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Analysis of Cooling Methods to Improve the Electrical Performance of Photovoltaic Modules

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ABSTRACT

The conversion of solar energy into electricity by photovoltaic solar modules causes the temperature of the photovoltaic solar cells to rise, reducing their electrical efficiency.

The heat dissipation of photovoltaic solar modules allows them to be cooled and the recovered heat can be used for residential and industrial applications. Many different cooling methods have been proposed to reduce the temperature of photovoltaic solar modules and improve electrical efficiency.

These photovoltaic solar module cooling methods are classified into active, passive and hybrid cooling. Although most solar module air cooling techniques have been investigated, air cooling methods that optimise heat transfer through structural configuration have not been collectively studied. This paper reviews recent work on air-cooling methods for solar photovoltaic modules, focusing on natural and forced air circulation, efficient solar radiation collection and conversion, and improved heat transfer coefficient by air convection in a duct. These air-cooling methods are examined, analysed and compared, and the prospects for these different techniques are proposed. The results showed that forced-air cooling coupled with fins/baffles using phase-change materials and bifacial and thermoelectric photovoltaic modules are the most promising, despite their complex structures and very high investment costs. Thanks to their efficient heat transfer, their storage of excess heat and their significant reduction in the temperature of solar PV modules, these cooling techniques, which are recommended for promotion, can ensure rational use of energy.

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تحليل طرق التبريد لتحسين الأداء الكهربائي للوحدات الكهروضوئية

ياو كومبات، كوكوو نووتيكا ، كوفي ابيدانوو، يندوبان كولاني،
كوملان دونالد اوكوو، بيرنالد اوبيزي .

ملخص: يؤدي تحويل الطاقة الشمسية إلى كهرباء بواسطة وحدات الطاقة الشمسية الكهروضوئية إلى ارتفاع درجة حرارة الخلايا الشمسية الكهروضوئية، مما يقلل من كفاءتها الكهربائية. يسمح تبديد الحرارة لوحدات الطاقة الشمسية الكهروضوئية بتبريدها ويمكن استخدام الحرارة المستردة في التطبيقات السكنية والصناعية. لقد تم اقتراح العديد من تقنيات التبريد المختلفة لتقليل درجة حرارة وحدات الطاقة الشمسية الكهروضوئية وتحسين الكفاءة الكهربائية. يتم تصنيف تقنيات تبريد وحدات الطاقة الشمسية الكهروضوئية هذه إلى تبريد نشط وسلبي وهجين. على الرغم من أن معظم تقنيات تبريد الهواء في وحدات الطاقة الشمسية قد تم التحقيق فيها، إلا أن تقنيات تبريد الهواء التي تعمل على تحسين نقل الحرارة من خلال التكوين الهيكلي لم تتم دراستها بشكل جماعي. تستعرض هذه الورقة الأعمال الحديثة حول تقنيات تبريد الهواء لوحدات الطاقة الشمسية الكهروضوئية، مع التركيز على دوران الهواء الطبيعي والقسري، وجمع الإشعاع الشمسي وتحويله بكفاءة، وتحسين معامل نقل الحرارة عن طريق الحمل الحراري للهواء في القناة. يتم فحص تقنيات تبريد الهواء هذه وتحليلها ومقارنتها، ويتم اقتراح آفاق هذه التقنيات المختلفة. وأظهرت النتائج أن التبريد بالهواء القسري المقترن بالزعانف/الحواجز باستخدام مواد تغيير الطور ووحدات الطاقة الكهروضوئية ثنائية الوجه والحرارية الكهربائية هي الأكثر واعدة، على الرغم من هياكلها المعقدة وتكاليف الاستثمار المرتفعة للغاية. بفضل نقل الحرارة بكفاءة، وتخزينها للحرارة الزائدة وانخفاضها الكبير في درجة حرارة وحدات الطاقة الشمسية الكهروضوئية، يمكن لتقنيات التبريد هذه، الموصى بالترويج لها، ضمان الاستخدام الرشيد للطاقة.

الكلمات المفتاحية – الطاقة الشمسية، وحدات الطاقة الشمسية الكهروضوئية، الكفاءة الكهربائية، تقنيات التبريد، المجمع الشمسي الكهروضوئي/الحراري الهجين.

1. INTRODUCTION

Almost all countries in the world rely primarily on coal, oil and natural gas to meet their energy needs. Available in limited quantities, these conventional energy sources are running out at an accelerating rate. The massive use of fossil fuels has a harmful effect on the environment, such as global warming due to the release of carbon dioxide. To meet these energy needs and solve the environmental problem, renewable energies are now an alternative to fossil fuels [1], [2]. Renewable energies have the potential to meet the world's various energy needs and have no harmful impact on the environment. Among these renewable energy sources, solar energy has proved to be the most promising. Photovoltaic (PV) solar cells convert solar energy directly into electricity. PV solar cells are made of semiconductor materials, the main material being silicon [3]. Two forms of energy can be produced from solar energy, depending on the conversion method used: electrical energy and thermal energy, using photovoltaic (PV) solar cells and solar thermal collectors respectively [4]. The different photovoltaic and thermal technologies for converting solar energy into electricity and heat are shown in figure 1.
When solar radiation is absorbed by a PV module, its temperature rises, generating unwanted heat and thus reducing its electrical efficiency [5], [6]. PV modules become less efficient as the temperature rises. It is therefore important to cool PV solar cells by removing this unwanted heat. Heat dissipation can take place in front of or behind the PV modules and can be used for residential and industrial applications [7], [8]. This lowers the operating temperature of PV modules and leads to improved electrical efficiency. Much research has been published on methods of cooling solar PV modules. A few important review articles have described two categories of cooling methods: passive cooling methods and active cooling methods [9], [10], [11], [12]. They have presented an exhaustive analysis of the different methods of cooling solar PV modules, their advantages and limitations. Active cooling methods include cooling by forced air circulation and cooling by the impact of air jets. As far as passive methods are concerned, microchannel

cooling, phase change material (PCM), thermoelectric and heat pipes are presented. Electrical efficiency and cost vary according to these cooling methods. Air-cooling methods focusing on heat extraction modes, efficient capture and conversion of solar radiation and optimisation of structural configuration have not been examined in detail collectively. This paper reviews recent work on air-cooling methods for solar photovoltaic modules, focusing on natural and forced air circulation, efficient solar radiation collection and conversion, thermal energy storage and improved heat transfer coefficient by air convection in a duct. A comparative analysis of these air-cooling methods was presented. This article is divided into six sections. Section 1 describes the background and problem of the work. Section 2 explains the internal and external factors of PV solar cells that influence their operating temperature. Section 3 examines modern solar PV module cooling methods from natural heat removal cooling, forced air circulation, thermal energy storage, efficient solar radiation conversion and collection, and structural configuration design to improve heat transfer. In section 4, the advantages and disadvantages of the cooling technologies examined are compared, with some recommendations proposed for further investigation in section 5. Finally, the conclusion is presented in section 6.

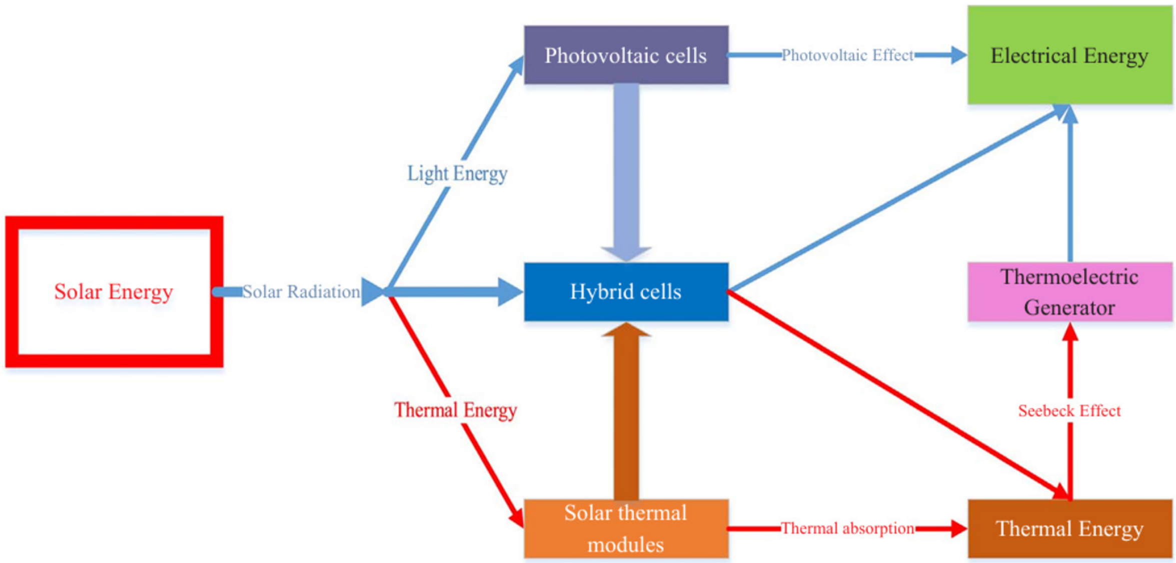


Figure 1: Different solar energy conversion technologies [13].

2. FACTORS INFLUENCING THE ELECTRICAL PERFORMANCE OF PHOTOVOLTAIC SOLAR MODULES

PV modules are spectrally selective absorbers that operate in a wavelength range of 0.35 μm to 1.2 μm and directly convert solar radiation into electricity [14]. The electrical efficiency of PV modules was therefore influenced by internal factors in PV solar cells and environmental factors. Factors such as PV solar cell temperature, solar irradiance, ambient temperature, air mass, humidity and dust affect the electrical performance of PV modules [15]. Solar irradiation and ambient temperature are factors that significantly affect the temperature of PV modules and therefore their electrical performance [16]. Figure 2 shows that increasing the temperature of the PV solar module strongly affects the open-circuit voltage but has no effect on the short-circuit current. In contrast to the PV solar module temperature, increasing solar irradiance strongly affects the short-circuit current but weakly affects the open-circuit voltage. Figure 3 shows the electrical efficiency of the PV module. This figure shows that the electrical efficiency is inversely proportional to the operating temperature of the PV module. As the temperature of the

PV module increases with solar irradiance, the electrical efficiency of the PV module decreases. Figure 4 (a) shows that the PV module temperature is linear with ambient temperature and decreases exponentially with increasing wind speed at solar irradiance levels [17]. Figure 4 (b) shows that dust deposited on the surface of a PV module increases the temperature of the PV module and consequently reduces its electrical output. Indeed, the deposition of dust increases the temperature of the PV module by 6% [17].

Consideration of the effect of wind in PV module temperature estimates and accurate knowledge of this behaviour is essential to optimise electricity production [18]. For example, high solar radiation contributes to heat dissipation from the solar PV module but increases its operating temperature [19]. In the presence of wind, the open-circuit voltage and maximum power at the point of maximum power are higher, while the short-circuit current was lower. When the PV module was tilted, the areas facing into the wind were cooled more [20]. A lower ambient temperature is useful both for heat dissipation and for improving the electrical efficiency of the PV module. Framed PV modules have a higher temperature gradient relative to their local temperature field than frameless glass PV modules. Framed PV modules facilitate more heat transport by conduction than by convection with ambient air, which was important for any solar power system [21]. The inclusion of PV module thermal inertia and wind speed in the temperature determination models resulted in a more accurate estimate of PV module temperature with 95% correlation and 3°C error [22].

The temperature distribution over the surface of PV modules depends largely on the geometry and material used in their design [23]. At high temperatures, amorphous silicon and copper-indium-gallium-selenide (CIGS) PV modules perform better than crystalline ones [24]. The temperature coefficient of power depends on the PV solar cell technology used and therefore the electrical efficiency of the PV module depends on it. According to Dash and Gupta [25], the power temperature coefficient of monocrystalline silicon-based PV modules was higher than that of other types of PV modules, while cadmium telluride (CdTe)-based PV modules offer better electrical efficiency due to its low temperature coefficient. Indeed, for monocrystalline, polycrystalline, CdTe-based and amorphous silicon-based PV solar cells, the power temperature coefficient decreases by -0.446%/°C, -0.387%/°C, -0.172%/°C and 0.234%/°C respectively [25]. The temperature of thin-film PV modules was lower than that of other technologies, and the influence of ambient temperature on PV module temperature decreases in high wind conditions. The electrical efficiency of amorphous silicon PV modules was lower than that of multicrystalline PV modules in all wind conditions [26].

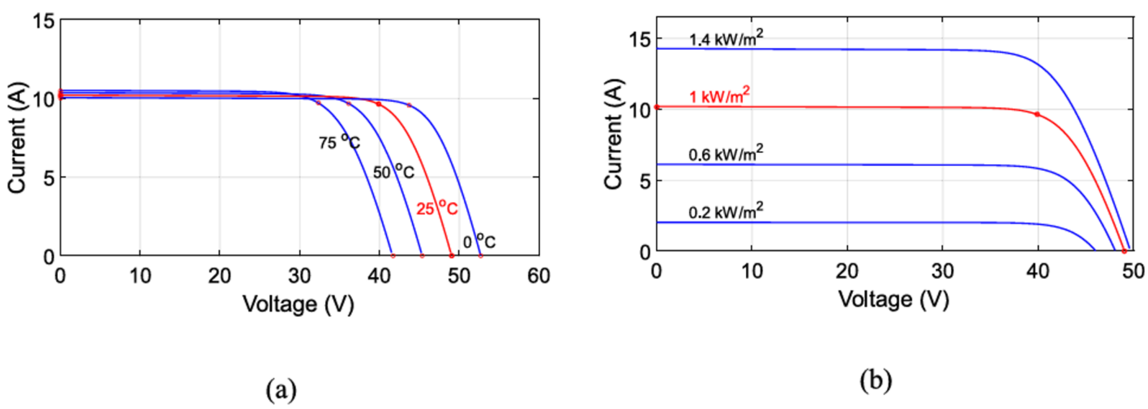


Figure 2: PV module current-voltage curves: (a) Variable PV module temperature; and (b) Variable solar irradiance [27].

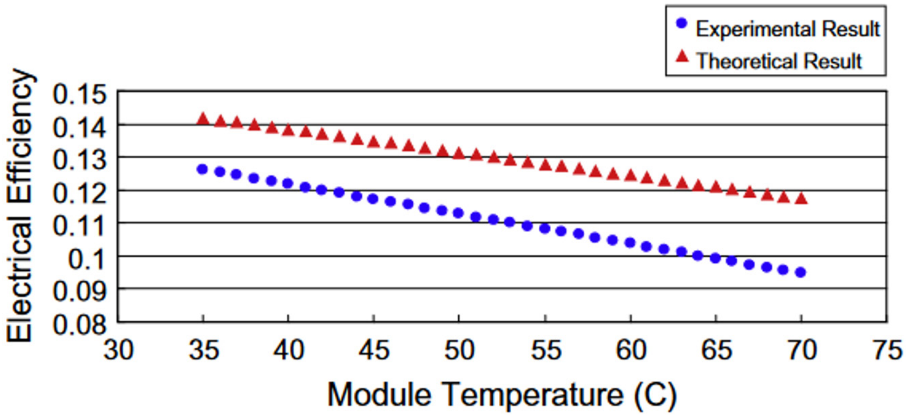
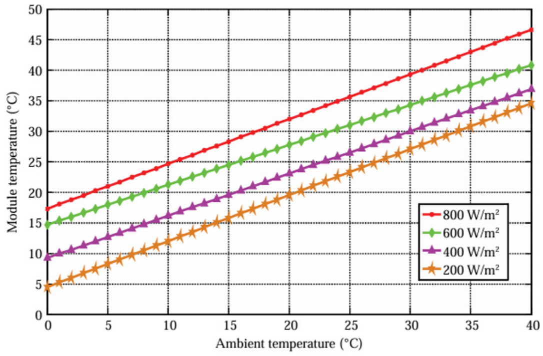
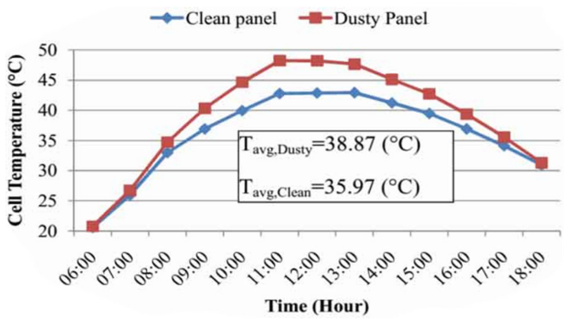


Figure 3: Electrical efficiency as a function of PV module temperature [28].





(a) **(b)**

Figure 4: PV module temperature: (a) as a function of ambient temperature at different levels of solar radiation; and (b) dusty and clean panels PV [17].

The unwanted heat obtained during the conversion of solar radiation into electricity by solar PV modules causes an increase in their operating temperature and consequently a drop in output voltage. Sani and Sule [29] have shown that an increase of 1°C corresponds to a decrease of 0.12 V or 0.5% in the electrical efficiency of the PV module. This negatively affects the output power and electrical efficiency of the solar PV module [29]. To avoid the decrease in electrical efficiency, various cooling methods for solar PV modules have been introduced with the objective of keeping the temperature of solar PV modules low and constant. In the following section, cooling methods by air circulation, thermal energy storage, efficient conversion of solar radiation collection and improvement of heat transfer coefficient by air convection are presented.

3. METHODS OF COOLING PHOTOVOLTAIC MODULES

In order to reduce the temperature of solar PV modules, different cooling techniques for solar PV modules have been studied in the literature. The main air-cooling methods are grouped into five (05) and are shown in Figure 5.

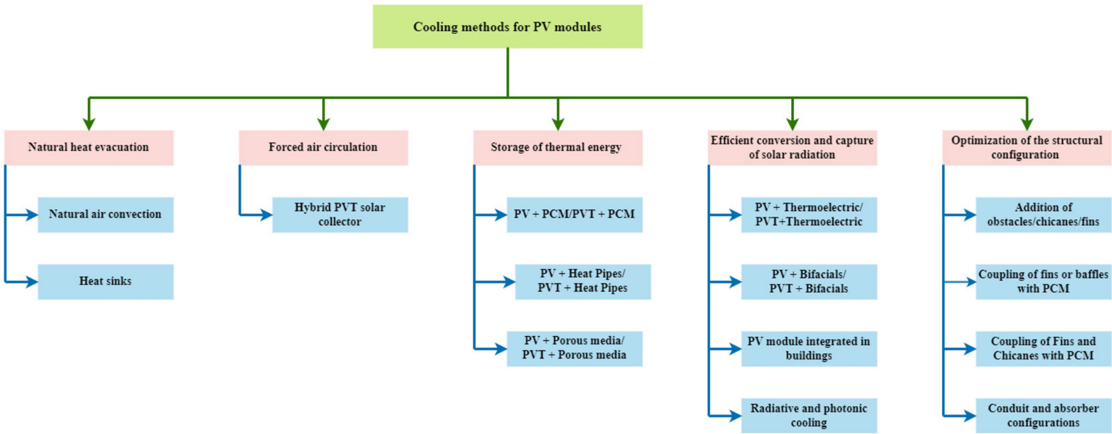


Figure 5: Classification of cooling methods for PV modules.

3.1. Cooling methods using natural heat dissipation

The natural heat dissipation cooling method uses the flow or circulation of air around the solar PV modules for natural heat dissipation. This involves finding an optimum tilt position for good ventilation of the PV solar module or attaching fins to the back of the PV solar module to facilitate airflow and heat extraction. This method requires no external power supply and has a low maintenance cost. However, this method gives a limited electrical efficiency of the solar PV modules and is highly dependent on the climatic conditions of the installation site, mainly wind speed. The main air-cooling methods and their impact on the performance of solar PV modules are discussed in the following subsections.

3.1.1. Cooling by natural air convection

The natural heat transfer mechanisms between the PV solar module and the surrounding environment are demonstrated in natural air cooling. These include conduction, convection and radiation to dissipate heat from the PV module without the intervention of an external energy source. The passive cooling of the PV module developed by the three-dimensional fluid dynamics of natural airflow and heat transfer was studied by Dabaghzadeh and Eslami [30]. Furthermore, an increase in the angle of inclination of the PV module at wind speeds greater than 1 m/s led to a 4°C increase in the temperature of the PV module and a decrease in its electrical efficiency. They also showed that a 90° wind direction achieved a 3°C cooling of the average temperature of the PV module [30].

Under transient conditions, the free convection currents in the inclined and horizontal positions of the PV module were weaker compared to those in the vertical position [31]. In addition, increasing the length of the PV module up to 1.3 m in an inclined position improves the heat transfer rate. However, beyond this length, the temperature of the PV module became high and the convective heat transfer coefficients were reduced regardless of the inclination. In the horizontal position, the convective heat transfer rate were lower, especially on the lower surface of the PV module [31]. Radiation, free convection and forced convection heat transfer mechanisms were involved in the dissipation of thermal energy generated on PV module surfaces to the surrounding environment [32]. The same authors developed a model that incorporates a forced convection control coefficient to track the effect of the PV module tilt angle on the forced convection heat transfer mechanism. The results obtained showed that the model was able to estimate the PV module temperature with an error of 0.927 °C and a correlation of 0.997 under the environmental conditions considered [32].

3.1.2. Cooling by heat sinks

With finned heat sinks, this cooling technique naturally removes heat from the PV module. It promotes heat transfer through natural turbulent air convection, resulting in a better cooling rate by reducing the temperature of the PV modules.

The temperature reduction of PV modules using air-cooled heat sinks has been studied numerically by Popovici et al. [33]. The heat sink was designed as a ribbed wall made of a material with high thermal conductivity. Using ANSYS-fluent software for turbulent flow, the results showed that the increase in electrical power produced by a PV module with ribs was 6.97% to 7.55% for angles of 90° to 45°, respectively. The same authors [33] also showed that the cooling of the PV module was directly proportional to the height of the ribs and inversely proportional to their angles of inclination. Hudişteanu et al. [34] evaluated the passive cooling of PV modules through perforated and non-perforated heat sinks. The PV module was tilted at an angle of 45° to the horizontal with the wind direction to the rear. The greatest cooling effect was achieved under low wind conditions and high levels of solar radiation. For a wind speed of 1 m/s, a solar irradiance of 1000 W/m^2 and an ambient temperature of 35°C, the electricity production of the PV module without cooling reached 83.33%, while when the PV module was cooled, the electricity production reached 88.74%, resulting in a 6.49% increase in electricity [34]. When the tedlar layer of a PV module was replaced with an aluminum alloy micro-fins heat sink, the temperature of the PV module was reduced by 14.65% and the improvement in electrical performance was 13% for electrical power and 13.32% for electrical efficiency [35]. The daily average was 11.02% for electrical efficiency, 40.94% for thermal efficiency and 51.9% for overall efficiency. According to a study by Ahmad et al. [36], the use of rectangular fins reduced the temperature of the PV module by 3.25°C with an improvement of 14.2% in electrical power. Similarly, the maximum voltage of the PV module increased from 17.2 V to 20.4 V when added fins while the fill factor increased from 0.744 to 0.826 [36]. An experimental study by Amber et al [37] of two different configurations of rectangular and circular fins applied to the rear face of monocrystalline PV modules is shown in Figure 6. The PV module with rectangular fins dissipated 155% more heat and generated 10.8% and 4% more power than the reference PV module and the module with circular fins, respectively. A 10.6% reduction in the temperature of the rectangular fin PV module and a 14.5% increase in its electrical efficiency were achieved. The circular fin module dissipated only 27% more heat than the reference PV module. The PV module with rectangular fins is recommended to optimize the performance of PV modules [37].

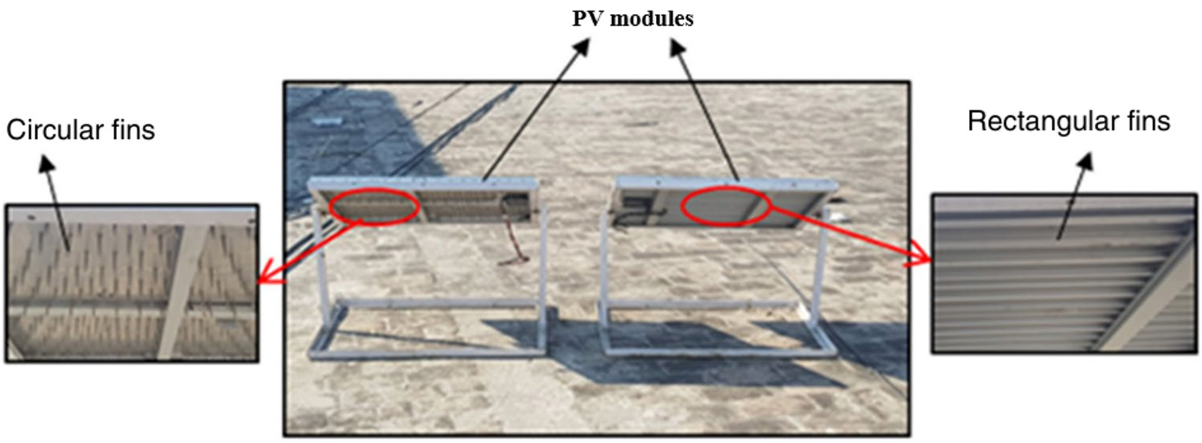


Figure 6: Experimental setup illustrating the arrangement of fins with PV modules [37].

The use of natural air convection cooling and finned heat sinks behind the PV modules provides an improved heat transfer zone with the ambient air via natural convection. However, despite a reduction in the temperature of the solar PV modules, this is limited due to the low convection coefficient of the air.

3.2. Forced air cooling methods

Forced air cooling is an active method that uses a forced air flow to reduce the temperature of the PV panels. An experimental study of active cooling of the PV module, shown in Figure 7 (a), requires a fan to increase the air mass flow rate. This increase in mass flow increases the convective heat transfer coefficient and thus leads to a high heat transfer rate [38]. Figure 8 (a) shows that as the air mass flow rate increases, the electrical efficiency of the PVT hybrid collector also increases. This means that the air mass flow rate helps to extract more thermal energy from the back of the PV module and maintain its electrical efficiency. Indeed, a comparative study of the performance of four different air-hybrid solar collector configurations under the same climatic conditions by Srimanickam [39] showed that the electrical efficiency increased from 9.8% to 12.9% for an air mass flow rate of 0.00847 kg/s and from 10.3% to 13.9% for an air mass flow rate of 0.0113 kg/s. The maximum thermal efficiency was between 4.3% and 12.4% respectively for an air mass flow rate of 0.00847 kg/s and between 6.5% and 15.9% for an air mass flow rate of 0.01130 kg/s [39]. Omer and Zala [40] have shown experimentally that the electrical efficiency and thermal efficiency of the PVT hybrid collector increase by 20% and 44% respectively when the air flow rate is increased from 0.024 to 0.057 m3/s. Kim et al. [41] showed that the PVT hybrid collector fitted with a heat recovery ventilator has an overall efficiency rate of 38%. To investigate the effect of corona wind from an electro-hydrodynamics study, an experimental study by Golzari et al. [42] showed that corona wind increases the heat transfer coefficient by 65% in the natural flow regime by producing a secondary flow and vortex, and consequently increased the efficiency of the single-pass air hybrid PVT collector. Ceylan et al. [43] also showed that the electrical efficiency of the PV module with cooling was about 13% and the electrical efficiency of the PV module without cooling was about 10%. A comparative study of a conventional PV module and a hybrid PVT single-pass air collector showed the effect of cooling on improving electrical and thermal efficiencies, with up to 44% compared to the PV module without active cooling [44].

An experimental study by Teo et al. [28], shown in Figure 7 (b), showed that the PV module temperature without cooling increased with electrical efficiency by 8% to 9%. With active cooling, the temperature of the PV module decreased; this led to an increase in the electrical efficiency of the PV module of 12% to 14% [29]. A study by Lyes et al. [45] also showed the effect of mass flow rate and air channel depth on the efficiency of an air hybrid PVT solar collector. The results showed that the overall efficiency of the air hybrid PVT solar collector increased from 60% to 75% and that the mass flow rate required to maintain the PV solar cells at a constant temperature decreased from 1.8 to 1.2 kg/s for an exchanger channel depth varying from 0.35 m to 0.05 m. They also found that the overall conversion efficiency of the hybrid PVT collector increased from 25% to 60% and the temperature of the PV solar cells decreased from 345 K to 335 K when the mass flow rate increased from 0.02 kg/s to 0.1 kg/s. For a flow rate of 0.0016 kg/s, an irradiation of 1000 W/m^2 and an ambient temperature of 20.15°C, the fluid outlet temperature reached 55.96°C according to El Hocine et al. [46]. The same authors also showed that the temperature of the PV solar cells decreased and reached 23.845°C with the increased mass flow rate up to 0.0256 kg/s. The electrical power also reached 59.434 W at the same flow rate. Another Computational Fluid Dynamics (CFD) study of a PV module with and without cooling showed that the temperature reached by an uncooled PV module was 74.87°C with an electrical power drop of 0.113% [47]. For a cooled PV module, its temperature was maintained at 45.9°C and its electrical power drops by 1.4 W [47]. The effect of high solar radiation using a concentrator significantly improved the electrical efficiency of the PV module. For an irradiation varying from 1000 to 5000 W/m^2 with an optimised flow rate of 180 L/h, the electrical and thermal energy of the PVT hybrid collector increased from 197 to 983 W and from 1165 to 5387 W, respectively. Electrical, thermal and overall efficiency reached 10.6%, 71% and 81.6%, respectively, at an irradiance of 5000 W/m² [48]. At an irradiation of 3000 W/m², the electrical power of a concentrating PV module increased by 190 W compared with 63 W at an irradiation of 1000 W/m². In addition, the electrical power and thermal energy increased by around 6.4 W and 31.3 W, respectively, for each 100 W/m² of increase solar irradiation [49].

Air impingement is a high heat transfer system used to cool the backside of PV modules. This cooling method is used to improve the energy performance of solar energy technologies such as PV modules, PVT hybrid collectors and concentrating PV modules [50]. The high heat transfer coefficient is achieved between the absorber plate and the air by using impact jets. Geometrical characteristics such as jet diameter, jet spacing and jet height influence the electrical performance of the PV module. An experimental study by Markal and Varol [51] on a PV module cooled by an incident air stream at different flow rates and different thermal loads showed that the PV module temperature increased significantly with increasing thermal load but decreased with increasing flow rate. The same authors also showed that the average surface temperature of the PV module decreased by 61.5% and the power output increased by 13.2% via to the air jet [51]. An experimental comparison of the cooling performance of two cooling schemes using zero and minimum cross-jet air was carried out. The results showed that the net power of the PV module cooled by the minimum cross-air jet increased by 6.60%. Therefore, minimum cross-jet cooling can contribute to increasing the profitability of the PV module. According to Ewe et al. [52], non-concentrating and with concentrating hybrid PVT hybrid (CPVT) cooled by impacting air jets produce more thermal and electrical energy [52]. A model of a PVT hybrid collector using impacting jets developed predicts a total daily energy of 10% and 11% of thermal and electrical energy, respectively [53]. Ul-Abdin et al. [54] investigated the performance of air-based hybrid PVT collectors and a multi-functional bi-fluid hybrid PVT collector with integrated storage tank and hot water controller, space heating and electricity generation for a single house. The results showed that the hybrid PVT without cover glass has the best cooling of the PV module while the dual channel hybrid PVT has the best air heating among the air-based hybrid PVT collector. The results also indicated that the use of an additional fluid improves electrical and thermal performance. Forced air circulation in a cooled air duct of PV solar modules highlights the design of hybrid photovoltaic/thermal (PVT) solar collectors.

The role of these systems is to better exploit unwanted heat into useful heat that can be used for domestic and industrial applications [14]. The hybrid PVT collector can therefore reduce, optimise and control the temperature of the PV module, improve electrical efficiency, save installation space for the consumer and increase surface shading during periods of high sunlight, thereby reducing the thermal load on the system [55].

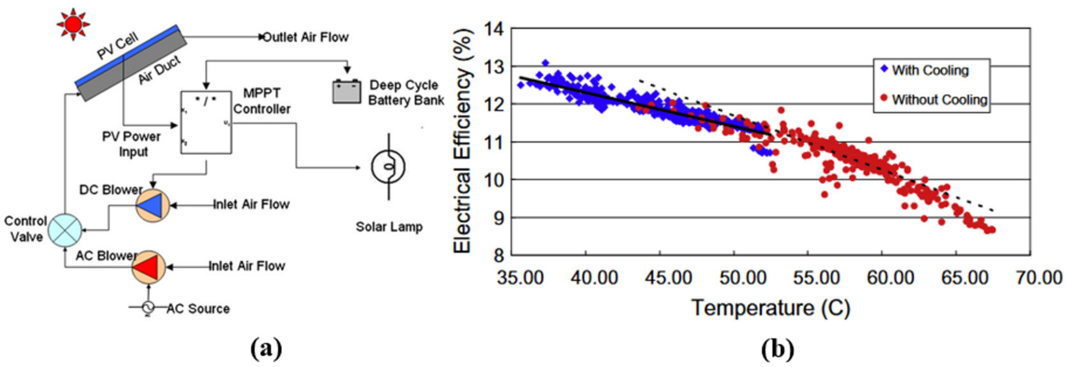


Figure 7: (a) Experimental set-up for forced air circulation in ac hybrid PVT collector; and (b) Electrical efficiency as a function of PV module temperature [19].

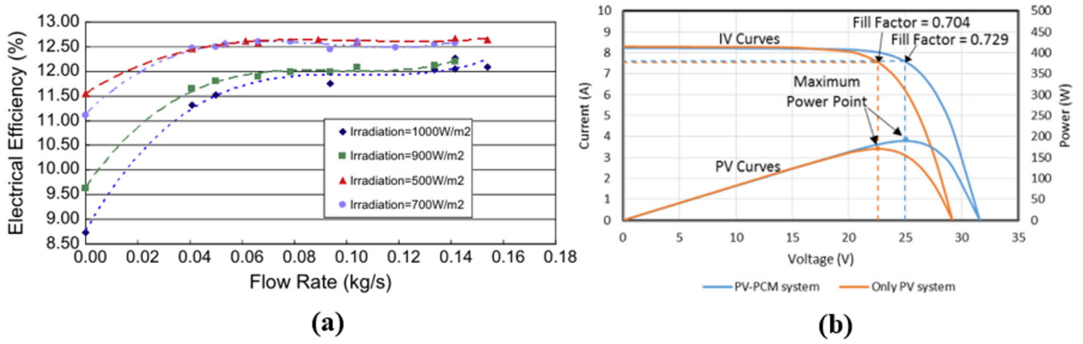


Figure 8: (a) Influence of air mass flow on efficiency [28]; and (b) PV/PCM and standard PV module current-voltage and power-voltage curves [56].

The PV module cooled by forced air circulation offers better cooling and higher energy conversion efficiency than natural air circulation. The electrical power and efficiency of PV modules obtained from these active cooling methods are mainly affected by the geometry of the single- or dual-channel cooling ducts, the glazing, the insulation, the large surfaces, the angle of inclination and their mass flow rates. These factors limit the electrical efficiency of PV modules.

3.3. Cooling methods using thermal energy storage

3.3.1. Cooling by integration of phase change materials

The integration of phase change materials (PCM) is a highly efficient cooling method with enormous potential for thermal energy storage. Integrating PCM into a PV module lowers its operating temperature and therefore increases electrical efficiency. Figure 8 (b) showed the effect of cooling the PV module with the PCM and without cooling the PV module. It showed that the PV module with cooling improved the open circuit voltage from 28 V to 31.25 V and the electrical power increased from 150 W to 200 W. The form factor increased from 0.704 to 0.729 for the PV module with cooling [56].

According to Kiwan et al. [57], when the PV module temperature exceeded the melting point temperature of PCM, the electrical efficiency of the PV module increased. However, when the temperature of the PV module was below the melting temperature of the PCM, the PCM negatively affected the electrical efficiency of the PV module. Integrating the RT35HC PCM with a thickness of 4 cm reduced the PV module temperature by 8°C compared to the reference PV module [58]. Numerical and experimental analysis of the temperature control of a PV module by integration of a PCM under Malaysian weather conditions has shown that a 2 cm wide PCM layer of RT 35 used results in the reduction of the PV module temperature by 10°C which remains constant for a period of 4 to 6 hours [59]. Analysis of the electrical performance of the tilted PV/PCM module, taking into account heat transfer due to the three heat transfer modes, was carried out by Khanna et al. [56]. The results showed that when the tilt angle increased from 0 to 90°, the temperature of the PV module with PCM decreased from 43.4°C to 34.5°C; this led to an increased electrical efficiency of the PV module from 18.1% to 19% [56]. A comparative study of PV, PV/PCM and finned PV/PCM modules taking into account the different heat transfer modes showed that the most appropriate depth of PCM is 2.8 cm for solar irradiation of 3 kWh/m^2/day and 4.6 cm for solar irradiation of 5 kWh/m^2/day for a PV/PCM module [60]. To keep the PV module temperature low, the best spacing between successive fins was 25 cm, the best fin thickness was 2 mm and the best fin length was where it touched the bottom of the air duct. For the finless PV/PCM module, the most appropriate depth of the PCM container was 2.3 cm for a solar irradiance of 3 kWh/m²/day and 3.9 cm for a solar irradiance of 5 kWh/m²/day [60]. The addition of PCM to PVT hybrid collectors has provided a dual benefit in terms of cooling PV solar cells and heat storage. Numerical and experimental studies of the energy performance of flat-plate PVT air collectors with PCM have been carried out in recent years. The position of the PCM layer in the hybrid PVT air collector had a significant effect on its energy performance. Indeed, a comparative study of the integration of an PCM in the air duct of a PVT hybrid collector showed that its electrical efficiency was 10.7% higher than that of a PVT hybrid collector without an PCM [61]. In addition, for a PVT hybrid collector with PCM, it has been verified that a 3 cm thick layer of PCM was excellent in terms of both electrical and thermal performance [61]. Systems such as PV/PCM, PV/PCM/thermoelectric and concentrated PV (CPV/PCM) have shown that cooling with PCM lowers the temperature of the PV module by 6°C on average and increased the electrical efficiency by 5.1% on average [62]. There was a 25% and 35% decreased in the temperature of the PV/PCM module and air hybrid PVT/PCM collector respectively compared to the standard PV module. As a result of this temperature drop, the electrical efficiency of the PV module increased by 14.12% and 19.75% for the PV/PCM module and air hybrid PVT/PCM collector respectively [63]. The daily electrical efficiency of the PVT/PCM hybrid air collector was 31.35% while that of the PV module was 13.12%, resulting in a 20.45% increase in the ability to extract useful energy from the sun by the PVT/PCM hybrid collector [64]. Four absorbers, placed in the PCM (pig fat-like PCM) layer of an air-powered hybrid PVT collector, balanced energy production [65]. An experimental study of a hybrid PVT/PCM air collector composed of a flexible copper-indium-gallium-selenide (CIGS) PV module, a flat plate solar collector and solid PCM showed that the temperature of the absorber plate and PV module was reduced by 15°C and 20°C for the hybrid PVT air collector without PCM. The PV module output power of the hybrid PVT/PCM collector increased by 6.7% compared to the air-based hybrid PVT collector without PCM [66]. An experimental evaluation of a nano-cooled hybrid PVT collector yielded thermal and electrical efficiencies of 72% and 13.7%, respectively [67]. Ahmed and Nabil [68] studied the influence of temperature on the electrical behavior of the PV module with and without forced convection cooling on three configurations, namely: a hybrid PVT collector with air channel under the plate, a hybrid PVT collector with a fin channel and a hybrid PVT collector with an embedded PCM between the fins. The results showed that increasing the thickness of the PCM improved the cooling of the PV module [68].

The addition of porous materials also plays an important role in the energy storage process. They have a very large influence on the electrical performance of a PV module. Ahmed and Mohammed [69] experimentally designed a PVT hybrid solar collector with a porous material and a cover and another PVT hybrid solar collector with a porous material and without a glass cover. The results of this investigation revealed that the highest daily electrical efficiency was 8.7% for hybrid PVT solar using porous material with a cover and the highest daily electrical efficiency was 10.91% with porous material without a glass cover. The use of porous material without a glass cover in the hybrid system is a desirable option when the hybrid PVT solar collector is used for electricity generation only. In addition, the reduction in the temperature of the PV solar cells with the increase in air velocity led to an increase in the electrical efficiency of the hybrid PVT collector. Tahmasbi et al. [70] used porous metal foams to cool PV solar cells and increase thermal and electrical efficiencies. The results showed that the use of porous media can improve electrical efficiency between 3 and 4% and between 10 and 40% for thermal efficiency with a pressure drop. The cooling of a solar PV module with a porous PCM at different inclination angles has been studied numerically and experimentally by Duan [71]. According to the author, the tilt angles resulted in low natural convection for the liquid PCM in the metal foam and the low convection plays a negative role in the melting process of the PCM. The melting time of the

PCM in the metal foam at 90° was 1.9 times greater than that at 0° when the porosity was 95%. Under the heat flux limit, the porous PCM with a higher porosity of 95% played a poor role in cooling the PV module. In addition, the temperature of the PV module increased when a porous PCM with a larger porosity equal to 95% was used, and the cooling time was twice as short as when a PCM with a smaller porosity (85% or 90%) was used. However, when the Rayleigh number increased from 1.4568.106 to 1.1654.1010, the time that maintained the temperature of the PV module from 40°C to 60°C decreased by 1.3 times [71].
Latent heat transfer through the PCM takes place during material melting, resulting in a high heat transfer rate. The electrical power and electrical efficiency of PV modules depend mainly on the thickness of the PCM. However, the application of PCM is limited by its high cost, toxicity and low thermal conductivity. The use of porous media increases the heat transfer area and therefore the electrical and thermal efficiency of the hybrid PVT solar collector.

3.3.2. Cooling by adding heat pipes

Heat pipes are an efficient heat transfer technology that uses the phase changes (evaporation and condensation) of the heat transfer fluid to transport a large amount of heat over a long distance. The use of heat pipes in an air flow channel of a hybrid PVT solar collector improves the electrical performance of PV modules. Numerical and experimental studies of the thermal and electrical performance of hybrid vacuum tube PVT collectors have been the subject of research in recent years. Nougblega et al. [72] showed that the hybrid vacuum tube PVT collector was thermally more efficient than a hybrid PVT with confined air blade and that an optimal flow rate maintained by a fan showed that the hybrid vacuum tube PVT collector was electrically efficient. Fan et al. [73] have developed a dual-pass PVT air heating system (PVT-SAH) integrated with heat pipes for applications requiring high temperature air. The hybrid PVT-SAH collector with heat pipes provided an efficient cooling effect to the PV module and improved the temperature uniformity of the PV module. The temperature variation over the length of the PV module for the proposed system and for the reference design was 9.4°C and 21°C respectively [73]. In addition, the maximum thermal efficiency of the PVT-SAH heat pipe collector was 69.2% compared to 61.7% for the reference design. Zhou et al. [74] have shown that the factors influencing the energy performance of the heat pipe hybrid PVT collector were mainly solar radiation, mass flow rate and wind speed. A numerical and experimental study showed that the thermal and electrical efficiencies of the heat pipe hybrid PVT collector were 41.9% and 9.4% respectively [75]. This cooling technique is a passive method that improves the electrical efficiency of solar PV modules. It does not consume electricity, but it is expensive.

3.4. Cooling by conversion and efficient capture of solar radiation

3.4.1. Radiative and photonic cooling

Radiative passive cooling, shown in Figure 9, is a method to dissipate excess heat from PV solar cells by the spontaneous emission of infrared thermal radiation [76]. This figure shows the thermal analysis involved in this cooling method. An experimental study by Zhao et al. [77] showed that the electrical performance of radiative cooling systems in the sky depended on weather conditions. Dumoulin et al. [78] studied the effect of radiative cooling from the sky on single junction PV solar cells on three semiconductor materials: silicon, gallium arsenide and perovskite. The numerical model developed, based on the heat balance, estimated the temperature and electrical power for the various PV solar cell technologies. The results showed that the broadband emissivity profile offered the best electrical performance for radiative sky cooling of single-junction PV solar cells. Numerical simulations also showed that radiative sky cooling reduced the temperature of PV solar cells by 10°C, increasing their power output by more than 5 W per 1 m². For silicon PV solar cells, a 20% reduction in parasitic absorption produced the same effect as a 10% increase in emissivity above 4mm. For gallium arsenide and perovskite PV solar cells, the effect was even more pronounced. However, radiative cooling of the sky was only feasible under controlled atmospheric conditions. Radiative night cooling was therefore a success in recent years [78]. Zhao et al. [79] designed a radiatively cooled PV module to generate electricity during the day by photovoltaic conversion and simultaneously obtain radiative cooling energy at night. On a sunny day, the electrical performance of the PV module showed that the average daily electricity generation and electrical efficiency were 94.0 W/m² and 14.9% respectively. The net cooling power was estimated at 72.94 W/m² when the temperature of the PV module was equal to the ambient air temperature [79].

Using the photonic cooling methods shown in Figure 10, in particular Doppler cooling on PV solar cells, improves the thermodynamic properties of semiconductor materials. Using a photonics approach, the main reason for the decrease in electrical efficiency due to heating of crystalline silicon PV solar cells is the increase in non-radiative recombination at high temperatures; this reduces the open-circuit voltage and the peak voltage [80]. The sub-bandgap radiation reflection method has shown that by reflecting sub-bandgap and ultraviolet radiation, solar cell output is reduced and by improving the optical absorption of PV solar cells, photocurrent is improved. Thanks to these photonic structures, the operating temperature of the PV module is reduced by 10 K and the efficiency is improved by 5.8%, compared with PV modules equipped with conventional coolers such as glass [80]. A study by Gordon et al. [81] showed that the ability of photonic cooling to provide semiconductor materials in the 100 K to 300 K range theoretically improved the electrical efficiency of PV modules by more than double the current practical results. However, when cooling semiconductor materials operated at low temperatures (below 100 K), PV solar cells acted as insulators. Thus, PV modules could therefore be optimized using photonic cooling systems [81]. The photonic cooling of PV solar cells in monocrystalline silicon gave a daytime electrical power of 99.2 W/m² and produced a night electric power of 128.5 W/m², respectively with an electrical efficiency of 6.9% and 30.5% higher than those of PV solar cells without photonic cooling [82]. Radiative and photonic cooling methods are innovative passive methods to improve the efficiency of PV solar modules by dissipating excess heat from PV solar cells through spontaneous emission of infrared thermal radiation. These methods use the ability of materials (gallium arsenide and perovskite) to emit infrared (IR) radiation to space (through the atmosphere) in the wavelength range from 8 µm to 13 µm to dissipate heat [77], [83]. This cooling technique does not consume any electrical energy, works day and night and significantly reduces the temperature of PV solar modules. However, the cost of the system is high and its performance depends on atmospheric constituents (atmospheric water vapour), sky conditions (clear or overcast), local wind speeds and unstable weather conditions. These two innovative methods are in the theoretical study and experimentation phase.

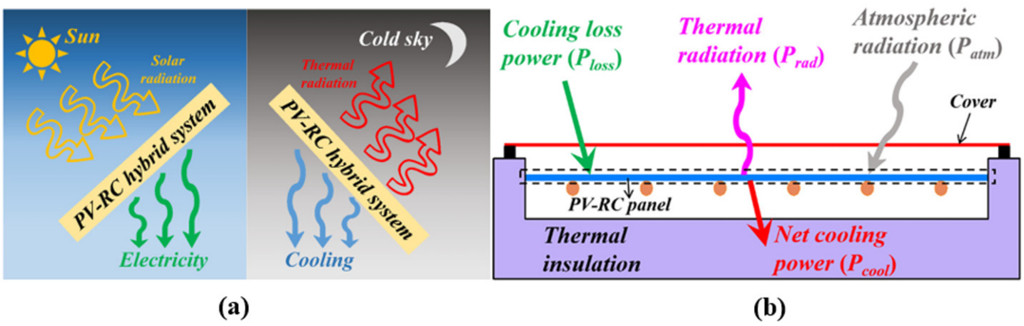


Figure 9: (a) Concept for using a radiative-cooled PV module; and (b) Radiated PV module thermal analysis diagram [79].

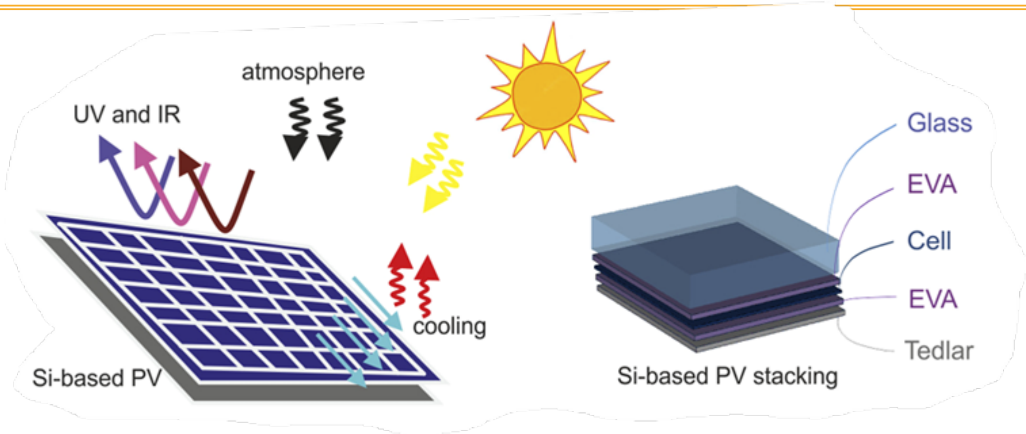


Figure 10: Schematic of cooling approaches for radiative and photonic thermal management of PV modules and stacking of crystalline silicon-based encapsulated PV module materials [80].

3.4.2. Cooling using thermoelectric generators

The use of thermoelectric cooling technique consists in integrating a Peltier module under the PV solar modules. Figure 11 shows that when an electric current flows through a thermoelectric module (made up of P- and N-type semiconductors), it creates a flow of heat from one side to the other, allowing heat to be extracted from the solar PV modules. A cross-sectional view showing a combined PV module and thermoelectric generator (PV/TE) is shown in Figure 12.

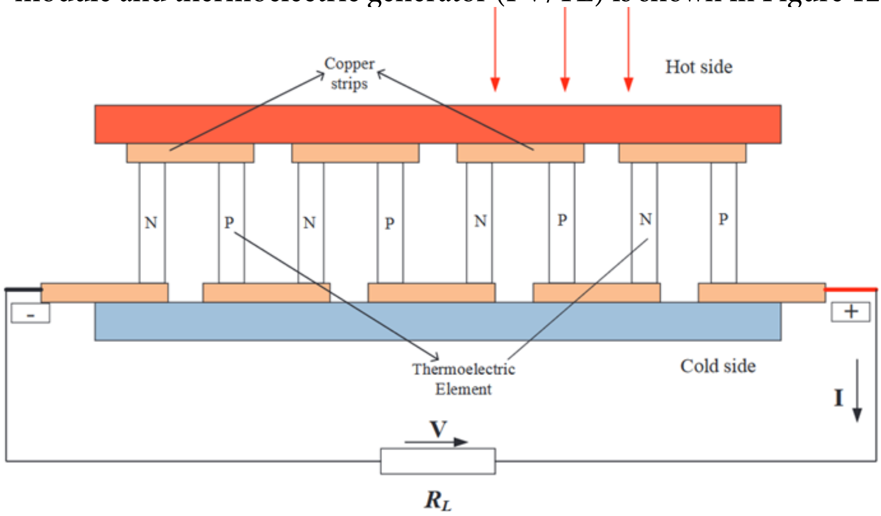


Figure 11: Basic thermoelectric generator structure [86].

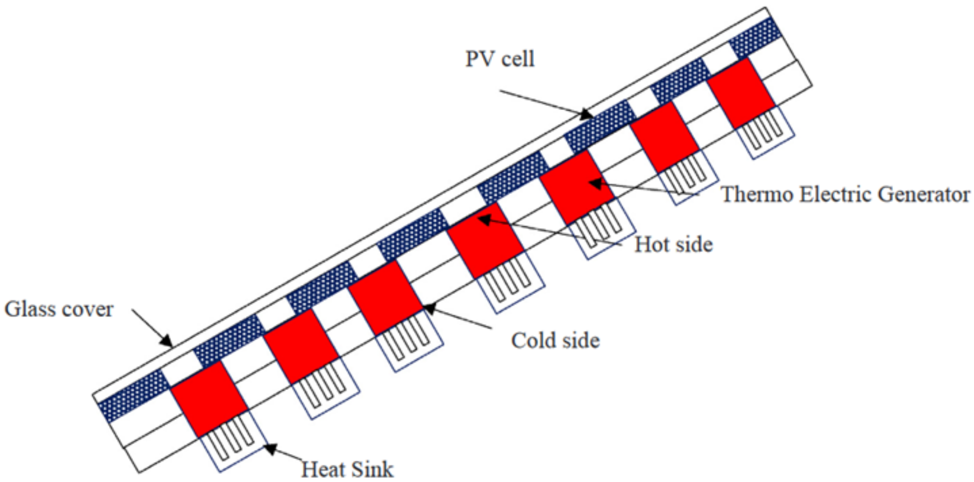


Figure 12: Cross-sectional view of the PV-TE module [86].

An experimental study of such a module showed that the electrical efficiency, front and back temperatures of the PV module and the air temperature at the PV/TEG module outlet were respectively 11.87%, 54.5°C, 43.1°C and 46.3°C [84]. A comparative study of the use of thermoelectric cooling and natural cooling of the PV module at free convection showed an increase in the electrical efficiency and power of the PV module of 10.50% and 10.50%, respectively [85]. According to Babu and Ponnambalam [86], the module PV/TE of different configurations generated 10-20% energy with an overall efficiency of 40-50%. The unconcentrated flat plate PV/TE module produced 5% more energy with an overall efficiency increase of 6% under standard conditions [86]. Compared with the conventional PV module, the electrical efficiency of the PV/TE module increased by 3.9% and the total efficiency of the system could reach 5.9% [87]. Bjørk and Nielsen [88] performed on four different types of commercial PV modules and a commercial thermoelectric generator based on bismuth telluride. For c-Si, CIGS and CdTe solar cells, the combined system produced lower power and had higher electrical efficiency than TEG. For the c-Si, CIGS and CdTe solar cells, the combined system produced lower power and had lower efficiency than the PV module alone. For a PV-Si solar cell, the total system performance was slightly increased by the TE [88].

Improved energy performance could also be achieved using hybrid PVT solar collector technology combined with thermoelectric generators. A numerical study by Salari et al. [89] showed that the electrical efficiency of the hybrid PVT collector and the hybrid PVT/TE collector were 6.23% and 10.41% respectively. By increasing the ambient temperature from 26 °C to 34 °C, the electrical efficiency of the hybrid PVT collector had decreased by 1,43% and the hybrid PVT/TE collector had increased by 0.82% [89]. For a semi-transparent PVT hybrid collector combined with a thermoelectric cooler, the electrical efficiency was higher than that of the semi-transparent PV module by 7.266% and higher than that of the semi-transparent PV-TE solar module by 4.723% [90]. In a steady state, an air hybrid PVT-TE collector provided maximum thermal and electrical efficiencies of 84% and 12%, respectively [91]. Finally, the electrical efficiency of the hybrid PVT/TE collector increased when V-grooves, aluminum fins and thin metal sheets were used in the air duct [92].

By effectively capturing solar radiation through a division of the solar spectrum, this cooling method improves electrical efficiency and extends the longer life of PV solar cells. This device constitutes a photovoltaic-thermoelectric hybrid module (PV/TE) which simultaneously intervenes the photovoltaic effect and the Peltier effect (thermoelectric). The Peltier effect allows PV solar cells to be cooled and keeps them operating at an ambient temperature that enables them to generate their maximum power [93]. Additional electricity generation via the Seebeck effect is also obtained. This cooling technique consumes a lot of electricity and the cost of thermoelectric materials is high and it is a theoretical study and experimentation phase to determine innovative thermoelectric materials.

3.4.3. Cooling using bifacial PV modules

The bifacial PV solar modules have two identical active surfaces front and back that can capture solar radiation with the surfaces on both sides according to the cross-sectional view of the bifacial hybrid PVT solar collector [see Figure 13]. Simultaneous absorption of sunlight through both surfaces results in improved power generation compared to conventional single-phase PV modules [94]. With a bifacial PV module, an output power ranging from 5 to 20% can be achieved. An experimental study by Appelbaum [95] showed that bifacial PV modules installed with optimal tilt angle could produce 32% more energy than vertical bifacial PV modules under the same environmental conditions. A study by Badran [104] showed that a vertically mounted bifacial PV module (VBPV) significantly outperformed vertically mounted monofacial PV modules (VMPV) and conventional tilted monofacial PV modules (TMPV) in terms of energy production [96]. The results showed an increase in daily energy production of 7.12% and 10.12% compared with the VMPV module, and an improvement of 26.91% and 22.88% compared with the TMPV module, in the early morning and late afternoon respectively. Seasonal analysis showed average power gains of 11.42% in spring, 8.13% in summer, 10.94% in autumn and 12.45% in winter compared with the VMPV module. Compared with the TMPV module, these gains are even greater, peaking at 24.52% in winter [96]. These results demonstrate the exceptional efficiency of the VBPV module in harnessing solar energy under a wide range of environmental conditions.

The bifacial hybrid PVT collector is now considered attractive because of its potential to improve overall collector performance from the same surface of the PV module. A hybrid PVT collector with a bifacial PV module could produce about 40% more electrical energy than a single-face hybrid PVT collector [94]. A study of bifacial dual-pass and single-single hybrid PVT collectors showed that overall efficiencies of 45% to 63% was observed for the parallel dual-pass bifacial hybrid PVT collector. Therefore, the parallel dual-pass bifacial hybrid PVT collector was preferred because it generates up to 20% more total energy than the single-channel collector despite its low daily exergy efficiency [97]. An experimental analysis of four bifacial PV modules with four different fill factors of hybrid air PVT collectors showed that the dual-pass parallel flow design gave the highest energy efficiency from 51% to 67%, and the single-pass design reported the lowest total energy efficiency of 28% to 49% with a fill factor of 0.7. The single-pass bifacial hybrid PVT collector design was the best option if electrical energy was the desired output energy. However, the dual-pass parallel flow design was the best option if thermal energy was the desired output energy [97].

Unlike single-face PV modules, bifacial PV modules have both front and rear light sensitivity, which gives them high electrical efficiency. The design of the single-channel bifacial hybrid PVT collector is better when electrical energy is desired and if thermal energy is desired, the dual-channel parallel flow design is the best option. This method effectively captures solar radiation and has a better efficiency by reflection and albedo. It is a promising innovation, but its effectiveness depends heavily on the installation site (low albedo) and has a very high cost.

3.4.4. Cooling using PV modules integrated in buildings

Building-integrated PV modules (BIPV) are power generation systems that are integrated into a roof, facade or windows of buildings. The integration of PV modules into buildings is a cooling method for PV solar cells that maximizes the capture of solar radiation in useful energy. The improvement of electrical performance of PV panels integrated into buildings by passive cooling has been investigated experimentally and numerically by Hamed et al. [98]. They showed that the BIPV with a narrow channel reduced the operating temperature of the PV panel. This improvement in heat transfer from the PV panel has reduced the temperature of the PV panel by 5 to 10°C. The results also showed that the presence of a 30 cm channel under the PV module could increase electrical output by 3% to 4%. Thus, the inclusion of a channel resulted in passive cooling through radiative and convective heat exchange [98]. When the mass flow rate was 0.04 kg/s during PV module cooling, energy and exergy efficiencies reach 11.9% and 12.4%, respectively [99]. Cooling could thus increase electricity production by 7% to15%. The BIPV module had a significant influence on heat transfer through the building envelope due to the modification of the thermal resistance by adding or replacing building elements. Wang et al. [100] designed four PV modules integrated into different buildings: the BIPV with ventilated air blade, the BIPV with non-ventilated air blade, the BIPV roof-mounted module and the conventional roof without the

PV module and without air blade. The simulation results showed that the ventilated air blade BIPV module was suitable for summer application as this integration resulted in low cooling load and high electrical efficiency. In winter, the BIPV module with unventilated air blade was more appropriate due to the combination of low thermal load through the roof and high electrical efficiency of the PV module [100].

When air hybrid PVT collectors were integrated into buildings, they provided more useful energy per unit area than solar PV modules alone. Several analytical, numerical and experimental studies of the performance of air hybrid PVT collectors integrated into buildings have been carried out in recent years. Kim et al. [101] experimentally conducted a comparative study between a hybrid PVT air-integrated solar collector (BIPVT) and a building-integrated PV module. The results showed that the hybrid BIPVT collector could maintain a lower temperature of the PV solar module than the BIPV with a temperature difference of about 22°C. The hybrid BIPVT collector could also maintain an electrical efficiency of 14% even when the solar radiation was high compared to 12% of the BIPV module. Another comparative study of semi-transparent hybrid PVT collectors integrated in the building and opaque hybrid PVT collectors integrated in the roof of a room with and without air duct was carried out by Vats and Tiwari [102]. Results showed that a maximum ambient air temperature of 18°C and a minimum ambient air temperature of 2.3°C were observed for the semi-transparent PVT collector without an air duct and the opaque hybrid PVT solar collector. Yang [103] conducted another comparative study which showed that the use of semi-transparent PV modules in hybrid PVT collectors increased thermal efficiency by up to 7.6% compared to opaque hybrid PVT collectors, especially when combined with multiple entries. A semi-transparent hybrid PVT collector integrated on the roof (room 1) to study the performance of a room (room 2) showed that the optimal thickness of the roof for minimum temperature fluctuations inside the room was between 0.30 m and 0.40 m. Due to direct heating, room 1 reached very high temperatures (above 40°C) and could therefore be used as a greenhouse for drying high value crops [104]. A numerical analysis of the transient mixed convective air flow in a solar building stack was performed on a hybrid PVT solar collector using a flow function and vorticity formulation [105]. The hybrid PVT building collector model offered good electrical performance while the hybrid PVT reverse solar chimney collector provided good thermal efficiency. Another study on a hybrid PVT solar fireplace integrated into the building for natural room cooling was digitally analyzed by using mixed convection [106]. The results of the analysis showed that the increase in Reynolds number led to higher airflow for passive cooling and better electrical efficiency of PV solar cells. The performance evaluation of a hybrid PVT double-pass solar collector showed that the temperature of the outlet air was 63°C at a mass flow rate of 0.017 kg/s and the electrical, thermal and overall efficiency were 12.65%, 56.73% and 85% respectively at a flow rate of 0.031 kg/s. In addition, the optimum electrical power and thermal energy reached 50.57 W and 389.37 W at 0.031 kg/s [107]. Lukasik and Wajs [108] studied the influence of forced air cooling conditions of a BIPVT module and 25 mm and 50 mm flow channel height on its electrical and thermal performance. The highest electrical efficiency obtained experimentally was 5.76% for a 50 mm high channel, volumetric flow rate of 7.5 m 3/h and solar radiation equal to 600 W/m². With a solar radiation of 300 W/m², the highest thermal efficiency obtained was 48.70%. The system with the highest thermal potential was found to be in the 25 mm channel configuration.

The integration of PV modules into buildings is a cooling method for PV solar cells that maximizes the capture of solar radiation in useful energy and thermally isolates the system. This cooling method is complex and very expensive to install. BIPV modules also reduce the building's electrical requirements and air conditioning costs when PV modules are used to protect the building. Currently, the gradual decrease in PV module prices is expected to drive the market for building-integrated PV facades at different levels (individual buildings, city blocks and cities). The growth of the PV façade market with ventilation systems for heat recovery is expected to be adopted in cities worldwide as highlighted by Yu et al. [109]. These authors quantified the building-integrated photovoltaic potential of facades and roofs in 120 cities worldwide, taking into account the diversity of urban morphologies and climatic conditions in an estimation framework shown in Figure 14. Using a holistic methodology and 3D building footprint models with various sources of meteorological data, the results on 120 typical cities around the world showed that the rate of solar radiation received by facades is very competitive with that from roofs, with an average facade-to-roof ratio of 100.7%. What's more, 35.9% of facades receive even more radiation than roofs, further underlining their potential as viable solar surfaces [109].

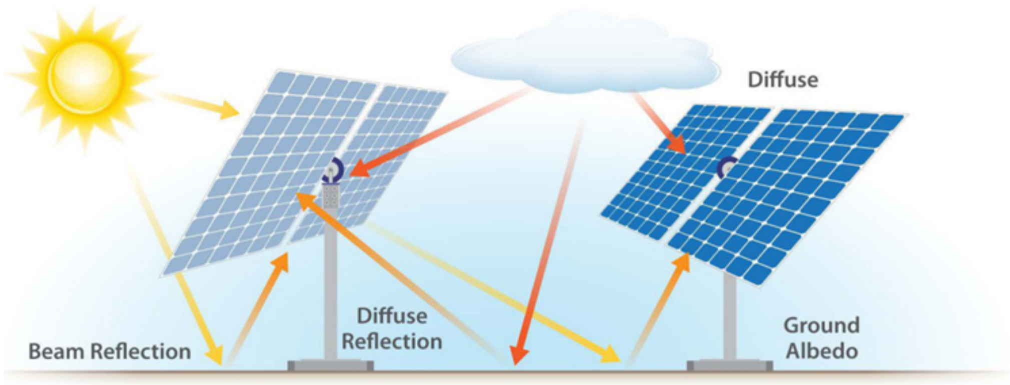


Figure 13: Illustration of the operation of a bifacial PV module [110].

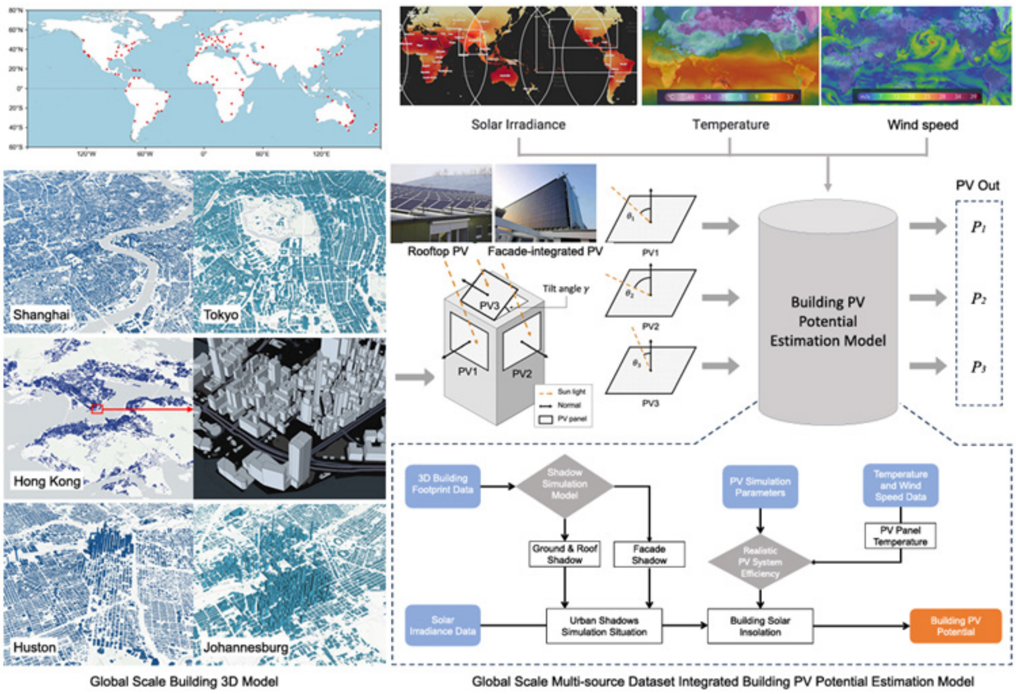


Figure 14: Framework for estimating the photovoltaic potential of building façades and roofs worldwide [109].

3.5. Cooling by optimizing the structural configuration

3.5.1. Cooling by adding obstacles or baffles or fins

The optimal heat extraction from PV solar cells is achieved by adding or attaching obstacles behind the PV solar module. Several configurations using different shapes of obstacles in the airflow channels of air hybrid PVT collectors have been proposed in previous studies. Rectangular, triangular, inclined, perforated, curved, V-shaped and T-shaped baffles combined with fins were used as artificial roughness, generating turbulence in the air ducts for improved system cooling. The application of triangular baffles in an air-cooled hybrid PVT collector improved heat transfer in the air duct by cooling the PV solar cells [111]. The arrangement of the triangular baffles and the height of the air gap at the back of the PV module had an effect on the electrical performance of the air hybrid PVT collector [112]. The electrical performance of the hybrid PVT collector improved when the horizontal spacing of the baffles was wider and the vertical spacing was narrower, while a high number of baffles decreased the electrical efficiency according to Yu et al. [112]. According to the same authors, the length of the baffles was less than 150 mm and the slope of the baffles greater than 30° to obtain better air mixing in the duct. In addition, a collector slope of -30° moved the vortices towards the center of the channels, unlike a slope of +30°, which improved the heat transfer rate [112]. The use of perforated baffles in an air-cooled hybrid PVT collector showed that the total exergy efficiency of the air-cooled hybrid PVT collector with perforated baffles ranges from 24.8% to 30.5% when the total energy efficiency ranged from 44.1% to 63.3% [113]. With curved baffles, thermal and electrical efficiencies varied from 37.1% to 6.4%. With curved baffles, thermal and electrical efficiencies ranged from 37.1% to 6.4% and the annual heat gain was 644 kWh and the annual electrical power generated was 118 kWh [114]. When triangular-shaped obstacles were used in the air duct of a hybrid PVT collector, the daily average thermal, electrical, overall and exergy efficiencies were 24.73%, 15.59%, 62.83% and 15.57%, respectively, while these efficiencies for an unobstructed air hybrid PVT collector were 17.08%, 15.30%, 54.47% and 15.13% respectively [115]. The annual energy and exergy yield of the hybrid PVT collector with triangular obstacles were 12.84% and 1.98%. These values were higher than those of the air-cooled hybrid PVT collectors without obstacles. The triangular and perforated obstacles introduced in the flow channel of figure 15 (a) could therefore effectively improve the electrical power of the air-cooled hybrid PVT collector. Figure 15 (b) shows that beyond the Reynolds number is equal to 1000, the temperature of the PV module with fins was lower than that of the PV module without fins. The temperature was therefore inversely proportional to the increase in the Reynolds number; this was due to the fact that the coefficient of heat transfer by convection was directly proportional to the Reynolds number.

Figure 16 shows the integration of the fins (single or multiple) into the air flow channel. This integration increases the heat transfer area between air and duct. The use of a hybrid PVT solar collector with fins to cool the PV panel has higher efficiency than the hybrid PVT solar collector without fins. Indeed, a numerical study conducted by Zohri et al. [116] showed that the maximum output temperature results, thermal efficiency and electrical efficiency of a hybrid air hybrid PVT collector with fins were respectively 41,39°C, 43% and 14%. An energy and exergetic analysis of a hybrid air PVT collector with and without fins conducted by a theoretical approach for solar radiation ranging from 600 W/m² to 800 W/m² and mass flow rates of 0,01 kg to 0.05 kg/s showed that the maximum air temperature at the outlet and the overall efficiency of the hybrid PVT air collector with fins were respectively, 39.93°C and 55%. The energy efficiency of the air hybrid PVT hybrid collector with fins was 7% and the exergetic efficiency was 1% [117].

An air-cooled hybrid PVT solar collector with a double-pass configuration and with vertical fins in the channel, perpendicular to the airflow direction was studied by Kumar and Rosen [118]. The addition of extended fins significantly reduced the temperature of the PV modules from 82°C to 66°C. With the addition of the rectangular fins, the maximum thermal efficiency and electrical efficiency obtained were 56.19% and 13.75% respectively for four fins at a mass flow rate of 0.14 kg/s and solar irradiance of 700 W/m². Operating costs were reduced because the aluminium fins and metal foil fins were small compared with the width/length and depth/length ratios of the hybrid PVT collector [119]. A simple heat extraction method using a thin flat metal sheet suspended in the middle of the air duct or fins on the rear wall of an air duct has been investigated by Tonui and Tripanagnostopoulos [120] to improve the performance of the PV module. Under natural air flow, the temperature reached around 12°C in the early afternoon on sunny days and led to sufficient air flow for adequate air ventilation. For forced convection with a flow rate of 60 m3/h and a duct depth of 15 cm, the use of fins gave an overall efficiency of 30%, followed by thin sheet with 28%. The reference hybrid PVT collector with an overall efficiency of 25% for the models studied and the suggested modifications gave better electrical performance due to the cooling of the PV module. The parametric analysis showed that the mass flow rate, and therefore the thermal efficiency, decreased with increasing ambient temperature and increased with increasing tilt angle for a given level of insolation. It was also showed that there was an optimum airflow channel depth at which the mass flow rate was at its maximum and was between 0.05 and 0.1 m for the different configurations [120]. According to Kalkan et al. [121], optimum operating conditions were achieved for a hybrid PVT collector with a length of 1.5 m, a channel height of 1 cm and an air velocity of 2.3 m/s. For the optimal design, the overall efficiency and output temperature values were evaluated at 53.4% and 310.9 K respectively. Parametric analysis showed that the addition of fins improved the overall efficiency of the hybrid PVT collector by up to 19%. However, the addition of fins did not significantly affect the outlet air temperature nor did it improve the overall efficiency of the hybrid PVT collector above a critical channel height. Tabet et al. [122] showed that the electrical efficiency of the air hybrid PVT collector increased as the number of fins increases. Al-Damook et al. [123] showed in their study that the use of offset fins had a significant impact on the electrical and thermal efficiencies of the hybrid PVT collector. The maximum combined efficiency for the PVT hybrid collector with offset fins was 84.7%, whereas the hybrid PVT collector without fins was 51.2%. Gholampour and Ameri [124] showed that the energy and exergy efficiency of the hybrid PVT collector increased with increasing fin number and height. The same authors suggested that optimal operation of the PVT hybrid collector required a mass flow rate of 0.074501 kg/s and a number of fins of 7.915937. Finally, when the collector was operated at a high mass flow rate, the temperature of the PV solar cells was reduced and the electrical efficiency of the PV module was increased [125].

With the application of circular ribs in the air duct of a hybrid PVT collector as shown in Figure 17 (a), the temperature of the PV solar cells dropped by 10°C compared to the hybrid PVT collector without ribs at an inlet air velocity between 1 and 3.5 m/s. The presence of the ribs induced large recirculation zones so that the air cooled near the bottom of the channel was partially re-injected upwards to extract heat from the PV cells. Similarly, the electrical efficiency of PV solar cells depended on their temperature and increased with increasing incoming air velocity. The rib configuration, where the ratio of the distance between the circular ribs to their diameter was 8, offered better performance [126]. According to Popovici et al. [33], the increase in maximum power produced by the PV module with ribs was 6.97% to 7.55% for rib angles of 90° to 45°, respectively compared to the PV module without ribs. Finally, according to Saadi et al. [127], increasing the number of triangular ribs decreased the PV solar cell temperature and increased the hybrid PVT collector outlet air temperature [see Figure 17 (b)]. The inter-rib spacing provided the turbulent air flows that promote heat transfer by forced convection within the airflow channel and could be optimized for all values of inlet air velocity [127].

The attachment of obstacles in the air duct increases the heat transfer coefficient between circulating air and the absorber of an air hybrid PVT collector by improving this energy performance [128]. This method extends the air flow in the air duct by improving heat transfer and reducing areas of thermal stagnation. The arrangement of obstacles in the air flow channel requires a study of computation fluid dynamics CFD to optimize system performance.

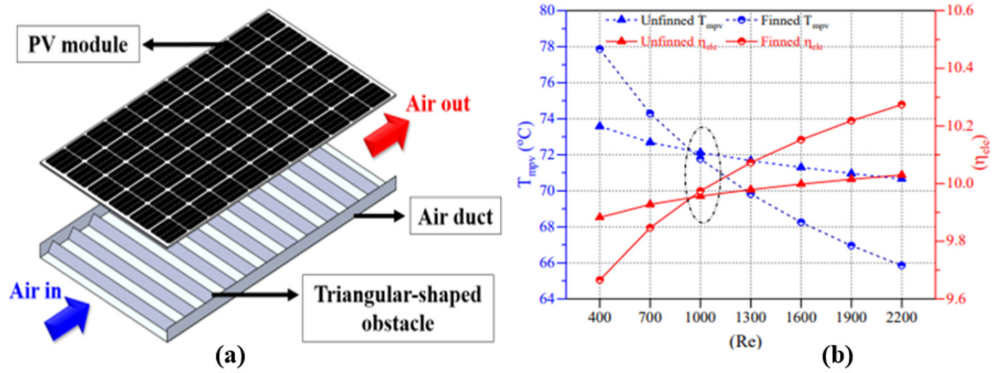


Figure 15: (a) Air hybrid PVT collector with triangular obstacles [115]; and (b) Effect of the increase in temperature of the PV module on electrical efficiency in different ranges of Reynolds number for air hybrid PVT collectors with and without fins [123].

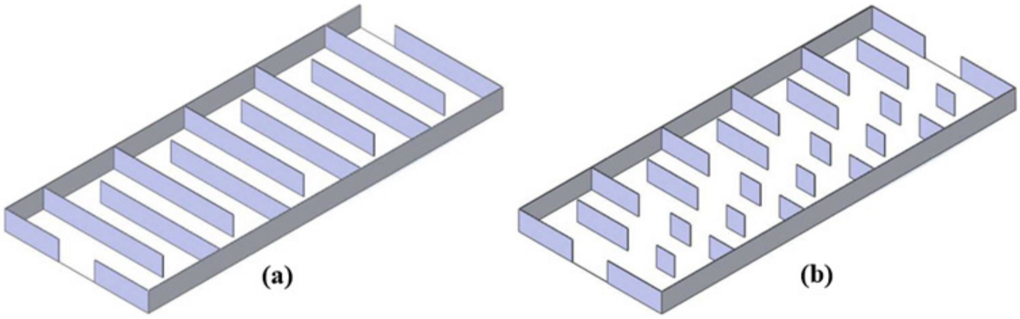


Figure 16: (a) single fin channel; and (b) multiple fin channel [128].

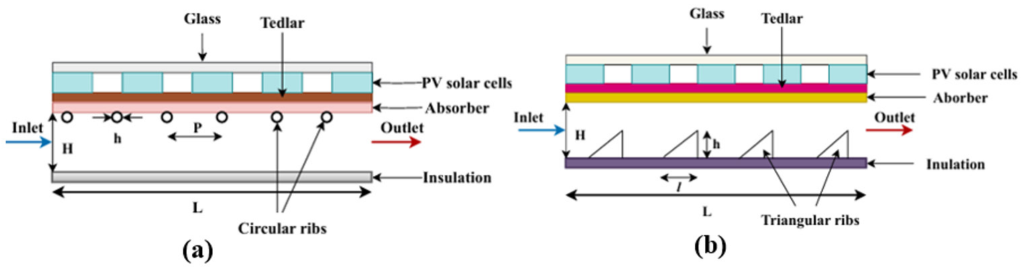


Figure 17: (a) Configuration of the circular ribs under the PV module [126]; and (b) geometric configuration with triangular ribs [127].

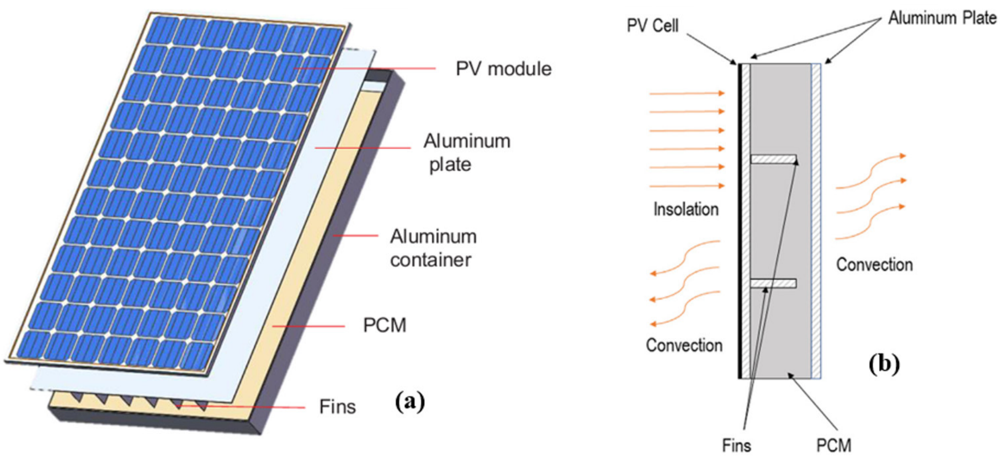


Figure 18: (a) 3-D view of the PV/PCM module; and (b) Cross-sectional view of the PV/PCM module [129].

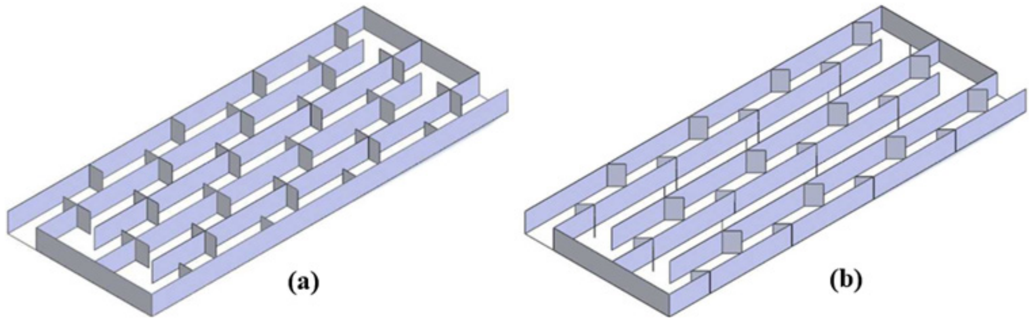


Figure 19: (a) Channel with fin coupling and T-shaped baffles; and (b) Channel with fin coupling and V-shaped baffles [128].

3.5.2. Fin coupling cooling or/and baffles with PCM

The coupling of the fins or obstacles with the PCM regulates the temperature of the PV modules by improving their electrical performance. The use of PCM coupled to fins has led to a good distribution of module temperature compared to the use of single PCM, significantly improved cooling of the PV module and leads to high outlet air temperatures [68], [130].

A numerical study of fin coupling to PCM by Ma et al. [129] showed that an increase of 100 W/m² in solar radiation could result in an increase of about 5°C in the PV module temperature and that optimum performance could be achieved when the melting temperature of the PCM was slightly higher by 5°C than the ambient temperature. According to Abdulmunem and Jalil [130], coupling the fins to the PCM as shown in Figure 18 accelerated the melting of the PCM by 3.5 min at a depth of 2 cm and by 14 min at a depth of 3 cm compared to using the PCM alone. The temperature of the PV module decreased by 18.3% using only PCM and by 27.8% when the PCM was coupled to the fins compared to the PV module without PCM. Furthermore, for good temperature control of the PV/PCM module with fins, the best spacing between successive fins was 25 cm, the best fin thickness was 2 mm and the best fin length was where it touched the bottom of the air duct [60]. An experimental analysis of the energy and exergy efficiencies of five different absorber configurations in the airflow channel of a hybrid PVT collector was carried out by Srimanickam and Sarayan [128]. These were a reference airflow channel, a single-fin channel, a multifin channel, fins coupled to T-baffles and fins coupled to V-baffles. Experimental results showed that the maximum electrical efficiency was found to be 13.70% at a mass flow rate of 0.00565 kg/s and 14.27% at a mass flow rate of 0.00847 kg/s. Similarly, thermal efficiency was 14.12% at an air mass flow rate of 0.00565 kg/s and 20.81% at an air mass flow rate of 0.00847 kg/s. The coupling of the fins to the V-shaped baffles showed the highest electrical and thermal performance compared with the other configurations because of its physical geometry rich in artificial roughness [128]. Figure 19, which shows the coupling of fins and baffles, therefore ensures good turbulent air flow in the duct, which increases the electrical performance of the hybrid PVT collector.

The coupling of fins or obstacles with the PCM with PV modules or hybrid solar collectors PVT greatly improves the electrical efficiency of PV solar cells. This cooling method lengthens the path of air flow in the channel and thus increases the coefficient of heat transfer by convection.

3.5.3. Cooling by modifying heat exchanger design parameters

This method involves modifying the airflow channel and the absorbers, using extended surfaces in the airflow channels behind the solar PV module. This increases the heat transfer area between the surface of the absorber and the air circulating in the duct. These factors or sub-techniques of this cooling method include the dimensions of the absorber and flow channels, the design of single or multiple air channels, the integration of porous media in the air channels and the development of innovative absorber plates. These design parameters influence the energy performance of hybrid PVT collectors. Farshchimonfared et al. [131] showed that the optimal depth of the air flow channel increased as the length-width ratio (L/W) and the surface area of the hybrid PVT air collector increased. In addition, the optimum depth for a hybrid PVT collector with specified areas and values of the L/W ratio considered varied between 0.09 and 0.026 m.

The direction of air flow had an effect on the electrical and thermal efficiency of single-pass and double-pass hybrid PVT air collectors with rectangular fin absorbers. The use of a dual-pass hybrid PVT air collector increased its performance compared to single-pass hybrid PVT. With an air mass flow rate of 0.048 kg/s, the thermal efficiency reached 73.23% and the electrical efficiency 10.16% [132]. A comparative study of a solar PV module, a standard hybrid PVT air solar collector, an air-based glazed hybrid PVT collector and a double-pass air glazed hybrid PVT collector showed that the overall efficiency of the double-pass air glazed hybrid PVT collector was 74% higher than other solar systems with an air flow rate of 0.023 kg/s. By integrating an indirect solar dryer system into the hybrid PVT collector, the electrical, thermal and overall efficiencies had reached 10.5%, 70% and 90% respectively for a flow rate of 0.0155 kg/s [133].

Absorbers of different shapes increase the airflow path in a hybrid PVT collector; this improves its energy performance. An examination by Wu et al. [134] showed that there were seven different types of thermal absorbers and four corresponding integration methods for various hybrid PVT collectors. Absorbers such as heating micro-channel heat pipe network, extruded heat exchanger, roll-bond heat exchanger and cotton wick structure were promising compared with traditional thermal absorbers, such as sheet and tube structure, the rectangular tunnel with or without fins/grooves and flat tube due to significant improvement in efficiency, structure, weight and cost, etc. The vinyl acetate-based integration method was the best option for integrating PV module with thermal absorber compared to other conventional methods such as direct contact, thermal adhesive and mechanical fixation. According to Jin et al. [135], the single-pass hybrid PVT collector with a rectangular tunnel absorber provided better electrical and thermal efficiency than the hybrid PVT collector without a rectangular tunnel absorber. The electrical, thermal and overall efficiencies obtained were respectively 10.02%, 54.70% and 64.72% for a solar irradiance of 817.4 W/m², a mass flow rate of 0.0287 kg/s and an ambient temperature of 25 °C [135].

Three heat exchanger designs, namely V-grooved, honeycomb and stainless steel wool, located at the rear of the PV module, were individually designed and tested by Othman et al. [136]. With a solar irradiance of 828 W/m² and a mass flow rate of 0.11 kg/s, the maximum thermal efficiency of the V-grooved system was 71%, that of the stainless steel wool was 86% and that of the honeycomb was 87%. The electrical efficiency of the system was 7.04%, 6.88% and 7.13% respectively. These results showed that the PVT hybrid solar collector with hexagonal honeycomb heat exchanger performs best. The honeycomb structure, with its large surface area in contact with the rear of the PV module and its ability to even out air flows, improved heat transfer from the rear of the PV module to the ambient air. Hussain et al. [137] showed that with the same heat exchanger, an irradiance of 828 W/m² and a mass flow rate of 0.11 kg/s, the thermal efficiency of the honeycomb PVT hybrid solar collector was 87% and without the honeycomb it was 27%. The electrical efficiency of the PV module, meanwhile, increased by 0.1% for the honeycomb PVT hybrid solar collector. When a V-groove absorber was used, the output temperature, thermal efficiency and electrical efficiency were 75.96°C, 80.10% and 24% respectively according to Zohri et al. [138]. A theoretical and experimental study of a V-groove absorber showed that the electrical, thermal and overall efficiencies were in the range 10.39% to 10.26%, 41.78% to 41.57% and 52.17% to 51.81% respectively [139]. An energy analysis of a V-groove hybrid PVT collector at steady state showed that the average energy efficiency was 65.52% and 66.73% for theoretical and experimental studies, respectively [117]. Yu et al. [140] analyzed the heat transfer in parallel cooling channels with periodically expanded grooves. The presence of periodically expanded grooves caused vortex in the grooves and pressure losses in parallel cooling channels. The average temperature of the PV module with periodically expanded grooves was about 4 K lower than that of a smooth channel. A theoretical and experimental study of a V-wave absorber in an air-powered hybrid PVT collector provided exergetic efficiencies of 13.36% and 12.89%, respectively [141]. Sandooghdar et al. [142] used corrugated surfaces to cool PV solar cells. The results showed that a channel with wavelength/amplitude ratios of 0.1 and 1 showed the strongest increase in overall efficiency, 20.41% compared to conventional hybrid PVT solar collectors at the Reynolds number of 40,000.

Modification of the structure of the standard flat-air hybrid PVT collector by removing the top glass layer or adding a gap with an upper glass layer or creating a double pass channel for cooling PV solar cells, effectively improved the overall performance of the PVT hybrid collector. According to El-Hamid et al. [143], the average daily overall energy and exergetic efficiencies were 85.06% and 13.92% for the single-glazed and double-pass hybrid PVT collector respectively and 82.12% and 12.95% for the double-glazed hybrid PVT collector. In addition, the single-pass double glazing configuration with air blade had the lowest thermal and electrical efficiencies. Omer and Zala [40] experimentally showed that the overall daily efficiency of a glass-coated hybrid PVT collector was 90.48% while that of the non-glass-coated PVT collector was 62.16%. An experimental study of two air duct configurations, one double-pass and the other single-pass, using an air hybrid PVT collector showed that the average electrical efficiency increases from 14.23% to 14.81% with an increase in the mass flow of air. In addition, the average overall efficiency increased from 49.44% to 71.54% [144]. To determine the optimal configuration, Dadioti [145] studied the parameters that influence the optimal performance of hybrid PVT solar collectors. The simulation results showed that single-cover, glazed PVT hybrid air solar collectors proved to be the optimal configuration for residential applications where power generation was a priority. The cooling technique by optimizing the structural configuration optimizes the performance of PV and PVT systems. This method seems very promising, as it increases the intensity of turbulence, generates secondary flows and improves mixing fluid flows. However, these performances are mainly affected by the geometry of single-track or double-track cooling channels, glazing, dimensions of obstacles and absorbers, insulation, extended surfaces, the angle of inclination as well as the mass flow rates of air.

4. COMPARATIVE ANALYSIS OF COOLING METHODS

It is clear from this review that the electrical performance of PV modules is negatively affected by the increase in temperature of PV solar cells during operation. Approaches to improving the electrical performance of PV modules are summarised in Table 1 below. This table shows the techniques, sub-techniques, advantages and disadvantages of using different methods to cool PV modules. The analysis of this table shows that all cooling methods are used to keep the temperature of PV modules at a low and constant level and to increase their electrical performance. When these cooling methods become complex, it is necessary to use computational software for the modeling and simulation of the process of heat transfer and cooling of PV modules. A numerical simulation of mono (1-D), di (2-D) and three-dimensional (3-D) mathematical models, whether they are in steady-state or in dynamic mode allow to determine the temperature distribution of the PV module by numerically solving the governing energy equations. 1-D models provide more accurate results than 2-D and 3-D models because factors such as mesh quality, assumptions, and boundary conditions affect accuracy. However, they do not account for fluid flow in all directions. In the 2-D and 3-D models, heat transfer by conduction and convection is taken into account but the calculation cost is very high during the simulation.

Table 1: Summary of PV solar module air cooling methods reviewed.

Cooling method	Sub-technique	Advantages	Disavantages
Cooling by natural heat dissipation	Natural air convection	-No power supply -Strong free convection currents in vertical positions -Improvement of electrical efficiency - Low cost	-Low free convection currents in inclined and horizontal positions -Dependence on climatic conditions
	Heat sinks	-Heat transfer by turbulent natural convection -Reduction of temperature of PV modules	-Additional cost of heat sinks -Dependence on climatic conditions
Cooling by forced air circulation (Hybrid PVT solar collector)	Hybrid PVT solar collector	- Simultaneous production of electricity and heat -Increase in electrical efficiency	-Electric power consumption of fans -High cost of Hybrid PVT collector
	Impact of air jets	-High heat transfer coefficient -Improved performance	-Very high cost -Energy consumption -Use of an autotransformer
Cooling by thermal energy storage	PCM	-The PCM are very efficient and offer a huge potential for thermal energy storage and have good thermal inertia -No electricity consumption -Optimized performance	-Additional cost of PCM -Low thermal conductivity of the PCM -Low convection coefficient negatively affects PCM fusion -PCM are toxic and corrosive
	Heat pipes/ porous media	-Heat pipes and porous media provide good thermal inertia -No electricity consumption -Optimized performance	-Additional cost of heat pipes/ porous media -Complex system -Improved electrical efficiency of PV module -High porosity PV module temperature increase
Cooling by capture and efficient conversion of solar radiation	PV modules + thermoelectric generators	-Efficient and maximum capture of solar radiation -Additional power generation by the Peltier effect	-Atmospheric conditions must be controlled -Electricity consumption -Very high cost
	Bifacial PV modules	-Efficient and maximum capture of solar radiation -Increased efficiency electricity by reflection and albedo	-Very high initial cost -Decreased electrical efficiency for dark soil (low albedo)
	PV modules integrated in buildings	-Saving of installation space -Thermal insulation of the installation -Limited effectiveness	-Complex system -Very high cost of installation -External energy consumption for PVT
	Radiative and photonic cooling	-Generation of electricity during the day and night for the radiative -No electricity consumption -Net reduction of temperature	-Dependence on climatic conditions and need to control them -Very high cost

Cooling by optimizing the structural configuration	Addition of obstacles/baffles/ fins	-Improvement of heat transfer coefficient -Decrease in temperature of PV modules	- High calculation costs - High cost of PVT hybrid system -External energy consumption - Pressure loss resulting in additional costs
	Coupling of fins or/and baffles with PCM	-Extended flow direction -Huge potential for thermal energy storage -Decrease in temperature of PV modules	-System complexity and very high cost -High porosity PCM increases the temperature of PV module -External energy consumption
	Conduit and absorber configurations	-Increased heat transfer area -Better heat transfer	-System complexity and very high cost -External energy consumption - Pressure loss resulting in additional costs

Table 2 presents a comparison between the different cooling methods discussed in this article on the basis of electrical efficiency and thermal efficiency. Factors such as wind speed, mass flow rate, inlet temperature, different air flow channel configurations, addition of fins, baffles and PCM and the coupling of several thermal management methods contribute positively to the cooling of PV modules. Factors including wind speed, mass flow rate, fins improve the coefficient of convection heat transfer and therefore reduce the temperature of PV modules. However, not all of them contribute to improved electrical efficiency. Factors such as high solar radiation, ambient temperature and inlet temperature affect the cooling of PV modules. For example, a higher ambient temperature would prevent heat transfer from PV modules to the environment and reduce the cooling effect of PV modules. Similarly, a melting temperature of the PCM higher than the temperature of the PV module prevents cooling of the latter. Other factors that have been negative to the cooling of PV modules include channel lengths and a very large number of fins, obstructions and baffles. Increased channel length can improve the heat exchange surface and thus promote cooling, but it also increases the retention time of heat in the channels, thereby preventing its rapid evacuation. In addition, some sub-techniques such as air impact cooling and heat pipe are also interesting solutions to improve heat flow or provide a lower air outlet temperature to evacuate excess heat.

Table 2: Comparative analysis of PV module cooling methods.

Cooling technology	Factors or sub-techniques	Electrical efficiency	Thermal efficiency	Remarks
Natural heat evacuation	Natural air convection	✓	X	-Dissipation of heat on the surface of PV modules to the environment by turbulent natural convection of air -A cooling effect is low
	PV + Fins	✓	X	
Forced air circulation (Hybrid PVT solar collector)	Solar irradiance	X	✓	-A low mass thermal capacity and heat transfer coefficient, -A limited cooling effect and mass flow of air is important. It is therefore used for the production of low-temperature thermal energy
	Wind speed	✓	X	
	Air flow rate	✓	✓	
	Impact of air jets	✓	✓	

Storage of thermal energy	PV + PCM	✓	X	PCMs can store excess heat from the PV module and release it again. The low thermal conductivity of PCMs reduces the cooling advantage of PV modules.
	PV + PCM + Fins	✓	X	
	PVT + PCM	✓	X	
	Heat pipes	✓	✓	
	Porous media	✓	✓	
Efficient conversion and capture of solar radiation	PV + Thermoelectric generators	✓	X	-Maximization of solar radiation capture and conversion -Heat dissipation by infrared radiation -Improvement of the thermodynamic properties of semiconductor materials -Depends on the emissivity spectrum of the PV module surface for the radiative
	PVT + Thermoelectric generators	✓	✓	
	Bifacial PV	✓	X	
	Bifacial PVT	✓	✓	
	PV integrated in buildings	✓	X	
	PV integrated in buildings + PCM	✓	X	
	PVT integrated into buildings	✓	✓	
	PVT integrated with buildings + PCM	✓	✓	
	Radiative and photonic materials	✓	X	
Optimization of the structural configuration	Expanded Groove Absorber	✓	✓	-Optimization of structural configuration improves heat transfer and reduces temperature of PV modules -Complexity of the configuration resulting in increased investment and maintenance costs
	Curve Groove Absorbers	✓	✓	
	Rectangular Tunnel Absorber	✓	✓	
	Microchannel heat pipes	✓	✓	
	Baffles	✓	✓	
	Fins + PCM	✓	✓	
	Baffles + PCM	✓	✓	
	Single or Multiple Baffles	✓	✓	
	Fins + Baffles	✓	✓	
	Fins + PCM	✓	✓	
	Baffles + PCM	✓	✓	
	Fins + Baffles + PCM	✓	✓	

✓ : The factor or sub-technique has a positive effect.
X : The factor or sub-technique has a negative effect.

5. RECOMMENDATIONS FOR FUTURE WORK

Based on the literature review, it would be interesting to explore hybrid cooling techniques that combine several thermal management methods to improve the reliability and efficiency of solar energy production, thereby reducing operating costs and carbon emissions. The economic benefits of implementing such a technique include increased energy production (electricity and heat), reduced maintenance costs and an extended lifetime for PV modules. In the case of forced air circulation cooling, it is difficult to simultaneously improve the electrical performance of cogeneration systems for electricity and useful heat. It is therefore preferable to optimise the design of an air-cooled hybrid PVT solar collector according to the specific priority energy requirements for the production of electricity or useful heat. For example, with forced air convection cooling methods, studies can focus on the following points:

(1) Optimisation of the geometrical properties of the airflow channels and operating conditions to achieve efficient thermal management of PV modules offering improved performance at an affordable cost. For example, the airflow direction, the structure and shape of the absorber and flow channels, the geometrical dimensions of the flow channels and obstacles, the geometrical shapes of the baffles (vanes coupled to T-baffles, vanes coupled to V-baffles, T-baffles, vanes coupled to V-baffles) as reported in the experimental study of Srimanickam et al. [38] must be taken into account in future work in order to improve the thermophysical properties of the air circulating in the channel.

(2) Studies could also focus on energy storage by coupling the fins with the baffles and using different types of PCMs with different melting points and thermophysical characteristics to find the best-performing PCMs that offer optimum thermal capacity at an affordable cost.

(3) For the future of sustainable construction, new-generation materials (double-junction PV solar cells, organic solar cells, etc.), IBPV solar modules and hybrid PVT solar collectors integrated into buildings coupled with PCMs or intelligent systems for efficient thermal management will provide affordable, healthy and less expensive energy. Integrating IBPV modules into new construction and renovation projects will enable cities to increase their production of renewable energy, as highlighted by Yu et al. [109]. This integration will contribute to the objectives of carbon neutrality and mitigation of the impacts of climate change.

(4) Explore the use of new innovative materials for passive radiative and photonic cooling. Radiative materials such as nanophotonic materials, metamaterials, paints and coatings and photonic crystals using antireflective and light-trapping surfaces, back reflectors, spectrum splitters, absorption enhancers, radiation coolers or electron transport layers [146].

(5) It is also important to carry out an economic study of each photovoltaic system for a given locality. Improving the efficiency of solar PV modules would be more beneficial in terms of greenhouse gas emissions per unit of electricity produced compared to power plants currently using fossil fuels.

6. CONCLUSION

In this article, we examined the cooling techniques of PV modules and their influences on the performance of PV modules. It highlights the efforts of researchers around the world to improve the performance of photovoltaic systems. A clear distinction between cooling methods allowing natural heat evacuation, forced air circulation, efficient thermal energy storage, the efficient capture and conversion of solar radiation and the optimization of structural configurations were presented. The impact of PV modules temperature on their performance was discussed, and a detailed discussion was conducted on the coupling effect of different cooling methods (PCM + Fins, PCM + Baffles, PCM + Fins + Baffles) in the forced air flow channel on the performance of the hybrid PVT solar collector. Based on the analysis and results presented in this paper, further research and development into more efficient cooling methods for PV modules is required. Improving the convection coefficient in the case of forced air circulation is a major challenge. New innovative materials for passive radiative and photonic cooling and the integration of IBPV modules into new construction and renovation projects in cities will increase their production of reliable, cost-effective renewable energy.

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