archives
of thermodynamics
Vol. **44**(2023), No. 4, 581–617
DOI: 10.24425/ather.2023.149720

Photovoltaic panels cooling technologies: Comprehensive review

OSAMA ABD AL-MUNAF IBRAHIM
SAIF ALI KADHIM*
MOAFAQ KASEIM SHIEA AL-GHEZI

Mechanical Engineering Department, University of Technology – Iraq, Baghdad 10066, Iraq

Abstract The solar radiation absorbed by photovoltaic panels is not fully utilized in the production of electricity. When the photovoltaic panels are exposed to solar radiation, part of the energy of the incident radiation is transformed into heat accumulated inside these panels. The heat accumulated inside the photovoltaic panels causes two types of losses. The first type of losses is the increase in the operating temperature of the panels and the deterioration of their efficiency and life span. The second type of losses explains that part of the energy of the incident radiation is transformed into heat inside the panels and does not contribute to the production of electrical energy. There are several cooling systems that have been applied to photovoltaic panels for the purpose of regulating their temperature including air, water, and nanofluid cooling systems, which are mostly done by placing a solar collector in the back side of the photovoltaic panels (PV/T). There is also a recently used system that uses phase change material (PCM) in cooling. This paper provides a comprehensive review of several cooling methods and their improvements that researchers have focused on. Through this review, it is clear that the best improvement in the performance of the photovoltaic panel occurs when using PCM because of the high heat transfer coefficient of these materials. Performance improves more when the addition of nanoparticles to the phase change material (PCM-Np) and also when merging (PCM) with (PV/T).

Keywords: Solar energy; Photovoltaic panels; Solar collector; Cooling; Phase change materials

*Corresponding Author. Email: 20292@uotechnology.edu.iq

1 Introduction

The world is moving towards exploiting and benefiting from renewable energy as clean energy. This energy can be obtained from wind, water, earth and sun. One of those clean energies is solar energy because it does not contain harmful emissions (carbon dioxide, carbon monoxide, etc), and has zero waste generation [1]. Solar energy provides the world's energy requirements such as electricity, hot water, etc. to a limited extent, but it has begun to escalate in recent years [2–6]. Photovoltaic (PV) panels consist of solar cells that use solar energy to generate electrical energy from solar radiation, and their use has spread greatly in recent years because they are considered clean energy that has no side effects on the environment, no fuel costs, and are inexpensive in terms of maintenance. This explains the increase in global demand for solar energy. In addition to the fact that photovoltaic systems can provide electrical energy at night in the absence of sunlight by using batteries and charging them during the day and then using them at night. These features encouraged investors and global energy producers to expand toward the production of electric energy utilizing photovoltaic panels [7]. Photovoltaic cell consists of semiconductors, usually silicon that are compressed into a specially treated wafer to form an electric field positive at one end and negative at the other. When the light energy reaches the cell, electrons are released from the atoms in the semiconductor material. The electrons reach a higher energy state to generate electricity and the electrons are collected in the form of an electric current [8]. Photovoltaic panels have been recognized all over the world due to their inexpensive maintenance and operating costs [9]. The global market of photovoltaic panels in 2019 released a report stating that there was a 12% increase in the installation of photovoltaic panels from 2018 to 2019 [10]. Exactly at the end of 2019, a total of (720 GW) of photovoltaic panels have been installed worldwide, and the capacity of photovoltaic panels will be around (8500 GW) as expected by 2050 [11, 12], as illustrated in Fig. 1.

The disadvantages of the available photovoltaic units are that electricity production is not high because they produce approximately 5% to 25% of the electricity harvested from solar radiation [12], and because solar radiation generates heat in the photovoltaic panels [13]. The generation of heat resulting from solar radiation raises the photovoltaic panel operating temperature, and this has a negative effect on its electrical performance [14] and lifespan [15], and causes an increase in the recovery period [16].

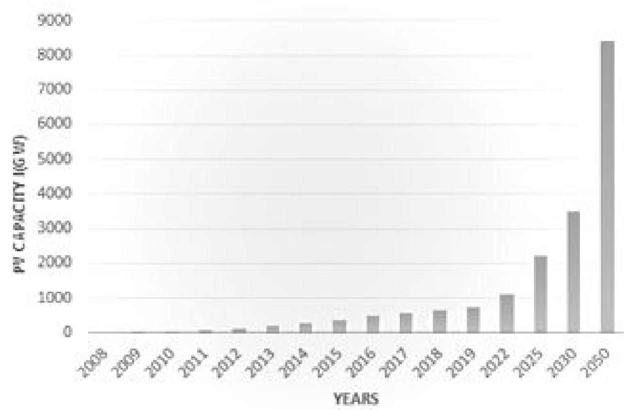

Figure 1: The growth of photovoltaic panel capacity globally [12].

Manufacturers of photovoltaic panels set their test temperature to operate optimally at 25°C. Practically the maximum efficiency of photovoltaic panels is in the operating temperature range from 15°C and 35°C. Any increase in the temperature of the photovoltaic panels leads to a deterioration in their efficiency. It has been reported by the National Renewable Energy Laboratory that the impact of high operating temperatures of photovoltaic panels outside the recommended range leads to a deterioration in efficiency between 0.005–0.008 per year. To ensure that photovoltaic panels operate at maximum efficiency, their temperature must be controlled within 15–35°C, hence the idea of cooling photovoltaic panels [2].

Many researchers suggested multiple cooling solutions, such as taking advantage of the heat absorbed from photovoltaic panels as useful thermal energy, and this is named the hybrid photoelectric/thermal system [17]. The obtained heat from this system is used in heating domestic water [18], drying food [19], ventilation [20], and some other applications. Hybrid systems need less space than photovoltaic panels to obtain the same amount of energy [21]. Therefore, some researchers have placed a solar thermal collector behind the photovoltaic panels to harvest most of the energy that is disposed from the solar panels to avoid its loss and reuse it for productive purposes [22, 23], as illustrated in Fig. 2.

The photovoltaic panels will not operate in standard conditions but close to them, with good productivity, and take advantage of the heat transferred by refrigerants (air, water, and nanofluids) in many other applications [24]. This technique has several options in which more hybrid configurations can

Figure 2: Solar photovoltaic system combined with solar thermal system in a hybrid photovoltaic thermal (PV/T) system [23].

be considered [25] such as using silicon or non-silicon materials in manufacturing photovoltaic cells, or solar thermal collectors [26].

Researchers exploited the hybrid system of photovoltaic panels to develop it using water in cooling with different techniques, whether through copper tubes or spraying water, and others [27–30]. The other researchers used a phase change material (PCM) to store heat such as paraffin wax, sheep fat, etc. It was concluded that when nanoparticles are added to the phase-changing materials (PCM-Np) in the photovoltaic panels cooling systems, the efficiency and the heat capacity of these systems improve. This means that they can absorb larger amounts of heat accumulated inside the photovoltaic panels and reduce their operating temperature, thus increasing the efficiency of those panels [31–36].

This study provides a comprehensive review of the most prominent technologies used in photovoltaic solar panel cooling, such as cooling by water or nanofluid or air through tubes, cooling by water spraying, and cooling by using phase change material (PCM), etc., then, comparing these technologies and highlighting the advantages and disadvantages of each.

2 The temperature effect on the performance of photovoltaic panels

When the photovoltaic panel is exposed to sunlight, energy is transmitted to the electron resulting from the fall of photons generated from solar radiation on the atom, and this energy enables the electron to move to the conduction zone and release from the valence zone [37]. Raising an electron to the conduction zone requires the least energy required, and this energy is called the gap energy. This energy is equal to the energy of a photon and can be expressed by Eq. (1) [38]:

$$E_G = E = h\,f\,, \tag{1}$$

where: E_G – the bandgap energy (J), E – the energy of a photon, h – Planck constant $= 6.63 \cdot 10^{-34}$ Js, f – frequency of solar radiation photons (Hz).

The solar cells operating temperature (photovoltaic panel) increases due to the thermal loss of electrons [13]. An electron releases energy when it crosses the conduction zone when it returns to the same range. Heat is generated in the photovoltaic panel and its operating temperature increases as a result of the energy emitted from the electron while crosses the conduction zone and returns to the same zone again [39]. In the event that the electron does not have enough energy to cross the conduction zone, the electron discharges energy on its way back to the valence zone. This energy will lead to an increase in temperature [40]. A photon hits an electron with energy equal to the band gap energy, this causes the electron to move to the conduction zone from the valence zone. This means that when the photon's energy is greater than the bandgap energy, the excess energy results in the heat for the materials. When the energy of a photon is less than the band gap energy, the electron is excited to the conduction zone from the valence zone and instantly back to the valence zone and electron energy is emitted as heat, that heat called band gap losses [37,41].

The dependence of the temperature on the efficiency of the photovoltaic panel obtained from the dependence of the open circuit voltage on the temperature is as follows [41,42]:

$$\eta_e = \frac{V_{oc}\,I}{G_T\,A}\,, \tag{2}$$

$$\frac{d(V_{oc})}{dt} = \frac{1}{T_{pv}}\left(V_{oc} - \frac{E_G}{q}\right), \tag{3}$$

where: η_e – electrical efficiency of the photovoltaic panel, V_{oc} – open circuit voltage (V), I – supplied current (A), G_T – incident solar radiation (W/m^2), A – panel area (m^2), T_{pv} – photovoltaic panel operating temperature (°C), q – heat losses (J).

Because $\dfrac{E_G}{q}$ will be greater than V_{oc}, the change in the open circuit voltage $\left(\dfrac{d(V_{oc})}{dt}\right)$ will be negative due to the increase in temperature. Therefore, when the operating temperature rises, the open circuit voltage of the photovoltaic panels decreases [43]. Figure 3 shows the change in voltage and current at different temperatures and Fig. 4 shows the open circuit voltage and the power of the photovoltaic panel ($P_{\max}$) for crystalline silicon solar cell. If the temperature is increased, the short circuit current (I_{sc}) is increased by a little [44, 45].

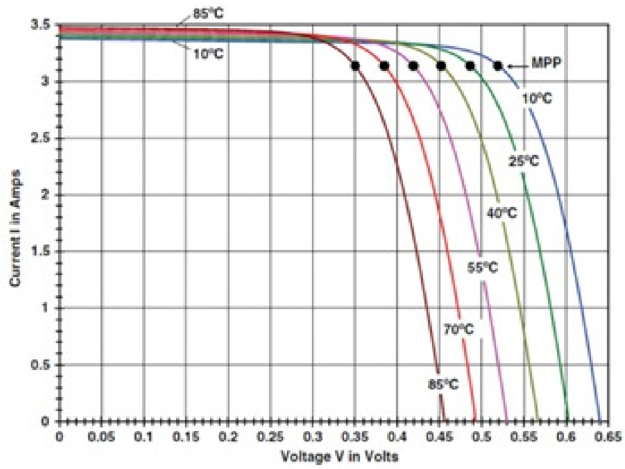

Figure 3: The change in voltage and current with temperatures as a parameter [13].

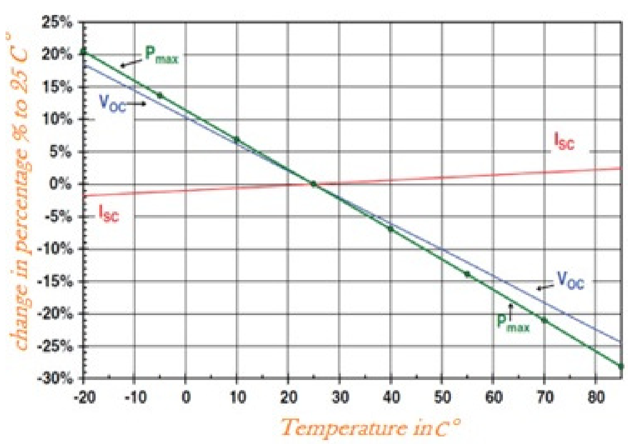

Figure 4: The change of V_{oc}, $P_{\max}$, and I_{sc} with temperature [13].

The researchers had an active role in studying the effect of high temperature of photovoltaic panels in different climatic conditions on their electrical performance. Wysocki and colleagues [46] studied how photovoltaic energy from the sun converts to a semiconductor in the case of a different bandgap from 0.7 to 2.4 V and at temperatures ranging from 0–400°C. In the case of temperature increase, the electrical performance is significant in high bandgap semiconductors. They found that gallium arsenide (GaAs) performs well at temperatures less than 200°C.

Akhmad *et al.* [47] examined two different PV modules for their electrical performance and used (amorphous silicon – polycrystalline silicon) in outdoor conditions in Japan. The efficiencies of crystalline crystals and amorphous silicon decreased by (92% and 89%), over 2 years from the beginning of their installation because of the effect of its temperature increase and ageing of modules.

Radziemska *et al.* [48] changed the temperature from 22°C to 70°C for a monocrystalline PV panel and observed a 0.8% decrease in PV output power. Radziemska *et al.* [49] and Meneses-Rodrĭěguez *et al.* [50] tested the effect of increasing the temperature on a silicon crystal panel. The results of the study explain that when the plate temperature was increased by one degree Kelvin, the output power and efficiency reduction rate were about 0.65% and 0.08%, respectively.

Brinkworth *et al.* [51] and Usami *et al.* [52] studied the effect of increasing the temperature on the photovoltaic panels (cadmium telluride) made of stainless steel layer and showed that the OCV (open circuit voltage) decreases linearly in the case of increasing temperature with a slope 2.5 mV/°C.

Huang *et al.* [53] studied how different temperatures affect photovoltaic panels behaviour and found a good result with the relationship as shown in Eq. (4):

$$V_{oc} = A_{oc} - C_T\,T_J\,, \tag{4}$$

where: A_{oc} – intercept coefficient, C_T – temperature coefficient (V/°C), T_J – solar cell junction temperature (°C). It is clear from Eq. (4) that the open circuit voltage (OCV) in the photovoltaic panel decreases in the case of increasing temperature.

Singh and Ravindra [54] conducted a theoretical study to investigate the effect of temperature on the electrical properties of photovoltaic panels. The study included an analysis of the performance of several types of photovoltaic cells (GaAs, Ge, InP, Si, CdTe, CdS) for operating temperature ranges between (273–523 K), a solar spectrum (0 AM and 1.5 AM) found a direct relationship between the temperature increase and the reverse saturation current, while the relationship between the temperature and the performance of the photovoltaic panels is inverse. In addition, the bandgap decreased with increasing temperature, which consequently led to increase the current of the short circuit.

Bando *et al.* [55] conducted an investigation to study how the photovoltaic units are degraded after a long period of time up to (28 years) in a desert area. After the detection procedure, the coating material was discoloured and the glass was broken and scratched, discharged, discoloured and hot spots formed; the energy decline rate for the year was 1.2%.

It is clear from the previously mentioned papers that the electrical performance is affected when the operating temperature of photovoltaic panels is changed, meaning that the electrical performance decreases with increasing temperature and vice versa in multiple climatic conditions. High temperatures shorten the life span of photovoltaic panels. Therefore, controlling and managing high temperatures is necessary [56,57]. The researchers made many attempts to improve the performance of the photovoltaic cell by using various techniques in its cooling, which will be discussed in the next sections.

3 Cooling of photovoltaic panels by water and nanofluids

The simplest type of photovoltaic panel cooling system consists of a heat exchanger installed on the back surface of the photovoltaic panels [58], as in Fig. 5. The main component of the heat exchanger are tubes usually made of copper through which the heat transfer fluid (water) passes. The heat is absorbed from the photovoltaic panel through the pipes, then transmit-

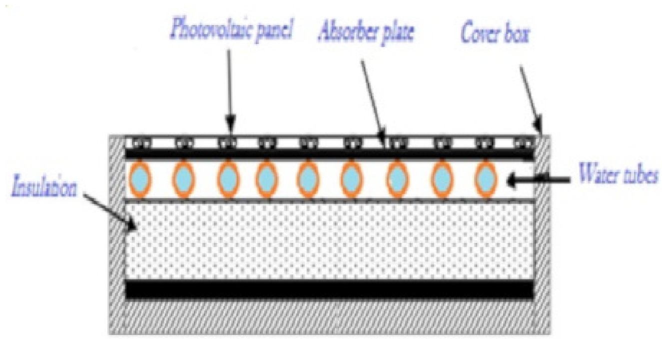

Figure 5: Cross section of photovoltaic panel water cooling [59].

ted to the cooling medium to be removed to the outside or used in other applications such as heating residential homes, for example. These systems can be complicated by changing the composition of the heat exchanger by changing the shape and type of material from which these tubes are made, in addition to changing the heat transfer fluid (cooling medium), such as using oils, phase-changing materials, or adding nanoparticles to these cooling media. There are other techniques for cooling photovoltaic panels with water like spraying and immersion.

Different researchers conducted different studies of water cooling photovoltaic cells using different heat absorber designs, for example, Huang *et al.* [60] used different types of crystal heat absorbers aimed at increasing the efficiency of photovoltaic panels, some of which consist of tubes in the form of channels of tube spacing W and diameter D equal to 6.2 and 10, respectively. The others consist of polycarbonate, this type showed the best results in the thermal performance of the panels. The test was carried out on a daily basis, the average solar radiation ranged according to the hours of the day, starting from 250 W/m^2 in the early morning to 850 W/m^2 in the middle of the afternoon; the readings were taken for several days. The ambient temperature ranged from 25°C to 34°C, according to the days of the test. The results showed a direct behaviour between the water temperature and the PV panel temperature, and a daily electrical efficiency for conventional PV was found at 9%.

Chow *et al.* [59] used an aluminum heat sink and its flow channels were made in a rectangular shape, the readings were taken on one summer day from 8:00 to 16:00, and recorded every 5 minutes. The absorptivity of the photovoltaic panel was 0.8, the emissivity was 0.8, the intensity of solar radiation was 800 W/m^2, the ambient temperature was 20°C, and the wind speed was 2.5 m/s, the daily thermal efficiency ranged from 37.6% to 48.6%, and daily electrical efficiency ranged from 10.3% to 12.3%.

Ji *et al.* [61] studied the pipe size effect and water mass flow rate on thermal and electrical performance. The test was conducted for three days to check the performance of the electrical power and for 3 different flow rates. Increasing the size of the tube led to a high heat loss from the outer tube surface, in addition to an increase in the water mass flow rate to more than 0.03 kg/s. These led to a decrease in the operating temperature of the photovoltaic panel due to the increase in the rate of heat transfer by increasing the conduction between the photovoltaic panels and the outer surfaces of tubes on the one hand, and on the other hand, increasing the heat transfer by convection between the inner surface of the tubes and the cooling medium that passes inside them. On days 2 and 3, it was observed that the daily electrical energy output improved slightly, despite the increase in the flow rate from 0.1 to 0.9 kg/s. On day 3, however, power output only improved by less than 10 W. The highest solar radiation intensity was 432 W/m^2 and the ambient temperature was 25°C.

Ibrahim *et al.* [62] carried out simulations of different heat absorbers and discovered that the so-called spiral type heat absorbers had a high performance in general, this performance attributed to the hollow tubes that are used, and these tubes are rectangular in shape. The tests were at an ambient temperature of 25°C. It was observed in the results that the design of the spiral flow gave the highest total efficiency (thermal and electrical) of 68%, but the serpentine flow design gave the lowest total efficiency of 45%, relative to the flow rate.

Bahaidarah *et al.* [63] made a performance test on a photovoltaic panel cooled by water on the back surface (by canals), from 9 am to 4 pm during one day. The surface temperature of the photovoltaic panel was 45°C, while it decreased when using water to 34°C. The energy production of the PV system with water was approximately four times higher than that of the PV system alone. Also, the results showed a decrease in the operating temperature of the photovoltaic panel and an increase in electrical efficiency that reached 2.7% when using cooling technology.

Matias *et al.* [64] investigated the possibility of increasing the PV output power by reducing the operating temperature, as their production increased after using water at a flow rate of 0.6 l/s at an initial temperature of the photovoltaic panel 25°C equal to the ambient temperature. The photovoltaic panel produced maximum power during test day 63.09 W without cooling and in the case of cooling it produced 78.74 W.

Fakouriyan *et al.* [65] conducted an empirical analysis of the efficiency of photovoltaic panels and they made a comparison in the case of presence or absence of the cooling system. During the test day at the ambient temperature of 37°C, a power improvement of 10 watts was obtained, and the panel surface temperature without and with cooling was 62°C or 44°C, respectively. It was also concluded that the daily electrical efficiency of photovoltaic panels without a cooling system was 10.9%, while the daily electrical efficiency of the same panels with a cooling system improved to 12.3%.

Moharram *et al.* [66] used the technique of spraying with water only once and during a specified period of time to improve the performance of the cell. They discovered through their studies that this method is useful and can be used in the regions where the weather is characterized by high temperatures or is dusty. The PV panel temperature was 45°C and the ambient temperature was 35°C. The test was conducted in two days, a day in June and a day in July were chosen. They have concluded that the cooling rate of the photovoltaic panels was 2°C/min and this led to an improvement in efficiency and output power for these cells. The maximum electrical efficiency of the PV panel improved from 10.5% to 12%; this means that the electrical efficiency improved by 1.5% in July.

Nižetić *et al.* [67] worked on regulating the temperature of the photovoltaic panel by using the technique of spraying water on PV front and back surface with a flow rate of 225 l/h and a pressure of 4.8 bar, as shown in Fig. 6. The test was conducted on a clear summer day, and the ambient temperature ranged from 27°C to 30°C, and the solar radiation rate ranged between 810 W/m^2 and 850 W/m^2. It was noticed that cooling from the back surface lowered the temperature more than what happened in the surface frontal, therefore, the maximum electrical efficiency during the test improved from 13.92% to 15.92%, and the maximum output power increased by 4.9 W. It is worth noting that droplet size is a key parameter in cooling effectiveness [68].

Figure 6: Cooling the front and the backside of the photovoltaic panel [67].

Mehrotra *et al.* [69] used a water immersion cooling technique for photovoltaic panels, as shown in Fig. 7. The test was conducted in April during 6 days, the average intensity of solar radiation ranged between 670 and 1170 W/m^2 during the day, and the ambient temperature ranged between 33.5 and 38.4°C. They showed that there is an increase in the daily electrical efficiency of the photovoltaic panel by $\sim 1\%$ when immersed to a depth of 1 cm.

Abdulgafar *et al.* [70] presented the study for the cooling of PV panels through the water immersion technique. The tests are done on a small polycrystalline silicon panel with different depths from 1 to 7 cm. On the test day, conditions were as follows: the average solar radiation value – 700 W/m^2, the ambient temperature – 36°C, and the water temperature range was between 28–30°C. Through the results, it was observed that the best power output was at a depth of 1 cm with solar radiation of 444 W/m^2, which reached 0.111 W.

Figure 7: Photovoltaic panel immersion technique [69].

The PV cooling system technology has been upgraded by using additives for water such as nanomaterials and alcohols to create liquids with high thermal properties to obtain the best rate of heat transfer between photovoltaic panels and the solar thermal absorber. Several researchers presented studies on the usage of nanofluids to cool photovoltaic panels. Aberoumand *et al.* [71] used Ag/water nanofluid for cooling a PV/T system, by using 4 wt% nanofluids (with the turbulent flow), the test was conducted during 7 consecutive days in June, the average solar radiation ranged from 400–850 W/m^2, and the ambient temperature was 25°C. It was observed that the electrical efficiency during daylight hours ranged between $\sim 8.1{-}9.8\%$,

$\sim$ 9.4−10.9% and $\sim$ 10.3−12.2% for no cooling, water cooling and nanofluid cooling, respectively.

Al-Ghezi *et al.* [72] used a nanofluid consisting of copper oxide nanoparticles and surfactants dispersed in water with different weight concentrations as cooling fluids. The test was conducted during one day, and the ambient temperature was 25°C, the solar radiation rate ranged from 250–1000 W/m^2. The results showed that the daily electrical efficiency of the photovoltaic panel was enhanced by 2.9% approximately when using the prepared nanofluid (2.0% nano-CuO), compared to the use of water only.

Murtadha *et al.* [73] used titanium dioxide nanofluid with different weight concentrations as a cooling fluid in two passes circulation as shown in Fig. 8, to lower the PV panel surface temperature and improve the performance of the photovoltaic/thermal system. Standard test conditions during test day were: ambient temperature equal to 25°C and the solar radiation intensity ranged from 501 to 866 W/m^2. It was discovered that the cooling system reduced the surface temperatures by 19.0% at a higher weight concentration, the results showed that the increase in the daily electrical efficiency was 1.26% compared to the use of water during the test day.

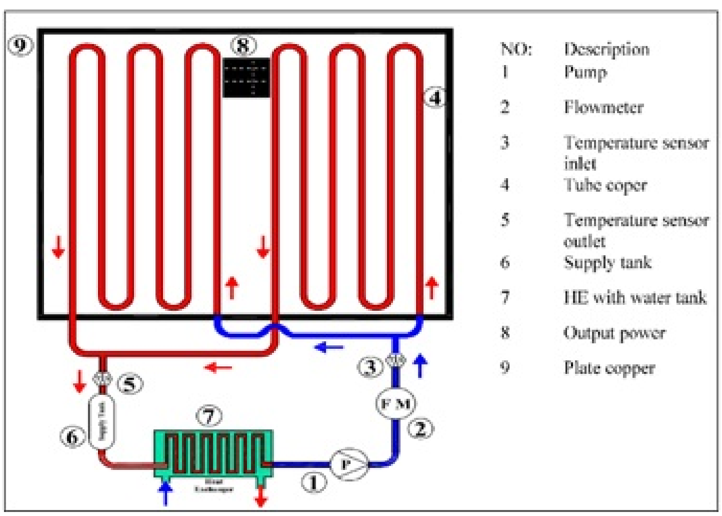

Figure 8: Schematic diagram of two passes fluid circulation in PV/T system [73].

Sathyamurthy *et al.* [74] used a hybrid nanofluid (carbon nanotube & aluminum oxide/water) as a cooling fluid. The tests were conducted at an ambient temperature ranging between 25–35°C. The intensity of solar radiation ranged between 100–1050 W/m^2. The maximum temperature of the photovoltaic panel was 56°C without cooling, and 30°C with cooling during the test day. The electrical efficiency increased during the noon by 4.5% and 2%, compared to those without cooling and with water cooling, respectively.

Ebaid *et al.* [75] used two types of nanofluids, namely Al_2O_3 in a water-polyethylene glycol mixture at pH 5.7, and TiO_2 in a water-cetyltrimethyl ammonium bromide mixture at pH 9.7 with three concentrations of weight. Results showed on the test day that the nanofluid cooled PV panel in both types caused a higher decrease in the average PV panel temperature compared with the cooled cell with water and without cooling. In addition, electrical analysis of power and efficiency showed that TiO_2 nanofluid gives better performance at all volume flow rates. The concentrations studied were compared with water cooling and without cooling. The increase in the daily electrical efficiency of photovoltaic panels in the presence of nanofluid is 0.82% and for water cooling is 0.48% compared to the absence of cooling.

Kazem *et al.* [42] used a fluid consisting of water, copper oxide nanoparticles, and ethylene glycol to cool a photovoltaic panel. The results showed that the daily efficiency of the photovoltaic panel was enhanced by 2.5% for the prepared nanofluid (2.0% nano-CuO) compared to the use of the base fluid only (water).

4 Cooling of photovoltaic panels by air

In these cooling systems, the working fluid (cooling medium) is air. Air flows under conditions of forced or natural flow. The fluid flows through openings or channels at the top of the photovoltaic panel and at the bottom of it. The fluid (air) flows up and under the photovoltaic panel, and the air cools it by convection [76]. Adding fins behind the photovoltaic panel increases convective heat losses from the photovoltaic panel [77], as shown in Fig. 9. The heated air which is obtained can be used in several applications.

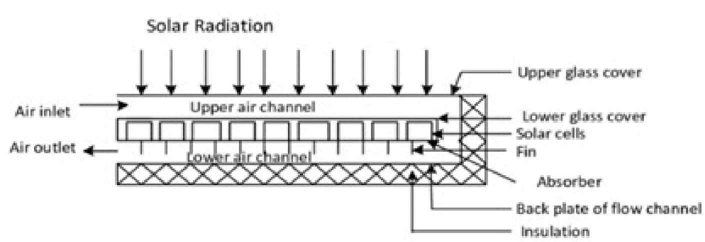

Figure 9: Cross-sectional view of double-pass air photovoltaic panel with fins [77].

The performance of air-cooled photovoltaic panels has been investigated by numerous researchers using different heat sink designs by controlling the flow of different masses of coolant (air). This process was done by Sopian *et al.* [78] who studied the photovoltaic panel cooled by air at 0.046 kg/s where the maximum enhancement in electrical and thermal performance was obtained.

Air-cooled photovoltaic panel experimental analysis was performed by Othman *et al.* [79] who combined a photovoltaic panel with a composite parabolic collector and fins using forced air convection. The effect of increasing the flow rate on the electrical efficiency was small in relation to the amount of air entering where the best increase in electrical efficiency did not exceed 1% at conditions of a flow rate of 2 kg/s in the test day, constant solar radiation of 500 W/m^2 and an ambient temperature 31–32°C. The thermal performance increased significantly under these conditions.

Tripanagnostopoulos [80] made a different development in the photovoltaic panel by using a thin metal plate in the centre of the channel and embedded fins behind the channel's back wall. This led to an increase in the daily electrical efficiency to 1.9% at an ambient temperature of 20°C during the test day.

Sopian *et al.* [81] improved the thermal efficiency of an air-cooled photovoltaic system using porous media in the bottom channel of the coupling. The thermal efficiency was very close between the values obtained theoretically and experimentally for solar radiation of less than 570 W/m^2, the introduction of porous media into the second channel increases the heat transfer area. At an ambient temperature of 33.5°C, at radiation intensity from 546 W/m^2 to 614 W/m^2, the thermal efficiency ranged from 70–90%. It can also be seen that the thermal efficiency increases with the increase in solar radiation.

Mohd *et al.* [82] performed a study to investigate PV performance improvement using a grooved absorbent plate by a solar simulator with intensities set at 386 W/m^2 and 817 W/m^2. The study found an increase in daily electrical efficiency by about 1% and thermal efficiency that may reach 30% when using this type of absorbent plate. They found that the electrical and thermal efficiency increase when the radiation intensity and air velocity increase.

Hussain *et al.* [83] placed an aluminum honeycomb heat exchanger absorbent plate behind the monocrystalline photovoltaic panel and studied the effect of different masses of air from the air. The highest daily thermal efficiency achieved was 87% at an air mass flow rate of 0.11 kg/s and irradiance of 828 W/m^2. The system of honeycomb photovoltaic panels shows better results for electrical efficiency at the same air flow rate. The daily electrical efficiency improved from 7% to 7.13% compared to the case of absence of the heat exchanger.

Mazón-Hernández *et al.* [84] conducted research on the effect of cooling air freely as well as when it is forcibly passed on photovoltaic panels at different velocities 2 m/s and 4 m/s. Air was projected into a channel of variable height. The tests were conducted in one day under different ambient temperatures ranging between 5–30°C. Forced convection with an air velocity of 4 m/s gave the best performance, as the daily electrical efficiency improved by 0.8 to 1%. The operating temperature of the photovoltaic panel was about 45°C, then decreased by about 15°C when subject to forced air cooling.

Popovici *et al.* [85] used the heat sinks cooling method to improve the efficiency of the photovoltaic panels that contain ribs set at different angles (45°, 90°, and 135°). The average operating temperature of the photovoltaic panel was 41.87°C, while the maximum operating temperature was 56°C during a clear summer day. The highest energy was obtained during the day at an ambient temperature of 25°C where the maximum electrical power of the photovoltaic panels increased from 6.97% to 7.55% relative to the results of the base case for angles 45° and 90°.

5 Cooling of photovoltaic panels by using phase change materials

Phase change materials (PCMs) offer an attractive solution because they have a heat capacity several times greater than systems based on cooling by air or water. This is because these materials are capable of absorbing and releasing a large amount of latent thermal energy by changing their state from one phase to another (solid to liquid) or vice versa within a certain temperature range [86]. Because of the low storage capacity of the thermal photovoltaic system based on water and air, researchers were inspired to develop a thermal management system that stores latent heat with phase change materials. These materials have the ability to absorb heat and release it during the melting or solidifying process. Phase change materials keep absorbing heat without an increase in the operating temperature and when these materials solidify, they release latent heat to the environment [87]. When using these materials in the heat storage process, the temperature of the storage materials is kept constant [88]. Consequently, phase change materials are very convenient for the thermal control of photovoltaic panels [89]. In the 1980s and early 1990s, phase-change materials found their way into solar energy applications [90].

5.1 Classifying phase change materials

Phase change materials are used in photovoltaic panels for the purpose of storing thermal energy. These materials have three known states: solidification, solubility, and gaseousness. The states of solidification and fusion are considered among the basic properties [91]. These materials are energy storage materials whose fusion temperature is high [92]. Phase change materials are classified into three types: organic, inorganic and eutectics, each has merits and demerits [88], which can be distinguished on the basis of the latent heat of fusion and temperature of the melt, as shown in Fig. 10.

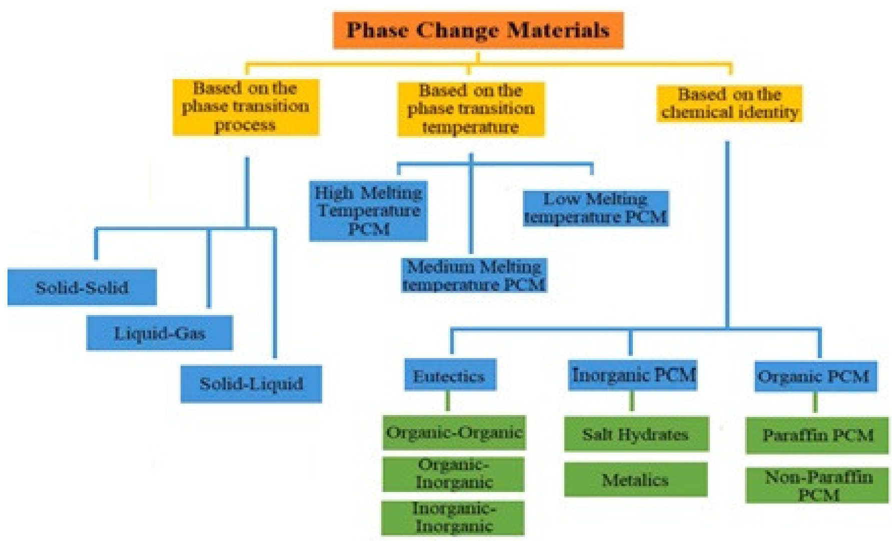

Figure 10: Phase change material description chart [93].

5.2 Selection criteria for phase change materials

Several types of phase change materials are available that have been used by many researchers. Therefore, care must be taken in choosing the phase change materials because of their great importance. Sharma *et al.* [94], Abhat [95], Sarbu and Sebarchievici [96] indicate that these materials have multiple properties that must be taken into consideration such as chemical, thermal, physical and economic properties in order to reach the optimum thermal performance. However, no substance possesses all of these properties [97].

In the case of selecting a phase change material, the temperature of the phase transition is determined, which in turn is dependent on the melting temperature of the phase change material. The phase change materials absorb heat after completing the melting phase without raising its temperature. Moreover, thermal conductivity is a requirement for the selection of phase-change materials as well as a heat storage density to complete the melting phase. On the other hand, the main characteristics of the photovoltaic system based on phase change materials are uniform cooling of the photovoltaic panel [98], high rate of heat absorption, long-term cyclic stability with a greater mass density, absence of super-cooling, immobile parts, significantly lower maintenance cost and ease of use for practical applications [17]. It is assumed that phase change materials that are environmentally friendly are selected. It should be noted that most phase change materials are very expensive materials in the commercial market.

5.3 Improving phase change materials

Researchers have been widely using phase change materials in controlling the thermal control of photovoltaic panels. Many researchers recommended that the melting temperature of these materials is 25°C, and this temperature is suitable for the photovoltaic panel in terms of thermal control in summer [99, 100]. Other researchers have chosen a high melting point for phase change materials to suit the conditions of a warm climate [101]. The melting point of these materials is the key factor that improves the thermal performance of photovoltaic panels to obtain high electrical power. To have good thermal control of the PV panel, the temperature of the PV panel should be higher than the melting temperature of the phase change materials [102]. The operating factors of phase change materials, for example, the layer thickness and melting temperature were improved in order to improve the thermal management of the photovoltaic panel; the phase change materials were improved by exposing them to different solar radiation and temperature [103].

PCMs are installed on the back of the photovoltaic panel and placed inside a container as shown in Fig. 11 [104], the container in some cases made of aluminum and isolated from the outside with a wooden box. One of the advantages of PCMs is that when they absorb heat from the photovoltaic panel, the operating temperature does not increase but is regulated [105]. Some researchers studied the behaviour of heat absorption of phase change materials with its temperature, as shown in Fig. 12. As the temperature of the PCM rises as a result of heating, then heat absorption occurs by the PCM, and at the same time, its temperature remains almost constant [106]. It is useful to control a constant temperature of the PCM to maintain a continuous heat sink and to avoid overheating it to its maximum capacity.

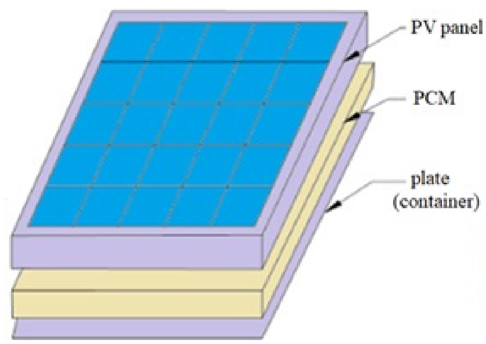

Figure 11: PCM installation in PV panel [104].

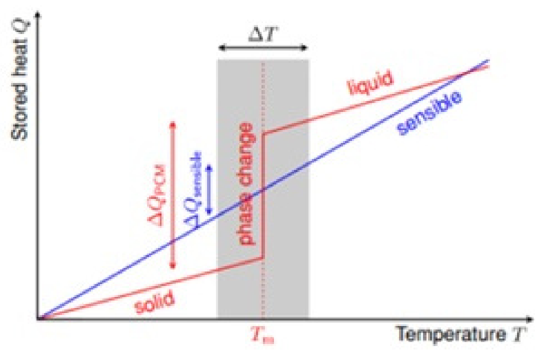

Figure 12: Thermal behaviour of PCM [106].

5.4 The most prominent studies to increase the performance of PV panel using PCM

Most researchers in this field (cooling by PCM) have used Rubitherm (RT) which is an organic phase change material. The solid-to-liquid fusion process (and vice versa) is utilized for these materials in order to store and release heat at a temperature depending on their melting point due to their specific purity and composition. These phase-change materials exhibit a remarkable latent heat capacity in narrow temperature ranges. They are chemically inert and have an indefinite lifetime. It has many types such as RT25–RT20 (paraffin wax), GR40 (Rubitherm GmbH 2000), etc. [107].

Simulations were made for three models of different metals to preserve the phase-changing materials, and fins were added to the metals, as done by Huang *et al.* [108] who found that using this system with fins would well regulate the operating temperature of the photovoltaic panels. The radiation intensity was 1000 W/m^2 and the melting point of the paraffin wax (PCM) was 32°C. Aluminum and copper fins were used in it. The average temperature for aluminum was 38.3°C and for copper was 37.6°C for the test time. The time taken in the test was from 0 to 100 minutes. The ambient temperature was 20°C. Simulation and theoretical analysis of paraffin wax and its thermal behaviour were made, showing that it had a significant effect on reducing the temperature of the photovoltaic panel, and storing heat and keeping it in aluminum containers (aluminum is considered a good material for container manufacturing and has a low cost). The photovoltaic panel temperature was controlled under 38°C for 1.5 hours during the day.

Huang *et al.* [109] introduced various shapes of fins such as straight, wire matrix, ribbon matrix, and a container filled with phase change materials RT25 and GR40. The solar radiation was 750 W/m^2 and the ambient temperature was 23°C. It was found that the temperature of the photovoltaic panel can be kept below 29°C if the type of fins called wire-array is used for a long time with the RT25. It is proved that RT25 has a better temperature control of the PV panel and thus may provide a potential increase in electricity.

Hasan *et al.* [99] made four systems of phase change photovoltaic materials: system 1 of aluminum, having an internal width of 5 cm; system 2 of perspex, having an internal width of 5 cm; system 3 of aluminum, having an internal width of 3 cm; system 4 of the perspex, with an inner width of 3 cm, using five different phase change materials (RT20, capric palmitate, capric lauric acid, calcium chloride and salt hydrate commercial blend SP22). The melting temperature for PCMs was 25 ± 4°C and the radiation intensity was 1000 W/m^2. The temperature of the photovoltaic panels was reduced by 10°C as a maximum.

Huang *et al.* [110] studied and evaluated the thermal performance of the photovoltaic phase change system by using three different types of phase change materials such as WaxsolA, RT27 and RT35. Note that the temperature was reduced by 21°C compared to a regular PV panel when using the RT27 at a radiation intensity of 750 W/m^2. Its melting point is 25–28°C, and the ambient temperature is 19°C.

Huang *et al.* [111] manufactured photovoltaic phase change material systems by placing and mixing the phase change materials: RT21, RT24, RT27, RT31 and RT60 in a container. Mixing the two materials RT27 and RT24 contributed to the effect of decreasing the temperature of the photovoltaic panels, and reduced the temperatures to 21°C and 25°C. The largest received electrical energy was 1.9 kWh/day with respect to the reference PV panel in one-day performance in June.

Japs *et al.* [112] mixed an aluminum polymer complex with paraffin-based phase change materials in variable-material bags. These bags are well-wrapped and glued behind the photovoltaic panel. The readings were stable for a period of time at the temperature of the photovoltaic panel compared to the normal panel, and this period was 5.5 hours. During the test day, which was on July 21, the maximum temperature of the ordinary PV panel reached 53–55°C, while the maximum temperature of the photovoltaic module containing phase change materials reached 45–48°C. It can be concluded that the high heat capacity of the PCM storage leads to a higher output of electrical energy, and the higher thermal conductivity of PCM results in a lower operating temperature of the PV panel.

Hasan *et al.* [113] used three types of phase change materials to reduce the temperature of the photovoltaic panel (cool it), and these materials are salt hydrates, fatty acids, paraffin wax, and RT22. It was pointed out that the phase change material used should have a melting temperature close to the operating temperature of the photovoltaic panel. The fusion temperature of the mixtures is high, however, the mixture is easy to melt and has a melting temperature and a solidification temperature between 19°C and 25°C. The mixture has a melting point temperature that is close to the temperature of the photovoltaic panel (25°C). Eventually, this is good for controlling the temperature of the photovoltaic panel.

Hasan *et al.* [114] conducted an empirical study in Ireland and Pakistan, and as it is known that the climate of Ireland is cold and the climate of Pakistan is hot and dry, they used two measuring devices of phase change materials to evaluate the performance of capric palmitate and salt hydrate. The use of salt hydrates in the photovoltaic phase change material system lowered the temperature of the photovoltaic panel by 10°C and 21.5°C in Ireland and Pakistan, respectively. The experiments were conducted in

3 days with solar radiation ranging between 400–950 W/m^2. The melting point of PCM with CaCl26H2O was 8.29°C. An improvement in electrical energy by 3% was found when using PCM with $CaCl_{26}H_{2O}$.

Indartono *et al.* [115] used yellow petroleum jelly as a phase change material which was contained in an aluminum rectangular tube and located at the back part of the photovoltaic panel. This study compared the performance of two photovoltaic panels; the first one used PCM, and the second one was without PCM. The result was that the photovoltaic panel surface with PCM has lower temperature compared to PV without PCM, and the daily electrical efficiency of the photovoltaic panel increased by (2–3)% during test day.

Hasan *et al.* [116] enhanced the PV efficiency and avoided heat transfer to the inner spacing by using RT42 in the system based on adding phase changing materials to photovoltaic panels. This contributed to lowering the photovoltaic panel temperature by 12.3°C and 22.6°C from the front and back surfaces of the panel. An increase in the daily electrical efficiency of the photovoltaic panel was observed between 5.5–7.2%.

Hachem *et al.* [117] regulated the temperature of the polycrystalline photovoltaic panel by using pure phase-change materials, petroleum jelly, and impure phase-change materials such as copper and graphite in different amounts. Pure petroleum jelly lowered the temperature by 6.5°C resulting in a 3% increase in electrical performance compared to a conventional PV panel. Copper and graphite lowered the temperature of the PV plate by 6.3°C for a longer period of time compared to petroleum jelly, and the electrical performance increased to 5.8%.

Lim *et al.* [118] carried out a two-dimensional thermal analysis, using a computer program to evaluate the thermal behaviour of two impure phase change materials: petroleum jelly and coconut oil. These materials were placed in a container made of steel of aggregate type in a bag of plastic. The maximum temperature drop was 4°C and a 6% enhancement in electrical efficiency when petroleum jelly was introduced into the disc container.

Karthik *et al.* [119] used $Na_2SO4.10H_2O$ as a phase change material for the thermal management of a photovoltaic panel. The test was conducted on a day in May. The photovoltaic panel peak temperature was 8°C lower compared to no phase-change material, which enhanced its electrical efficiency by 4% at noon.

Ezan *et al.* [120] developed a computer program to study natural convection and its effect on a photovoltaic phase change material system. One of these models was a photoelectric phase change material system whose thermal conductivity is controlled, heat transfer does not occur naturally, and the second is a photoelectric phase change material system whose convection is controlled (natural convection). Increasing the solar radiation from 400 to 800 W/m^2 led to an increase in convective heat transfer in the liquid phase change material. The thickness of 10 cm achieved the highest electrical efficiency, increased by 3.11% as compared to the no-phase condition of the materials.

Some researchers developed the technology of a PV cooling system by combining two or more phase change materials (hybrid PCM) for the purpose of using them to cool photovoltaic panels.

Karami *et al.* [31] studied how to increase the electrical efficiency of a photovoltaic unit by using graphite, paraffin, and coconut oil compound as phase change materials. They proved that when adding graphite powders to coconut oil increases the thermal conductivity of the photovoltaic panels, and when using coconut oil and paraffin together by half each, leads to a uniform distribution of temperatures on the surface of the photovoltaic panel compared to pure beef tallow and paraffin. The average temperature was 64.02°C and the resulting power reached 4.875 W.

Zohra *et al.* [121] conducted a numerical study where they combined two types of phase change materials RT42 and RT62. These two materials have different melting points. Through simulations, the authors noticed a significant improvement in the behaviour of thermal systems and a decrease in the production and storage time by about 20 minutes, where the storage time was reduced by 10%.

Other researchers carried out additional experiments on photovoltaic panels by adding nanoparticles to phase change materials (PMC-Np) and learning their effect on the performance of the panels. Nada *et al.* [122] conducted a study to improve the thermal performance and electrical efficiency of photovoltaic units using a phase change material with Al_2O_3 nanoparticles. The test conditions on the test day were as follows: the ambient temperature between 30–39°C and the solar radiation was 1100 W/m^2. After analyzing the results, it was found that integrating PCM with the PV module reduces and regulates the module temperature, which leads to an improved module power and efficiency. The addition of Al_2O_3 nanoparticles to PCM increases the temperature-regulating potential. It reduced the temperature of the units by 8.1°C and 10.6°C, and it increased their efficiency from 15.1% to 15.95% and from 15.1% to 17.1%, respectively. The voltage open circuit (VOC) increased in the case of PCM compared to the normal case by 0.5 V, and the power increased by 5 W.

Siahkamari *et al.* [35] conducted an experimental investigation that focused on using a new phase change material in a photovoltaic panel to increase its cooling. This material absorbs heat from the surface of the photovoltaic unit well and controls its heat capacity and raises the overall efficiency of the system. To delay the dissolution of PCM, they used sheep fat as a phase change material; to increase the efficiency of this material, copper nanoparticles were added to it. The authors found from their research experiments that using lipids and copper nanoparticles (PCM-Np) the maximum temperature of the photovoltaic panel during the examination day reached 87°C in the absence of refrigeration, and when using PCM sheep fat and copper nanoparticles, it is decreased to 60°C. The highest electrical energy obtained during the 1.5 hour test period at a water flow rate of 31 ml/s was 26.2%, compared to 24.6% electrical energy obtained at a flow rate of 6 ml/s. In the case of sheep fat alone, the efficiency improved from 18.2 to 19.5% when the flow rate was changed from 6 to 31 ml/sec, and in the case of paraffin wax, the efficiency improved from 11.8 to 13% at the same flow rates.

Jamil *et al.* [123] conducted an experimental study of cooling PV panels using PCM and three different types of nanoparticles with different concentrations 0.25% wt and 0.5% wt blended with PCM. The test was conducted within one day. The results showed that the use of PCM-Np was better compared to PCM by lowering the temperature and increasing the electrical efficiency, and the high concentration of nanoparticles yielded better results compared to the low concentration in PCM-Np. The maximum electrical efficiency at the highest concentration, for PV-PCM (MWCNTs) was 12.07%. For PV–PCM (GNPs), the max. electrical efficiency was 12.10%, for PV–PCM (MgO) – 11.9%, for PV-PCM – 11.74% and for PV – 10.98%.

Some researchers conducted studies on thermal photovoltaics combined with phase change material (PV/T)/PCM system and others developed this system by adding nanoparticles to the working fluid such as water or others. Malvi *et al.* [124] performed a numerical study and simulation on a thermoelectric system with PCM. The performance was evaluated in relation to the various thermal and physical properties of PCM in addition to the water flow change. Copper tubes were used inside PCM behind the photovoltaic panel. The photovoltaic panel combined with PCM absorbs heat during the day and extracts the heat stored in PCM at night by running water through the copper tubes. The heat storage capacity is better compared to normal PCM. The radiation intensity was 1000 W/m^2 and the melting point of PCM was 28°C. The data was recorded within 24 hours.

The operating temperature was 36°C and the water flow rate was more than 5 l/h. The performance of the photovoltaic panel increased by 2.3% from 1.46 to 1.49 kWh/day.

Yin *et al.* [125] used a similar material (phase change material) called functionally graded material for the PV modules. This material is a mixture of aluminum and polyethylene with a high density. Copper tubes are placed behind the photovoltaic panel. The flow rate for water with different masses was 33 ml/min and 66 ml/min. The temperature was 50 and 55°C for the photovoltaic panel without water flow with irradiation of 850 W/m^2 and 1100 W/m^2. In the case of cooling, the temperature of the photovoltaic panel decreased and stabilized at 32°C and 38°C with a flow of 33 ml/min and 66 ml/min. The daily electrical efficiency of the photovoltaic panel increased to 14.5% from 13.1%.

Browne *et al.* [126] conducted an experimental study on a thermoelectric system in which water is used and a phase change material is added to it. In this pilot study, the water pipe is integrated with the phase change material in the photovoltaic panel back wall. The melting point of the PCM was 22.4°C, and the radiation intensity ranged between 200–1000 W/m^2. The test was conducted over a period of 7 days. It was found through the simulation conditions that the improvement was in the first three days of the test, the difference in the temperature of the inlet and outlet was approximately 8°C.

Sardarbadi *et al.* [127] studied the effect of using water and zinc oxide/water with and without a phase change material as coolant mediums for a photovoltaic panel, in terms of increasing their efficiency and decreasing their temperature. The radiation intensity ranges from 600 to 1000 W/m^2 during the test day. The temperature absorption in the photovoltaic panel occurs by the phase change material PCM, as a result of which the panel surface temperature is reduced and its temperature is stable. Also, a high-temperature absorption occurs by the ZnO nanofluid/water due to its high thermal conductivity value due to the addition of nanoparticles. This heat absorption also led to an increase in thermal energy. The best increase in average power output is about 13% while using PCM in the PV/T system compared to the normal photovoltaic system.

Al-Waeli *et al.* [32] performed modelling to experimentally verify the thermal system of photovoltaic panels using coolant nanofluid and nanophase change materials. A mathematical model for the energy balance of the nanofluid system and the thermal regime of the photovoltaic panel using nanophase change materials was proposed and tested. The deviation between the calculated and measured electrical and thermal efficiencies was found 3.72% and 5.05%, respectively. The temperature was measured at different stages to confirm the results. It was shown that the temperature of the liquid increases through heat transfer in different phases with the highest temperature being 60.45°C. Finally, the overall efficiency of the thermal photovoltaic system improved to 85.7%, which is very good for high temperatures.

Al-Waeli *et al.* [36] conducted a performance evaluation of the thermal system of the photovoltaic panel using improved paraffin and nanofluids, which helps in optimizing the heat transfer process. The permeable nanofluid will gain more heat, as shown in Fig. 13. The cooling of the photovoltaic panel led to maintaining its electrical efficiency. While using nanofluids for cooling, the efficiency was about 13.7% compared to the traditional photovoltaic panel about 7.1%.

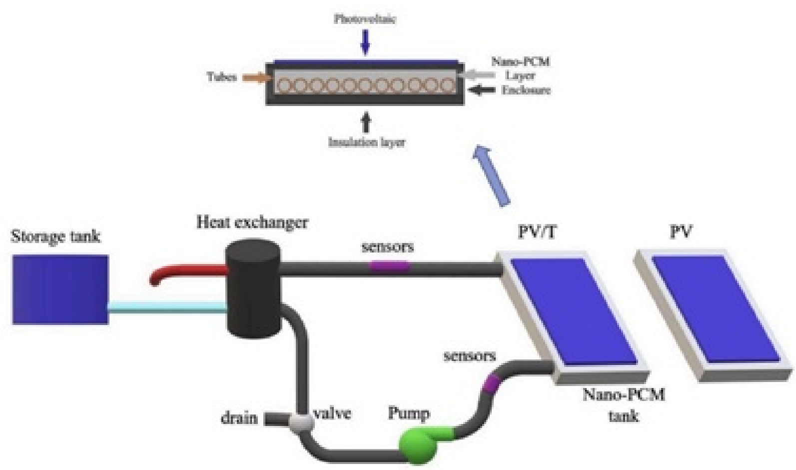

Figure 13: A schematic diagram of the PV/T system and a cross-section of the collector [36].

6 Advice for future research

As mentioned in the previous research on the thermal management of photovoltaic panels and methods of cooling them and increasing their electrical efficiency, multiple methods and techniques were used to cool photovoltaic panels, including air cooling (forced convection and free convection), water cooling (pipes, spraying, and immersion), in addition, technical additives to water, and also using phase change materials (pure and impure). Recently, researchers relied in their studies on the use of phase change materials added to them with nanofluids or nanomaterials to improve the electrical efficiency of photovoltaic panels *via* reducing their temperature.

Here are some tips on how to develop future research.

1. Most of the research and studies conducted on photovoltaic panels based on phase change material showed positive results, but it was for a short time, so it is better to conduct experiments over a longer time for the purpose of evaluating phase change materials and their thermal management with photovoltaic panels.

2. It is recommended to design and develop new types of solar thermal systems and to use new and different materials to study their impact and effectiveness.

3. The nanofluid, when it acts as a medium in the photovoltaic panel system, can improve heat transfer when combined with phase change materials.

4. Consider the solidification process and not just focus on the melting process. Sometimes secondary cooling of phase change materials leads to incomplete solidification that reduces the performance of these materials in a short period.

5. Integrate phase change materials with the thermal system of photovoltaic panels. Such a (photovoltaic thermal) system depends on the phase change material and the addition of nanoparticles to the phase change material or working fluid, to obtain the best results. It is recommended to conduct further research in this aspect.

7 Conclusions

The previous literature discussed numerous studies on the thermal control of photovoltaic panels using several cooling methods that are still under research, study and development. The experiments that are being conducted on this topic are still in place so as to reach the best results. Some experiments are sometimes expensive for researchers, and others are not. It has been noted from the presented studies that the best of these methods is the one using phase change materials (PCMs) because they absorb heat from the photovoltaic panel at a high rate, and this is what makes these materials a great solution in the present time for thermal management. PCMs regulate the temperature of the photovoltaic panel depending on their thermal properties and the addition of nanomaterials enhances these properties. These materials are characterized by their good storage density and thermal conductivity, which enables them to regulate the temperature of photovoltaic panels. These are essential features to achieve better thermal performance. However, the use of these materials is expensive and their storage capacity is limited in case the maximum storage capacity is reached, when the temperature increases and this is a negative trait of the photovoltaic panel. In the second place, the use of nanofluids comes as a great solution for cooling photovoltaic panels, but it is more expensive compared to water, which in turn is considered better than using air in the process of cooling photovoltaic panels. The main focus of researchers is to reach the best results to improve the efficiency of photovoltaic cells, as they generate clean energy, and the topic is still under testing and development, so it is possible that the currently costly technologies will be inexpensive in the future, just as photovoltaic cells were very expensive in the past. Therefore, it is difficult at the present time to determine the best technology for use in terms of both: performance and cost.

Received 30 January 2023

References

[1] Duffie J.A., Beckman W.A., Blair N.: *Solar Engineering of Thermal Processes, Photovoltaics and Wind*. Wiley, 2020.

[2] Krawczyk P., Badyda K.: *Two-dimensional CFD modeling of the heat and mass transfer process during sewage sludge drying in a solar dryer*. Arch. Thermodyn. **32**(2011), 4, 3–16. doi: 10.2478/v10173-011-0028-y

[3] Al-Maliki W.A.K., Mahmoud N.S., Al-Khafaji H.M., Alobaid F., Epple B.: *Design and implementation of the solar field and thermal storage system controllers for a parabolic trough solar power plant*. Appl. Sci. **11**(2021), 13, 6155. doi: 10.3390/app11136155

[4] Kadhim S.A., Ibrahim O.A.A.M.: *Improving the thermal efficiency of flat plate solar collector using nano-fluids as a working fluids: A Review*. Iraqi J. Ind. Res. **8**(2021), 3, 49–60. doi: 10.53523/ijoirVol8I3ID86

[5] Al-Ghezi M.K., Ahmed R.T., Chaichan M.T. *The influence of temperature and irradiance on performance of the photovoltaic panel in the middle of Iraq*. Int. J. Renew. Energ. Dev. **11**(2022), 2, 501–513. doi: 10.14710/ijred.2022.43713

[6] Kadhim S.A., Al-Ghezi M.K., Shehab W.Y.: *Optimum orientation of non-tracking solar applications in Baghdad City*. Int. J. Heat Technol. **41**(2023), 1, 125–134. doi: 10.18280/ijht.410113

[7] Patel M.R., Beik O.: *Wind and Solar Power Systems: Design, Analysis, and Operation*. CRC, 2021.

[8] Armaroli N., Balzani V.: *Towards an electricity-powered world*. Energ. Environ. Sci. **4**(2011), 9, 3193–3222. doi: 10.1039/C1EE01249E

[9] Diwania S., Agrawal S., Siddiqui A.S., Singh S.: *Photovoltaic–thermal (PV/T) technology: a comprehensive review on applications and its advancement*. Int. J. Energ. Environ. Eng. **11**(2020), 1, 33–54. doi: 10.1007/s40095-019-00327-y

[10] IEA: *Status of Power System Transformation 2019*. IEA, Paris 2019.

[11] Gielen D., Gorini R., Wagner N., Leme R., Gutierrez L., Prakash G., Renner M.: *Global Energy Transformation: A Roadmap to 2050*. IRENA, 2019.

[12] Hosenuzzaman M., Rahim N.A., Selvaraj J., Hasanuzzaman M., Malek A.A., Nahar A.: *Global prospects, progress, policies, and environmental impact of solar photovoltaic power generation*. Renew. Sust. Energ. Rev. **41**(2015). 284–297. doi: 10.1016/j.rser.2014.08.046

[13] Häberlin, H.: *Photovoltaics: System Design and Practice*. John Wiley & Sons, 2012

[14] Al Tarabsheh A., Voutetakisb S., Papadopoulosb A.I., Seferlisb P., Etiera I., Saraereha O.: *Investigation of temperature effects in efficiency improvement of non-uniformly cooled photovoltaic cells*. Chem. Eng. T. **35**(2013), 1387–1392. doi: 10.3303/CET1335231

[15] Teo H.G., Lee P.S., Hawlader M.N.A.: *An active cooling system for photovoltaic modules*. Appl. Energ. **90**(2012), 1, 309–315. doi: 10.1016/j.apenergy.2011.01.017

[16] Agrawal B., Tiwari G. N.: *Life cycle cost assessment of building integrated photovoltaic thermal (BIPVT) systems*. Energ. Buildings **42**(2010), 9, 1472–1481. doi: 10.1016/j.enbuild.2010.03.017

[17] Islam M.M., Pandey A.K., Hasanuzzaman M., Rahim N.A.: *Recent progresses and achievements in photovoltaic-phase change material technology: a review with special treatment on photovoltaic thermal-phase change material systems*. Energ. Convers. Manage. **126**(2016), 177–204. doi: 10.1016/j.enconman.2016.07.075

[18] Kalogirou S.A., Tripanagnostopoulos Y.: *Hybrid PV/T solar systems for domestic hot water and electricity production*. Energ. Convers. Manage. **47**(2006), 18-19, 3368–3382. doi: 10.1016/j.enconman.2006.01.012

[19] Mortezapour H., Ghobadian B., Minaei S., Khoshtaghaza M.H.: *Saffron drying with a heat pump–assisted hybrid photovoltaic–thermal solar dryer*. Dry. Technol. **30**(2012), 6, 560–566. doi: 10.1080/07373937.2011.645261

[20] Lin W., Ma Z., Sohel M.I., Cooper P.: *Development and evaluation of a ceiling ventilation system enhanced by solar photovoltaic thermal collectors and phase change materials*. Energ. Convers. Manage. **88**(2014), 218–230. doi: 10.1016/j.enconman.2014.08.019

[21] Sathe T.M., Dhoble A.S.: *A review on recent advancements in photovoltaic thermal techniques*. Renew. Sust. Energ. Rev. **76**(2017), 645–672. doi: 10.1016/j.rser.2017.03.075

[22] Tonui J.K., Tripanagnostopoulos Y.: *Improved PV/T solar collectors with heat extraction by forced or natural air circulation*. Renew. Energ. **32**(2007), 4, 623–637. doi: 10.1016/j.renene.2006.03.006

[23] Sahay A., Sethi V. K., Tiwari A.C., Pandey M.: *A review of solar photovoltaic panel cooling systems with special reference to Ground coupled central panel cooling system (GC-CPCS)*. Renew. Sust. Energ. Rev. **42**(2015), 306–312. doi: 10.1016/j.rser.2014.10.009

[24] Al-Waeli A.H., Kazem H.A., Sopian K., Chaichan M.T.: *Techno-economical assessment of grid connected PV/T using nanoparticles and water as base-fluid systems in Malaysia*. Int. J. Sustain. Energ. **37**(2018), 6, 558–575. doi: 10.1080/14786451.2017.1323900

[25] Devendiran D.K., Amirtham V.A.: *A review on preparation, characterization, properties and applications of nanofluids*. Renew. Sust. Energ. Rev. **60**(2016), 21–40. doi: 10.1016/j.rser.2016.01.055

[26] Ebrahimnia-Bajestan E., Moghadam M. C., Niazmand H., Daungthongsuk W., Wongwises S.: *Experimental and numerical investigation of nanofluids heat transfer characteristics for application in solar heat exchangers*. Int. J. Heat Mass Tran. **92**(2016), 1041–1052. doi: 10.1016/j.ijheatmasstransfer.2015.08.107

[27] Raju M., Sarma R.N., Suryan A., Nair P.P., Nižetić S.: *Investigation of optimal water utilization for water spray cooled photovoltaic panel: A three-dimensional computational study*. Sust. Energ. Tech. As. **51**(2022), 101975. doi: 10.1016/j.seta.2022.101975

[28] Yildirim M.A., Cebula A., Sułowicz M.: *A cooling design for photovoltaic panels–Water-based PV/T system*. Energy **256**(2022), 124654. doi: 10.1016/j.energy.2022.124654

[29] Singh K., Singh S., Kandpal D.C., Kumar R.: *Experimental performance study of photovoltaic solar panel with and without water circulation*. Mater. Today-Proc. **46**(2021), 6822–6827. doi: 10.1016/j.matpr.2021.04.393

[30] Mohammed M.F., Daud H.A., Ekaab N.S.: *Numerical study of cooling system for photovoltaic thermal collector*. J. Eng. Sci. Technol. **16**(2021), 6, 4817–4832.

[31] Karami B., Azimi N., Ahmadi S.: *Increasing the electrical efficiency and thermal management of a photovoltaic module using expanded graphite (EG)/paraffin-beef tallow-coconut oil composite as phase change material*. Renew. Energ. **178**(2021), 25–49. doi: 10.1016/j.renene.2021.06.067

[32] Al-Waeli A.H., Chaichan M.T., Sopian K., Kazem H.A., Mahood H.B., Khadom A.A.: *Modeling and experimental validation of a PVT system using nanofluid coolant and nano-PCM*. Sol. Energy **177**(2019), 178–191. doi: 10.1016/j.solener.2018.11.016

[33] Chintakrinda K., Weinstein R.D., Fleischer A.S.: *A direct comparison of three different material enhancement methods on the transient thermal response of paraffin phase change material exposed to high heat fluxes*. Int. J. Therm. Sci. **50**(2011), 1639–1647. doi: 10.1016/j.ijthermalsci.2011.04.005

[34] Al Hariri A., Selimli S., Dumrul H.: *Effectiveness of heat sink fin position on photovoltaic thermal collector cooling supported by paraffin and steel foam: An experimental study*. Appl. Therm. Eng. **213**(2022), 118784. doi: 10.1016/j.applthermaleng.2022.118784

[35] Siahkamari L., Rahimi M., Azimi N., Banibayat M.: *Experimental investigation on using a novel phase change material (PCM) in micro structure photovoltaic cooling system*. Int. Commun. Heat Mass **100**(2019), 60–66. doi: 10.1016/j.icheatmass transfer.2018.12.020

[36] Al-Waeli A.H., Sopian K., Kazem H.A., Chaichan M.T.: *Evaluation of the electrical performance of a photovoltaic thermal system using nano-enhanced paraffin and nanofluids*. Case Stud. Therm. Eng. **21**(2020), 100678. doi: 10.1016/j.csite.2020.100678

[37] Solanki C.S.: *Solar Photovoltaics: Fundamentals, Technologies and Applications* (3rd Edn.). PHI learning Pvt. Ltd., Delhi 2015.

[38] Smets A.H., Jäger K., Isabella O., Swaaij R.A., Zeman M.: *Solar Energy: The Physics and Engineering of Photovoltaic Conversion, Technologies and Systems*. UIT Cambridge, 2015.

[39] Mukerjee A.K., Thakur N.: *Photovoltaic Systems: Analysis and Design*. PHI Learning Pvt. Ltd., Delhi 2011.

[40] Tiwari G.N., Dubey S.: *Fundamentals of Photovoltaic Modules and Their Applications*. RSC, 2009.

[41] Goswami D.Y.: *Principles of Solar Engineering*. CRC Press, 2015

[42] Kazem H.A., Chaichan M.T., Al-Waeli A.H.: *Effect of CuO-water-ethylene glycol nanofluids on the performance of photovoltaic/thermal energy system: an experimental study*. Energ. Source. A **44**(2022), 2, 3673–3691. doi: 10.1080/15567036.2022.2070305

[43] Kaldellis J.K., Kapsali M., Kavadias K.A.: *Temperature and wind speed impact on the efficiency of PV installations. Experience obtained from outdoor measurements in Greece*. Renew. Energ. **66**(2014), 612–624. doi: 10.1016/j.renene.2013.12.041

[44] Fesharaki V.J., Dehghani M., Fesharaki J.J., Tavasoli H.: *The effect of temperature on photovoltaic cell efficiency*. In: Proc. 1st Int. Conf. on Emerging Trends in Energy Conservation ETEC, Tehran, 20-21, Nov. 2011.

[45] Bagienski W., Gupta M.C.: *Temperature dependence of polymer/fullerene organic solar cells*. Sol. Energ. Mat. Sol. C. **95**(2011), 3, 933–941. doi: 10.1016/j.solmat.2010.11.026

[46] Wysocki J.J., Rappaport P.: *Effect of temperature on photovoltaic solar energy conversion*. J. Appl. Phys. **31**(1960), 3, 571–578. doi: 10.1063/1.1735630

[47] Akhmad K., Kitamura A., Yamamoto F., Okamoto H., Takakura H., Hamakawa Y.: *Outdoor performance of amorphous silicon and polycrystalline silicon PV modules*. Sol. Energ. Mat. Sol. C. **46**(1997), 3, 209–218. doi: 10.1016/S0927-0248(97)00003-2

[48] Radziemska E., Klugmann E.: *Thermally affected parameters of the current–voltage characteristics of silicon photocell*. Energ. Convers. Manage. **43**(2002), 14, 1889–1900. doi: 10.1016/S0196-8904(01)00132-7

[49] Radziemska E.: *The effect of temperature on the power drop in crystalline silicon solar cells*. Renew. Energ. **28**(2003), 1, 1–12. doi: 10.1016/S0960-1481(02)00015-0

[50] Meneses-Rodrıĕguez D., Horley P.P., Gonzalez-Hernandez J., Vorobiev Y.V., Gorley P.N.: *The effect of temperature on the power drop in crystalline silicon solar cells*. Sol. Energy **78**(2005), 2, 243–250. doi: 10.1016/j.solener.2004.05.016

[51] Brinkworth B.J., Sandberg M.: *Design procedure for cooling ducts to minimise efficiency loss due to temperature rise in PV arrays*. Sol. Energy **80**(2006), 1, 89–103. doi: 10.1016/j.solener.2005.05.020

[52] Usami A., Seki S., Mita Y., Kobayashi H., Miyashiro H., Terada N.: *Temperature dependence of open-circuit voltage in dye-sensitized solar cells*. Sol. Energ. Mat. Sol. C. **83**(2006), 6-7, 840–842. doi: 10.1016/j.solmat.2008.09.040

[53] Huang B.J., Yang P.E., Lin Y.P., Lin B.Y., Chen H.J., Lai R.C., Cheng J.S.: *Solar cell junction temperature measurement of PV module*. Sol. Energy **85**(2011), 2, 388–392. doi: 10.1016/j.solener.2010.11.006

[54] Singh P., Ravindra N.M.: *Temperature dependence of solar cell performance – an analysis*. Sol. Energ. Mat. Sol. C. **101**(2012), 36–45. doi: 10.1016/j.solmat.2012.02.019

[55] Bandou F., Arab A.H., Belkaid M.S., Logerais P.O., Riou O., Charki A.: *Evaluation performance of photovoltaic modules after a long time operation in Saharan environment*. Int. J. Hydrogen Energ. **40**(2015), 39, 13839–13848. doi: 10.1016/j.ijhydene.2015.04.091

[56] Krauter S.: *Increased electrical yield via water flow over the front of photovoltaic panels*. Sol. Energ. Mat. Sol. C. **82**(2004), 1-2, 131–137. doi: 10.1016/j.solmat.2004.01.011

[57] Vokas G., Christandonis N., Skittides F.: *Hybrid photovoltaic–thermal systems for domestic heating and cooling – a theoretical approach*. Sol. Energy **80**(2006), 5, 607–615. doi: 10.1016/j.solener.2005.03.011

[58] Michael J.J., Iniyan S., Goic R.: *Flat plate solar photovoltaic–thermal (PV/T) systems: A reference guide*. Renew. Sust. Energ. Rev. **51**(2015), 62–88. doi: 10.1016/j.rser.2015.06.022

[59] Chow T.T., He W., Ji J.: *Hybrid photovoltaic-thermosyphon water heating system for residential application*. Sol. Energy **80**(2006), 3, 298–306. doi: 10.1016/j.solener.2005.02.003

[60] Huang B.J., Lin T.H., Hung W.C., Sun F.S.: *Performance evaluation of solar photovoltaic/thermal systems*. Sol. Energy **70**(2001), 5, 443–448. doi: 10.1016/S0038-092X(00)00153-5

[61] Ji J., Han J., Chow T.T., Yi H., Lu J., He W., Sun W.: *Effect of fluid flow and packing factor on energy performance of a wall-mounted hybrid photovoltaic/water-heating collector system*. Energ. Buildings **38**(2006), 12, 1380–1387. doi: 10.1016/j.enbuild.2006.02.010

[62] Ibrahim A., Othman M.Y., Ruslan M. H., Alghoul M., Yahya M., Zaharim A., Sopian K.: *Performance of photovoltaic thermal collector (PVT) with different absorbers design*. Wseas Trans. Env. Dev. **5**(2009), 3, 321–330.

[63] Bahaidarah H.M., Rehman S., Gandhidasan P., Tanweer B.: *Experimental evaluation of the performance of a photovoltaic panel with water cooling*. In: Proc. 39st Photovoltaic Specialists Conf. (PVSC), IEEE, 2987-2991, June 2013. doi: 10.1109/PVSC.2013.6745090

[64] Matias C.A., Santos L.M., Alves A.J., Calixto W.P.: *Increasing photovoltaic panel power through water cooling technique*. Trans. Env. Electr. Eng. **2**(2017), 1, 60–66.

[65] Fakouriyan S., Saboohi Y., Fathi A.: *Experimental analysis of a cooling system effect on photovoltaic panels' efficiency and its preheating water production*. Renew. Energ. **134**(2017), 1362–1368. doi: 10.1016/j.renene.2018.09.054

[66] Moharram K.A., Abd-Elhady M.S., Kandil H.A., El-Sherif H.: *Enhancing the performance of photovoltaic panels by water cooling*. Ain Shams Eng. J. **4**(2013), 4, 869–877. doi: 10.1016/j.asej.2013.03.005

[67] Nižetić S., Čoko D., Yadav A., Grubišić-Čabo F.: *Water spray cooling technique applied on a photovoltaic panel: The performance response*. Energ. Convers. Manage. **108**(2016), 4, 287–296. doi: 10.1016/j.enconman.2015.10.079

[68] Mzad H., Otmani A.: *Simulation of photovoltaic panel cooling beneath a single nozzle based on a configurations framework*. Arch. Thermodyn. **42**(2021), 1, 115–128. doi: 10.24425/ather.2021.136950

[69] Mehrotra S., Rawat P., Debbarma M., Sudhakar K.: *Performance of a solar panel with water immersion cooling technique*. Int. J. Sci. Env. Technol. **3**(2014), 3, 1161–1172.

[70] Abdulgafar S.A., Omar O.S., Yousif K.M.: *Improving the efficiency of polycrystalline solar panel via water immersion method*. Int. J. Innov. Res. Sci. Eng. Technol. **3**(2014), 1, 8127–8132.

[71] Aberoumand S., Ghamari S., Shabani B.: *Energy and exergy analysis of a photovoltaic thermal (PV/T) system using nanofluids: An experimental study*. Sol. Energy **165**(2018), 167–177. doi: 10.1016/j.solener.2018.03.028

[72] Al-Ghezi M.K., Abass K.I., Salam A.Q., Jawad R.S., Kazem H.A.: *The possibilities of using nano-CuO as coolants for PVT system: An experimental study*. In: J. Phys.: Conf. Series, IOP Publishing, **1973**, 1, 012123, Aug. 2021. doi: 10.1088/1742-6596/1973/1/012123

[73] Murtadha T.K., dil Hussein A.A., Alalwany A.A., Alrwashdeh S.S., Ala'a M.: *Improving the cooling performance of photovoltaic panels by using two passes circulation of titanium dioxide nanofluid*. Case Stud. Therm. Eng. **36**(2022), 102191. doi: 10.1016/j.csite.2022.102191

[74] Sathyamurthy R., Kabeel A.E., Chamkha A., Karthick A., Muthu Manokar A., Sumithra M.G.: *Experimental investigation on cooling the photovoltaic panel using hybrid nanofluids*. Appl. Nanosci. **11**(2021), 2, 363–374. doi: 10.1007/s13204-020-01598-2

[75] Ebaid M.S., Ghrair A.M., Al-Busoul M.: *Experimental investigation of cooling photovoltaic (PV) panels using* (TiO_2) *nanofluid in water-polyethylene glycol mixture and* (Al_2O_3) *nanofluid in water-cetyltrimethylammonium bromide mixture*. Energ. Convers. Manage. **155**(2018), 324–343. doi: 10.1016/j.enconman.2017.10.074

[76] Hussain F., Othman M.Y H., Sopian K., Yatim B., Ruslan H., Othman H.: *Design development and performance evaluation of photovoltaic/thermal (PV/T) air base solar collector*. Renew. Sust. Energ. Rev. **25**(2013), 431–441. doi: 10.1016/j.rser.2013.04.014

[77] Kumar R., Rosen M.A.: *Performance evaluation of a double pass PV/T solar air heater with and without fins*. Appl. Therm. Eng. **31**(2011), 8-9, 1402–1410. doi: 10.1016/j.applthermaleng.2010.12.037

[78] Sopian K., Liu H.T., Kakac S., Veziroglu T.N.: *Performance of a double pass photovoltaic thermal solar collector suitable for solar drying systems*. Energ. Convers. Manage. **41**(2000), 4, 353–365. doi: 10.1016/S0196-8904(99)00115-6

[79] Othman M.Y.H., Yatim B., Sopian K., Bakar, M.N.A.: *Performance analysis of a double-pass photovoltaic/thermal (PV/T) solar collector with CPC and fins*. Renew. Energ. **30**(2005), 13, 2005–2017. doi: 10.1016/j.renene.2004.10.007

[80] Tripanagnostopoulos Y.: *Aspects and improvements of hybrid photovoltaic/thermal solar energy systems*. Sol. Energy **81**(2007), 9, 1117–1131. doi: 10.1016/j.solener.2007.04.002

[81] Sopian K., Alghoul M.A., Alfegi E.M., Sulaiman M.Y., Musa E.A.: *Evaluation of thermal efficiency of double-pass solar collector with porous–nonporous media*. Renew. Energ. **34**(2009), 3, 640–645. doi: 10.1016/j.renene.2008.05.027

[82] Mohd Y.O., Hafidz R., Kamaruzzaman S., Jin G.L.: *Performance study of photovoltaic-thermal (PV/T) solar collector with grooved absorber plate*. Sains Malaysiana **38**(2009), 4, 537–541.

[83] Hussain F., Othman M.Y., Yatim B., Ruslan H., Sopian K., Anuar Z., Khairuddin S.: *Comparison study of air base photovoltaic/thermal (PV/T) collector with different design of heat exchanger*. In: World Renew. Energ. Forum, WREF **1**(2012), 189–194.

[84] Mazón-Hernández R., García-Cascales J.R., Vera-García F., Káiser A.S., Zamora B.: *Improving the electrical parameters of a photovoltaic panel by means of an induced or forced air stream*. Int. J. Photoenergy **2013**(2013). doi: 10.1155/2013/830968

[85] Popovici C.G., Hudişteanu S.V., Mateescu T.D., Chereches N.C.: *Efficiency improvement of photovoltaic panels by using air cooled heat sinks*. Enrgy. Proced. **85**(2016), 425–432. doi: 10.1016/j.egypro.2015.12.223

[86] Senthil R., Patel A., Rao R., Ganeriwal S.: *Melting behavior of phase change material in a solar vertical thermal energy storage with variable length fins added on the heat transfer tube surfaces*. Int. J. Renew. Energ. Dev. **9**(2020), 3, 361–367. doi: 10.14710/ijred.2020.29879

[87] Tatsidjodoung P., Le Pierrès N., Luo L.: *A review of potential materials for thermal energy storage in building applications*. Renew. Sust. Energ. Rev. **18**(2013), 327–349. doi: 10.1016/j.rser.2012.10.025

[88] Zhou D., Zhao C.Y., Tian Y.: *Review on thermal energy storage with phase change materials (PCMs) in building applications*. Appl. Energ. **92**(2012), 593–605. doi: 10.1016/j.apenergy.2011.08.025

[89] Ma T., Yang H., Zhang Y., Lu L., Wang X.: *Using phase change materials in photovoltaic systems for thermal regulation and electrical efficiency improvement: a review and outlook*. Renew. Sust. Energ. Rev. **43**(2015), 1273–1284. doi: 10.1016/j.rser.2014.12.003

[90] Wang F., Maidment G., Missenden J., Tozer R.: *A review of research concerning the use of PCMs in air conditioning and refrigeration engineering*. Adv. Building Technol. **II**(2002), 1273–1280. doi: 10.1016/B978-008044100-9/50158-3

[91] Günther E., Hiebler S., Mehling H., Redlich R.: *Enthalpy of phase change materials as a function of temperature: required accuracy and suitable measurement methods*. Int. J. Thermophys. **30**(2009), 4, 1257–1269. doi: 10.1007/s10765-009-0641-z

[92] Qureshi Z. A., Ali H.M., Khushnood S.: *Recent advances on thermal conductivity enhancement of phase change materials for energy storage system: a review*. Int. J. Heat Mass Tran. **127**(2018), 838–856. doi: 10.1016/j.ijheatmasstransfer.2018.08.049

[93] Kumar R.R., Samykano M., Pandey A.K., Kadirgama K., Tyagi V.V.: *Phase change materials and nano-enhanced phase change materials for thermal energy storage in photovoltaic thermal systems: A futuristic approach and its technical challenges*. Renew. Sust. Energ. Rev. **133**(2020), 110341. doi: 10.1016/j.rser.2020.110341

[94] Sharma A., Tyagi V.V., Chen C.R., Buddhi D.: *Review on thermal energy storage with phase change materials and applications*. Renew. Sust. Energ. Rev. **13**(2009), 2, 318–345. doi: 10.1016/j.rser.2007.10.005

[95] Abhat A.: *Low temperature latent heat thermal energy storage: heat storage materials*. Sol. Energ. **30**(1983), 4, 313–332. doi: 10.1016/0038-092X(83)90186-X

[96] Sarbu I., Sebarchievici C.: *A comprehensive review of thermal energy storage*. Sustain. **10**(2018), 1, 191. doi: 10.3390/su10010191

[97] Ma T., Li Z., Zhao J.: *Photovoltaic panel integrated with phase change materials (PV-PCM): technology overview and materials selection*. Renew. Sust. Energ. Rev. **116**(2019), 109406. doi: 10.1016/j.rser.2019.109406

[98] Bahaidarah H.M., Baloch A.A., Gandhidasan P.: *Uniform cooling of photovoltaic panels: A review*. Renew. Sust. Energ. Rev. **57**(2016), 1520–1544. doi: 10.1016/j.rser.2015.12.064

[99] Hasan A., McCormack S.J., Huang M.J., Norton B.: *Evaluation of phase change materials for thermal regulation enhancement of building integrated photovoltaics*. Sol. Energy **84**(2010), 9, 1601–1612. doi: 10.1016/j.solener.2010.06.010

[100] Waqas A., Jie J., Xu L.: *Thermal behavior of a PV panel integrated with PCM-filled metallic tubes: An experimental study*. J. Renew. Sust. Energ. **9**(2017), 5, 053504. doi: 10.1063/1.4995022

[101] Nada S.A., El-Nagar D.H.: *Possibility of using PCMs in temperature control and performance enhancements of free stand and building integrated PV modules*. Renew. Energ. **127**(2018), 630–641. doi: 10.1016/j.renene.2018.05.010

[102] Kant K., Shukla A., Sharma A.: *Ternary mixture of fatty acids as phase change materials for thermal energy storage applications*. Energ. Rep. **2**(2016), 274–279. doi: 10.1016/j.egyr.2016.10.002

[103] Kazemian A., Khatibi M., Ma T.: *Performance prediction and optimization of a photovoltaic thermal system integrated with phase change material using response surface method*. J. Clean. Prod. **290**(2021), 125748. doi: 10.1016/j.jclepro.2020.125748

[104] Sharaf M., Yousef M.S., Huzayyin A.S.: *Review of cooling techniques used to enhance the efficiency of photovoltaic power systems*. Environ. Sci. Pollut. R. **29**(2022), 18, 26131–26159. doi: 10.1007/s11356-022-18719-9

[105] Stultz J.W., Wren L.C.: *Thermal performance testing and analysis of photovoltaic modules in natural sunlight*. Jet Propulsion Laboratory, Pasadena 1978.

[106] Günther E., Hiebler S., Mehling H., Redlich R.: *Enthalpy of phase change materials as a function of temperature: required accuracy and suitable measurement methods*. Int. J. Thermophys. **30**(2009), 4, 1257–1269. doi: 10.1007/s10765-009-0641-z

[107] https://www.rubitherm.eu/en/productcategory/organische-pcm-rt (accessed 15 Dec. 2022).

[108] Huang M.J., Eames P.C., Norton B.: *The application of computational fluid dynamics to predict the performance of phase change materials for control of photovoltaic cell temperature in buildings*. In: Proc. World Renewable Energy Cong. VI, Pergamon, Jan. 2000, 2123–2126. doi: 10.1016/B978-008043865-8/50454-2

[109] Huang M.J., Eames P.C., Norton B.: *Phase change materials for limiting temperature rise in building integrated photovoltaics*. Sol. Energy **80**(2006), 9, 1121–1130. doi: 10.1016/j.solener.2005.10.006

[110] Huang M.J., Eames P.C., Norton B., Hewitt N.J.: *Natural convection in an internally finned phase change material heat sink for the thermal management of photovoltaics*. Sol. Energ. Mat. Sol. C. **95**(2011), 7, 1598–1603. doi: 10.1016/j.solmat.2011.01.008

[111] Huang M.J.: *The effect of using two PCMs on the thermal regulation performance of BIPV systems*. Sol. Energ. Mat. Sol. C. **95**(2011), 3, 957–963. doi: 10.1016/j.solmat.2010.11.032

[112] Japs E., Sonnenrein G., Steube J., Vrabec J., Kenig E., Krauter S.: *Technical investigation of a photovoltaic module with integrated improved phase change material*. In: Proc. 28st Eur. Photovoltaic Solar Energy Conf. Exhib., Paris, Sep. 2013, 500–502.

[113] Hasan A., McCormack S.J., Huang M.J., Norton B.: *Characterization of phase change materials for thermal control of photovoltaics using differential scanning calorimetry and temperature history method*. Energ. Convers. Manage. **81**(2014), 322–329. doi: 10.1016/j.enconman.2014.02.042

[114] Hasan A., McCormack S.J., Huang M.J., Sarwar J., Norton B.: *Increased photovoltaic performance through temperature regulation by phase change materials: Materials comparison in different climates*. Sol. Energy **115**(2015), 264–276. doi: 10.1016/j.solener.2015.02.003

[115] Indartono Y.S., Suwono A., Pratama F.Y.: *Improving photovoltaics performance by using yellow petroleum jelly as phase change material*. Int. J. Low-Carbon Technol. **11**(2016), 3, 333–337. doi: 10.1093/ijlct/ctu033

[116] Hasan A., Alnoman H., Rashid Y.: *Impact of integrated photovoltaic-phase change material system on building energy efficiency in hot climate*. Energ. Buildings **130**(2016), 495–505. doi: 10.1016/j.enbuild.2016.08.059

[117] Hachem F., Abdulhay B., Ramadan M., El Hage H., El Rab M.G., Khaled M.: *Improving the performance of photovoltaic cells using pure and combined phase change materials – Experiments and transient energy balance*. Renew. Energ. **107**(2017), 567-575. doi: 10.1016/j.renene.2017.02.032

[118] Lim J. H., Lee Y. S., Seong Y. B.: *Diurnal thermal behavior of photovoltaic panel with phase change materials under different weather conditions*. Energies **10**(2017), 12, 1983. doi: 10.3390/en10121983

[119] Karthick A., Murugavel K.K., Ramanan P.: *Performance enhancement of a building-integrated photovoltaic module using phase change material.* Energy **142**(2018), 803–812. doi: 10.1016/j.energy.2017.10.090

[120] Ezan M.A., Yüksel C., Alptekin E., YılancıA.: *Importance of natural convection on numerical modelling of the building integrated PVP/PCM systems*. Sol. Energy **159**(2018), 616–627. doi: 10.1016/j.solener.2017.11.022

[121] Zohra M.B., Riad A., Hassoune H., Alhamany, A., Mansouri M.: *A new system for the production and storage of thermal energy based on two complementary and different types of phase changing materials*. Case Stud. Therm. Eng. **26**(2021), 101072. doi: 10.1016/j.csite.2021.101072

[122] Nada S.A., El-Nagar D.H., Hussein H.M S.: *Improving the thermal regulation and efficiency enhancement of PCM-Integrated PV modules using nano particles.* Energ. Convers. Manage. **166**(2018), 735–743. doi: 10.1016/j.enconman.2018.04.035

[123] Jamil F., Ali H. M., Nasir M.A., Karahan M., Janjua M.M., Naseer A., Pasha R.A.: *Evaluation of photovoltaic panels using different nano phase change material and a concise comparison: An experimental study.* Renew. Energ. **169**(2021), 1265–1279. doi: 10.1016/j.renene.2021.01.089

[124] Malvi C.S., Dixon-Hardy D.W., Crook R.: *Energy balance model of combined photovoltaic solar-thermal system incorporating phase change material.* Sol. Energy **85**(2011), 1440–1446. doi: 10.1016/j.solener.2011.03.027

[125] Yin H.M., Yang D.J., Kelly G., Garant J.: *Design and performance of a novel building integrated PV/thermal system for energy efficiency of buildings*. Sol. Energy **87**(2013), 184–195. doi: 10.1016/j.solener.2012.10.022

[126] Browne M.C., Lawlor K., Kelly A., Norton B., Mc Cormack S.J.: *Indoor characterisation of a photovoltaic/thermal phase change material system.* Energy. Proced. **70**(2015), 163–171. doi: 10.1016/j.egypro.2015.02.112

[127] Sardarabadi M., Passandideh-Fard M., Maghrebi M.J., Ghazikhani M.: *Experimental study of using both ZnO/water nanofluid and phase change material (PCM) in photovoltaic thermal systems.* Sol. Energy **161**(2017), 62–69. doi: 10.1016/j.solmat.2016.11.032