. The evaporative cooling was accomplished with a layout similar to the natural convection one, but with the addition of a wet fabric placed at the bottom of the channel and its wetness maintained by a water spraying system. Therefore, in the case of evaporative cooling, the latent heat of water plays a role in absorbing more heat compared to natural convection. In the same study, it is observed that the natural convection with a narrower air gap (30 mm and 60 mm) proves to be ineffective since it raises the panel temperature. This is due to the resistance offered by the friction to the natural convection currents in the cooling channel.

In summary, previous studies had shown that active cooling via forced air flow can enhance the efficiency of PV panels. The effectiveness of cooling using forced (active) air flows depends on several factors such as the speed of the fans used (i.e., typically more cooling can be achieved at higher fan speeds), whether the fan is used either at the rear or the front of the PV panel (with front cooling generally more effective than rear cooling) and the environmental conditions (e.g., higher wind speeds, lower ambient temperatures and/or greater cloud coverage all increase PV cooling). Simultaneous cooling using front water cooling and rear air cooling has shown particular promise, compared to using such approaches independently. Either way, as stated earlier, any efficiency benefits need to be placed in the context of the added system complexity, cost, and power consumption. The implementation of these solutions will be feasible only if the performance benefits outweigh the added costs, which in many cases is a challenge.

3.1.2 Liquid cooling

The cooling of PV panels can be achieved by using several liquids, but the most common liquid is water. Water has a higher density (997 kg/m³), specific heat capacity (4184 J/kg K) and thermal conductivity (0.6 W/m K) than air (density = 1.225 kg/m, specific heat capacity = 1012 J/kg K, thermal conductivity = 0.020 W/m K) and can deliver higher heat transfer coefficients relative to air (for a given geometry and similar flow velocities). This is because the convective heat transfer coefficient depends on the fluid density, thermal conductivity, and specific heat capacity. Relevant thermal management can be done by front or rear cooling based on the surface of the PV panel from which the heat is extracted.

Mah et al. [52] tested the performance of a retrofitted rooftop PV system with water-film cooling on the front of the PV panels. The electrical performance was improved by 15 % with an optimised water flow rate of 6 L/min at solar irradiance of 1150 W/m^2. Similarly, Prudhvi and Sai [53] studied the performance of a PV panel by cooling the panel using a front water-cooling technique. Water was circulated over the front side (top) of the panel with the help of a pump, which in this work had a power consumption of 36 W. The hot water leaving the panel was then circulated through an underground pipe using "groundwater tunnelling". An assessment of energy savings in this work showed an improvement of 7.8 % in the net efficiency of the panel. Kordzadeh [54] suggested that one of the best ways for improving PV system operation and performance involves cooling with thin water films. A schematic of their PV water-pumping system is shown in Fig. 6. Results generated with this apparatus revealed that there was a significant increase in the generated electricity as the system water pumping rate was increased.

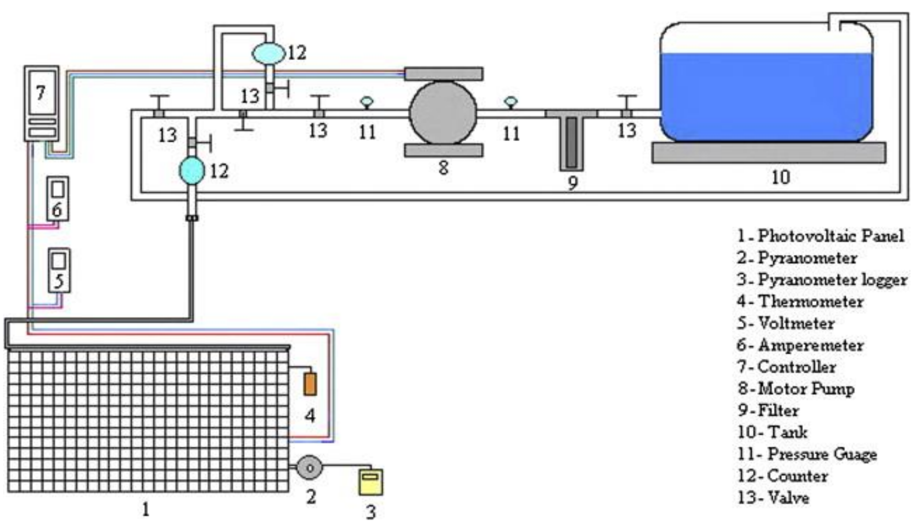

Fig. 6. Schematic of a PV water pumping system used in the study [54].

Shahverdian et al. [55] utilised a dynamic multi-objective optimization method to optimise and control the flow rate of the water used for cooling PV panels, with the aim of minimising water consumption while maximising power output. Their simulations showed that the average and maximum temperatures of the water-cooled PV panel with the optimal flow rate can be reduced by 54 % and 61 %, compared to a PV panel without water cooling. Hadipour et al. [56] compared the performance of steady-spray and pulsed-spray water cooling systems for PV panels. The testing results showed that the maximum power output of the PV panel increased by 33% and 26 % by using the steady-spray and pulsed-spray water cooling, compared to a PV panel without water cooling. The water consumption of the pulsed-spray cooling system is only one-ninth of that of the steady-spray cooling system. Therefore, the levelised cost of energy (LCOE) of the PV panel with pulsed-spray cooling was reduced by 76 % relative to the PV panel with steady-state cooling owing to the significantly reduced water consumption.

Dorobantu et al. [57] also considered a front water-cooling technique. The water flowed from a tube over the top of the panel, cooling the panel and also eliminating debris, which can affect performance detrimentally but also lead to physical damage. The experiment was done using a PV panel with an area of 0.56 m^2 using free-flowing water at a rate of 0.03 kg/s. It was noted that the output electric power increased by 4 W due to a corresponding decrease in the PV temperature. In related work, Moharram et al. [58] also conducted experiments in which water was used for PV panel cooling, although no air-cooling was considered. In these experiments, non-pressurised water was sprayed over PV panels when the panel attained a maximum attainable temperature (MAT), i.e., 45 °C. It was observed that the water cooling enhanced the efficiency of the panel, and that operating the cooling system for 5 min resulted in a decrease in the solar cells temperature by 10 °C, and thereby an increase in the solar cell efficiency by 13 %.

From the aforementioned studies, it can be deduced that front surface cooling is effective in reducing pumping costs, especially in hot climate conditions. However, a key drawback is the evaporation of water over the solar cells, which requires continuous replenishment, but which also significantly hinders the solar radiation reaching the cells through absorption. With respect to the various front water-cooling approaches and designs, spray cooling can lead to more water wastage compared to film cooling, and pulsed spray cooling can minimise the wastage. At the same time, film cooling is the most suitable for water reuse, via recovery and recirculation. It remains uncertain whether pulsed spray cooling at regular intervals or spraying the water after the PV panel achieves a set maximum temperature is the most effective cooling solution, so further research should be conducted to compare these two front water-cooling scenarios.

Concerning rear water cooling, Zondag et al. [59] developed an advanced numerical model for determining the thermal output of a hybrid PV-T collector based on a sheet-and-tube design. The temperature distribution and heat flow over the surface of and through the integrated panel are shown in Fig. 7. Their results revealed that the electrical and thermal efficiencies of the combined system were

6.7 % and 33 %, respectively, compared to 7.2 % for a conventional standalone PV panel and 54 % for a conventional standalone solar-thermal collector. Active rear water cooling is usually accomplished with the aid of pipes that are fitted at the rear side of a panel, with such arrangements also suitable in PV-T applications. A further discussion on hybrid PV-T water collectors is provided in Section 7.

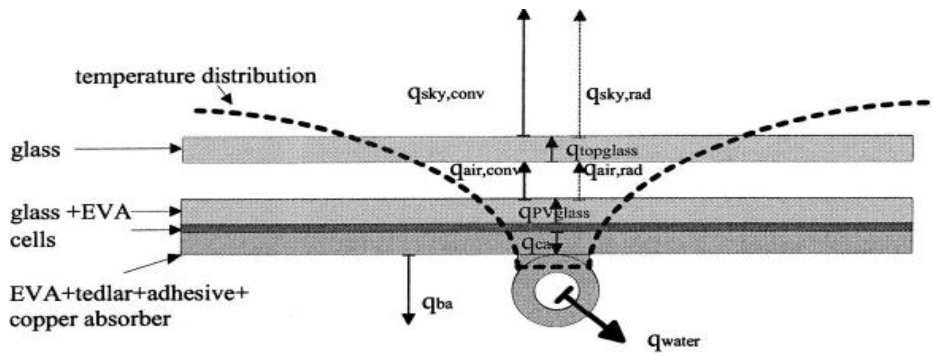

Fig. 7. Temperature distribution over a PV panel with water circulation [59].

Beyond conventional rear water-cooling systems designed for PV-T applications, some further innovative designs have proposed by researchers aimed at reducing the water utilisation necessary for PV cooling. Musthafa [60] considered a sponge attached to the backside of a PV panel for cooling purposes. The results from these experiments showed a 4 °C temperature reduction and a 2.6 % efficiency increase. Such a sponge system uses capillary action to drive a cooling water flow, and the utilisation of a reduced quantity of water might be attributed to the decreased volume of water contacting the rear surface of the panel due to the presence of the sponge. The cost of the sponge in this solution is low, however, a projected lifetime of about 6 months for the sponge requires a level of maintenance in this solution, which nevertheless is relatively simple to undertake.

Abdelrahman et al. [61] studied the effects of front cooling (film water cooling), direct contact rear water cooling and combined cooling, accomplished via the use of two water pumps. The first pump was operated to provide a water film flow over the front side of the panel, while the second pump was used to recirculate water through a finned duct attached to the bottom of the panel. The experimental results showed that the PV panel temperature was reduced by 16 °C, 18 °C and 25 °C and the daily power output was enhanced by 22 %, 30% and 35% for front cooling, rear cooling and combined cooling, in all cases relative to a standalone PV panel without additional cooling, with tests done on typical sunny June and July days in Cairo. The rear cooling was more efficient than the front cooling. The combination of the front and rear cooling resulted in the best cooling performance.

Several studies have compared water and air cooling, which has aided our understanding of the potential and relative technical (performance, operational) and economic characteristics of each approach. Specifically, Bevilacqua et al. [62] performed a long-term evaluation (8 months) of different cooling methods based on spray cooling, spray cooling with metallic plate and forced ventilation, on the rear side of the panel. A maximum temperature reduction of about 26 °C was obtained on sunny days for spray cooling relative to the panel with no cooling. Spray cooling at the rear side produced a maximum cooling effect in the hot months, as a higher cooling demand is satisfied with water-based cooling. Meanwhile, forced ventilation provided a better cooling effect in winter months since the ambient air temperature was low enough to serve as an effective heat-carrying fluid. Irwan et al. [63] compared the performance of a PV panel with front water cooling with that of a PV panel with regular air cooling. Their outdoor experiment results showed that water cooling is more effective than air cooling. The PV panel with front water cooling generated 6.8 % more output power than the PV panel with air cooling on a typical March day in Malaysia. Furthermore, studies have also employed combined active water and air cooling. Leow et al. [64] demonstrated an enhanced cooling effect by using a brushless fan for rear cooling and a water pump for front cooling. This system was controlled by a microcontroller and temperature sensor. Sensors were used to control the on and off switching of the hybrid system automatically when the temperature changed beyond the set maximum temperature. The outdoor experiment results indicated an increase in the average output voltage, current and output power by 5 %, 40 % and 43 %, respectively. The panel temperature decreased by 6.8 °C on a typical March day in Malaysia with an average ambient temperature of 33.6 °C.

Other research has considered oils as a cooling medium. Sun et al. [65] investigated direct-liquid cooling of a CPV panel using dimethyl silicone oil as the liquid, which flowed through a narrow rectangular chamber in thermal contact with the PV cell, thereby maintaining an average cell temperature within the range of 20-30 °C at 910 W/m^2 with the oil inlet temperature of 15 °C. It was reported that the cell temperature was relatively uniform and that the electrical performance of the cells immersed in the silicon oil was stable, with no obvious efficiency degradation observed even after being immersed for 270 days.

The studies summarised above demonstrated that active (i.e., pumped) water or oil flows can be used to cool PV panels effectively. Water can be circulated through a PV panel either over or under the PV cells, or both over and the cells at the same time. Using water as a coolant has shown better results than active air cooling, however, careful consideration is needed for the use of water in the water-stressed area. It is noted that passive cooling techniques based on air and water, which are discussed in the next section, are arguably considered by some investigators as more effective than active cooling techniques overall since additional parasitic power consumption is not required to promote cooling. A summary of further studies on PV panel efficiency enhancement by active water cooling is provided in Table 1.

Table 1. Summary of research aimed at efficiency enhancement of PV panels by active water cooling.

Nature of work	**Method**	**PV panel temperature reduction**	**Efficiency enhancement**	**Observation/remark**	**Ref.**
Experimental	Thin-film water cooling on the film side and finned water duct at the rear side	Average temperature reduction by 4 °C	Electrical efficiency enhancement by 12 %	Integration of water absorption sponge on the rear of PV panels can reduce their temperature over prolonged periods by passing water drop by drop through a sponge to maintain wet conditions over the panel.	[60]
Experimental and numerical	Water splashed on the front side of the panel in a non-pressurised way	Cooling of PV panel for 5 min resulted in a 10 °C temperature drop	Water cooling resulted in electrical efficiency enhancement of 13 %	It was observed that water cooling can clean and cool PV panels in hot and sandy regions, resulting in better performance.	[58]
Experimental	Water flowed through a tube over the array surface	Temperature reduction of about 25 °C at solar noon	-	Results show that this method can improve the optical properties of the array surface and increase the overall efficiency of the system.	[54]
Experimental and numerical	Water flowed through multi-header microchannels	Temperature reduction of 19 % for multi-header channel	Power output increased by 28 % for the multi-header micro-channel compared to a single-header channel	The multi-header channel can allow a greater temperature reduction and electrical efficiency improvements to the wider system.	[66]
Experimental and numerical	Surface cooling technique	Average temperature reduction by 16 °C	Power enhancement of about 15 % during peak radiation conditions	Better PV cooling due to the straight connection between the PV panel surface and water. The surface can be dust-free thanks to continuous water flow. Overall PV efficiency is higher.	[67]
Experimental	Spraying of water over the PV panel front surface	Decrease in operating temperature by 5 °C to 23 °C	With water cooling, the output power of the PV panel increased by 9.7 % to 22 %	Results showed a reduction in operating temperature and an increase in output power of the PV panel with a water-cooling system.	[68]
Experimental	Water spray cooling on the front and back sides of the panel	Average PV panel temperature dropped to 32 °C from 52 °C	Front and back side PV panel cooling by spraying water results in an increase in power output by 16 % and 5.9 % respectively	The proposed water spray cooling procedure enhanced the performance of the PV panel and also kept the panel clean from dust particles.	[69]
Experimental and numerical	Water cooling on the backside of the panel	The temperature of the PV panel dropped to 34 °C from 45 °C	The PV panel electrical efficiency increased by 9.1 %	Energy generated by the hybrid water cooled PV system was nearly four times that of the PV without cooling.	[70]

3.2 Passive thermal management

Although active cooling by forced convection has been proven to be capable of improving the electrical efficiency of PV panels, major drawbacks arise from the parasitic power consumption associated with circulating the coolant and the additional costs of the pumping and hydraulic components (e.g., valves, fittings), as well as the necessary fluid circuits and conduits. These difficulties are not encountered or are circumvented by employing passive cooling methods, which have therefore also attracted attention.

Passive cooling relies on the cooling of PV panels without the use of pumps or fans, but often using natural convection of fluids such as air, water, etc., and/or by using radiative heat loss enhancement, surface structures, emissivity control, etc. Since no pump, fan or associated components are required by these methods, the pumping/blowing costs (and the related system complexity) are removed, making these solutions, generally, more cost-effective, with less required maintenance. Furthermore, since the energy required for coolant circulation is no longer required, and even though the use of forced convection is associated with higher heat transfer rates and can allow lower PV temperatures, it is still possible for passive cooling methods to reach higher overall efficiencies relative to active cooling alternatives. Passive cooling that relies on convective heat removal can be sub-divided into air cooling, water cooling, fin cooling, heat pipe cooling, and PCM integrated cooling, and these are addressed in the present section.

3.2.1 Passive air cooling

Air cooling via passive approaches has attracted particular attention in recent decades. Advantages of this approach include: (i) minimal material requirements, (ii) low operating costs, (iii) no power consumption compared to active cooling, and (iv) easy handling. However, some disadvantages also arise, primarily from key thermal properties of air relative to those of water, e.g.: (i) poor thermal conductivity (i.e., heat transfer), and (ii) low heat capacity (i.e., storage density).

Naghavi et al. [71] investigated the natural air movement beneath a PV panel through numerical assessments. Their results showed that temperature differences of 12 ± 5 °C and 18 ± 5 °C could be obtained when the air gap between the rooftop and panel rear surface was 200 mm and 250 mm, respectively, relative to a panel with no gap. A larger air gap allows a greater volume of air to flow and, thus, it can remove heat from the rear side of the panel through convection effectively. Hernandez et al. [72] studied PV panel cooling by placing a panel on the steel roof of an industrial building. The PV panel was cooled by placing air channels underneath it with natural or forced convection cooling. The experimental results showed that the PV panel temperature with the natural convection cooling is around

5 °C lower than that without natural cooling on the back. In this case, research can be extended to analyse the temperature on the roof and relate it to the panel temperature since higher roof temperatures can decrease the effectiveness of the cooling effect produced by natural convection of air because air gets heated by both panels as well as the roof. Although the PV panel with forced convection cooling was able to generate 3-5 % more electricity than the PV panel with natural convection cooling, the forced convection cooling required a fan to maintain the air flow at 4 m/s in the channels. Therefore, comparing the net power produced by both active and passive cooling approaches will be a more pragmatic approach, but in the reviewed study, proper inference could be made due to the paucity of power consumption data of the fan.

Tonui and Tripanagnostopoulos [73] developed a validated model to investigate the natural convection cooling performance of two different types of low-cost air channels designs, i.e., inserting a flat thin metal sheet (TMS) in the middle of the air channel in one type and attaching fins on the back wall of the channel on the other type. The fins configuration exhibited better thermal performance relative to TMS configuration, which can be explained due to the higher surface area achieved by the extended surface offered by fins, which provides a better overall heat removal rate.

Shahsavar et al. [74] attached an air channel with TMS below a glazed PV panel as shown in Fig. 8. The air channel was used to cool the PV panel by natural convection cooling. The outlet air temperature reached 48 °C when the solar irradiance was 880 W/m^2. The air channel was able to effectively remove the waste heat in the PV panel and generate additional thermal energy. The electrical and thermal efficiencies were around 8 % and 32 %, respectively. However, the authors did not mention the PV temperature change compared to a standalone PV panel, and this hinders solid inferences regarding the effectiveness of the implemented cooling system. This is because it is uncertain whether the air channel offers better performance since channelling can either reduce the replacement rate of air or can increase the velocity of the air flow compared to the case without channels. To verify this, experimental research is recommended to compare performance relative to a reference PV system.

Fig. 8. Photograph of the practical implementation of the PV-T air system used in Ref. [74].

Rahimi et al. [75] investigated the idea of integrating wind and solar energy to produce more electrical power efficiently. In this concept, which is shown in Fig. 9, the air flows through a converging section (conical tube) and strikes the turbine (wind vane rotor). The experiment was performed for various solar intensities and two different wind velocities of 0.88 and 2.67 m/s. The turbine was designed to direct the air flow radially outwards to the divergent section and the opening of which faced the PV panel's rear surface for producing the required cooling effect. Therefore, the wind collected from the conical tube served two purposes: (i) acting as coolant fluid for the PV cells, whose operating temperature was observed to decrease on average by 21 °C at a constant solar irradiance of 910 W/m^2, and (ii) for generating electrical energy using a turbine. The results showed an overall increase in power generation by 36 % relative to a standalone PV cell without cooling.

Another study by Valeh-e-Sheyda et al. [76] experimented with a similar concept of integrating wind turbines and solar energy into a single system. In this system, the turbine used was of an axial type and the velocity of air flow (3 m/s and 5 m/s) was greater than that used in the previous study. The results indicated an enhancement of power output by 47 %. This larger improvement can be pinpointed to design characteristics and higher wind velocity. In general, the exit velocity of the fluid from axial turbines is higher than from radial turbines, which makes axial turbines less effective and suitable for multi-stage purposes [77]. But in the case of PV cooling, the exit velocity of air from the turbine is significant in providing effective cooling since convective heat transfer is enhanced with an increase in fluid velocity and the higher the heat transfer rate, the better will be the PV performance. On the other hand, the input velocity itself is higher in the later study, which favours the improvement of the performance of both the wind turbine as well as the PV cooling. Therefore, a greater enhancement in power was obtained in the later study compared to the former study. However, a major limitation with this hybrid solar and wind turbine power generation approach arises from its complex design and channeling of the air flow which makes it more suitable for active cooling. Such cooling systems may be appropriate for windy regions, while the velocity of air flow can be hampered (due to turbine) even if the system employs active cooling that, in turn, affect the thermal performance of the cooling system.

A range of studies that have been undertaken in the context of achieving PV panels efficiency improvements by passive air cooling is tabulated in Table 2.

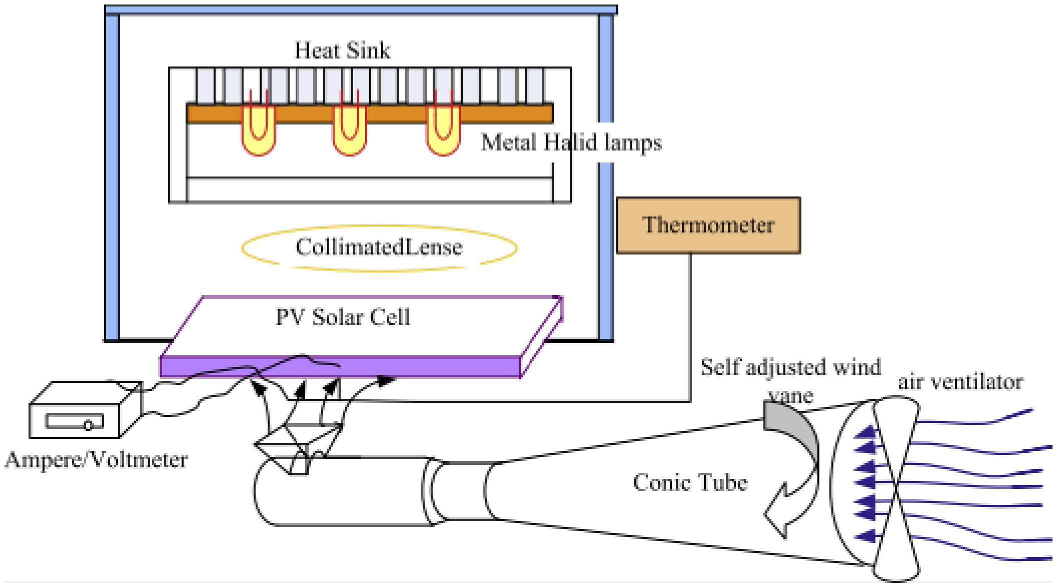

Fig. 9. Schematic of the hybrid wind-PV jet-impingement system for PV panel cooling [75].

Table 2. Summary of research aimed at efficiency improvement of PV panels by passive air cooling.

Nature of work	Temperature reduction	Efficiency enhancement	Observation/remark	Ref.
Numerical	Minimum temperature reduction of 10 °C was achieved	Maximum power output of the PV panel increased from 7.0 % to 7.6 % relative to a conventional PV panel	Results showed that the heat transfer rate and air flow inside the ventilated channel were influenced by the angle of the ribs; specifically, PV panel cooling was directly proportional to the height and inversely proportional to the inclination angle of the ribs.	[74]
Experimental and numerical	Average temperature decrease of 21 °C was accomplished	Overall power output of both PV panels and wind turbines increased by 36 %	The combined hybrid system was capable of cooling PV panels, thereby increasing their power output and producing power from a turbine.	[75]
Experimental	Operating temperature reduced by 18.3 °C	Electrical efficiency increased by 7.9 %	The temperature of PV panels was maintained lower while operating under direct sunlight by radiative passive cooling. A thin material layer over the solar cells was used, which was transparent at solar wavelengths but had higher emissivity in the IR (thermal) wavelengths, thereby emitting significant thermal radiation that cooled the PV panel and enhanced performance.	[78]
Numerical	PV cell temperature reduced by about 7 to 16 °C when the flow rate reached 1.6 to 5 g min^{-1}	Electrical efficiency is enhanced between 12 % to 23 %	A mixture of air and naturally occurring water vapour used as the heat transfer fluid enhanced the electrical performance of a PV panel. The studied system performed best at low flow rates. To improve the performance of PV panels, it was suggested that the panels can be installed in locations where vaporisation occurs naturally.	[79]
Experimental	PV panel integrated with clay reached a maximum temperature of 45 °C whereas PV panel without clay reached a temperature as high as 85 °C	Maximum increase in both output voltage and power of 19 % was achieved	Incorporated a clay layer on the back side of a PV panel and a thin film of water vaporised. This lowered the PV operating temperature and enhanced its efficiency. The method was reported as being efficient, cost-effective, stable and environmentally friendly.	[80]
Experimental	An average PV temperature drop of 14 °C was achieved	Overall power output of the system improved up to 47 %	A hybrid wind-driven ventilator and PV system maintained a suitable environment inside the building by air ventilation and maintained a lower PV cell temperature. The hybrid system resulted in higher electrical energy generation from the PV and dynamo.	[76]

3.2.2 Heat sink and fin cooling

A heat sink in this context is a heat exchanger that transfers the heat generated, e.g., at the surface of a PV panel, to a fluid medium, often air or a liquid coolant, thereby dissipating the heat away from the panel and regulating the device's temperature. When heat dissipation at the heat sink relies on natural convection, the rate of heat dissipation achieved will vary with the angle at which it is placed. Nair et al. [34], demonstrated that it is possible to reduce the temperature of a PV panel by using a passive cooling technique employing a heat sink. The experiment was performed on a clear summer day and it was shown that the PV panel temperature reached at a heat-sink angle of 45° was lower than that reached at 135°, which was recorded to be the maximum temperature. The maximum power production from the same study was also measured and found to increase by 7.0 % at a heat-sink angle of 90° and 7.6 % at 45°, relative to benchmark PV panels that did not adopt any cooling.

In related work, Chandrasekar and Senthilkumar [81] experimentally cooled a PV panel by using fins and natural convection. Cotton wicks were attached to aluminium fins and connected to the back of the PV panel, as shown in Fig. 10, to enhance the overall heat transfer rate. It was shown that the aluminium heat spreader along with wet cotton wicks showed better cooling performance compared to the heat spreader alone. It was noted that the maximum PV temperature decreased by around 6 °C and that there was a 14 % increase in the electrical power output from the PV panel. Similarly, Varkute et al. [82] also performed an experiment using fins to cool a 160× CPV panel. In this work, a multi-junction solar cell was placed on a copper block with fins. The rate at which the heat is dissipated from the block with fins was further enhanced by circulating water actively below the fins. The panel temperature was maintained at around 45 °C, which was significantly lower than that expected for the case in which no thermal management was employed (by about 58 °C). In another study, Zubeer et al. [83] examined the role of forced and natural air circulation on the performance of PV panels. An experiment was performed using an air channel modified to boost the transfer of heat in two different ways: (i) by inserting a thin flat metallic sheet in the centre of the channel, and (ii) by joining rectangular fins at the rear side of the panel. The results revealed that fins allowed greater thermal efficiency and better operating performance than the metal sheet system.

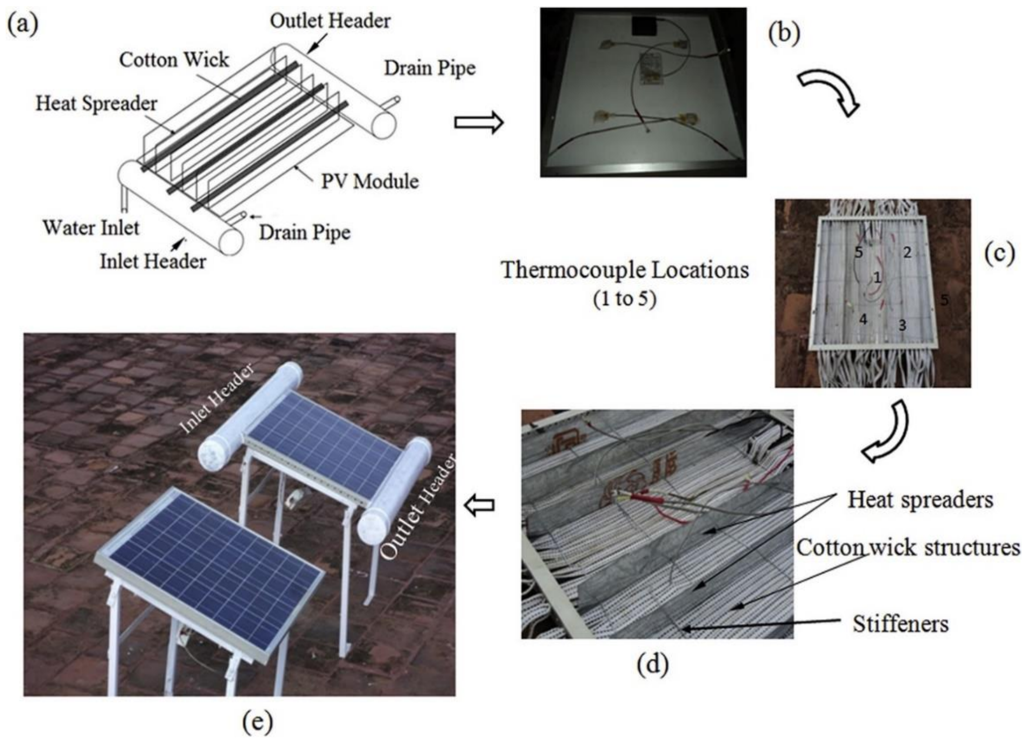

Fig. 10. Experimental photographs from [81]: (a) backside of PV panel, (b) thermocouple locations, (c) fins joined with wick structures, (d) stiffeners, and (e) final fabricated arrangement.

Idoko et al. [84] explored the operating performance of a PV panel involving two different passive techniques, namely passive air and passive water cooling. As shown in Fig. 11, aluminium fins were attached to the bottom of a PV panel for air cooling, while cold water was manually sprayed over the top surface of the same PV panel to further enhance the cooling effect. It was observed that the temperature of the PV panel with the integrated air and water cooling was reduced by 20 °C and the power output was raised by 21 W relative to a PV panel without cooling under a solar irradiance of 1080 W/m^2.

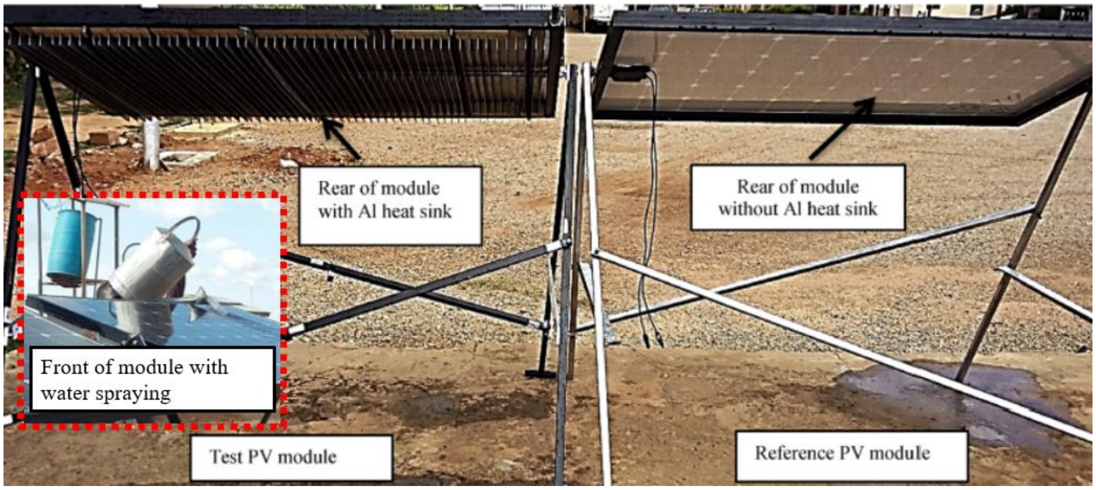

Fig. 11. Experimental apparatus showing fins connected to the backside of a PV panel [84].

Othman et al. [85] investigated a hybrid PV-T solar air heater system with fins connected to the absorber surface to enhance the heat convection. The schematic of the hybrid PV-T system explored in this study is shown in Fig. 12. Air flows through the upper channel and then through the bottom channel with fins. The thermal and electrical efficiencies were absolutely improved by around 20 % and 0.5 % as the air mass flow rate increased from 0.027 to 0.181 kg/s.

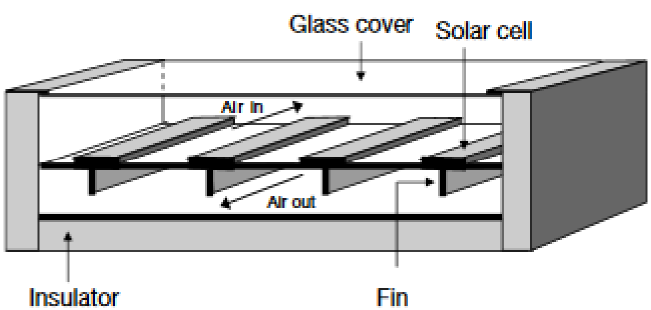

Fig. 12. Schematic of the PV-T solar air heater with fins investigated in the study [85].

Recent scientific literature has also emphasised modifying the heatsink profile and fin orientation to enhance the heat transfer rate. For instance, Hernandez-Perez et al. [86] modified the heatsink geometric parameters to enhance the passive cooling ability of the fins attached to PV panels. The authors proposed a discontinued finned heatsink that helped in inducing air flow in multiple directions which in turn enhanced the heat transfer rate. Numerical simulation showed a temperature reduction of 7 °C which was close to the experimental results (a drop of 5 °C).

The typical fin shapes/geometries used for the passive cooling of PV panels (or, similarly, of PV cells in PV-T collectors) often tend to be longitudinal, rectangular and baffled fins. The performance of PV panels can also be enhanced by using heat pipes, which is the subject of the following section.

Research results have shown that heat sinks and fins are effective in reducing the operating temperature and increasing the electrical conversion efficiency of PV panels. The cooling effect of fins strongly depends on the material and geometric parameters of the fins. The performance of fin cooling for PV panels is summarised and compared in Table 3. The cooling effect of fins usually increases with an increase in the fin length. Most research only focusses on the improvement of panel efficiencies induced by the additional fin structures, but only a few studies investigate the additional cost of the fins (and other related components), which should be considered in future research. Fin structures have also been widely investigated and applied in other fields such as electronic cooling systems and domestic space heaters. Therefore, lessons from the use of fins in other fields can also be applied to PV panels for cooling.

Table 3. Summary of research aimed at efficiency enhancement of PV panels by fin cooling.

Nature of work	**Temperature reduction**	**Efficiency enhancement**	**Observation/remark**	**Ref.**
Experimental	-	Up to 5.5 % relative increase in peak power	Passive cooling technique in aluminium fins was mounted on the rear side of a PV panel with conductive epoxy glue, which resulted in lower PV temperatures and enhanced efficiency and lifetime of PV panel.	[87]
Experimental and numerical	Overall thermal resistance with a flared-fin heat sink was 10 % lower than that of a rectangular-fin heat sink	-	The number and length of fins in a flared-fin heat sink had a significant influence on thermal performance. However, the inclination angle of the fins did not strongly affect thermal performance. It was observed that 15 to 18 fins resulted in optimum system performance.	[88]
Experimental	Maximum surface temperature obtained by a finned panel (with 10 mm thick and 5 mm high porous aluminium fins) was 48 °C	Highest output power of the panel without fins, with 6 mm fins and 10 mm fins, was 41.8 W, 44.7 W and 47.9 W, respectively, and panel with 10 mm fins showed maximum power enhancement of 14 % compared to panel without fins	Integrating porous fins into a PV panel enhanced the overall performance.	[89]
Experimental	Average temperature of the front surface was reduced by 6.1 °C	Electrical efficiency enhanced by 1.8 %	PV panel temperature was always lower than the maximum allowable temperature due to constant heat absorption by the finned plate which acted efficiently as a heat sink.	[90]
Numerical	Reported a 3 °C drop in operating temperature	Electrical efficiency enhanced by 2.6 %	Integration of fins can reduce operating temperature and improve efficiency. Fins can be integrated with other solutions/approaches for much better results.	[91]

3.2.3 Heat pipe cooling

Another method for passive cooling relies on the use of heat pipes, owing to their simplicity and low-cost relative to active cooling approaches. The characteristic feature of heat pipe cooling is that a very high rate of heat transfer can be achieved relative to other passive cooling means, due to internal phase change [92]. For this reason, one area where the employment of heat pipes has attracted attention, owing to their high heat transfer rates, is in the cooling of CPV systems. For CPV, a review study highlighted that acetone and ethanol yield better performance (when used as heat transfer fluids, HTFs) since they can produce 7- and 3-times higher cooling effects, respectively, compared to water [93]. Further, the inclusion of fins in the condenser section could improve the thermal performance but the spacing of fins is recommended to be higher than the thickness of the fluid boundary layer to prevent flow blockage due to the boundary layer.

Heat pipes are readily used in combination with other solutions and approaches, such as air or water cooling, as applied to both PV panels and also hybrid PV-T collectors, aimed at further maximising the overall performance of PV panels [73,82]. In most designs where heat pipes are employed, the heat absorbed by the working fluid is eventually rejected to the surroundings (most often, ambient air), possibly through a heat sink, by using natural convection (air cooling). In these cases, a challenge arises from the fact that the dominant thermal resistance lies in the latter process of heat rejection.

Al-Amri [94] experimented with PV panels using passive and active cooling techniques in the harsh climate of Saudi Arabia, with passive cooling accomplished in this work with the aid of heat sinks in one configuration, while another configuration integrated heat sinks with a PCM. On the other hand, the actively cooled PV modules consisted of heat pipes and a liquid immersion cooling technique. The results showed that a PVT collector with heat pipes and also immersed in water can result in uniform distribution of temperature across the panel and an overall maximum temperature drop of 53 % was obtained relative to the best passively cooled configuration (heat sinks). Since the climatic conditions of Saudi Arabia are extreme, the cooling demand is greater and thus, the heat pipe configuration was effective in transferring heat while the water medium absorbed the heat from the collector. The result also showed that the steady-state temperature of the PV panel was reduced by 21 %, 25 % and 48 %, for ethylene glycol, engine oil, and active cooling without immersion, respectively.

Hughes et al. [92] conducted an experiment in which a PV panel was cooled by using a heat pipe passive cooling technique. These experiments showed that fins on the heat pipe were significantly more effective than bare heat pipes alone, which suggests that (as mentioned above), the dominant thermal resistance in this system is outside of the heat pipe component itself. Similarly, Tang et al. [95]

experimentally examined the cooling performance of heat pipe array for PV panel cooling. The evaporator section of the heat pipe array was attached to the back of the PV panel while the condenser section was passively cooled by water or air. The results showed that when using the passive air cooling on one end of the heat pipes, the electrical power output of the panel could be increased by 8.4 % and the temperature reduced by 4.7 °C relative to a PV panel without cooling, whereas when using the passive water cooling, the power output could be further increased by 14 % and the temperature reduced by 8 °C. The authors concluded that the use of heat pipes along with water cooling was better than natural (passive) air cooling.

Gang et al. [96] proved that the heat-pipe-based PV-T collector had an anti-freezing ability and had a good performance in cold regions. The distance between adjacent heat pipes had a significant influence on the performance of the PV-T collector. The overall energy efficiency (electrical + thermal) increased from 45 % to 55 % as the distance decreased from 0.15 m to 0.05 m. However, the cost of heat pipes also increased linearly as the decrease of distance. Gang et al. [97] went a step further and undertook an annual energy analysis of a heat pipe integrated PV-T system for three different climatic regions in China, i.e., Beijing, Lhasa and Hong Kong. A schematic view of the heat pipe integrated PV-T collector and overall testing arrangement are shown in Fig. 13 and Fig. 14, respectively. With auxiliary heating equipment, these systems delivered annual thermal energy outputs of 1870 MJ/m^2, 3330 MJ/m^2, and 2350 MJ/m^2, and annual electrical energy outputs of 265 MJ/m^2, 466 MJ/m^2, and 328 MJ/m^2, for Hong Kong, Lhasa, and Beijing, respectively.

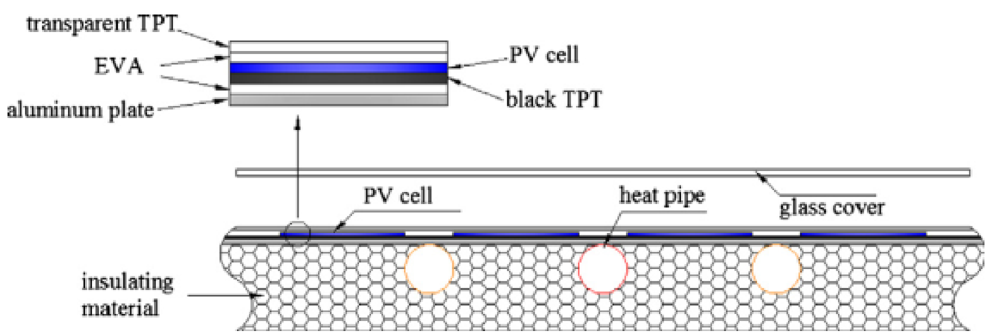

Fig. 13. Schematic cross-sectional view of the heat pipe PV-T collector in the study [97].

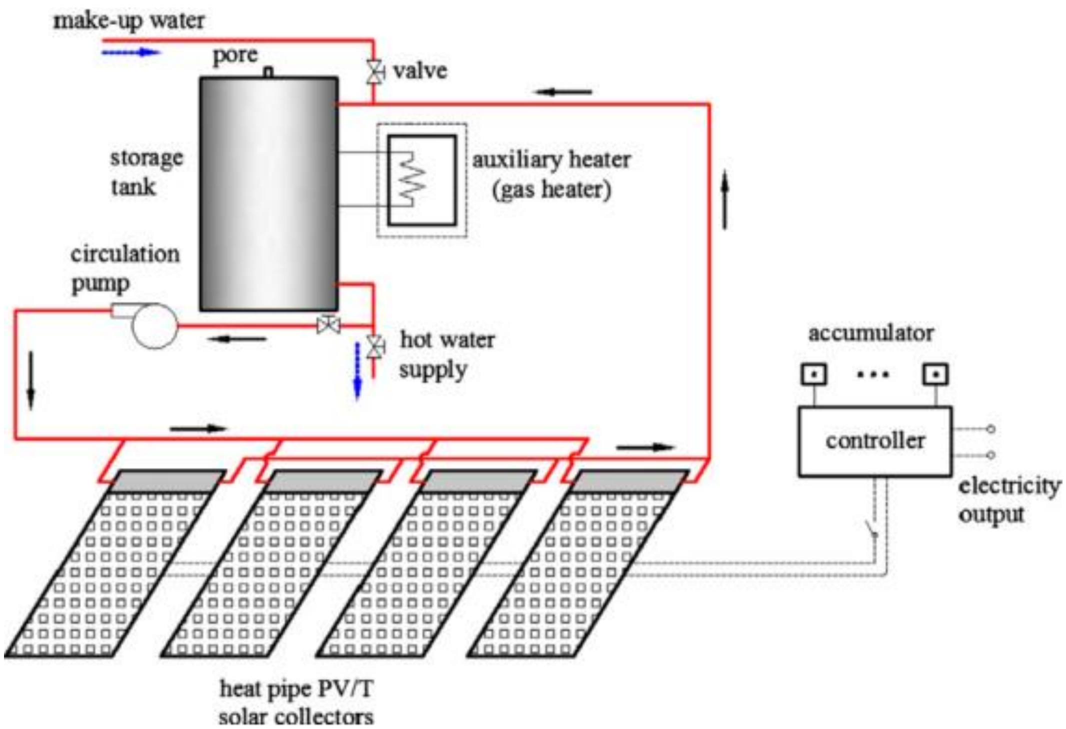

Fig. 14. Schematic diagram of heat pipe integrated PV-T collectors and system used in the study by [97].

Ren et al. [98] focussed on reducing the cost of loop-heat pipe for solar PV-T systems. When the width of the heat pipe's evaporator portion was reduced from 26 to 10 mm, the electrical and thermal efficiency was decreased by only 0.03 % and 2.5 %. As a whole, the system cost was estimated to be mitigated by 29 % with a minor trade-off in performance. Hongbing et al. [99] studied a PV-T system integrated with a heat pipe arrangement. Heat pipes were used to transfer the thermal energy from the PV-T collectors to a water tank for water heating purposes. The results showed that the thermal efficiency increased at higher solar irradiance, as expected, but also that the thermal efficiency of the collectors decreased during the afternoon when the water temperature was high compared to the condensation temperature of the heat pipe. Interestingly, these experiments showed that heat pipes can improve the total operating performance of the system with additional thermal output, thereby giving higher thermal efficiency and also a higher electrical efficiency than conventional air/water-based cooling methods. A summary of studies published in the area of PV cooling via the use of heat pipes is summarised in Table 4.

Table 4. Summary of research aimed at efficiency enhancement of PV panels by heat pipe cooling.

Nature of work	Temperature reduction	Efficiency enhancement	Observation/remark	Ref.
Experimental and numerical	PV cell maintained at an operating temperature of 30 °C	-	Finned heat pipe arrangement maintained the PV cell at lower temperature and both thermal and electrical energy were obtained simultaneously.	[92]
Experimental	Temperature reduction of 8 °C achieved	Electrical efficiency increased by 3.0 % with a maximum power output increase of 14 %	Heat pipe array using air- and water-cooling techniques resulted in temperature reduction and energy enhancement of the PV panel.	[95]
Experimental	-	-	Reduction in useful thermal energy between 23 % and 38 % and the electrical energy efficiency varied between 1.5 % and 4.3 % because, in the system without auxiliary heating equipment, the water was heated only by solar energy.	[97]
Experimental	-	With an increase in water flow from 5 L/min to 9 L/min, the electrical efficiency decreased from 12 % to 11 % and the thermal efficiency decreased from 19 % to 16 %	Thermal efficiency of heat pipe PV-T system increased at higher solar irradiance and decreased with increasing inlet water temperature and water flow rates, while the electrical efficiency decreased with increasing solar irradiance, inlet water temperature and flow rate.	[99]

4. Radiative thermal management

Radiative thermal management comprises a variety of passive design and operational methods that typically do not require external energy consumption [100,101]. The earth's atmosphere has a transparent window for infrared (IR) radiation from 8 to 13 μm, corresponding to peak thermal radiation wavelengths at 362 K and 223 K according to Wien's law. Thus, terrestrial bodies with a typical ambient temperature can dissipate heat to outer space by thermal radiation. Radiative cooling technology for PV cells has generated significant interest in recent years.

The first study of radiative cooling for silicon cells was conducted by Zhu et al. [78] at Stanford University in 2014. They investigated three radiative cooling emitters: the ideal emitter, a 5-mm-thick SiO_2 flat emitter, and a SiO_2 pyramid emitter, as shown in Fig. 15(a). SiO_2 is transparent at solar wavelengths while also to have a high emissivity at IR wavelengths as shown in Fig. 15(b). The emissivity of the SiO_2 pyramids structure approximated the ideal emitter. Their simulation results showed that passive radiative cooling was able to lower the operating temperature of a silicon solar cell by 18.3 °C at a solar irradiance of 800 W/m^2. Zhu et al. [102] tested the practical radiative cooling effect for silicon solar cells in an outdoor experiment. A 500-μm-thick SiO_2 wafer was drilled with a 4-μm-diameter micro-holes array as shown in Fig. 15(c) and covered on a silicon cell as a radiative cooling emitter. The solar cell with passive radiative cooling is about 13 °C cooler than the bare silicon solar cell in a non-wind environment.

A detailed review of passive daytime radiative cooling can be found in Bijarniya et al. [103]. In this work, the authors elucidated the fundaments, material aspects, structures and configurations, influence of environmental factors as well as potential research opportunities and challenges. Safi and Munday [104,105] proposed a different passive radiative cooling structure for solar cells as shown in Fig. 16. A radiative emitter with micro fins was placed on the back of a solar cell to absorb waste heat and then dissipated heat by thermal radiation to cold outer space through the atmosphere transparent window. Their simulation results showed that GaAs solar cell was cooled by 18 °C with the assist of radiative cooling in the standard terrestrial environment, which yielded a 0.9 % higher efficiency in absolute terms. The effect of passive radiative cooling for solar cells was more significant in an extra-terrestrial environment where convective cooling can be ignored. The electrical efficiency of GaAs solar cells was absolutely improved by 0.4-2.6 % in an extra-terrestrial environment of near-earth orbit.

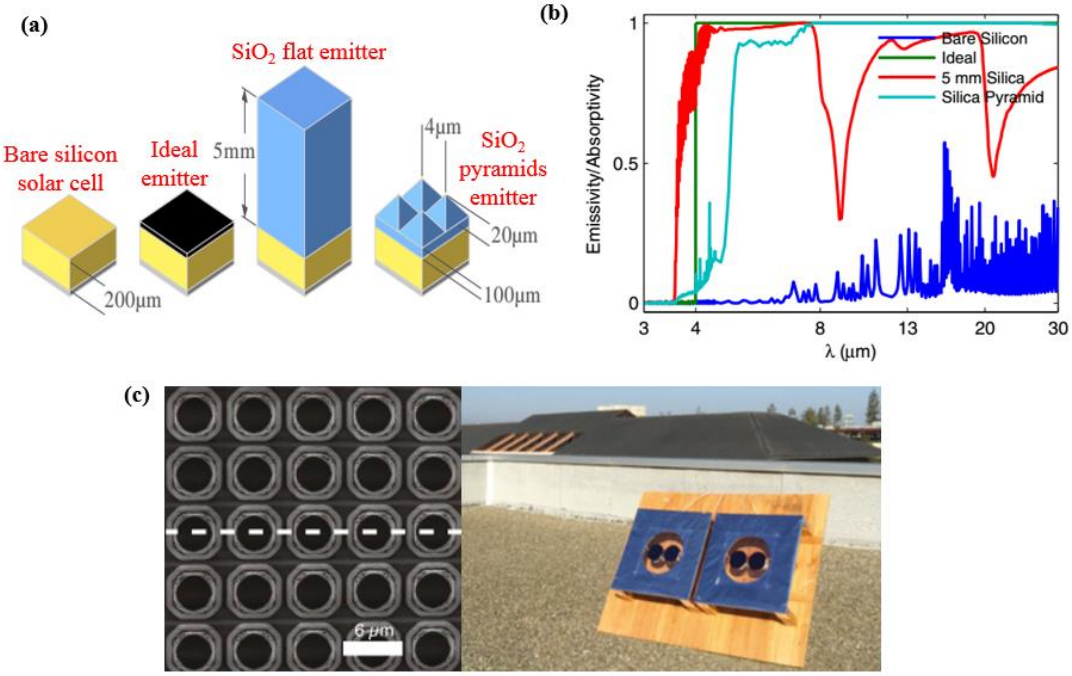

Fig. 15. (a) Different radiative structures for silicon cells [78]. (b) Emissivity of different emitters in the IR wavelength range [78]. (c) SEM image of the radiative cooling emitter and the outdoor test rig [102].

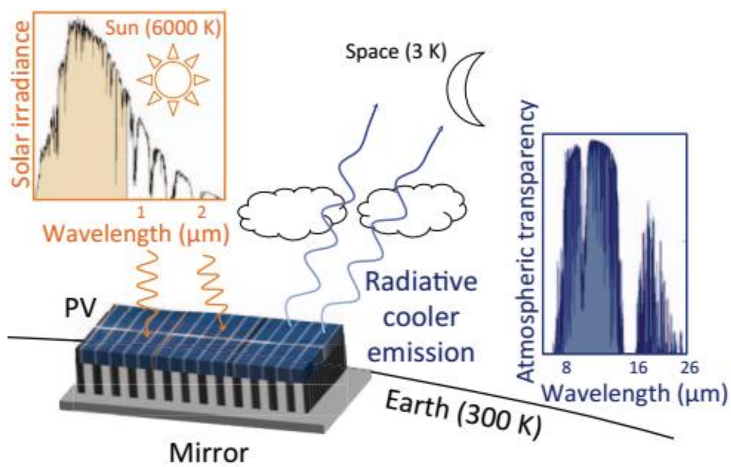

Fig. 16. Passive radiative cooling with a radiative emitter attached to the back of a solar cell [104,105].

However, the feasibility of the above passive radiative methods was questioned by Gentle and Smith [106]. Commercial PV panels usually have a low-iron glass coversheet above the cells. These authors found that commercial glass is a good radiative cooling emitter with an emissivity even slightly higher than SiO_2 at IR wavelengths. Their simulation results showed that even the ideal black-body emitter could not add an extra cooling of 1.5 °C compared to normal glass-covered solar panels in a real terrestrial environment. Green and Bremner [107] also declared a similar doubt in their review article. They thought low-iron glass in standard PV panels approximated the ideal radiative cooling emitter. Zaite et al. [108] used a night-time radiative cooling technique on a PV-T water-based collector system to enhance electrical efficiency and the reliability of PV panel. The results showed that with the proposed technique, the daily temperature of the PV panel could be reduced by 3 °C to 5 °C and the electrical energy generated by the system enhanced by 5.5 % to 6.2 % compared to a conventional PV-T collector. The results also showed that the proposed method saved 18.5 kWh of annual electrical energy due to the night radiative cooling.

Zhao et al. [109] tried to improve the radiative cooling effect of a commercial glass-covered silicon PV panel. However, the PV panel temperature could only be further reduced by 1.8 °C even in an ideal situation, so they concluded that enhancing the radiative cooling of commercial PV panels might have limited value. Li et al. [110] compared the performance of PV panels with and without an additional radiative cooling coating. Their experimental results showed that additional radiative cooling could only reduce the PV panel temperature by less than 1 °C (the limitation is around 2 °C). More recently, Wang et al. [111] utilised a pyramid-textured PDMS film to provide radiative cooling for encapsulated commercial silicon cells. A 2 °C drop in the PV temperature was observed during outdoor testing.

A review on photonic structures, configurations and spectral modification approaches suitable for PV is presented by Shanmugam et al. [112]. Li and Fan [113] designed a comprehensive photonic approach for solar cell cooling as illustrated in Fig. 17(a). A spectral-selective photonic cooler was covered on a silicon PV panel. Only the effective spectrum for silicon cells of 0.4-1.1 μm could pass through the layer of the photonic cooler. The rest of the solar spectrum of 1.1-4 μm, which could not be utilised by silicon cells, was reflected to the sky and thus reduced waste heat in solar cells. This thin-film photonic cooler also had a high emissivity at the infrared wavelength range and thus had a good radiative cooling effect. The thin-film photonic cooler is a stack of Al_2O_3/SiN/TiO_2/SiO_2 layers as shown in Fig. 17(b). This kind of thin-film spectral splitting material has also been widely investigated and applied in concentrated hybrid PV and thermal (CPVT) systems [114]. Sun et al. [115] investigated comprehensive spectral-splitting and radiative cooling for different solar cells. Their results presented that this comprehensive cooling method could lower the temperature of a commercial PV panel by 6 °C which yielded a 0.5 % absolute increase in electrical efficiency and may extend the lifetime by 80 % under one-sun conditions. More recently, Zahir et al. [116] also utilised a similar selectively-reflective and radiative cooling coating to reduce the operating temperature of Si PV panels. The operating temperature of a tested PV panel was reduced by 5.4 °C with the aid of the cooling coating. However, the final cost of such advanced photonic structures remains unclear at present, and the PV efficiency improvement is still limited, thus it is still difficult to justify the techno-economic benefits of such photonic structures. Future research on PV radiative cooling should also consider the balance between the additional cost and electrical (or other, if relevant) energy efficiency improvements.

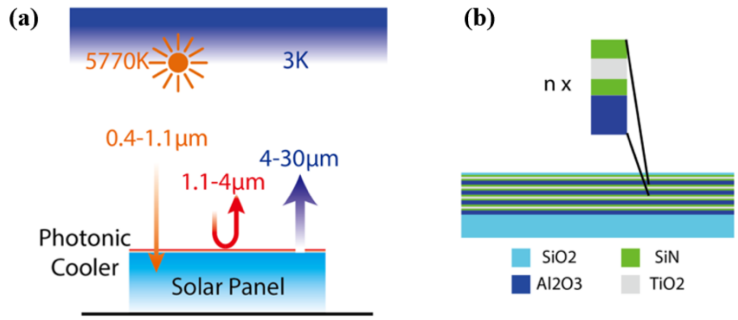

Fig. 17. (a) A comprehensive photonic approach for solar cell cooling with spectral splitting and radiative cooling, and (b) structure of the photonic cooler [113].

5. Phase change material integration

The use of phase changing materials (PCMs) for thermal management (and/or the provision and integration of thermal storage capabilities) can be considered a conduction-based passive thermal management method. Here, a PCM with suitable characteristics, such as a large heat of fusion and a sharp melting point, is employed to absorb and release heat as it changes phase from solid to liquid and vice versa at a near-constant temperature, thereby acting as a latent heat storage medium [117-119].

Predicting accurately the heat transfer and phase-change processes in any PCM store/space requires sophisticated computational tools. Models for predicting the solid-liquid interface location in PCM stores have been developed, along with models to predict and compare temperature and heat flux distributions and how these evolve within various stores/spaces, with various materials and in different applications (e.g., [22,120-122]). A model of PCM melting in a finned PCM store was developed by Lamberg [123], who showed that the model was valid when the weight to height ratio was less than 6 and when the fin length was less than 0.06 m. An error of ± 10 % was obtained while preferring a one-dimensional analytical solution compared to a two-dimensional analytical solution. This derived model resulted in a better prediction of solid-liquid location in a finned PCM based system and is suitable for pre-designing PCM based systems, including in PV applications. Elsheniti et al. [124] proposed an enhanced one-dimensional PV-PCM model, which showed good agreement with data for various orientations ranging from 0 to 90° as well as for the aspect ratios of two, four and eight. The maximum values of errors/deviations for the lowest and highest aspect ratios were 0.7 % and 1.8 %.

Similar research is encouraged as this is crucial in developing a range of suitable numerical design tools. Nizetic et al. [125] undertook a study where instead of using a single container filled with a PCM, several smaller containers filled with PCMs were integrated at the back of a PV panel. Their experimental results showed that using multiple containers enhanced the performance of the panel by 11 % and at the same time resulted in reductions in both PCM and aluminium costs by 47 % and 36 %. Mahdi et al. [126] also showed that longer and more effective thermal management of PV panels can be achieved by integrating multiple PCMs. Their results showed that by choosing multiple PCMs with appropriate thermophysical properties, the energy charge capacity and melting time can be improved up to 3.4 %, and 18 % relative to a single PCM. In other related work, Yousef et al. [127] experimented on a PV panel integrated with paraffin wax (PV-PCM), and a PV panel integrated with aluminium foam embedded in PCM (PV-PCM/AF), and compared results with conventional unmodified PV panels in both summer and winter weather conditions. In this work, it was show that during the summer the electrical efficiencies of the PV-PCM and PV-PCM/AF systems were higher by 9 % and 14 % relative to a reference panel, whereas in the winter these modified panels enhanced the PV panel efficiency by 3.7 % and 4.8 %, respectively. Gao et al. [128] experimentally showed that combining a phase change cooling technique with porous media in a PV-T collector. The average electrical efficiency of the PV panel was enhanced by 9.7 %, 17 % and 15 % for flow rates of 0.004 kg/s, 0.007 kg/s and 0.009 kg/s.

Lamberg [129] performed a numerical investigation regarding phase-change processes in PCMs. The results revealed that, during the melting process of PCM, natural convection in the liquid phase was critical for heat transfer enhancement. This agreed with many other studies, which found that melting (charging) is faster than freezing (discharging) owing to the solid PCM layer that is first formed over the heat exchanger surfaces in the latter, which has a higher thermal resistance than natural convection heat transfer [121,130]. It was observed that on average, installing a layer of PCM at 2.6 kg per m^2 over the rear surface of PV panels reduced the operating temperature by 1 °C during peak hours [131]. Thus, the PCM can reduce a panel's operating temperature by up to 20 °C and the electrical conversion efficiency can be increased by 5 % [132,133]. The experimental arrangement by Brano et al. [134] for performance analysis of PV on integration with PCM is shown in Fig. 18.

(a) (b)

Fig. 18. (a) PCM encapsulated in plastic bags, and (b) PV-PCM integrated panel [134].

Wei et al. [135] conducted an experiment using tea-light candles as the PCM for solar panel cooling. In this experimental arrangement, PCM was used to fill the gaps between parallel aluminium tubes, which were fitted into a stainless-steel container, which was covered by a wooden plate for thermal insulation. The surface temperatures at all parts of the PV panel were recorded. It was noted in this study that the highest temperature was recorded in the centre of the PV panel. The PV electrical efficiency with cooling was 15 %, which was only slightly higher (by ~3 %) than that without cooling, so it was concluded that a tea-light candle material may not be an effective PCM for the thermal management of PV panels. One of the important reasons behind this finding was that the melting point of the tea-light candle is too high (> 50 °C), leading to a high operating temperature (~53 °C) of the PV panel. The authors then concluded that a PCM with a melting point lower than 40 °C is more suitable for PV cooling.

Paraffins, which are common organic materials whose phase-change properties lend them to PCM latent energy storage, are prominently used in the thermal management of electronics. Sharma et al. [136] found that building-integrated PV systems (BIPV) with paraffin (RT42) based PCM can improve electrical efficiency by 7.7 % while decreasing the temperature by 3.8 % at an irradiance of 1000 W/m^2. Preet et al. [137] explored different PV-T collectors with water circulation and PCM integration and compared these to conventional PV panels. The developments in this work demonstrated that the operating temperatures of the water-based PV-T and PVT-PCM collectors were much lower than those of conventional PV panels. Specifically, temperature reductions of up to 20 °C were achieved in water-based PV-T and up to 30 °C in water-based PVT-PCM collectors were reported. Fig. 19 shows the heat transfer mechanisms in a PVT-PCM collector and how the PCM was integrated within the structure.

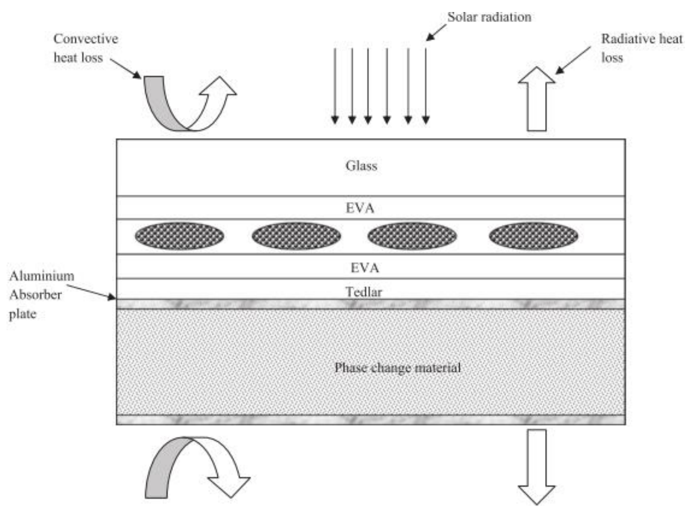

Fig. 19. Heat transfer path to and from PV with PCM [137].

In the case of most PCMs, including organic PCMs, although these materials have a high energy density thanks to their high latent heat capacity, the thermal conductivity is low. The addition of high thermal conductivity material additives can be used to improve the thermal conductivity of suitable PCMs [130.138-140]. Tan et al. [141] undertook a thorough analysis to determine the electrical and thermal performance of a PV panel using a PCM with different fin configurations, with results showing that PV panel temperatures could be reduced by 15 °C with a 12-fin configuration, relative to a reference panel without PCM integration or fins. The electrical efficiency of PCM-cooled PV panels with 12-fins, 6-fins, 3-fins and no fins were 5.4 %, 3.4 %, 2.9 % and 1.0 % higher than the reference PV panel, respectively. Similarly, Huang et al. [142] studied PV panel performance by integrating PCMs with different fin configurations. The study showed that the heat transfer rate within the PCM was raised by the use of fins and, subsequently, there was a major temperature drop on the PV panel front surface. With certain fin intervals, convection rates increased and there was a reduction in thermal stratification of the PCM.

Rajvikram et al. [143] experimented with a PV panel embedded with a PCM attached to an aluminium plate. From outdoor experiments, a 24-25 % improvement in the PV conversion efficiency was observed compared to the reference panel subjected to no cooling. Rajvikram and Sivasankar [144] proceeded to enhance the heat transfer rate to the PCM with an external heat sink to regulate the temperature. Maximum electrical efficiency of 17 % was reported, which is considered very reasonable. Hasan et al. [145] enhanced the efficiency of a PV-PCM system by employing water circulation through the panel. The stored heat from the PCM was used for hot water for domestic applications. The experiments revealed improvements to both the electrical and thermal efficiencies, of 1.3 % and 41 % (in absolute terms), respectively. Proceeding further, Hasan et al. [146] performed outdoor experiments and simulation analysis with calcium chloride hexahydrate and capric acid-palmitic acid eutectic mixtures as two different PCMs at two different locations for PV cooling (Dublin, Ireland and Vehari, Pakistan). The study evaluated the performance of these PCMs in enhancing the efficiency of PV panels. The results showed that calcium chloride hexahydrate performed better at both locations. Compared to capric-palmitic acid, calcium chloride hexahydrate resulted in a 3-4 °C higher PV temperature drop and 3 % more power generation in Vehari, Pakistan. Comparing the two location climates, it was concluded that PCM-integrated PV systems are more suitable in hot and stable climatic conditions.

Khanna et al. [147] developed a model of a tilted PV-PCM system to identify the temperature of the system in different situations and reported that the electrical efficiency of the PV panel increased, thanks to the PCM integration. The efficiency was further enhanced by increasing the tilt angle due to the larger heat extraction by the PCM and reduced the PV temperature. The study also revealed that heat losses from the top surface of the PV panel decreased at higher wind azimuth angles, and suggested that PCMs with a melting point close to ambient are most appropriate for PV cooling. A schematic of energy flows in a PCM integrated PV panel is shown in Fig. 20.

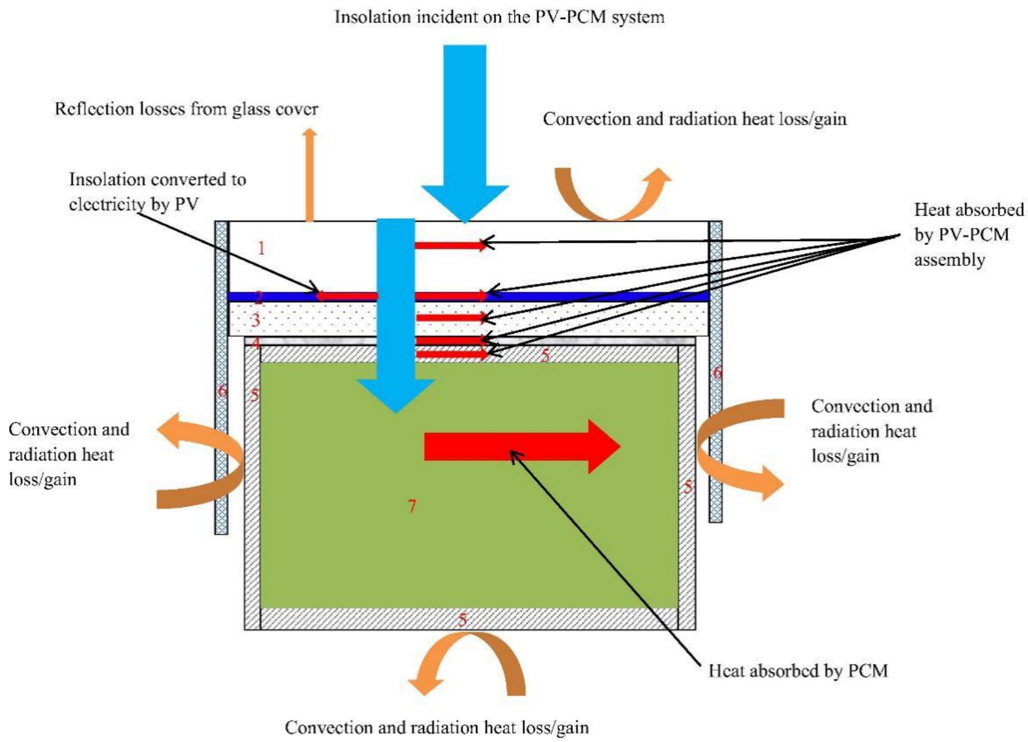

Fig. 20. Energy flows in the PV-PCM integrated system considered in the study [146].

In related work, Manikandan et al. [148] showed that a significant temperature reduction can be obtained by the integration of suitable PCMs into CPV collectors. Results in this study showed that both the power output and efficiency increased with an increase in concentration ratio and fill volume of PCM. The temperature of the CPV was measured and found to be 55 °C and 32 °C at PCM heights of 0.75 mm and 3 mm, respectively, indicating that additional PCM content (by volume) had the potential to significantly reduce the temperature. PCM integration (at a concentration ratio of 3 and PCM height of 3 mm) resulted in CPV output power and efficiency enhancements of 27 % and 22 %, respectively.

The global annual energy output of PCM-integrated PV panels was analysed by Smith et al. [149]. PCMs with a melting point from 0 °C to 50 °C were examined, to determine suitable PCMs at different locations. Locations with high insolation and reduced annual climate variations were shown to benefit the most by PCM-integrated panels. When employing optimal PCMs, the annual PV energy output in regions such as eastern Africa and South America (e.g., Mexico) increased by 6 %, while in regions such as Southern Asia, the rest of Africa, Central and South America, the Middle East, and the Indonesian archipelago, the energy output increased by 5 %, relative to PV panels without PCM cooling. On the other hand, the annual energy output in more Northern climates, such as Europe, increased between 2 % and 5 %. Fig. 21 shows an energy balance diagram presenting the energy flows in the PV-PCM system presented in the study [149].

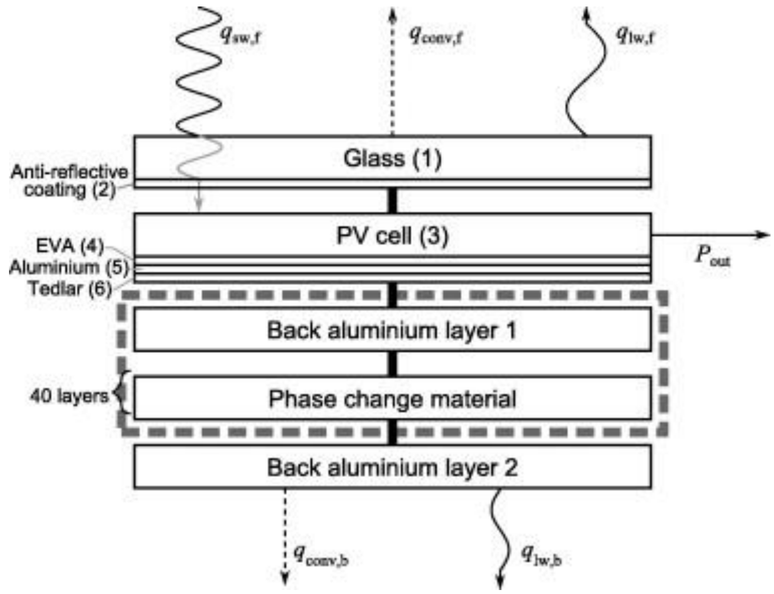

Fig. 21. Energy fluxes in the PV-PCM system presented in the study [149].

Hasan et al. [150] undertook a study to determine the effectiveness of PCMs when integrated within PV panels. Five different PCMs, namely $CaCl_2.6H_2O$, paraffin wax, SP22, capric-lauric acid and capric-palmitic acid, were evaluated. Experiments were conducted to determine the key thermal properties of all five PCMs using differential scanning calorimetry (DSC) and the temperature history method (THM). DSC is a standard method used for measuring the thermal properties of small samples of materials, in the range of 3-10 mg. THM is a method that allows the properties of larger samples, up to 40 mg, to be measured. Additionally, THM determines the PCM under-cooling properties — a feature that is not available via the DSC method. The results showed that capric-palmitic acid was the best PCM for the adopted PV panel. Capric-palmitic acid had the highest latent heat and showed the greatest capacity for regulating/controlling the PV cell temperature. Furthermore, in regions where the climate was hot, the temperature of the panel was found to exceed the upper limit of the generally allowable operating temperature range of PV panels (from -40 °C to 80 °C). Operation in these conditions can quickly lead to cell delamination, rapid degradation, physical damage and failure.

Savvakis et al. [151] analysed two PV/PCM systems, one of which employed RT 27 PCM while the other used RT 31 PCM. These investigations of PV/PCM systems were performed on a 10-Wp PV panel, and it was demonstrated that the peak temperature could be reduced by 6.4 °C and 7.5 °C for 260 g of RT 27 and RT 31, respectively, under hot and sunny Mediterranean conditions. Another approach by Velmurugan et al. [152] emphasised the utilisation of PCMs for thermal management via both convective and radiative means, but with the avoidance of conduction. In this experimental study, a cylindrical tube PCM matrix was utilised which was not kept in direct contact with the rear side of the PV panel. This helped reduce the heat transfer from the PCM to the panel which in turn avoided the abrupt temperature rise that resulted when the PCM was in the liquid state. As a result of this arrangement, the heat was transferred from the PV panel to the PCM matrix only by means of convection and radiation. The optimised spacing between the panel and the PCM matrix was found to be 6 mm and a temperature reduction of 2.5 °C, as well as an increase in the electrical output by 0.2 %, was obtained and reported by the authors compared to a control panel without a PCM.

An important consideration when using PCM-based solutions is that if the PCM is not chosen appropriately for a particular design and application, this may lead to a deterioration in performance, i.e., an increase in the temperature of a PV panel. This was demonstrated explicitly in the experimental investigations by Bayrak et al. [153], where the utilisation of PCMs resulted in a negative effect on PV panel output power if the PCM temperature was higher than the PV panel surface temperature. Further, Madurai Elavarasan et al. [154] experimentally investigated the characteristics of OM29 PCM for the summer season in Southern India. These experiments proved that OM29 did not reduce the temperature after 9 am since the ambient temperature exceeded the melting point of the PCM and resulted in poor performance. Such research has indicated that for the selection of suitable PCMs, real-time temperature data, in particular, the maximum and average operating temperature of the PV panel surface, along with knowledge of the ambient temperature at the region under consideration are of utmost importance in selecting an appropriate PCM for optimum performance.

In summary, a diverse collection of studies, from which is it difficult to draw consistent, cross-cutting conclusions due to the vast array of collector types, design parameters and application conditions and characteristics, have shown some evidence that PCMs can play a role in enhancing the efficiency of cooling, although the opposite has also been reported in cases where the PCM was not suitable. According to the studies introduced in this section, the melting point of the PCM is the most critical parameter in these applications, as the operating temperature of a PV panel is always slightly higher than the melting point of the PCM. Therefore, it is of importance to select a PCM with a low melting point for effective PV cooling. Of note is that the PCM can only absorb a limited amount of heat. Thus, the heat capacity of the PCM is also an important parameter, which should be large enough to absorb the waste heat in PV panels over a whole day. Therefore, the density and specific heat capacity of the PCM should be carefully considered. Additional heat transfer structures, such as fins, can be used to enhance the heat transfer between the PV panel and the PCM, thus further decreasing the PV temperature. The heat absorbed by the PCM can be further used for downstream thermal demands, e.g., space heating, hot water, etc., which is a promising way to improve the overall efficiency of the solar system and the economic viability of such projects. Additional studies on PV cooling with the use of PCMs are tabulated in Table 5.

Table 5. Summary of research aimed at PV-PCM integrated systems for efficiency enhancement.

Nature of work	PCM used	Efficiency enhancement	Observation/remark	Ref.
Experimental	Paraffin wax RT42	Electrical efficiency increased by 7.7 %	BICPV-PCM integrated system resulted in an average temperature reduction of the PV panel by 3.8 °C in contrast to a naturally ventilated PV panel.	[136]
Experimental and numerical	Paraffin wax RT27	-	Usage of PCM with internal fins gave better temperature regulation on the PV surface compared to the usage of a single flat aluminium plate. The fins also reduced thermal stratification in the PCM, and thereby enhanced the overall system performance and efficiency.	[142]
Experimental and numerical	Paraffin wax RT25	-	PV front temperature maintained below 36.4 °C for 80 min by using PCM with a melting point of 32 °C under solar irradiance condition of 1000 W/m^2 and an ambient temperature of 20 °C, in a system with fins.	[155]
Experimental	Petroleum jelly	Electrical efficiency increased by 21 %	Petroleum jelly has better performance in BIPV applications. The average power and efficiency of the PV panel with PCM located on a concrete roof increased by 23 % and 21 % relative to a PV panel without PCM.	[156]
Experimental	Paraffin wax RT35		The peak temperature of the PV-PCM panel was 11 °C lower compared to the conventional PV panel for a time of 4 hours.	[157]
Experimental and numerical	Paraffin wax RT42	Average efficiency increased by 6.6 % in January and 5.2 % in April	PV-PCM performance varied with the season. During summer, due to the high ambient temperature, the PCM remained in the liquid state for most of the time, whereas, during winter the PCM was mostly solid. On average, the PCM resulted in a PV temperature drop of 10.5 °C, which led to an increase in the power output of the system by 5.9 %.	[158]
Numerical	Paraffin wax	An average efficiency enhancement of 2.1 % observed	The electricity generation efficiency of PV-MEPCM integrated system (microencapsulated PCM (MEPCM) with a melting point of 30 °C and PCM layer thickness of 3 cm) was a little over 19 %, which was 2.0 % higher than the efficiency of an equivalent standalone PV cell (no PCM).	[159]
Experimental	Paraffin wax RT55 with Al_2O_3 as nanoparticle	System output increased by 13 %	PCM was suspended with 2 % Al_2O_3 nanoparticles to enhance the heat conduction. Integration of the BIPV panel with the PCM increased its average efficiency by 14 % relative to a PV panel without PCM.	[160]

Experimental	Lauric acid	Maximum efficiency enhancement of 14 % achieved at a flow rate of 4 L/min	PVT-PCMs were more economical and attractive in the long run than standalone PV. The payback time of the PVT-PCM collector and standalone PV panel are 4 and 6 years, respectively.	[161]
Experimental	Inorganic Glauber salt ($Na_2SO_4.10H_2O$)	Electrical efficiency increased by 10 %	BIPV-PCM system showed a lower peak instantaneous temperature than a PV panel, which increased the electrical conversion efficiency. Experiments showed that the integrated system reduced the surface temperature by 8 °C and increased the efficiency of the system by 10 % relative to a conventional PV panel.	[162]

6. Utilisation of nanoparticle suspensions (nanofluids)

In this section, the use of nanofluids for convective heat transfer enhancement is emphasised. Although the cost of nanofluids is generally high, their use can allow higher heat transfer rates (fluxes) compared to other forced convection cooling techniques. Therefore, nanofluids can significantly reduce the temperature of PV panels compared to other cooling technologies and thus, enhance PV efficiency. On the other hand, the employment of nanofluids has faced some controversy and challenges more recently, and a remaining crucial element that needs to be considered carefully concerns the limitations related to their use in practice and any proposed solutions in applications of interest. Typical issues involve agglomeration, separation, loss of performance, limited lifetimes and high maintenance costs, but also issues relating to safety and environmental implications that are non-trivial [163].

Abu-Rahmeh [164] investigated the operating performance of a PV panel using various cooling techniques, namely natural-convection passive cooling, fins, water and nanofluid cooling. The authors demonstrated an electrical efficiency enhancement of up to ~3 % (relative to a benchmark case without nanoparticles) could be achieved by using a nanofluid (0.04 % wt. TiO_2/water) as a cooling medium. Gangadevi et al. [165] also performed an experiment to cool a PV panel using a nanofluid (Al_2O_3). The ordinary PV temperature rose to 70 °C which in turn curtailed the lifespan of PV panels. But, with 2 % wt. of Al_2O_3/water (nanofluid), the temperature decreased to 36 °C. From the results, it was concluded that, with 2 % wt. of Al_2O_3/water (nanofluid), the overall efficiency increased to 58 % which was higher than those cooled with water and 1 % wt. of Al_2O_3/water (nanofluid). Sardarabadi et al. [166] investigated the performance of a PV panel when cooling it using a nanofluid coolant combined with PCM integration. An experimental study was conducted using ZnO/water nanofluid and PCM for cooling the PV panel. The results showed that, with the PCM/nanofluid as a cooling medium, the electrical output was increased by 13 % compared to a conventional PV panel. The simultaneous use of both nanofluid and PCM in the cooling system increased the overall exergy efficiency by more than 23 % compared to the conventional PV panel.

Stalin et al. [167] investigated experimentally the effect of a nano-PCM (CuO with paraffin wax) on the performance of PV panels. Results showed that with the integration of the nano-PCM, the peak temperature of the PV panel can be reduced by 49 °C (32 %). The results also showed that thanks to the nano-PCM, the daily PV panel efficiency increased by 8.5 %. Karaaslan and Menlik [168] numerically investigated the performance of PV-T collectors with mono- and hybrid-nanofluids, and showed that enhancements in the thermal efficiency with a hybrid nanofluid (CuO + Fe/water) of 2.0 % and 5.4 % compared to a mono-nanofluid (CuO/water) and base fluid (pure water), respectively. It was also observed that the electrical efficiency was 11.4%, 11.5% and 11.6% when utilising pure water, the mono-nanofluid and the hybrid-nanofluid as the working fluid. Sohani et al. [169] performed an analysis of a PV-T system using different nanofluids namely Al_2O_3, TiO_2, and ZnO to determine the most suitable nanofluid based on reliability, efficiency, energy, economic and environmental criteria. From this study, it was concluded that the PV-T system based on the ZnO nanofluid had the best performance in terms of annual energy production and average electrical and thermal efficiencies of 633 kWh, 15 %, and 48 %. Jamil et al. [170] also studied PV panels integrated with different types of nanoparticles integrated with PCM (PT-58), and demonstrated experimentally that peak temperature reductions of 9.9 °C and 5.0 °C can be achieved with 0.5 wt% of graphene nanoplatelets-PCM and PV-PCM panel compared to a conventional reference PV panel.

Ghadiri et al. [171] proceeded further to consider the use of nanofluid cooling in PV-T collectors, by investigating the effect of ferrofluid (Fe_3O_4-water) as a coolant on the performance of a PV-T collector using different weight concentrations. Fig. 22 shows a diagram of the ferrofluid-cooled PV-T system in this study. The results from this experimental campaign revealed that the thermal and electrical efficiencies of the ferrofluid-cooled PV-T system applying an alternating magnetic field with a frequency of 50 Hz can be enhanced in relative terms by around 55 % and 5.7 % relative to a conventional water-cooled PV-T system at a solar irradiance of 1100 W/m^2. Also focussing on PV-T collectors, Aberoumand et al. [172] experimentally found that the performance of a PV-T system with Ag/water nanofluid as the cooling medium showed significant enhancement in the thermal, electrical, and exergy efficiencies of the collector. The schematic of this PV-T cooling system is shown in Fig. 23. Another experiment on PV-T cooling with PCM and nanofluid circulation to enhance heat transfer and raise overall efficiency was reported by Al-Waeli et al. [173]. This PV-T PCM-nanofluid system increased the electrical efficiency from 9.9 % to 14 % compared to a conventional water-cooled PV-T system, while also increasing the thermal efficiency from 35 % to 72 %.

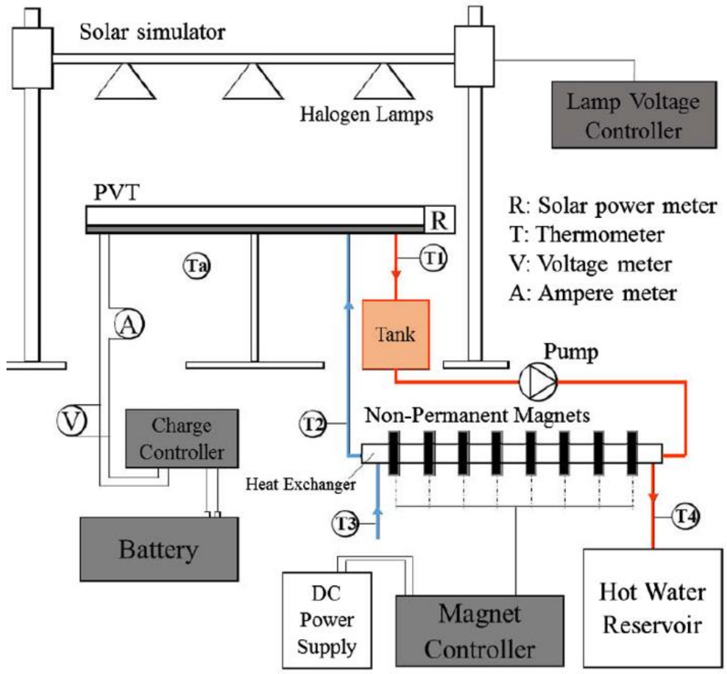

Fig. 22. Schematic of the PV-T system with nanofluid as tested in the study [171].

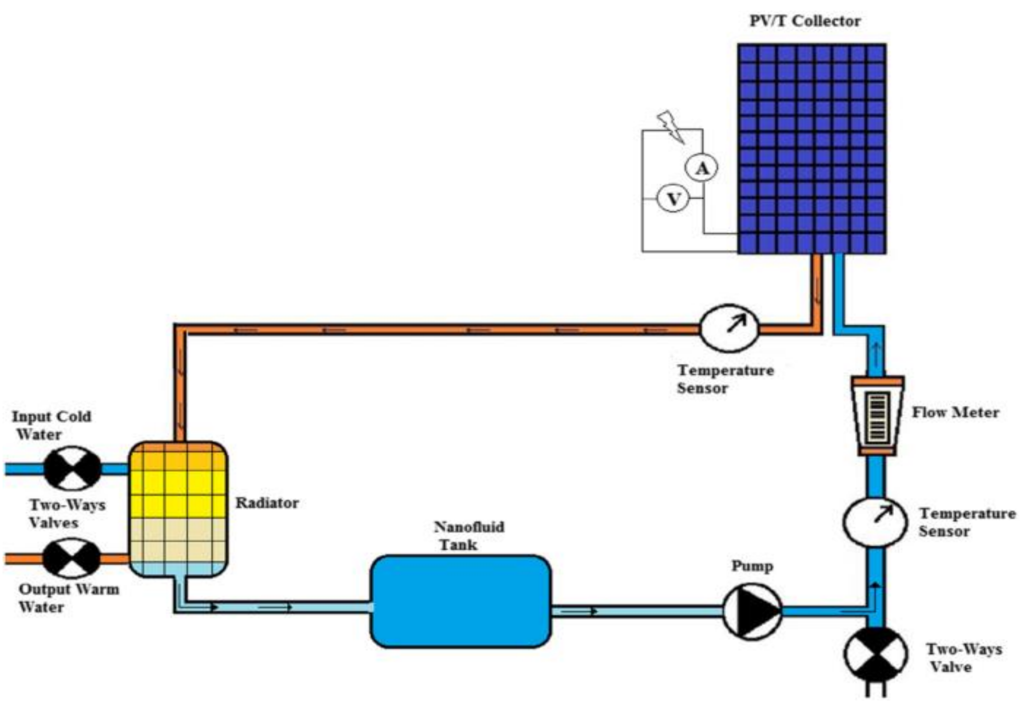

Fig. 23. Schematic of PV-T system with nanofluids used in the study [172].

Nanofluids diversify the research, innovation and development opportunities for improving the efficiency of PV panels, as well as the application opportunities of the technology, however, non-trivial challenges remain that are linked to the use of nanoparticles. For example, Rostami et al. [174] proposed a novel configuration for cooling PV panels in which CuO nanofluids and water were used as coolants and in which high-frequency ultrasound waves were utilised as a part of the solution to atomise the CuO nanofluid and water, acting to resolve a common problem that arises when using nanofluids. When using 0.8 w/v of nanofluid, an increase in the maximum power of close to 50 % was reported, however, such solutions are associated with added costs and operational/design complexity that need to be considered. A list of studies using different nanofluids suitable for cooling PV is provided in Table 6.

Table 6. Summary of research aimed at nanofluid/nanoparticle-cooled PV systems for efficiency enhancement.

Nature of work	Nanofluid/Nanoparticle used	Efficiency enhancement	Observation/remark	Ref.
Experimental	Al_2O_3	With 2 wt% Al_2O_3/water nanofluid, the electrical, thermal and overall efficiencies of the PV-T system were improved by 13 %, 45 %, and 58 % compared to water	Al_2O_3/water nanofluid cooling resulted in a temperature reduction of PV panel by 36 °C.	[165]
Experimental	ZnO/water	13 % electrical and 48 % thermal	PV-T collector with PCM and nanofluid had a 23 % higher exergy efficiency relative to PV only system.	[166]
Experimental	Ferrofluid (Fe_3O_4/water)	With a 3 wt% concentration of nanofluid, the total efficiency of the system enhanced by about 45 %	Electrical efficiency increased by nearly 4.8 % when using a ferrofluid with distilled water.	[171]
Experimental	Ag/water	Hybrid PV-T system with nanofluid exergy efficiency improved by 50 % and 30 % compared to PV with no cooling and with water cooling	With turbulent flow and 4 % wt. of nanofluid, the PV panel power output increased by about 35 % and 10 % compared to PV panels without cooling and with water cooling, respectively.	[172]
Experimental	SiC/water	6.6 % electrical and 38 % thermal	PV-T system gave electrical power of 121 W while, for PV panel, it was 61 W. Maximum thermal energy gain of the hybrid system was 72 % greater than PV-T with the PCM water system.	[173]
Numerical	Ag/water	Thermal, electrical and overall exergetic efficiency improved by 1.7 %, 12 % and 14 %, respectively	PV-T nanofluid system with optimised thermal and optical properties produced 1.3 MWh/m^2 of high-grade exergy in a year with the lowest exergy payback time of 2 years. The hybrid system also showed the potential to prevent 448 kg of $CO_2(eq)/m^2$ emissions per year.	[175]

7. Combined, integrated photovoltaic-thermal designs

Hybrid PV-T collectors and systems recover waste heat from PV cells and complement the electrical power output of these cells by providing an additional thermal output, thereby generating both electrical and thermal energy outputs from the same collector. In a conventional PV-T solar collector, a coolant (often water or air) flows typically below the PV cells, and removes heat from the cells; if designed to improve electrical performance, the system can be operated to lower their operating temperature [176,177]. A typical PV-T arrangement, with a water circuit and hot water tank, is shown in Fig. 24. The heat obtained from such a hybrid system can be utilised in many applications for domestic space heating, hot water supply, swimming pool heating, etc. [178]; it can also be upgraded with heat pumps, converted to cooling, or even used for secondary power generation [179,180]. Potential advantages of using PV-T systems include: (i) dual-energy outputs (electrical and thermal) from the same area and system, (ii) the occupation of less space compared to standalone equivalent to PV and solar-thermal systems for the same delivered energy outputs, (iii) lower system costs compared to standalone equivalent systems, and (iv) alleviation of thermal degradation of the PV cells, and thereby, life enhancement.

Fig. 24. Photograph of solar water heating system with PV-T collectors [181].

Rosli et al. [182] examined PV-T systems experimentally by using two different working fluids, i.e., air and water. It was stated that the water-cooling technique was cost-efficient, and yielded better efficiency than the air-cooling technique. The PV-T systems using water and air as the coolant were 8 % and 5 % more expensive than plain polycrystalline PV panels, however, if the piping and circulating pump costs are also included, then the overall cost increases by 10 % and 8 %, respectively. Tonui and

Tripanagnostospoulos [183] investigated the operating performance of air-based PV-T collectors and their experimental results gave a good agreement with theoretical predictions. Generally, PV-T/air systems are used in agriculture, industrial and other applications. A series of experiments were designed so as to enhance the PV-T/air collector performance by attaching thin metallic sheets (TMSs) or fins at the rear side of the air channels. TMSs inserted in the middle of the air channel at the back of the collector doubled the removal of heat compared to a normal panel with a single-pass air channel. Fins connected to the back wall of the air channel increased the temperature of outlet air and thus, increased the extracted heat. The experiments concluded that fins provide better cooling performance in high altitude regions; whereas TMSs can be used in low altitude regions as well as offer a wall shading effect.

Also in related work, Noro and Lazzarin [184] studied a PV-T system for a typical 77 m^2 two-stage Italian house in Venice, Rome and Crotone. The unglazed PV-T collector was able to cover 72 % and 41 % of the domestic electricity and heat demands of the house in Rome, while the discounted payback period (DPP) was estimated to be around 9-13 years. Furthermore, Metwally et al. [185] developed two cooling models of PV panels namely: (i) an active cooling system using thermoelectric generators, and (ii) a hybrid cooling system using the thermoelectric generator and PCM. They showed that the electrical power generation of the system can be enhanced up to 20 % at irradiation flux of 760 W/m^2 and 30% at 1150 W/m^2, using hybrid cooling. Sudhakar et al. [186] also experimented on PV panels using a hybrid cooling technique incorporating PCM (OM35) and water cooling, and showed that PV cooling techniques involving top to bottom water circulation with PCM give optimum performance with a decrease in average temperature by 5.4 °C, an increase in energy production by 12 %, an electrical efficiency enhancement of 12 %, a peak overall exergy output of 26 %, and an exergy efficiency enhancement of 8 %.

Srimanickam et al. [187] considered a PV-T collector with V-baffled channels. Their experimental apparatus is shown in Fig. 25. The PV cells were cooled by air which was forced to pass through the rear surface of the collector. The study recorded hourly variations of thermal efficiency, equivalent thermal efficiency and overall thermal efficiency. To understand the characteristics of a PV-T system using aluminium substrate instead of glass, an experiment was performed by Pang et al. [188] in which cooling is accomplished by natural air in one case and forced water circulation in another case. The results showed that the electrical efficiency obtained using the aluminium substrate was almost 20 % higher than that obtained using a glass substrate. Though the cost was high, aluminium gave a better lifetime and flexibility to the collector compared to glass. Chauhan et al. [189] simulated the performance of a PV-T/air system under the weather conditions of four different cities in India (i.e., New Delhi, Jodhpur, Bangalore and Srinagar). The simulation results showed that both the electricity and thermal outputs of the PV-T collector in Jodhpur were nearly twice of those in New Delhi. Another experiment was conducted for four configurations of solar air collectors (glass to glass PV panel with and without duct; glass to Tedlar PV panel with and without duct) in New Delhi. The results revealed that PV panels with a duct could achieve annual average electrical efficiencies reaching 10 %, which was 6.8 % higher (in relative terms) than the panel configurations without a duct [190].

Fig. 25. Experimental arrangement used by Srimanickam et al. [187].

Guarracino et al. [191] developed a dynamic 3-D model of a hybrid PV-T collector with a sheet-and-tube thermal absorber. The outcomes revealed that the electrical and thermal outputs of the PV-T system strongly depended on the collector structure (glazing or unglazing), pump operation, differential thermostat controller, and choice of flow rate. The results also showed that the thermal efficiency can be increased by 10 % when ideally decreasing the emissivity of the solar cell from 0.9 to 0. Guarracino et al. [192] experimentally studied the performance characteristics of non-concentrating PV-T collectors under outdoor conditions. The outcomes showed that for the commercial PV-T collector tested, improvements to the thermal contact between PV cells and thermal absorber resulted in a 6-8 % increase in electrical efficiency and a 10 °C decrease in PV temperature. Herrando et al. [193] developed a model to study the performance of a hybrid PV-T collector for providing electricity and hot water. The outcomes showed that a PV-T system was able to save 16 tonnes of CO_2 over the lifetime, which was relatively 36 % higher than a PV-only system. A further study [194] presented 26 different options of absorber exchanger designs for hybrid PV-T solar collectors and compared these to a reference sheet-and-tube PV-T collector. It showed that a PV-T collector featuring a polycarbonate flat-box design which achieved a higher thermal performance compared to the reference collector (with a 4 % higher optical efficiency and 15 % lower heat-loss coefficient) and achieved a reduction in weight by 9 % and lowered the investment cost by 21 %.

Herrando et al. [195] examined the performance of a polymeric flat-box PV-T collector design and the performance of solar in combination with heat and power systems. The investigated systems displaced 1.65, 3.87 and 1.54 tons of CO_2 per year in London, Athens and Zaragoza, respectively. A further simulation study by the same group [196], using 3-D finite element and computational fluid dynamics showed that a hybrid PV-T system has the potential on average to cover around 50 % of total space heating and domestic hot water demand and around 87 % of total electricity demand. Also, another model was constructed to find out the techno-economic performance of a solar combined cooling, heating and power (S-CCHP) system based on hybrid PV-T collectors [197]. Kianifard et al. [198] modelled, designed and fabricated a novel PV-T collector in which the water was used as a heat collector in the serpentine half pipe instead of a full circular cross-section. The key highlight of using the half pipe was that it highly reduced the thermal resistances. The results showed that the thermal and electrical efficiency of the proposed model was 10-13 % and 0.4-0.6 % higher than the models of conventional collectors.

Ramos et al. [199] examined a hybrid PV-T system for combined heating, cooling and power provision for a metropolitan environment. The outcomes showed an overall efficiency of 70 % or higher with electrical efficiencies up to 15-20 % and thermal efficiencies over 50 %. Herrando et al. [200] also studied the performance of an integrated PV-T collector and heat pumps system for supplying domestic hot water, space heating and electricity to households. The outcomes showed that, in locations of Rome and Paris, the system covered more than 74 % of the domestic hot water, 100 % of the space heating and over 25 % of the electricity of households. Wang et al. [201] presented a hybrid PV-T collector for a sports centre application in Italy based on thermodynamic analysis of a solar combined heating and power system. It showed that 38 % of the electricity demand was contented and, also, the system covered 24 % of space heating demand and 58 % of the swimming pool and hot water heating demand. Mellor et al. [202] performed an experiment to enhance the thermal efficiency of hybrid PV-T collectors with minimum loss of electrical efficiency. The solar cells were coated with a spectrally-selective low-emissivity coating to reduce radiative thermal loss, and a nanotextured rear reflector was used to improvise the absorption of the near-infrared part of the solar spectrum for heat generation. A 20 % improvement in thermal efficiency could be achieved if the incident radiation was effectively absorbed and changed into useful heat.

Golzari et al. [203] experimentally presented a method to enhance the efficiency of a PV-T system by electro-hydrodynamics. It was found that the Corona wind enhanced the heat transfer coefficient of the system by 65 % while increasing the thermal efficiency of the system by 28 %. Based on the exergy concept (energy balance of different components), Sobhnamayan et al. [204] optimised a solar PV-T water system. Both exergy analyses, as well as energy analyses, were needed to obtain the exergy efficiency of a PV-T collector. The expressions were obtained for exergy of different parts of the PV-T collector, to obtain the exergy balance for different components of a PV-T collector. Some adjustments were made to modify the equations of exergy efficiency of the PV-T water collector and an advanced computer simulation program was developed to calculate the electrical and thermal efficiency parameters. The exergy efficiency of the PV-T water collector system optimised by a genetic algorithm reached 11 %.

. Farshchimonfared et al. [205] examined the electrical and thermal performance of a PV-T air collector system. The authors optimised the performance of the system with channel depth, mass flow rate of air per unit collector area and diameter of an air distribution duct. The results showed that the optimum channel depth value varies between 0.09 and 0.026 m and the optimum air distribution duct diameter varies between 0.3 and 0.5 m for the considered system. It is also observed that the optimum depth increases with both an increase in length to width ratio and in collector area.

Gagliano et al. [206] investigated the performance of conventional solar thermal plants (photovoltaics plus solar collector) and compared results with hybrid PV-T systems. The results showed that hybrid PV-T systems allowed a relative increase of exergy efficiency between 10 % and 15 % compared to a PV-only system in three cities, namely Catania, Split and Freiburg. Buonomano et al. [207] examined the technical and economic feasibility of PV-T collectors and compared the results with a conventional PV panel. The PV panel electrical efficiency was 18 %, which was greater than that of the PV-T collector, which was 12 %. However, the overall efficiency of the PV-T collector was 26 % greater than that of the PV panel which only had the electrical output.

Dannemand et al. [208] designed and investigated the operational behaviour of a solar PV-T assisted heat pump system to meet electrical and domestic heating demands. The hybrid system had an electrical efficiency of more than 14 % throughout the testing period. During summer, the PV-T system completely covered the domestic hot-water demand. However, during less sunny periods, the hot water tank had to be recharged by the brine-water heat pump to fulfil the hot water demand. Lebbi et al. [209] focussed on improving the energy performance of the PV-T system using a bi-fluid cooling approach, i.e., air and water which were used to cool the front and rear side of the PV cells, respectively. At a global solar irradiance of 650 W/m^2, the resulted improvement was about 5.7 % in electrical efficiency and an average temperature reduction of up to 15 °C was obtained. Further, the overall energy efficiency of the experimented system was found to be 85 %.

Aste et al. [210] conducted a combined experimental and modelling investigation of a PV-T system at three geographical (and climatic) locations, namely Paris, Milan and Athens. Their annual results showed that the overall efficiency of the PV-T collector was 33 %, 36 % and 41 % in Paris, Milan and Athens, respectively. According to annual irradiation on a horizontal plane, the thermal efficiency upsurges progressively from Paris to Milan to Athens. In the hybrid system, the achieved electrical efficiencies were 14 % in Paris, also 14 % in Milan, and 13 % in Athens. Liang et al. [211] designed and developed a hybrid PV-T solar collector with a 20-mm-thick graphite layer attached below the sheet-and-tube thermal absorber. The backplane of the PV-T collector had a 16.7 °C lower temperature than the standalone PV panel at a solar irradiance of around 1000 W/m^2. The daily average electrical efficiency of the PV-T collector was 6.5 %, which is higher than that of the standalone PV panel of 5.2 %.

Ebrahimi et al. [212] investigated both the efficiency and cost of 11 different PV-T systems with different working fluids (water and air), thermal absorbers (round and rectangular tubes), PV materials (mono-crystalline, poly-crystalline and amorphous Si) and glazing structures (single and double glazing). An analytical network process (ANP) was used to find the best design partially for Asia. They concluded that the best design is a non-concentrating, non-glazed design using water as the working fluid, based on the assumption that the electricity and thermal energy are of the same value for the decision-maker.

Spectral splitting is another promising approach for PV thermal management for electrical, thermal and combined generation applications [213-215]. PV cells are only effective to a part of the solar spectrum, while the rest of the spectrum has to be dissipated as waste heat in the PV cells. For example, Si solar cells are not able to electrically utilise the infrared spectrum ($\lambda > 1100$ nm) and also have very low efficiency in the ultraviolet spectrum range ($\lambda < 400$ nm). The diagram of a fluid-based spectral splitting PV-T collector is shown in Fig. 26 [216]. The channel above the PV cells is filled with flowing liquid, which can selectively absorb the unusable spectrum in advance, thus reducing the waste heat in PV cells. The rest of the spectrum, which is electrically effective to the PV cells, passes through the liquid filter channel. The flowing liquid filter acts as both the optical filter and the heat transfer fluid. Nanofluids have attracted particular attention as they are effective and suitable for spectral splitting PV-T collectors. Taylor et al. [214] developed a mathematical model to design nanofluid-based filters to match different solar cells. Common nanoparticles for the spectral splitting nanofluids include Ag/SiO_2, Ag/TiO_2, Au/SiO_2, ZnO etc. [213,214,217], while common base fluids include water, glycol, *Therminol* heat transfer oil, etc. An ideal optical filter can absorb ~25 % and ~38 % of the incident solar energy that is electrically unusable to Si and CdTe solar cells [218]. A recent review article by Huang et al. [216] and Liang et al. [217] summarised the development of spectral splitting PV-T technologies based on different nanomaterials.

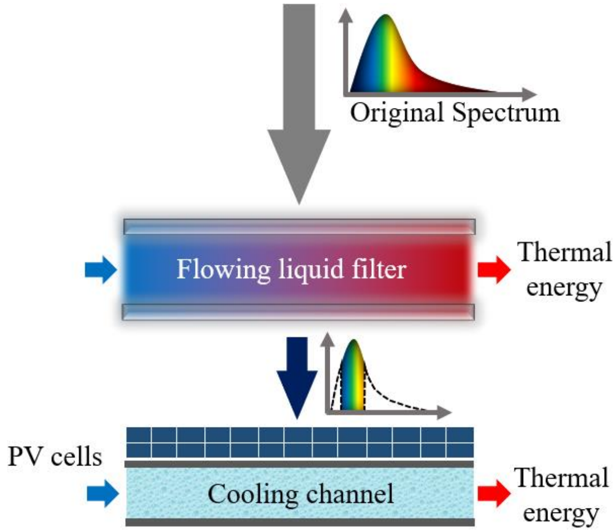

Fig. 26. Diagram of fluid-based spectral splitting PV-T collector [216].

In summary, PV-T systems provide a useful thermal output that can be used for multiple purposes, and to obtain higher overall efficiency. PV-T collector designs have relied on a combination of cooling/thermal management techniques, e.g., air/water cooling, fins, PCMs, etc., to enhance heat transfer, while nanofluids have also been used to enhance performance. Highlights from a range of studies on PV-T collectors and systems, in terms of thermal and electrical performance, are listed in Table 7.

Table 7. Summary of research aimed at PV cooling and efficiency enhancement when part of a hybrid PV-T collector system.

Nature of work	Fluid used	Efficiency enhancement	Observation/remark	Ref.
Experimental and numerical	Air	Highest overall efficiency achieved was 61-62 %, by a PV-T air glazed type collector with a finned back wall	The analytical results show that both high flow rates and small channel depths result in higher electrical efficiency and thermal output and may be suggested for efficient PV-T/air systems. However, this results in higher pressure drops and increased operating running costs of the system.	[183]
Experimental and numerical	Air	Fin integrated system gave the highest efficiency improvement followed by TMS system, ranging from 12 % to 20 %	PV-T based air circulation reduced PV panel temperature by a minimum of 5 °C. The results show that fin systems are suitable for high latitude regions (more heating) where the high heat gain is exploited in winter, whereas TMS systems are more suitable for low latitude regions and tropical countries to maximise both the improved heat gain and the wall shading effect.	[219]
Experimental	Air	With HRV, the overall efficiency of the PV-T collector was 38 % which included 15 % and 23 % electrical and mechanical efficiency, respectively	Heat recovery ventilated recovery systems can be coupled with air-type PV-T for enhancing build environment performance.	[220]
Experimental	Air	Thermal and electrical efficiencies increased by 40 % and 2.4 %, respectively, when the air flow rate per unit collector area increased from 0.01 to 0.07 $kgs^{-1}m^{-2}$	Exergy analysis is not an encouraging approach for investigating PV-T systems used for space heating.	[221]
Experimental and numerical	Air	An increase in air flow rate from 0.008 to 0.016 (kgs^{-1}) was associated with thermal, electrical and overall efficiencies improvements of 23 %, 14 % and 22 %	Uniform distribution of air on a PV panel prevents local excessive temperature on the panel. Using a concentrator with a reflector wall or increased air flow increases overall system efficiency by 41 % and 22 %, respectively.	[222]
Experimental	Water	Compared to a conventional PV panel, the average power of the PV-T collector tested here was 5.5 % higher	The overall power output of a PV-T system is higher due to the raise of its voltage because of the lower operating temperature of the PV cell. The electric power produced by conventional PV and PV-T systems is 61.7 W and 65.1 W, respectively.	[223]
Experimental and numerical	Water	With the tested hybrid PV-T system, 13 % and 53 % improvements of electrical and	The experimental results show the capacity of the hybrid system to produce about 20 L of water at 80 °C in a day with improved electrical efficiency.	[224]

		thermal efficiencies were obtained which compete well with the traditional system		
Experimental and numerical	Air	Overall system efficiency above 45 % was achieved	It is observed that, during winter, low flow rate air circulation systems perform better as high air temperature differences can be achieved. However, during summer, high flow rate systems achieve a lower operating temperature of a PV cell.	[225]
Experimental and numerical	Water	Maximum overall thermal and exergy efficiencies obtained were 34 % and 15 %, respectively	The experimental results show that, with the copper PV-T base water heating system, the electrical efficiency of the system reduces with a temperature rise. Due to better heat transfer between the PV cell and the flowing fluid, the maximum overall thermal energy of the proposed copper base PV-T collector is higher than that of the conventional Tedlar base PV-T collector.	[226]
Experimental and simulation	Air and Water	The daily rate of thermal gain and daily overall electrical gain is 2.5 % and 5.2 % higher for an aluminium base PVT-TEC water collector and opaque PVT-TEC water collector, respectively	The overall thermal and electrical efficiency of an opaque PVT-TEC water collector is higher than that of an opaque PVT-TEC air collector by 21 % to 22 % and 1.9 % to 2.8 %, respectively. The daily overall electrical energy gain and daily rate of thermal energy gain are highest for the aluminium base PVT-TEC water collector than the semi-transparent PVT-TEC water collector by 5.2 % and 2.5 %, respectively, and higher than the opaque PVT-TEC water collector by 2.6 % and 14 %, respectively.	[227]
Experimental	Air and Water	Net annual overall thermal energy and exergy gains were about 1290 kWh and 210 kWh, respectively, for an N-CPCT collector covered with water	The N-CPVT collector partially covered with water was chosen as the best choice for cooking and the N-CPVT collector with air was chosen as the best choice for space heating or drying processes.	[228]

8. Comparative analysis, research gaps and future prospects

This article has presented different PV cooling techniques and recent advancements in their development and application. Each technique has advantages and disadvantages and may be suitable in different cases depending on various factors such as the type of solar cell/panel, location, climatic variation and type of energy output (electrical or combination of electrical and thermal).

Knowledge of different PV panels and effective cooling strategies is significant for the better performance of the system. An understanding of the current literature may help researchers and engineers to design cost-effective and highly efficient integrated systems. From the above-discussed technologies, natural air convection (passive air cooling) is the simplest technique with low cost but is less efficient unless it is combined with other techniques. Moreover, the passive air-cooling method would generally be more suitable for higher altitudes places, where wind speed is high. But in regions with hot ambient conditions and high humidity, this method is less effective. Forced air cooling is associated with a faster rate of cooling compared to natural convection, but it introduces some parasitic power losses as it consumes electricity to cool the panels. Liquid-based cooling effectively reduces the panel temperature compared to air cooling owing to its higher flow rate and thermal conductivity. In particular, water is the most suitable liquid for such purposes, as it has good thermal conductivity and is naturally available. Furthermore, owing to the water shortages in some regions, this method cannot be implemented.

During peak radiation periods and in systems where the panel constantly receives direct sunlight such as in CPV, the temperature increase in the panel is undesirable. Under such conditions, non-conventional methods like air or water sometimes cannot provide the desired cooling power and uniform temperature distribution. Alternatively, heat pipe, PCM, or nanofluid cooling methods can perform better during high-intensity solar radiation by reducing the heating loads of the panel. However, heat pipes not only provide uniform heat distribution but also eliminate the freezing of thermosyphon tubes used in water-based cooling. Nanofluid cooling has the potential to remove heat from PV panels effectively, but is associated with challenges relating to practical implementation that are as yet not fully resolved, and when the system size is large this method becomes costly and complex. The melting point and heat capacity of PCMs are considered to be the most critical parameters. A PCM with a low melting point and high heat capacity can provide effective cooling for PV panels, and further adding a thermal enhancer to it improves its conductivity and therefore increases efficiency. Comparative analyses of different cooling techniques and their advantages and disadvantages are tabulated in Table 8.

Of key importance is the added complexity and cost associated with these cooling solutions, which make the decision to implement them over conventional PV system installations rest firmly on being able to prove that the benefits are enough to overcome these issues.

Some of the research gaps and future prospects are as follows:

- **System stability and optimisation:** The stability of the integrated system is an important parameter that needs to be considered. It is observed that integrated system involving cooling techniques experiences problem after some period of operation. Therefore, the selection of materials that are cost-effective, light in weight, highly stable with long effective long life needs to be worked upon as a part of future work.
- **Numerical modelling:** Numerical modelling provides first-hand results before carrying out the actual experiment. Further investigation in numerical modelling will help researchers to have an idea about the performance of the system under different climatic conditions. The advance numerical study can help in the design and development of the system according to the suitability of the location. This will help in saving time and money by avoiding several experiments to understand the system behaviour.
- **Sophisticated test facility requirement:** In order to have quality test with accurate data collection and further analysis, it is important to have a sophisticated test facility. Research in sophisticated test facilities will help to provide data collection facilities from sophisticated analytical equipment's to the scientific community for their advanced research at nominal charges. This will help in spectral measurements, phase change materials characterisation, quality documentation and taking adequate steps for continual improvement of the effectiveness of the system.
- **Yearlong experimentation:** In most of the studies carried out by the various researchers, it is observed that the experiment is done only for a few days or selected months of the year. To understand the performance of the system over a long period it is important to carry out the experimentation of the PV system with a different type of cooling technique for the complete year. Yearlong experimentation will give the reader a better understanding of the effect of different PV cooling techniques.
- **The combined effect of PV cooling and cleaning:** The performance of the PV panel is highly affected by its operating temperature and dust particle accumulated on its surface. A combined study including PV cooling and cleaning can be investigated to understand system performance due to both factors.
- **Techno-economic and environmental analysis:** There is a pressing need to investigate the payback period for the designed cooling system which can potentially bring the research closer to implementation and attract investors. Further, environmental analysis should deal with the overall lifecycle of the cooling system and its impact on the ecosystem. This will aid in optimising the usage of resources as well as minimising the environmental impact.

Table 8. Comparative analysis of various technologies for PV panel temperature regulation.

Temperature regulation method	*Technology Readiness Level (TRL)	Advantage	Disadvantage	Remarks	Reference
Passive air cooling	Mature technology	• No maintenance • Easy integration • No power consumption	• Non-uniform temperature regulation • Lower thermal conductivity of air	Passive air cooling is highly dependent upon wind speed and direction. PV panel efficiency enhancement is low due to the high operating temperature of the panel for most of the time.	[72,73]
Active air cooling	Mature technology	• Higher heat transfer rate compared to natural cooling • Independent of air speed and wind direction • Moderate PV operating temperature reduction	• Requires regular maintenance • Power consumption • Integration is complex compared to passive air cooling • System cost is comparatively high	Active air cooling is more effective than passive cooling. However, due to the poor thermal conductivity of air in contrast to water, the efficiency of the PV panel is not enhanced to a larger extent.	[183,224,229-231]
Water-based cooling	Mature technology	• Greater heat transfer rate compared to air • Greater heat capacity compared to air • Better thermal performance and temperature reduction	• The cost of the system is high due to additional equipment requirement • Water leakage/sealing may be a problem • Advanced operation and greater maintenance cost. • The overall system is bulky and occupies more space compared to an air-based system	A water-based cooling system has better performance. The hybrid PV-T system has higher electrical and thermal efficiencies. There is scope for more research in this technology with reflectors, better heat transfer fluids, etc., to enhance the overall efficiency of the system to a larger more extent.	[137,235,232-235]
Heat pipe cooling	Early technology	• Passive heat exchange • Efficient heat transfer • Easy to combine	• The overall cost of the system is high • PV temperature is not uniform		[14,236,237]

			• Performance depends upon wind speed and wind direction • Low heat transfer rate		
Phase change materials	Early technology	• Greater heat transfer rate compared to air and water • High heat absorption capacity due to latent effect • Lower operating temperature of the PV panel • Higher efficiency of PV panel • No power consumption • No noise	• Some of the PCMs are toxic and cause corrosion • The overall weight of the integrated system is high • Increase in the overall cost of the system • PCM leakage/sealing may be a problem • The cost of PCMs and the integrated system is high • After the complete life cycle of PCMs, there may be a problem with their disposal	PCM has a higher heat capacity and is suitable for heat collection from PV and transmitting it to another medium or surroundings. It is important to select PCMs with suitable melting temperatures for integration with PV panels so that performance can be enhanced throughout the year.	[136,238]
Nanofluid/ nanoparticles	Early technology	• The use of nanofluid/nanoparticles results in higher thermal conductivity • Better uniformity of temperature • Results in higher electrical efficiency	• The cost of the system is high • Cannot be used for multi-junction PV panels		[155,172,173,239]

* According to NASA, to identify the maturity level of a technology a measurement system named Technology Readiness Levels (TRL) is being used. [Available online]: www.nasa.gov/directorates/heo/scan/engineering/technology/txt_accordion1.html

9. Closing remarks and conclusions

Harvesting energy from the sun (i.e., solar energy) is of major interest today, and globally the most prominent renewable energy resource and market, as it is a clean, environment-friendly and renewable resource, but also cost-effective. Regulating the temperature of PV panels via appropriate thermal management solutions is advantageous in many applications, as it affects performance, operational characteristics and also service lifetime. The cooling of PV panels reduces the operating temperature of the cells and, thus, improves their efficiency, and also the rate of cell degradation, thereby extending system lifetime and reducing operational and maintenance costs. On the other hand, the benefits of implementing a cooling solution onto conventional PV panels and systems incur added complexity and costs, and it is necessary to ensure that these are significantly outweighed by the benefits that they enable. If this cannot be ensured, the practical implementation of a solution cannot be justified.

Cooling techniques suitable for PV panels generally depend on various factors, such as the PV panel type, system arrangement, etc., and, in the case of CPV systems, they also depend on the concentrator type, geometry and weather conditions. Relevant approaches can be classed as active or passive, and include the use of water, air, heat sinks, phase change materials, etc.

In this review, a comprehensive survey was first conducted to identify and explore various PV cooling solutions and related approaches. Currently, available active and passive cooling approaches with their classifications, characteristics and performance measures were introduced. Then an overview and commentary were provided of the potential performance improvements that these can enable to PV panel efficiency and lifetime. Further, insights were obtained into suitable applications, and the outcomes of some case studies where the developed techniques have been implemented in practice were presented and discussed. To extend the contributions, examinations were included of recent innovations, research and developments involving the employment and integration of appropriate phase change materials (PCMs), as well as the use of nanofluids. Furthermore, a focus was also placed on photovoltaic-thermal (PV-T) collectors and systems, and their operational and performance characteristics in different cases were provided. Finally, a comparative analysis of all the available PV cooling solutions was presented, aiming to guide next-generation technologies and future work in this space. Recommendations were drawn which will be beneficial for future research studies, and will assist engineers/professionals working on the science, design and applications of PV systems.

The important findings from this study are outlined below:

- Active cooling techniques, as expected, are more effective than passive cooling techniques. In many cases, however, passive cooling can replace active cooling to lower complexity or cost, especially in small-scale, private (rather than commercial) installations. In such cases, the use of PCMs and small concentrated PV panels designs, and also of passive radiative cooling approaches are preferred. When pumping costs are taken into account, especially for backside cooling, passive techniques can sometimes yield more power gain than active ones.
- The thermal management of PV cells when these are a part of hybrid PV-T collectors is a promising approach as the waste heat from the PV cells can be utilised for thermal applications. Such hybrid systems have an overall higher total energy output compared to two individual systems and have the benefit of compact design and better space use.
- When employing PV-T collectors, an active cooling system appears to be the most prominent solution in most applications, as it enables increased recovery of waste heat which in this type of collector is a useful output. Furthermore, active water cooling is the best solution when increasing electrical efficiency is the main goal. Therefore, future research should be focussed on the implementation of effective active water cooling of PV cells.
- Front surface cooling may be more economic in reducing pumping costs, especially in hot climate conditions; however, one obvious drawback of front-side cooling is water evaporation, which requires continuous replenishment of evaporated water. Otherwise, an additional cover is required which increases cost and weight.
- Air-cooled PV-T systems have better performance than conventional PV panels but are not as good as water-cooled PV-T systems, PV-PCM integrated systems or nanofluid cooling systems due to the low heat capacity of air. The overall system design is simple and has lower operation and maintenance costs. The system performance can be further enhanced by integrating other passive techniques such as fins integration, use of heat sink paste and PCM integration. The thermal output of the system can be used for space conditioning and other thermal applications for overall efficiency enhancement. Water-cooled PV-T system performance is better due to the higher heat capacity of water relative to air and the higher heat transfer coefficients of water flow relative to air flows.
- PCMs can store a significant quantity of thermal energy per unit volume relative to, e.g., water, due to the latent heat of fusion. The integration of PCMs with PV cells can play a significant role in the thermal regulation of PV temperature and the consequent enhancement of PV efficiency. Due to the good

thermal contact of PCM to the whole container surface at the rear of PV cells, a uniform temperature distribution can be achieved. Such PVT-PCM integrated systems result in better efficiency of the system and a dual-energy output. As a future study for the better performance of such systems, it is suggested to investigate the use of PCMs with optimal melting temperatures, matching the location which solidifies during the night and becomes liquid by absorbing heat from the PV panel during the day. Further research is required for increasing the thermal conductivity, stability and effective life/cycling behaviour of PCMs, as well as for reducing the cost of suitable PCMs.

- Nanofluids have higher heat transfer coefficients compared to water and can thereby enable a greater drop in PV operating temperatures at similar operating conditions. They can also be used in radiative control, spectral-splitting designs. Nanofluid-based cooling solutions applied to PV panels are a particularly effective approach for achieving higher performance compared to water-cooled PV-T systems, and the integration of nanoparticles with PCMs for PV cooling can enhance the overall performance of such solutions even further if implemented correctly. Nanofluid cooling merits further study, especially as nanofluids can also act as spectral filters, and promising research goals should include cost-effectiveness, improved stability and performance characterisation since the employment of nanofluids has faced challenges to their practical implementation that are associated with added cost, complexity, environmental impact, and have not yet been fully overcome.

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References

[1] Markides CN. The role of pumped and waste heat technologies in a high-efficiency sustainable energy future for the UK. Applied Thermal Engineering 2013;53:197–209.

[2] Shafiullah GM, Amanullah MTO, Ali ABMS, Jarvis D, Wolfs P. Prospects of renewable energy–a feasibility study in the Australian context. Renewable Energy 20212;39:183–97.

[3] Silva Herran D, Tachiiri K, Matsumoto K. Global energy system transformations in mitigation scenarios considering climate uncertainties. Applied Energy 2019;243:119–31.

[4] Shoeb M, Shafiullah GM. Renewable energy integrated islanded microgrid for sustainable irrigation—A Bangladesh perspective. Energies 2018;11:1283.

[5] Panos E, Densing M, Volkart K. Access to electricity in the World Energy Council's global energy scenarios: An outlook for developing regions until 2030. Energy Strategy Reviews 2016;9:28–49.

[6] Mrabet Z, Alsamara M, Saleh AS, Anwar S. Urbanization and non-renewable energy demand: A comparison of developed and emerging countries. Energy 2019;170:832–9.

[7] Gielen D, Boshell F, Saygin D, Bazilian MD, Wagner N, Gorini R. The role of renewable energy in the global energy transformation. Energy Strategy Reviews 2019;24:38–50.

[8] Shafiullah GM, Amanullah MTO, Stojcevski A, Ali ABMS. Integration of roof-top photovoltaic systems into the low voltage distribution network. Journal of Renewable and Sustainable Energy 2014;6:033135.

[9] Aleixandre-Tudó JL, Castelló-Cogollos L, Aleixandre JL, Aleixandre-Benavent R. Renewable energies: Worldwide trends in research, funding and international collaboration. Renewable Energy 2019;139:268–78.

[10] Helm C, Mier M. On the efficient market diffusion of intermittent renewable energies. Energy Economics 2019;80:812–30.

[11] Pravalie R, Patriche C, Bandoc G. Spatial assessment of solar energy potential at global scale. A geographical approach. Journal of Cleaner Production 2019;209:692–721.

[12] Kabir E, Kumar P, Kumar S, Adelodun AA, Kim KH. Solar energy: Potential and future prospects. Renewable and Sustainable Energy Reviews 2018;82:894–900.

[13] Rajvikram M, Leoponraj S. A method to attain power optimality and efficiency in solar panel. Beni-Suef University Journal of Basic and Applied Sciences 2018;7:705–708.

[14] Du D, Darkwa J, Kokogiannakis G. Thermal management systems for Photovoltaics (PV) installations: A critical review. Solar Energy 2013;97:238–54.

[15] Skoplaki E, Palyvos JA. On the temperature dependence of photovoltaic module electrical performance: A review of efficiency/power correlations. Solar Energy 2009;83:614–24.

[16] Champion Photovoltaic Module Efficiency Chart, https://www.nrel.gov/pv/module-efficiency.html [Accessed on November 2021]

[17] Bethel A, Jordan H, Kailyn S, Brodie Y, Jason D. Energy Education - Types of photovoltaic cells 2018. https://energyeducation.ca/encyclopedia/Types_of_photovoltaic_cells [accessed November 5, 2021].

[18] Office of Energy Efficiency and Renewable Energy. Solar Photovoltaic Cell Basics 2021, https://www.energy.gov/eere/solar/solar-photovoltaic-cell-basics [accessed November 5, 2021].

[19] Siecker J, Kusakana K, Numbi BP. A review of solar photovoltaic systems cooling technologies. Renewable and Sustainable Energy Reviews 2017;79:192–203.

[20] Maleki A, Haghighi A, El Haj Assad M, Mahariq I, Nazari MA. A review on the approaches employed for cooling PV cells. Solar Energy 2020;209:170-185.

[21] Hasanuzzaman M, Malek ABMA, Islam MM, Pandey AK, Rahim NA. Global advancement of cooling technologies for PV systems: A review. Solar Energy 2016;137:25–45.

[22] Velmurugan K, Kumarasamy S, Wongwuttanasatian T, Seithtanabutara V. Review of PCM types and suggestions for an applicable cascaded PCM for passive PV module cooling under tropical climate conditions. Journal of Cleaner Production 2021;293:126065.

[23] Ali HM. Recent advancements in PV cooling and efficiency enhancement integrating phase change materials based systems – A comprehensive review. Solar Energy 2020;197:163-198.

[24] Sargunanathan S, Elango A, Tharves Mohideen S. Performance enhancement of solar photovoltaic cells using effective cooling methods: A review. Renewable and Sustainable Energy Reviews 2016;64:382–393.

[25] Kandeal AW, Thakur AK, Elkadeem MR, Elmorshedy MF, Ullah Z, Sathyamurthy R, Sharshir SW. Photovoltaics performance improvement using different cooling methodologies: A state-of-art review. Journal of Cleaner Production 2020;273:122772.

[26] Haitham Bahaidarah MS, Ahmer Baloch AB, Gandhidasan P. Uniform cooling of photovoltaic panels: A review. Renewable and Sustainable Energy Reviews 2016;57:1520–1544.

[27] Hamzat AK, Sahin AZ, Omisanya MI, Alhems LM. Advances in PV and PVT cooling technologies: A review. Sustainable Energy Technologies and Assessments 2021;47:101360.

[28] Dubey S, Sarvaiya JN, Seshadri B. Temperature dependent photovoltaic (PV) efficiency and its effect on PV production in the world –A review. Energy Procedia 2013;33:311–21.

[29] Allouhi A, Kousksou T, Jamil A, Tarik El T, Mourad Y, Zeraouli Y. Economic and environmental assessment of solar air-conditioning systems in Morocco. Renewable and Sustainable Energy Reviews 2015;50:770–81.

[30] Kaushika ND, Reddy KS, Kaushik K. Sustainable energy and the environment : A clean technology approach, New Delhi: Springer 2016.

[31] Lazzarin RM, Noro M. Past, present, future of solar cooling: Technical and economical considerations. Solar Energy 2018;172:2–13.

[32] Armstrong S, Hurley WG. A thermal model for photovoltaic panels under varying atmospheric conditions. Applied Thermal Engineering 2010;30:1488–95.

[33] Khullar V, Tyagi H, Phelan PE, Otanicar TP, Singh H, Taylor RA. Solar energy harvesting using nanofluids-based concentrating solar collector, ASME 2012 Third International conference of Micro/Nanoscale Heat and Mass Transfer 2012;3:259.

[34] Nair KK, Jose J, Ravindran A. Analysis of temperature dependent parameters on solar cell efficiency using MATLAB. Int J Eng Dev Res 2016;4:536–41.

[35] Anderson WG, Tamanna S, Sarraf DB, Dussinger PM. Heat pipe cooling of concentrating photovoltaic (CPV) systems, 6th International Energy Conversion Engineering Conference 2008.

[36] Radziemska E. The effect of temperature difference on heat transport in solar cells. Archives of Thermodynamics 2003;24:83–95.

[37] Solanki CS. Solar photovoltaics: fundamentals, technologies and applications. PHI Learning Pvt. Ltd. 2015.

[38] Carlson DE. Low-Cost Power from Thin-Film Photovoltaics, in Johansson, T. B., Bodlund, B., and Williams, R. H. (eds.), Electricity: End Use and New Generation Technologies and Their Planning Implications, Lund University Press, Lund, 1989, pp. 595–626.

[39] Bhargava AK, Garg HP, Agarwal RK. Study of a hybrid solar system—solar air heater combined with solar cells. Energy Conversion and Management 1991;31:471–9.

[40] Khanna S, Sundaram S, Reddy KS, Mallick TK. Performance analysis of perovskite and dye-sensitized solar cells under varying operating conditions and comparison with monocrystalline silicon cell. Applied Thermal Engineering 2017;127:559–65.

[41] Dupre O, Vaillon R, Green AM. Thermal behavior of photovoltaic devices: physics and engineering. Springer 2018.

[42] Chander S, Purohit A, Sharma A, Nehra SP, Dhaka MS. A study on photovoltaic parameters of mono-crystalline silicon solar cell with cell temperature. Energy Reports 2015;1:104–9.

[43] Jiang JA, Wang JC, Kuo KC, Su YL, Shieh JC, Chou JJ. Analysis of the junction temperature and thermal characteristics of photovoltaic modules under various operation conditions. Energy 2012;44:292–301.

[44] Bhakre SS, Sawarkar PD, Kalamkar VR. Performance evaluation of PV panel surfaces exposed to hydraulic cooling – A review. Sol Energy 2021;224:1193–209.

[45] Anand A, Shukla A, Panchal H, Sharma A. Thermal regulation of photovoltaic system for enhanced power production: A review. J Energy Storage 2021;35:102236.

[46] Teo HG, Lee PS, Hawlader MNA. An active cooling system for photovoltaic modules. Applied Energy 2012;90:309–15.

[47] Farhana Z, Irwan YM, Azimmi RMN, Razliana ARN, Gomesh N. Experimental investigation of photovoltaic modules cooling system. 2012 IEEE Symposium on Computers & Informatics 2012:165–9.

[48] Syafiqah Z, Irwan Y, Amin N, Irwanto M, Leow W, Amelia A. Thermal and electrical study for PV panel with cooling. Indonesian Journal of Electrical Engineering and Computer Science 2019;7:492-9.

[49] Boulfaf N, Chaoufi J, Ghafiri A, Elorf A. Thermal study of hybrid photovoltaic thermal (PV/T) solar air collector using finite element method. International Journal of Renewable Energy Research 2016;6:171–82.

[50] Dehghan M, Rahgozar S, Pourrajabian A, Aminy M, Halek F-S. Techno-economic perspectives of the temperature management of photovoltaic (PV) power plants: A case-study in Iran. Sustainable Energy Technologies and Assessments 2021;45:101133.

[51] Almuwailhi A, Zeitoun O. Investigating the cooling of solar photovoltaic modules under the conditions of Riyadh. Journal of King Saud University - Engineering Sciences 2021.

[52] Mah CY, Lim BH, Wong CW, Tan MH, Chong KK, Lai AC. Investigating the performance improvement of a photovoltaic system in a tropical climate using water cooling method. Energy Procedia 2019;159:78-83.

[53] Prudhvi P, Sai PC. Efficiency improvement of solar PV panels using active cooling, 11th International Conference on Environment and Electrical Engineering 2012:1093–7.

[54] Kordzadeh A. The effects of nominal power of array and system head on the operation of photovoltaic water pumping set with array surface covered by a film of water. Renewable Energy 2010;35:1098–102.

[55] Shahverdian MH, Sohani A, Sayyaadi H, Samiezadeh S, Doranehgard MH, Karimi N, et al. A dynamic multi-objective optimization procedure for water cooling of a photovoltaic module. Sustainable Energy Technologies and Assessments 2021;45:101111.

[56] Hadipour A, Rajabi Zargarabadi M, Rashidi S. An efficient pulsed- spray water cooling system for photovoltaic panels: Experimental study and cost analysis. Renewable Energy 2021;164:867–75.

[57] Dorobantu L, Popescu MO, Popescu CL, Craciunescu A. Experimental assessment of PV panels front water cooling strategy. International Conference on Renewable Energies and Power Quality 2013;1:1–4

[58] Moharram KA, Abd-Elhady MS, Kandil HA, El-Sherif H. Enhancing the performance of photovoltaic panels by water cooling. Ain Shams Engineering Journal 2013;4:869–77.

[59] Zondag HA, De Vries DW, Van Helden WGJ, Van Zolingen RJC, Van Steenhoven AA. The thermal and electrical yield of a PV-thermal collector. Solar Energy 2002;72:113–28.

[60] Musthafa MM. Enhancing photoelectric conversion efficiency of solar panel by water cooling. Journal of Fundamentals of Renewable Energy and Applications 2015;5:10–4.

[61] Abdelrahman M, Eliwa A, Abdellatif OE. Experimental investigation of different cooling methods for Photovoltaic module. Joint Propulsion Conferences 2013:14-17.

[62] Bevilacqua P, Bruno R, Arcuri N. Comparing the performances of different cooling strategies to increase photovoltaic electric performance in different meteorological conditions. Energy 2020;195:116950.

[63] Irwan YM, Leow WZ, Irwanto M, Fareq M, Hassan SIS, Safwati I. Comparison of solar panel cooling system by using dc brushless fan and dc water. Journal of Physics: Conference Series 2015;622:012001.

[64] Leow W, Irwan Y, Irwanto M, Gomesh N, Safwati I. PIC 18F4550 Controlled solar panel cooling system using DC hybrid. Journal of Scientific Research & Reports 2014;3:2801–16.

[65] Sun Y, Wang Y, Zhu L, Yin B, Xiang H, Huang Q. Direct liquid-immersion cooling of concentrator silicon solar cells in a linear concentrating photovoltaic receiver. Energy 2014;65:264–71.

[66] Rahimi M, Asadi M, Karami N, Karimi E. A comparative study on using single and multi header microchannels in a hybrid PV cell cooling. Energy Conversion and Management 2015;101:1–8.

[67] Odeh S, Behnia M. Improving photovoltaic module efficiency using water cooling. Heat Transfer Engineering 2009;30:499–505.

[68] Irwan YM, Leow WZ, Irwanto M, Fareq M, Amelia AR, Gomesh N. Indoor test performance of PV panel through water cooling method. Energy Procedia 2015;79:604–11.

[69] Nizetic S, Coko D, Yadav A, Grubisic-Cabo F. Water spray cooling technique applied on a photovoltaic panel : The performance response. Energy Conversion and Management 2016;108:287–96.

[70] Bahaidarah H, Subhan A, Gandhidasan P, Rehman S. Performance evaluation of a PV (photovoltaic) module by back surface water cooling for hot climatic conditions. Energy 2013;59:445–53.

[71] Naghavi MS, Esmaeilzadeh A, Singh B, Ang BC, Yoon TM, Ong KS. Experimental and numerical assessments of underlying natural air movement on PV modules temperature. Solar Energy 2021;216:610-622.

[72] Hernandez RM, Cascales JRG, Garcia FV, Kaiser AS, Zamora B. Improving the electrical parameters of a photovoltaic panel by means of an induced or forced air stream. International Journal of Photoenergy 2013:1–10.

[73] Tonui JK, Tripanagnostopoulos Y. Performance improvement of PV/T solar collectors with natural air flow operation. Solar Energy 2008;82:1-12.

[74] Shahsavar A, Ameri M, Gholampour M. Energy and exergy analysis of a Photovoltaic-Thermal collector with natural air flow. Journal of Solar Energy Engineering 2012;134:1–10.

[75] Rahimi M, Valeh-e-sheyda P, Parsamoghadam MA, Masahi MM, Alsairafi AA. Design of a self-adjusted jet impingement system for cooling of photovoltaic cells. Energy Conversion and Management 2014;83:48–57.

[76] Valeh-e-sheyda P, Rahimi M, Parsamoghadam A, Masahi MM. Using a wind-driven ventilator to enhance a photovoltaic cell power generation. Energy and Buildings 2014;73:115–9.

[77] Wang H, Chao Y, Tang T, Luo K, Qin K. A Comparison of Partial Admission Axial and Radial Inflow Turbines for Underwater Vehicles. Energies. 2021;14(5):1514.

[78] Zhu L, Raman A, Wang K, Anoma MA, Fan S. Radiative cooling of solar cells. Optica 2014;1:32–8.

[79] Ebrahimi M, Rahimi M, Rahimi A. An experimental study on using natural vaporization for cooling of a photovoltaic solar cell. International Communications in Heat and Mass Transfer 2015;65:22–30.

[80] Alami AH. Effects of evaporative cooling on efficiency of photovoltaic modules. Energy Conversion and Management 2014;77:668–79.

[81] Chandrasekar M, Senthilkumar T. Experimental demonstration of enhanced solar energy utilization in flat PV (photovoltaic) modules cooled by heat spreaders in conjunction with cotton wick structures. Energy 2015;90:1401–10.

[82] Varkute N, Francis F, Kinny S, Sawant R, Ravichandran N. Hybrid cooling of multijunction concentrated photovoltaic cells. Proc. WRFER Int. Conf. Pune, India, 2017:48–53.

[83] Zubeer SA, Mohammed HA, Ilkan M. A review of photovoltaic cells cooling techniques. E3S Web of Conferences 2017;22:1–11.

[84] Idoko L, Anaya-lara O, McDonald A. Enhancing PV modules efficiency and power output using multi-concept cooling technique. Energy Reports 2018;4:357–69.

[85] Othman MY, Yatim B, Sopian K, Abu Bakar MN. Performance studies on a finned double-pass photovoltaic-thermal (PV/T) solar collector. Desalination 2007;209:43–9.

[86] Hernandez-Perez JG, Carrillo JG, Bassam A, Flota-Banuelos M, Patino-Lopez LD. Thermal performance of a discontinuous finned heatsink profile for PV passive cooling. Applied Thermal Engineering 2021;184:116238.

[87] Grubisic-Cabo F, Nizetic S, Coko D, Kragic IM, Agis P. Experimental investigation of the passive cooled free-standing photovoltaic panel with fixed aluminum fins on the backside surface. Journal of Cleaner Production 2018;176:119–29.

[88] Luo Q, Li P, Cai L, Chen X, Yan H, Zhu H. Experimental investigation on the heat dissipation performance of flared-fin heat sinks for concentration photovoltaic modules. Applied Thermal Engineering 2019;157:113666.

[89] Selimefendigil F, Bayrak F, Oztop HF. Experimental analysis and dynamic modeling of a photovoltaic module with porous fins. Renewable Energy 2018;125:193–205.

[90] Mays El A, Ammar R, Hawa M, Akroush MA, Hachem F, Khaled M. Improving photovoltaic panel using finned plate of aluminum. Energy Procedia 2017;119:812–7.

[91] Vittorini D, Cipollone R. Fin-cooled photovoltaic module modeling and Performances mapping and electric efficiency assessment under real operating conditions. Energy 2019;167:159–67.

[92] Hughes BR, Cherisa NPS, Beg O. Computational study of improving the efficiency of photovoltaic panels in the UAE. World Academy of Science, Engineering and Technology 2011;73:278–87.

[93] Senthil R, Madurai Elavarasan R, Pugazhendhi R, Premkumar M, Vengadesan E, Navakrishnan S, et al. A holistic review on the integration of heat pipes in solar thermal and photovoltaic systems. Solar Energy 2021;227:577–605.

[94] Al-Amri F, Maatallah TS, Al-Amri OF, Ali S, Ali S, Ateeq IS, et al. Innovative technique for achieving uniform temperatures across solar panels using heat pipes and liquid immersion cooling in the harsh climate in the Kingdom of Saudi Arabia. Alexandria Engineering Journal 2021.

[95] Tang X, Quan Z, Zhao Y. Experimental investigation of solar panel cooling by a novel micro heat pipe array. Energy Power Engineering 2010;2:171–4.

[96] Gang P, Huide F, Huijuan Z, Jie J. Performance study and parametric analysis of a novel heat pipe PV/T system. Energy 2012;37:384-395.

[97] Gang P, Huide F, Jie J, Tin-Tai C, Tao Z. Annual analysis of heat pipe PV/T systems for domestic hot water and electricity production. Energy Conversions and Management 2012;56:8–21.

[98] Ren X, Yu M., Zhao X, Li J, Zheng S, Chen F, Wang Z, Zhou J, Pei G, Ji J. Assessment of the cost reduction potential of a novel loop-heat-pipe solar photovoltaic/thermal system by employing the distributed parameter model. Energy 2020;190:116338.

[99] Hongbing C, Xilin C, Sizhuo L, Sai C. Experimental Study on the Energy Performance of PV-HP Water Heating System. Energy Procedia 2015;75:294–300.

[100] Raman AP, Anoma MA, Zhu L, Rephaeli E, Fan S. Passive radiative cooling below ambient air temperature under direct sunlight. Nature 2014;515:540.

[101] Zhai Y, Ma Y, David SN, Zhao D, Lou R, Tan G, Yang R, Yin X. Scalable-manufactured randomized glass-polymer hybrid metamaterial for daytime radiative cooling. Science 2017;355:1062–6.

[102] Zhu L, Raman AP, Fan S. Radiative cooling of solar absorbers using a visibly transparent photonic crystal thermal blackbody. Proceedings of the National Academy of Sciences 2015;112:12282–7.

[103] Bijarniya JP, Sarkar J, Maiti P. Review on passive daytime radiative cooling: Fundamentals, recent researches, challenges and opportunities. Renewable and Sustainable Energy Reviews 2020;133:110263.

[104] Safi TS, Munday JN. Improving photovoltaic performance through radiative cooling in both terrestrial and extraterrestrial environments. Optics Express 2015;23:A1120–8.

[105] Munday JN, Safi T. Radiative cooling of a GaAs solar cell to improve power conversion efficiency. IEEE 43rd Photovoltaic Specialists Conference 2016:1125–7.

[106] Gentle AR, Smith GB. Is enhanced radiative cooling of solar cell modules worth pursuing?. Solar Energy Materials and Solar Cells 2016;150:39–42.

[107] Green MA, Bremner SP. Energy conversion approaches and materials for high-efficiency photovoltaics. Nature Materials 2017;16:23.

[108] Zaite A, Belouaggadia N, Abid C, Ezzine M. Performance improvement of photovoltaic cells using night radiative cooling technology in a PV/T collector. Journal of Building Engineering 2021;42:102843.

[109] Zhao B, Hu M, Ao X, Pei G. Performance analysis of enhanced radiative cooling of solar cells based on a commercial silicon photovoltaic module. Solar Energy 2018;176:248–55.

[110] Li Z, Ahmed S, Ma T. Investigating the Effect of Radiative Cooling on the Operating Temperature of Photovoltaic Modules. Solar RRL 2021;5:2000735.

[111] Wang K, Luo G, Guo X, Li S, Liu Z, Yang C. Radiative cooling of commercial silicon solar cells using a pyramid-textured PDMS film. Solar Energy 2021;225:245-251.

[112] Shanmugam N, Pugazhendhi R, Madurai Elavarasan R, Kasiviswanathan P, Das N. Anti-Reflective Coating Materials: A Holistic Review from PV Perspective. Energies 2020;13:2631.

[113] Li W, Fan S. Nanophotonic control of thermal radiation for energy applications. Optics express 2018;26:15995–6021.

[114] Shou C, Luo Z, Wang T, Shen W, Rosengarten G, Wei W, Wang C, Ni M, Cen K. Investigation of a broadband TiO2/SiO2 optical thin-film filter for hybrid solar power systems. Applied Energy 2012;92:298–306.

[115] Sun X, Silverman TJ, Zhou Z, Khan MR, Bermel P, Alam MA. Optics-based approach to thermal management of photovoltaics: Selective-spectral and radiative cooling. IEEE Journal of Photovoltaics 2017;7:566–74.

[116] Zahir M, Benlattar M. Design of radiative cooler based on porous TiO 2 for improving solar cells' performance. Applied Optics 2012;60:445-451.

[117] Reddy KS, Mudgal V, Mallick TK. Thermal performance analysis of multi-phase change material layer-integrated building roofs for energy efficiency in built-environment. Energies 2017;10:1367

[118] Khanna S, Reddy KS, Mallick TK. Optimization of finned solar photovoltaic phase change material (finned PV PCM) system. International Journal of Thermal Science 2018;130:313–22.

[119] Singh P, Elavarasan RM, Kumar NM, Khanna S, Becerra V, Newar S, Sharma V, Radulovic J, Khusainov R, Hutchinson D. Photovoltaic Thermal Collectors with Phase Change Material for Southeast of England. In: Bose M., Modi A. (eds) Proceedings of the 7th International Conference on Advances in Energy Research. 2021, Springer Proceedings in Energy. Springer, Singapore.

[120] Zhang S, Feng D, Shi L, Wang L, Jin Y, Tian L, Li Z, Wang G, Zhao L, Yan Y. A review of phase change heat transfer in shape-stabilized phase change materials (ss-PCMs) based on porous supports for thermal energy storage. Renewable and Sustainable Energy Reviews 2021;135:110127.

[121] Gupta A, Mathie R, Markides CN. An experimental and computational investigation of a thermal storage system based on a phase change material: Heat transfer and performance characterization. Computational Thermal Sciences 2014;6:341-359.

[122] Rathore PKS, Shukla SK. Enhanced thermophysical properties of organic PCM through shape stabilization for thermal energy storage in buildings: A state of the art review, Energy and Buildings 2021;236:110799.

[123] Lamberg P. Approximate analytical model for two-phase solidification problem in a finned phase-change material storage. Applied Energy 2004;77:131–52.

[124] Elsheniti MB, Hemedah MA, Sorour MM, El-Maghlany WM. Novel enhanced conduction model for predicting performance of a PV panel cooled by PCM, Energy Conversion and Management 2020;205:112456.

[125] Nižetić S, Jurčević M, Čoko D, Arıcı M. A novel and effective passive cooling strategy for photovoltaic panel. Renewable & Sustainable Energy Reviews 2021;145:111164.

[126] Mahdi JM, Mohammed HI, Talebizadehsardari P. A new approach for employing multiple PCMs in the passive thermal management of photovoltaic modules. Solar Energy 2021;222:160–74.

[127] Yousef MS, Sharaf M, Huzayyin AS. Energy, exergy, economic, and enviroeconomic assessment of a photovoltaic module incorporated with a paraffin-metal foam composite: An experimental study. Energy 2022;238:121807.

[128] Gao Y, Hu G, Zhang Y, Zhang X. An experimental study of a hybrid photovoltaic thermal system based on ethanol phase change self-circulation technology: Energy and exergy analysis. Energy 2022;238:121663.

[129] Lamberg P, Lehtiniemi R, Henell AM. Numerical and experimental investigation of melting and freezing processes in phase change material storage. International Journal Thermal Science 2002;43:277–87.

[130] Reddy KS, Mudgal V, Mallick TK. Review of latent heat thermal energy storage for improved material stability and effective load management. Journal of Energy Storage 2018;15:205-227.

[131] Waqas A, Ji J, Xu L, Ali M, Zeashan, Alvi J. Thermal and electrical management of photovoltaic panels using phase change materials – A review. Renewable and Sustainable Energy Reviews 2018;92:254-271.

[132] Khanna S, Reddy KS, Mallick TK. Effect of climate on electrical performance of finned phase change material integrated solar photovoltaic. Solar Energy 2018;174:593–605.

[133] Khanna S, Reddy KS, Mallick TK. Optimization of solar photovoltaic system integrated with phase change material. Solar Energy 2018;163:591–9.

[134] Brano VL, Ciulla G, Piacentino A, Cardona F. Finite difference thermal model of a latent heat storage system coupled with a photovoltaic device: Description and experimental validation. Renewable Energy 2014;68:181–93.

[135] Wei NTJ, Nan WJ, Guiping C. Experimental study of efficiency of solar panel by phase change material cooling. IOP Conference Series: Materials Science and Engineering 2017;217:012011.

[136] Sharma S, Tahir A, Reddy KS, Mallick TK. Performance enhancement of a building-integrated concentrating photovoltaic system using phase change material. Solar Energy Materials and Solar Cells 2016;149:29–39.

[137] Preet S, Bhushan B, Mahajan T. Experimental investigation of water based photovoltaic/thermal (PV/T) system with and without phase change material (PCM). Solar Energy 2017;155:1104–20.

[138] Abdulmunem AR, Samin PM, Rahman HA, Hussien HA, Mazali II. Enhancing PV Cell's electrical efficiency using phase change material with copper foam matrix and multi-walled carbon nanotubes as passive cooling method. Renewable Energy 2020;160:663-675.

[139] Cheng P, Chen X, Gao H, Zhang X, Tang Z, Li A, Wang G. Different dimensional nanoadditives for thermal conductivity enhancement of phase change materials: Fundamentals and applications. Nano Energy 2021;85:105948.

[140] Punniakodi BMS, Senthil R. A review on container geometry and orientations of phase change materials for solar thermal systems. Journal of Energy Storage 2021;36:102452.

[141] Tan L, Date A, Fernandes G, Singh B, Ganguly S. Efficiency Gains of Photovoltaic System Using Latent Heat Thermal Energy Storage. Energy Procedia 2017;110:83–8.

[142] Huang MJ, Eames PC, Norton B, Hewitt NJ. Natural convection in an internally finned phase change material heat sink for the thermal management of photovoltaics. Solar Energy Materials and Solar Cells 2011;95:1598–603.

[143] Rajvikram M, Leoponraj S, Ramkumar S, Akshaya H, Dheeraj A. Experimental investigation on the abasement of operating temperature in solar photovoltaic panel using PCM and aluminium, Solar Energy 2019;188:327–338.

[144] Rajvikram M, Sivasankar G. Experimental study conducted for the identification of best heat absorption and dissipation methodology in solar photovoltaic panel. Solar Energy 2019;193:283–292.

[145] Hasan A, Alnoman H, Shah AH. Energy efficiency enhancement of photovoltaics by phase change materials through thermal energy recovery. Energies 2016;9:1-15.

[146] Hasan A, McCormack SJ, Huang MJ, Sarwar J, Norton B. Increased photovoltaic performance through temperature regulation by phase change materials: Materials comparison in different climates. Solar Energy 2015;115:264–76.

[147] Khanna S, Reddy KS, Mallick TK. Performance analysis of tilted photovoltaic system integrated with phase change material under varying operating conditions. Energy 2017;133:887–99.

[148] Manikandan S, Selvam C, Poddar N, Pranjyal K, Lamba R, Kaushik SC. Thermal management of low concentrated photovoltaic module with phase change material. Journal of Cleaner Production 2019;219:359–67.

[149] Smith CJ, Forster PM, Crook R. Global analysis of photovoltaic energy output enhanced by phase change material cooling. Applied Energy 2014;126:21–8.

[150] Hasan A, McCormack SJ, Huang MJ, Norton B. Characterization of phase change materials for thermal control of photovoltaics using differential scanning calorimetry and temperature history method. Energy Conversions and Management 2014;81:322–9.

[151] Savvakis N, Dialyna E, Tsoutsos T. Investigation of the operational performance and efficiency of an alternative PV + PCM concept. Solar Energy 2020;211:1283-1300.

[152] Velmurugan K, Karthikeyan V, Korukonda TB, Madhan K, Emsaeng K, Sukchai S, Sirisamphanwong C, Wongwuttanasatian T, Elavarasan RM, Alhelou HH, Subramaniam U. Experimental Studies on PV Module Cooling With Radiation Source PCM Matrix. IEEE Access 2020;8:145936-145949.

[153] Bayrak F, Oztop HF, Selimefendigil F. Experimental study for the application of different cooling techniques in photovoltaic (PV) panels. Energy Conversion and Management 2020;212:112789.

[154] Madurai Elavarasan R, Velmurugan K, Subramaniam U, Kumar AR, Almakhles D. Experimental Investigations Conducted for the Characteristic Study of OM29 Phase Change Material and Its Incorporation in Photovoltaic Panel. Energies 2020;13:897.

[155] Huang MJ, Eames PC, Norton B. Thermal regulation of building-integrated photovoltaics using phase change materials. International Journal of Heat and Mass Transfer 2004;47:2715–33.

[156] Indartono YS, Suwono A, Pratama FY. Improving photovoltaics performance by using yellow petroleum jelly as phase change material, International Journal of Low-Carbon Technologies 2016;11:333–7.

[157] Mahamudul H, Silakhori M, Metselaar IH, Ahmad S, Mekhilef S. Development of a temperature regulated photovoltaic module using phase change material for Malaysian weather condition. Journal Optoelectronics and Advanced Materials-Rapid Communications 2014;8:1243–5.

[158] Hasan A, Sarwar J, Alnoman H, Abdelbaqi S. Yearly energy performance of a photovoltaic-phase change material (PV-PCM) system in hot climate. Solar Energy 2017;146:417–29.

[159] Ho CJ, Jou BT, Lai CM, Huang CY. Performance assessment of a BIPV integrated with a layer of water-saturated MEPCM. Energy and Buildings 2013;67:322–33.

[160] Nada SA, El-Nagar DH. Possibility of using PCMs in temperature control and performance enhancements of free stand and building integrated PV modules. Renewable Energy 2018;127:630–41.
[161] Hossain MS, Pandey AK, Selvaraj J, Rahim NA, Islam MM, Tyagi VV. Two side serpentine flow based photovoltaic-thermal-phase change materials (PVT-PCM) system: Energy, exergy and economic analysis. Renewable Energy 2019;136:1320–36.
[162] Karthick A, Murugavel KK, Ramanan P. Performance enhancement of a building-integrated photovoltaic module using phase change material. Energy 2018;142:803–12.
[163] Mahian O, Bellos E, Markides CN, Taylor RA, Alagumalai A, Yang L, Qin C, Lee BJ, Ahmadi G, Safaei MR, Wongwises S. Recent advances in using nanofluids in renewable energy systems and the environmental implications of their uptake. Nano Energy 2021;86:106069.
[164] Abu-Rahmeh TM. Efficiency of photovoltaic modules using different cooling methods: A comparative study. Journal of Power and Energy Engineering 2017;5:32–45.
[165] Gangadevi R, Vinayagam BK, Senthilraja S. Experimental investigations of hybrid PV/Spiral flow thermal collector system performance using Al2O3/water nanofluid. IOP Conference Series: Materials Science and Engineering 2017;197:1–9.
[166] Sardarabadi M, Passandideh-Fard M, Maghrebi MJ, Ghazikhani M. Experimental study of using both ZnO/water nanofluid and phase change material (PCM) in photovoltaic thermal systems, Solar Energy Materials and Solar Cells 2017;161:62–9.
[167] Michael Joseph Stalin P, Prasad KS, Kumar KP, Hemadri G, Rajesh M, Kumar KP. Performance improvement of solar PV through the thermal management using a nano-PCM. Materials Today: Proceedings 2021.
[168] Karaaslan I, Menlik T. Numerical study of a photovoltaic thermal (PV/T) system using mono and hybrid nanofluid. Solar Energy 2021;224:1260–70.
[169] Sohani A, Shahverdian MH, Sayyaadi H, Samiezadeh S, Doranehgard MH, Nizetic S, et al. Selecting the best nanofluid type for A photovoltaic thermal (PV/T) system based on reliability, efficiency, energy, economic, and environmental criteria. Journal of the Taiwan Institute of Chemical Engineers 2021;124:351–8.
[170] Jamil F, Ali HM, Nasir MA, Karahan M, Janjua MM, Naseer A, et al. Evaluation of photovoltaic panels using different nano phase change material and a concise comparison: An experimental study. Renewable Energy 2021;169:1265–79.

[171] Ghadiri M, Sardarabadi M, Pasandideh-Fard M, Moghadam AJ. Experimental investigation of a PVT system performance using nano ferrofluids. Energy Conversion and Management 2015;103:468–76.

[172] Aberoumand S, Ghamari S, Shabani B. Energy and exergy analysis of a photovoltaic thermal (PV/T) system using nanofluids: An experimental study. Solar Energy 2018;165:167–77.

[173] Al-Waeli AHA, Sopian K, Chaichan MT, Kazem HA, Ibrahim A, Mat S. Evaluation of the nanofluid and nano-PCM based photovoltaic thermal (PVT) system: An experimental study. Energy Conversion and Management 2017;151:693–708.

[174] Rostami Z, Rahimi M, Azimi N. Using high-frequency ultrasound waves and nanofluid for increasing the efficiency and cooling performance of a PV module. Energy Conversion and Management 2018;160:141-149.

[175] Hassani S, Saidur R, Mekhilef S, Taylor RA. Environmental and exergy benefit of nanofluid-based hybrid PV/T systems. Energy Conversion and Management 2016;123:431–44.

[176] Sathe TM, Dhoble AS. A review on recent advancements in photovoltaic thermal techniques. Renewable and Sustainable Energy Reviews 2017;76:645–72.

[177] Preet S. Water and phase change material based photovoltaic thermal management systems: A review. Renewable and Sustainable Energy Reviews 2018;82:791–807.

[178] Wang K, Herrando M, Pantaleo AM, Markides CN. Technoeconomic assessments of hybrid photovoltaic-thermal vs. conventional solar energy systems: Case studies in heat and power provision to sports centres. Applied Energy 2019;254:1-27.

[179] Freeman J, Hellgardt K, Markides CN. An assessment of solar-powered organic Rankine cycle systems for combined heating and power in UK domestic applications. Applied Energy 2015;138:605-620.

[180] Najjaran A, Freeman J, Ramos A, Markides CN. Experimental investigation of an ammonia-water-hydrogen diffusion absorption refrigerator. Applied Energy 2019;256:113899.

[181] Fuentes M, Vivar M, Casa la JD, Aguilera J. An experimental comparison between commercial hybrid PV-T and simple PV systems intended for BIPV. Renewable and Sustainable Energy Reviews 2018;93:110–20.

[182] Rosli MAM, Mat S, Anuar MK, Sopian K, Sulaiman MY, Ellias S. Progress on Flat-Plate Water Based of Photovoltaic Thermal (PV/T) System: A Review. Iranica Journal of Energy and Environment 2014;5:407–18.

[183] Tonui JK, Tripanagnostopoulos Y. Air-cooled PV/T solar collectors with low cost performance improvements. Solar Energy 2007;81:498–511.

[184] Noro M, Lazzarin RM. Hybrid PhotoVoltaic-Thermal heat pump systems: Energy and economic performance evaluations in different climates. International Journal of Low-Carbon Technologies 2018;13:76–83.

[185] Metwally H, Mahmoud NA, Ezzat M, Aboelsoud W. Numerical investigation of photovoltaic hybrid cooling system performance using the thermoelectric generator and RT25 Phase change material. Journal of Energy Storage 2021;42:103031.

[186] Sudhakar P, Santosh R, Asthalakshmi B, Kumaresan G, Velraj R. Performance augmentation of solar photovoltaic panel through PCM integrated natural water circulation cooling technique. Renewable Energy 2021;172:1433–48.

[187] Srimanickam B, Vijayalakshmi MM, Natarajan E. Thermal analysis on photovoltaic thermal hybrid system with cooling channel with V-baffles. Indian Journal of Science and Technology 2015;8:1–5.

[188] Pang W, Zhang Y, Cui Y, Yu H, Liu Y, Yan H. Building Integrated Photovoltaic Module-Based on Aluminum Substrate With Forced Water Cooling, Journal of Solar Energy Engineering 2018;140:021005.

[189] Chauhan D, Shishodia Y, Agarwal S. Performance of Hybrid Air Collector under Different Condition. European Journal of Advances in Engineering and Technology 2015;2:69–75.

[190] Dubey S, Sandhu GS, Tiwari GN. Analytical expression for electrical efficiency of PV/T hybrid air collector. Applied Energy 2009;86:697-705.

[191] Guarracino I, Markides CN, Mellor A, Nicholas Ekins-Daukes J. Dynamic coupled thermal-and-electrical modelling of sheet-and-tube hybrid photovoltaic/thermal (PVT) collectors. Applied Thermal Engineering 2016;101:778–95.

[192] Guarracino I, Freeman J, Ramos A, Kalogirou S, Ekins-Daukes NJ, Markides CN. Systematic testing of hybrid PV-thermal (PVT) solar collectors in steady state and dynamic outdoor conditions. Applied Energy 2019;240:1014–30.

[193] Herrando M, Markides CN, Hellgardt K. A UK-based assessment of hybrid PV and solar-thermal systems for domestic heating and power: System performance. Applied Energy 2014;122:288–309.

[194] Herrando M, Ramos A, Zabalza I, Markides CN. A comprehensive assessment of alternative absorber-exchanger designs for hybrid PVT-water collectors. Applied Energy 2019;235:1583–602.

[195] Herrando M, Ramos A, Freeman J, Zabalza I, Markides CN. Technoeconomic modelling and optimisation of solar combined heat and power systems based on flat-box PVT collectors for domestic applications. Energy Conversion and Management 2018;175:67–85.

[196] Herrando M, Ramos A, Zabalza I, Markides CN. Structural characterization and energy performance of novel hybrid PVT solar-panels through 3-D FEM and CFD simulations. 30th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems 2017:1–12.

[197] Herrando M, Pantaleo MA, Wang K, Markides CN. Solar combined cooling, heating and power systems based on hybrid PVT, PV or solar-thermal collectors for building applications. Renewable Energy 2019;143:637–47.

[198] Kianifard S, Zamen M, Nejad AA. Modeling, designing and fabrication of a novel PV/T cooling system using half pipe. Journal of Cleaner Production 2020;253:119972.

[199] Ramos A, Chatzopoulou MA, Guarracino I, Freeman J, Markides CN. Hybrid photovoltaic-thermal solar systems for combined heating, cooling and power provision in the urban environment. Energy Conversion and Management 2017;150:838–50.

[200] Herrando M, Ramos A, Zabalza I, Markides CN. Energy performance of a solar trigeneration system based on a novel hybrid PVT panel for residential applications. ISES Solar World Congress 2017:1–12.

[201] Wang K, Herrando M, Pantaleo MA, Markides CN. Thermoeconomic assessment of a PV/T combined heating and power system for university sport centre of Bari. Energy Procedia 2019;158:1229–34.

[202] Mellor A, Guarracino I, Ferre Llin L, Alonso-Alvarez D, Riverola A, Thoms S, Paul DJ, Markides CN, Chemisana D, Maier S, Ekins-Daukes N. Specially designed solar cells for hybrid photovoltaic-thermal generators. 2016 IEEE 43rd Photovoltaic Specialists Conference 2016:2961-2963.

[203] Golzari S, Kasaeian A, Amidpour M, Nasirivatan S, Mousavi S. Experimental investigation of the effects of corona wind on the performance of an air-cooled PV/T. Renewable Energy 2018;127:284–97.

[204] Sobhnamayan F, Sarhaddi F, Alavi MA, Farahat S, Yazdanpanahi J. Optimization of a solar photovoltaic thermal (PV/T) water collector based on exergy concept. Renewable Energy 2014;68:356–65.

[205] Farshchimonfared M, Bilbao JI, Sproul AB. Channel depth, air mass flow rate and air distribution duct diameter optimization of photovoltaic thermal (PV/T) air collectors linked to residential buildings. Renewable Energy 2015;76:27–35.

[206] Gagliano A, Tina GM, Aneli S, Nižetić S. Comparative assessments of the performances of PV/T and conventional solar plants. Journal of Cleaner Production 2019;219:304–15.

[207] Buonomano A, Calise F, Vicidomini M. Design, simulation and experimental investigation of a solar system based on PV panels and PVT collectors. Energies 2016;9:1–17.

[208] Dannemand M, Perers B, Furbo S. Performance of a demonstration solar PVT assisted heat pump system with cold buffer storage and domestic hot water storage tanks. Energy and Buildings 2019;188-189:46–57.

[209] Lebbi M, Touafek K, Benchatti A, Boutina L, Khelifa A, Baissi MT, Hassani S. Energy performance improvement of a new hybrid PV/T Bi-fluid system using active cooling and self-cleaning: Experimental study. Applied Thermal Engineering 2021;182:116033.

[210] Aste N, Pero Del C, Leonforte F, Manfren M. Performance monitoring and modeling of an uncovered photovoltaic-thermal (PVT) water collector. Solar Energy 2016;135:551–68.

[211] Liang R, Zhang J, Ma L, Li Y. Performance evaluation of new type hybrid photovoltaic/ thermal solar collector by experimental study. Applied Thermal Engineering 2015;75:487–92.

[212] Ebrahimi M, Aramesh M, Khanjari Y. Innovative ANP model to prioritization of PV/T systems based on cost and efficiency approaches: With a case study for Asia. Renewable Energy 2018;117: 434-446.

[213] Huang G, Wang K, Markides CN. Efficiency limits of concentrating spectral-splitting hybrid photovoltaic-thermal (PV-T) solar collectors and systems. Light: Science & Applications 2021;10:28.

[214] Taylor RA, Otanicar T, Rosengarten G. Nanofluid-based optical filter optimization for PV/T systems. Light: Science & Applications 2012;1:e34.

[215] Wang K, Pantaleo AM, Herrando M, Faccia M, Pesmazoglou I, Franchetti B, Markides CN. Spectral-splitting hybrid PV-thermal (PVT) systems for combined heat and power provision to dairy farms. Renewable Energy 2020;159:1047-1065.

[216] Huang G, Riera Curt S, Wang K, Markides CN. Challenges and opportunities for nanomaterials in spectral splitting for high-performance hybrid solar photovoltaic-thermal applications: A review. Nano Materials Science 2020;2:182-203.

[217] Liang H, Wang F, Yang L, Cheng Z, Shuai Y, Tan H. Progress in full spectrum solar energy utilization by spectral beam splitting hybrid PV/T system. Renewable and Sustainable Energy Reviews 2021;141:110785.

[218] Huang G, Wang K, Riera Curt S, Franchetti B, Pesmazoglou I, Markides CN. On the performance of concentrating fluid-based spectral-splitting hybrid PV-thermal (PV-T) solar collectors. Renewable Energy 2021;174:590–605.

[219] Tonui JK, Tripanagnostopoulos Y. Improved PV/T solar collectors with heat extraction by forced or natural air circulation. Renewable Energy 2007;32:623–37.

[220] Ahn JG, Kim JH, Kim JT. A study on experimental performance of air-type PV/T collector with HRV, Energy Procedia 2015;78:3007–12.

[221] Farshchimonfared M, Bilbao JI, Sproul AB. Full optimisation and sensitivity analysis of a photovoltaic-thermal (PV/T) air system linked to a typical residential building. Solar Energy 2016;136:15–22.

[222] Amanlou Y, Tavakoli Hashjin T, Ghobadian B, Najafi G. Air cooling low concentrated photovoltaic/thermal (LCPV/T) solar collector to approach uniform temperature distribution on the PV plate. Applied Thermal Engineering 2018;141:413–21.

[223] Kazem HA. Evaluation and analysis of water-based photovoltaic/thermal (PV/T) system. Case Studies in Thermal Engineering 2019;13:100401.

[224] Cen J, du Feu R, Diveky ME, McGill C, Andraos O, Janssen W. Experimental study on a direct water heating PV-T technology. Solar Energy 2018;176:604–14.

[225] Sellami R, Amirat M, Mahrane A, Slimani MEA, Arbane A, Chekrouni R. Experimental and numerical study of a PV/Thermal collector equipped with a PV-assisted air circulation system: Configuration suitable for building integration. Energy and Buildings 2019;190:216–34.

[226] Fatima H, Tiwari GN. Theoretical validation of photovoltaic thermal (PVT) module with a copper base for thermal and electrical performance. Journal of Renewable Sustainable Energy 2019;11:1-10.

[227] Dimri N, Tiwari A, Tiwari GN. Comparative Study of photovoltaic thermal (PVT) integrated thermoelectric cooler (TEC) fluid collectors. Renewable Energy 2019;134:343–56.

[228] Tripathi R, Tiwari GN. Energy matrices, life cycle cost, carbon mitigation and credits of open-loop N concentrated photovoltaic thermal (CPVT) collector at cold climate in India: A comparative study. Solar Energy 2019;186:347–359.

[229] Kaplani E, Kaplanis S. Thermal modelling and experimental assessment of the dependence of PV module temperature on wind velocity and direction, module orientation and inclination. Solar Energy 2014;107:443–60.

[230] Krauter S. Increased electrical yield via water flow over the front of photovoltaic panels. Solar Energy Materials and Solar Cells 2004;82:131–7.

[231] Sotehi O, Chaker A, Maalouf C. Hybrid PV/T water solar collector for net zero energy building and fresh water production: A theoretical approach. Desalination 2016;385:1–11.

[232] Cai J, Ji J, Wang Y, Zhou F, Yu B. A novel PV/T-air dual source heat pump water heater system: Dynamic simulation and performance characterization. Energy Conversion and Management 2017;148:635–45.

[233] Al-Shamani AN, Alghoul MA, Elbreki AM, Ammar AA, Abed AM, Sopian K. Mathematical and experimental evaluation of thermal and electrical efficiency of PV/T collector using different water based nano-fluids. Energy 2018;145:770–92.

[234] Turnpenny JR, Etheridge DW, Reay DA. Novel ventilation cooling system for reducing air conditioning in buildings. Part I: Testing and theoretical modelling. Applied Thermal Engineering 2000;20:1019–37.

[235] Shukla A, Kant K, Sharma A, Biwole PH. Cooling methodologies of photovoltaic module for enhancing electrical efficiency: A review. Solar Energy Materials and Solar Cells 2017;160:275–86.

[236] Stropnik R, Stritih U. Increasing the efficiency of PV panel with the use of PCM. Renewable Energy 2016;97:671–9.

[237] Arıcı M, Bilgin F, Nizetic S, Papadopoulos AM. Phase change material based cooing of photovoltaic panel: A simplified numerical model for the optimization of the phase change material layer and general economic evaluation. Journal of Cleaner Production 2018;189:738–45.

[238] Kibria MA, Saidur R, Al-Sulaiman FA, Aziz MMA. Development of a thermal model for a hybrid photovoltaic module and phase change materials storage integrated in buildings. Solar Energy 2016;124:114–23.

[239] Al-Waeli AHA, Chaichan MT, Sopian K, Kazem HA., Mahood HB, Khadom AA. Modeling and experimental validation of a PVT system using nanofluid coolant and nano-PCM. Solar Energy 2019;177:178–91.