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A review of passive cooling of photovoltaic devices

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A R T I C L E I N F O

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Solar farm
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A B S T R A C T

Our planet's ecosystems depend on the energy received from the sun to form a bubble of life. Technically, other sources of energy are converted from solar energy. An effective way to directly convert solar energy to electricity is through photovoltaic devices. They could be manufactured on small scales and used in pocket calculations up to large scales power plants. These power stations, known as a solar farm, is composed of grid-connected photovoltaic arrays. The conventional solar cells' efficiency, ceiled by the Shockley-Queisser limit, is in the range of 15%–25%. The rest of the solar energy is converted to heat which would have a detrimental influence on power production and the life span of photovoltaic devices. Hence, employing cooling systems to regulate their operative temperature is crucial. Passive cooling technologies without consuming additional power and with little maintenance cost could be a practical option. In this study, the extensive work of researchers applying passive cooling techniques is gathered and compared. Also, the study will shed light on finding an appropriate cooling technique concerning geographical or environmental conditions. Papers related to each specific passive method are discussed, and the challenges which have remained unsolved are noted. Finally, most of the papers with different environmental conditions are mentioned in an inventory which makes the comparison and evaluation easier. Among the six passive cooling methods, natural air ventilation is economically the most viable option. Hence, designing complex fin structures to help enhance air ventilation is recommended for most of the problems. In the case of water cooling, floatovoltaics are highly recommended because of supplementary advantages such as reducing the algae growth and evaporation rate.

1. Introduction

Renewable energies are a sort of energy that could be naturally replenished over a relatively short time scale. Solar, wind, hydro, geothermal, wave, biomass, hydrogen, etc., are all considered renewable energies (Dixit, 2020). Among all different types of renewable energies, solar energy has become an outstanding option since it possesses a lot of advantages such as:

1 Being every day available, even on cloudy days, it is possible to harness this vast clean energy.
2 Most techniques of converting solar energy to electrical/thermal energy possess a low initial cost.
3 Virtually it requires no maintenance cost since photovoltaic (PV) modules have a long lifespan of over 30 years.
4 The possibility of installing PV modules of any size or scale from small residential applications to enormous solar farms.
5 PV modules' aesthetic with the least environmental impact compared to the other types of renewable energy has been improved.

Because of the aforementioned benefits, even the countries far from the equator are attracted to solar energy, not to mention the tropical countries where solar intensity is high enough to operate solar farms with capacities ranging from 10 (MW) to 150 (MW) (Jacobson, 2009). Generally, there are three approaches to convert this clean energy into applicable electrical/thermal forms of energy: solar updraft towers, solar thermal collectors, and solar cells. Each method has its advantages and disadvantages. Considering all pros and cons together, solar cells may tip the balance in their favor. For instance, a solar updraft tower requires a very high capital cost and is less efficient than PV. In the case of electricity production, solar cells can directly convert the light's photon energy into electrical power. In contrast, solar thermal collectors or solar updraft towers require many priceless auxiliary devices such as turbines, generators, piping, etc (Das and Chandramohan, 2022; Saad et al., 2022; Rushdi et al., 2021). Besides all the benefits that crystalline silicon solar cells could bring, some barriers may limit our goal in the

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Nomenclature

I	Current [A]
V	Voltage [V]

Subscripts

amb	Ambient
sc	Short-circuit
oc	Open-circuit

Abbreviations

BIPV	Building-integrated photovoltaic
FPV	Floating photovoltaic
HP	Heat pipe
HP-PV/TEG	Heat pipe-based photovoltaic thermoelectric generator
PCM	Phase change material
PHP	Pulsating heat pipe
PV	Photovoltaic
PVT	Photovoltaic thermal
PV-TGS	Photovoltaic-thermoelectric generation hybrid system
PV-TCS	Photovoltaic-thermoelectric cooling hybrid system
SBS	Spectral beam splitter
SCD	Simultaneous charging and discharging
STC	Standard test conditions
TEG	Thermoelectric generator

usage of these aesthetic devices. Being fragile and sensitive to dust accumulation (Kazem et al., 2020), having a relatively low efficiency (15%–25%) (Kumar et al., 2020a), and being sensitive to its operating temperature (Kandeal et al., 2020) are just a few challenges that lie ahead of researchers. Based on these criteria, thousands of papers are published to overcome these issues and flatten the road of progress for the next generation of research papers. In this study, operating temperature affection on PV modules is considered for analysis.

The sensitivity of PV modules to operating temperature is about 0.4%–0.65% decrease in its electrical efficiency with each degree of temperature rise (Su et al., 2017; Rahman et al., 2015). The rationale behind this phenomenon is well explained by Baghzouz (2017). According to his report, with the temperature rise of a PV module, the short-circuit current (I_{SC}) slightly increases. However, the open-circuit voltage (V_{OC}) and power output decrease sharply. For instance, with each degree of temperature rise, crystalline silicon cells show a 0.37% and 0.5% drop in V_{OC} and maximum power available, respectively. This drop is dominant compared to the 0.05% increase in I_{SC} per degree Celsius increase. All is said and done, it can be concluded that PV modules could operate with higher efficiency on cold than hot days. Since deserts are good places for solar farms to get operational, investigating their weather condition is essential. Taking the "Lut Desert" in Iran as an example, in the daytime in summer, the ambient temperature reaches up to 50 ◦C, and at night, it is dropped by about 10–20 ◦C. As claimed by J. van Helden et al. (van HeldenWim et al., 2004), on sunny days PV modules could reach temperatures as high as 35 ◦C above ambient temperature, which means the PV laminates are exhibited to harsh thermal stresses during the day and night. Moreover, if solar cell temperature exceeds a specific limit, for a long time it will be degenerated (Muneeshwaran, 2020). For these reasons, designing a cooling field for a PV module is vital. In the next paragraph, different types of PV cooling technologies are discussed and compared with each other.

Mainly the PV cooling technologies could be categorized into three groups:

1 Passive cooling (no requirement for extra energy)
2 Active cooling (requires extra energy)
3 Combination of active and passive cooling

These methods are thoroughly studied by M. Gharzi et al. (2020). Based on their outcome the combination of active and passive cooling is the most effective way in terms of sustaining the PV electrical efficiency and utilizing the thermal energy. Nevertheless, the active technique alone or integration of it with other techniques requires supplementary apparatuses such as (Moharram et al., 2013):

1 Piping (to circulate the cooling fluid)
2 Pump (to drive the cooling fluid)
3 Manometer (to measure the cooling fluid pressure)
4 Flowmeter (to measure the mass/volume flow rate of the coolant fluid)
5 Controllers and sensors (to control the flow rate of the cooling fluid at different times)
6 Condenser (to cool down the working fluid)

The above items are just a few examples of essential devices for cooling PV panels in a solar farm. If the solar farm is located far from the residential, commercial, or industrial areas which would be likely to happen, (since a vast useless land is required for the installation of a solar farm), the gained heat from the PV panels could not be used. Therefore, the thermal efficiency of the system will be zero. Besides all the additional costs incurred by the supplementary devices, the parasitic loss of PV panels to circulate the working fluid is another issue needed to be considered. Consequently, the active cooling techniques are highly efficient in places where hot air/water is required so that the photovoltaic thermal (PVT) systems are put into action (Pang et al., 2020). In such cases, the cooling system not only boosts the electrical efficiency but also provides thermal energy so that overall efficiency is yielded (Parsa et al., 2022).

The passive cooling technique is another effective approach to cool the PV modules without consuming extra energy. In this technique, the stored heat of a PV module is transferred to the ambient through radiation, natural convection, evaporation, and splitting the spectrum with the least environmental impact (Ramkiran et al., 2021). These passive methods would be practical and effective in cooling solar farm panels. Each technique has its attributes in terms of electricity improvement, initial investment, and maintenance costs. The comparison of attributes described above is mentioned in T. Ma et al. (2019) (Table 1.).

It is noteworthy to mention that Table 1 contents are a small portion of its main reference which included both active and passive techniques.

In this paper, various PV passive cooling methodologies such as natural ventilation, liquid immersion or floating, heat pipe, thermoelectric, phase change material, and spectral beam splitter are thoroughly discussed in section 2. For each passive method, some state-of-the-art papers are presented and supplementary recommendations are provided after that. In section 3 all previously mentioned papers are summarized in a Table to simplify the comparison. Since the summarized Table is based on environmental conditions and the solar intensity applied to the specific problem it could facilitate choosing the cooling method for future work. In the end, the conclusion section is prepared

Table 1
Comparison of different passive cooling techniques (Ma et al., 2019).

	Electricity improvement	Initial investment	Maintenance cost
Natural ventilation	✓	✓	×
Liquid immersion	✓✓	✓✓	×
Heat pipe	✓✓	✓✓	×
Phase change material	✓✓✓	✓✓✓✓	×

Notes: "×" means no or very little, "✓" meaning the lowest, and "✓✓✓✓✓" representing the highest.

and future work development is mentioned for each technique.

2. Passive cooling methodologies

Regulating PV panel temperature to ensure optimal performance and a long life span is not covert to anyone. Active methods would be a challenging task for cooling solar farm panels which have undergone installation on vast barren land. Finding a suitable passive cooling method based on geographical location is the key to overcoming the challenge. In 2016, A. M. Elbreki et al. (2017) comprehensively reviewed both active and passive cooling techniques for the thermal regulation of PV module temperature. However, since global warming and water shortage have become two urgent problems that are threatening our future, in the past five years a large number of studies have been conducted concerning PV modules/panels. Fig. 1 depicts the escalating number of published papers in Elsevier with a focus on “Photovoltaic”. As a consequence, the number of papers regarding “Photovoltaic” and “Passive Cooling” has dramatically increased and this elevation is clearly shown in Fig. 2. Eventually, in the past 5 years there is no review paper with the aim of the passive cooling approach of PV panels/modules, it seems necessary to gather the most up to date published papers to blaze the trail of finding the most suitable passive cooling techniques apply to a solar farm.

2.1. Natural ventilation

PV cooling under natural convection of air or water is the easiest and cheapest method to implement (Vittorini and Cipollone, 2019). Building-integrated photovoltaics (BIPV) is a solution to alter conventional buildings to zero energy buildings (Rosa, 2020). In the work of B. J. Brinkworth et al. (1997), it has been tried to reduce the PV cladding temperature by inducing the natural convection of air through a duct behind the PV panels. Fig. 3 represents the schematic work of their experimental and numerical study. Based on their simulation they were successful in designing some basic parameters such as the height and depth of the cooling duct. Moreover, with the natural convection occurring behind the PV panels, the solar cell temperature has decreased about 15–20 K. This was a significant reduction to gain more power from PV cladding for walls and roofs of buildings. Since the main focus of this paper is to cool solar panels that could be used in a solar farm, reference (Brinkworth et al., 1997) was just an example of how remarkably natural convection could reduce solar panels’ temperature and hence boost their power output.

A. E. Mays et al. (MaysAhmad et al., 2017) have experimentally studied the cooling of a polycrystalline module with 30 W capacity on a sunny day in Beqaa. Results showed that using aluminum finned plates

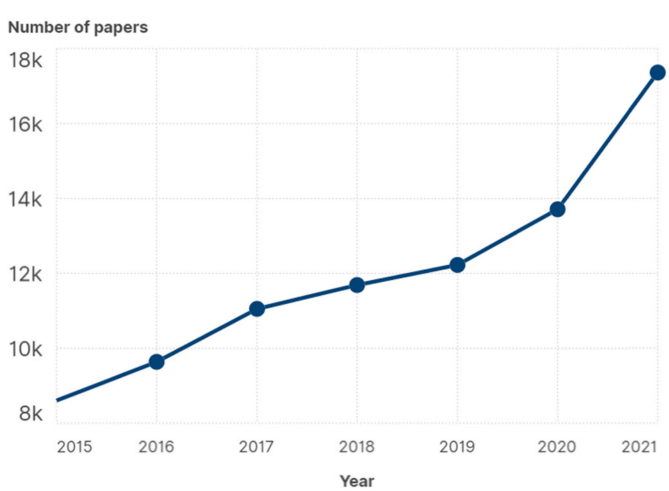


Fig. 1. Number of published papers with a focus on “Photovoltaic”.

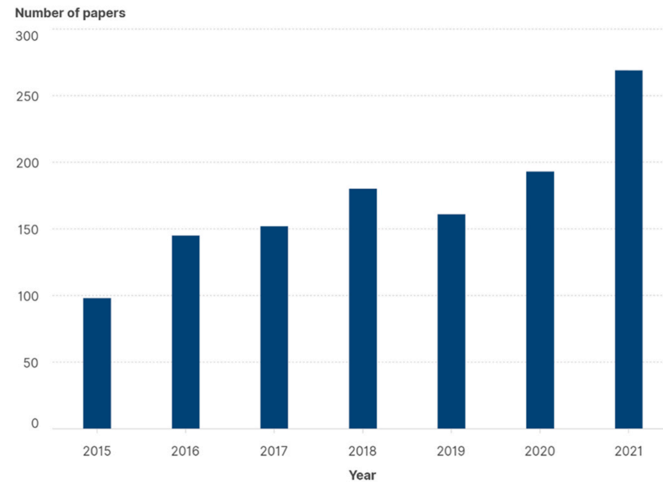


Fig. 2. Number of published papers with a focus on “Photovoltaic” and “Passive Cooling”.

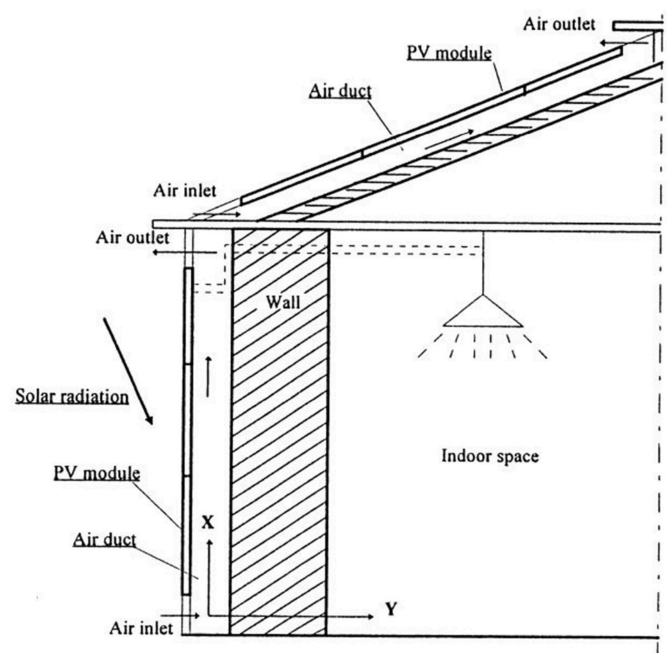
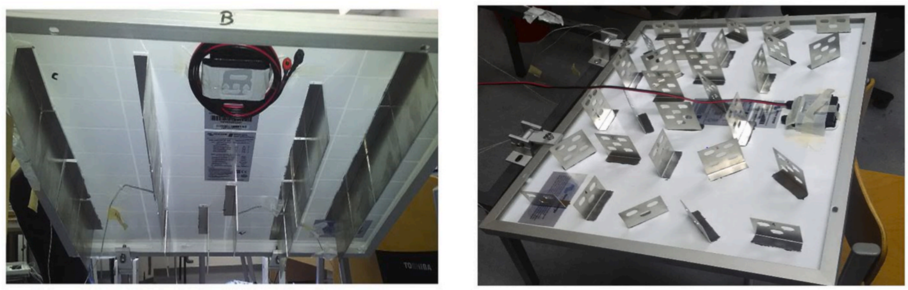


Fig. 3. Schematic presentation of PV cladding for walls and roofs of buildings used in Ref (Brinkworth et al., 1997).

behind PV module could increase the electrical efficiency by an average of 1.77% while the power output was enhanced by an average of 1.86 W. F. Grubisic-Cabo et al. (Grubišić-Čabo et al., 2018) have proposed two L-profile aluminum fins configurations which in the first configuration the fins were positioned in parallel, while in the second configuration the fins were positioned randomly (Fig. 4). The second configuration showed better improvement in reducing the PV panel temperature, probably because of the ease in air movement through perforated randomly positioned fins. Further experiments were conducted for the second configuration in November for the city Split in Croatia. The results showed a 2% electrical efficiency improvement compared to the bare reference panel.

Another case study was done by F. Bayrak et al. (Bayrak and Hakan, 2019) in Elazig city of Turkey. In order to analyze fin numbers and their arrangements on a PV panel, 10 cases named A1-A10 were considered and studied from 9:00 a.m. to 4:00 p.m. Since the heat transfer



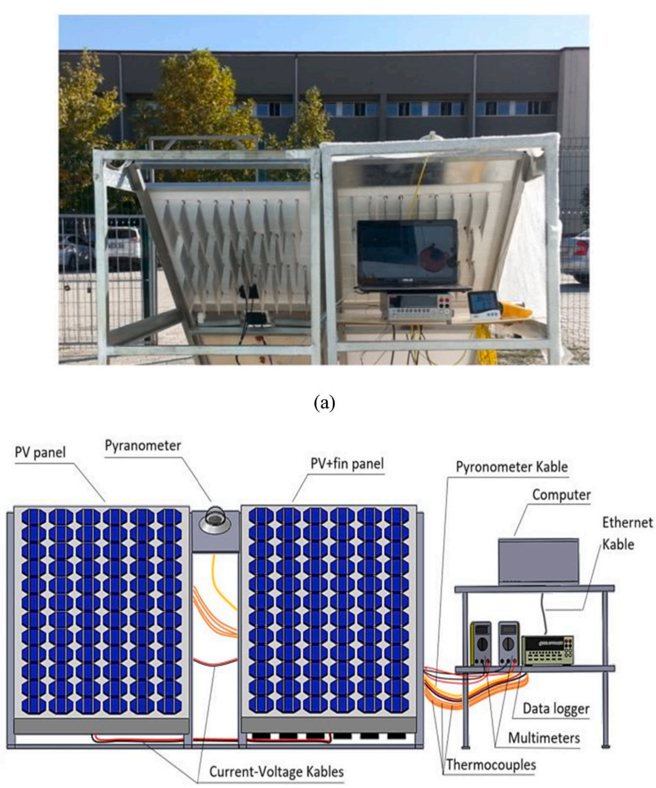
(a) (b)

Fig. 4. Two different L-profile fin configurations were used in the work of Ref (Grubišić-Čabo et al., 2018).

coefficient was assumed to be a linear function of wind speed (Duffy and Beckman, 2013), the wind effect was also considered in their research work. In terms of efficiency, case A5 with 26 staggered-vertical fins stands out from the pack with the maximum energy and exergy efficiencies of 11.55% and 10.91% respectively. In terms of fin length, interestingly, the cases with 7 cm fin length outperformed those with 12 cm in both horizontal and vertical arrangements. Fig. 5 represents their experimental work.

Recently, A.M. Elbreki et al. (2021), experimentally analyzed the cooling of a PV module using fins and a planar reflector at the geographical location of the National University of Malaysia. Two different heat sink configurations including longitudinal and lapping fins were chosen as the passive cooling system. Economic analysis has also been done to find out the shortest payback period of each cooling system compared with the reference module. In the latter study, under an average solar irradiance of 1000 W/m^2 and ambient temperature of 33 ◦C, passive cooling with lapping fins was used, which resulted in a mean PV module temperature, electrical efficiency, and power output of 24.6 ◦C, 10.68%, and 37.1 W, respectively, as the best performance. Concerning the economic point of view, the analysis indicated that the payback periods of PV modules with longitudinal, lapping fins, and bare PV modules are 4.2, 5, and 8.4 years, respectively. Therefore, a cooling system with lapping fins could be a promising option to maintain the PV module temperature at lower levels. Fig. 6 shows their experimental work on the 7th floor at the solar energy research institute of the National University of Malaysia. Considering the fin geometry, in a very recent study E. Z. Ahmad et al. (2021) numerically investigated a truncated multi-level fin heat sink attached to the bottom of a PV module. From their results, it can be derived that the truncated multi-level fin heat sink design offered a 6.13% lower average temperature compared to the conventional rectangular design. While the previous study has focused on fin geometry I. Marinic-Kragic et al. (Marinić-Kragić et al., 2020), have come up with the idea of changing the PV architecture by making a slit on a PV panel. Their simple but effective modification has decreased the panel temperature by 3 ◦C.

A solar power plant known as a solar park or solar farm is designed by a large-scale grid-connected photovoltaic system whose power output is more than 1 MW. While most of the studies were focused on the PV panels' inclination angle to absorb the sunlight as much as possible, A. Glick et al. (2020) studied the influence of PV panels' arrangement on the incoming wind flow. Fig. 7 shows the schematic diagram of their experimental work. In their study, the inclination angle of the PV panels has been changed and upper and lower surface heat transfer coefficients have been calculated. As depicted in Fig. 7, the −30° inclination angle showed the largest heat transfer on the lower surface. Therefore, it was recommended to enhance the sub-panel flow through height optimizations or the use of deflectors to enhance the lifetime and efficiency of PV



(b)

Fig. 5. Two views of the experimental setup: (a) real photograph, and (b) schematic view of Ref (Bayrak and Hakan, 2019).

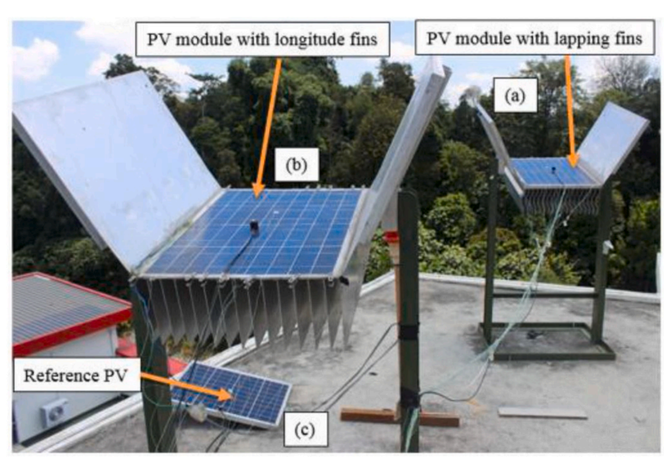


Fig. 6. Experimental setup of work (Elbreki et al., 2021).

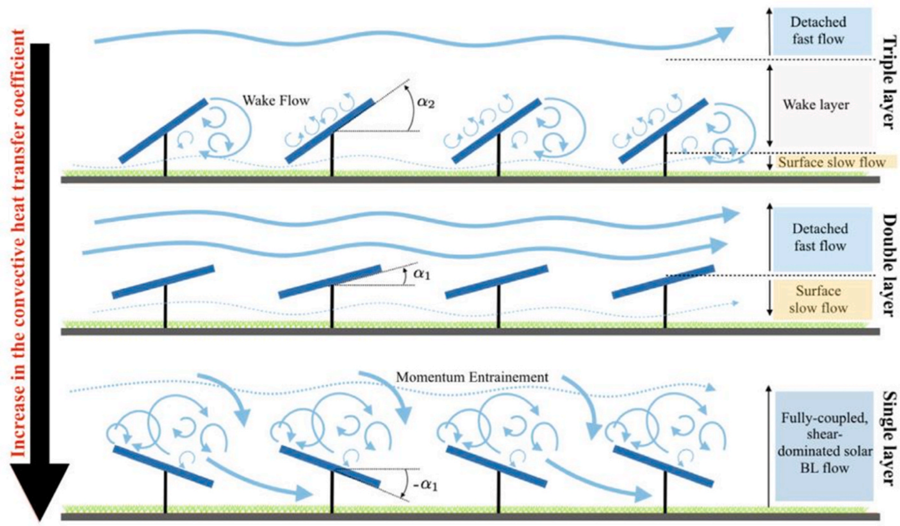
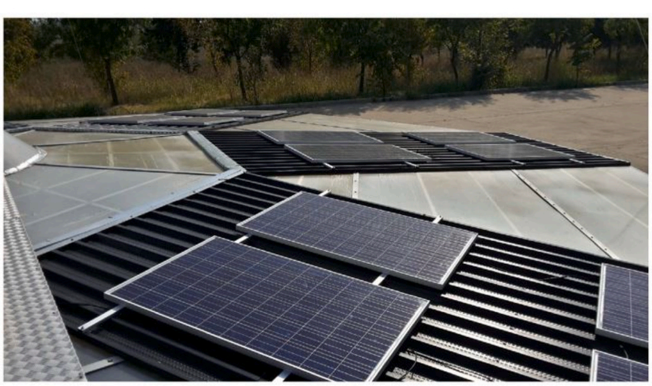


Fig. 7. Schematic diagram of different solar farm arrangements used in Ref (Glick et al., 2020).

panels. It can be clearly understood from this study how remarkably the incoming natural airflow could enhance the lifetime and efficiency of PV panels. Regarding the previous quote, a question may arise: Is it possible to maintain the incoming airflow during the PV panels' operation? Well, it would be possible if the solar updraft tower is combined with PV panels. Installing PV panels on the collector of a solar updraft tower brings advantages that have been well described in the work of (Eryener and Kuscu, 2018). Fig. 8 shows the experimental work of D. Eryener and H. Kuscu. They have reported that the integrated PV panels efficiency of the hybrid system was higher than the stand-alone PV panels.

(a) Top view of hybrid solar updraft tower



(b) Close-up view of PV panels installed on the solar updraft tower's collector

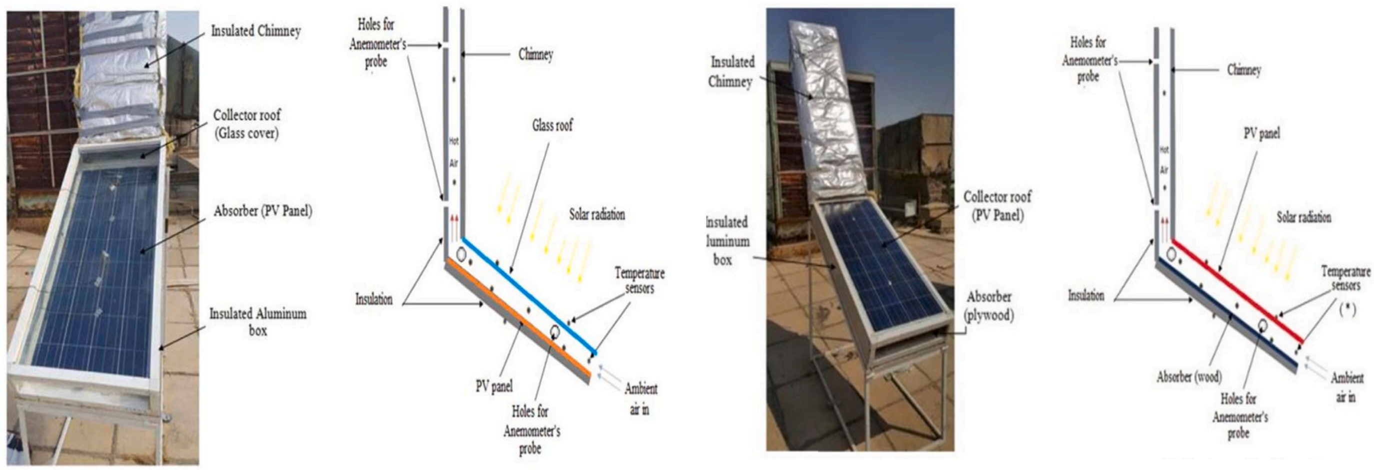
Fig. 8. Experimental work of Ref (Eryener and Kuscu, 2018).

O.K. Ahmed and A.S. Hussein (Ahmed and Hussein, 2018), have experimentally studied the hybrid combination of solar chimney and PV panels in Kirkuk city, Iraq. In their experimental work, two different setups have been examined and compared with each other. These two setups are shown in Fig. 9. The results showed that even though system (A) had a higher thermal gain, overall, system (B) had a superior performance than (A). The reason was that in system (B) the PV panel was positioned on top of the chimney collector while system (A) was positioned underneath so that due to the greenhouse effect it gets hotter and the electrical efficiency drops. They have reported that in system (A) the maximum temperature reached 90 ◦C while in system (B) it was below 67 ◦C.

The hybrid combination of PV panels and solar chimneys could bring us the advantage of less land occupation for the same power output. The objective, however, is important. If a solar chimney is constructed for air purification, then the air flow rate through the solar chimney has a preference for engineers over the power output of the hybrid system. M.-H. Huang et al. (2020) numerically and experimentally studied the behavior of such hybrid combinations for various objectives. Their experimental setup is shown in Fig. 10. They have reported that if the solar chimney is operated alone then the volumetric flow rate would be maximum, whereas the power output would be minimum. Therefore, PV panels are recommended to be combined with a solar chimney to generate more electricity. Regarding PV panel positioning, the same conclusions have been derived compared to the work of (Ahmed and Hussein, 2018). The predicted average temperature of the PV panels at the top and bottom were 50.01 ◦C and 67.32 ◦C, respectively. Although the thermal air flow rate is reduced by combining the PV panels with a solar chimney, the total airflow rate increases if a suction fan is applied. Please note that the fan power is supplied by the PV panels.

2.2. Liquid immersion or floating

Submerging PV panels in a liquid is a highly efficient passive method of cooling them. Because in this case, the PV panel area which is in contact with the coolant medium is maximized and also there would be no thermal resistance (Wang et al., 2009). According to G. M. Tina et al. (2012), "this proposed solution is effective where both the ambient temperature and the level of irradiance, along the year, are quite high." In their study crystalline silicon panels were submerged at different water depths so that they were able to study the optical properties of



(a) System A (b) System B

Fig. 9. Two different setups were tested at the same environmental conditions (Ahmed and Hussein, 2018).

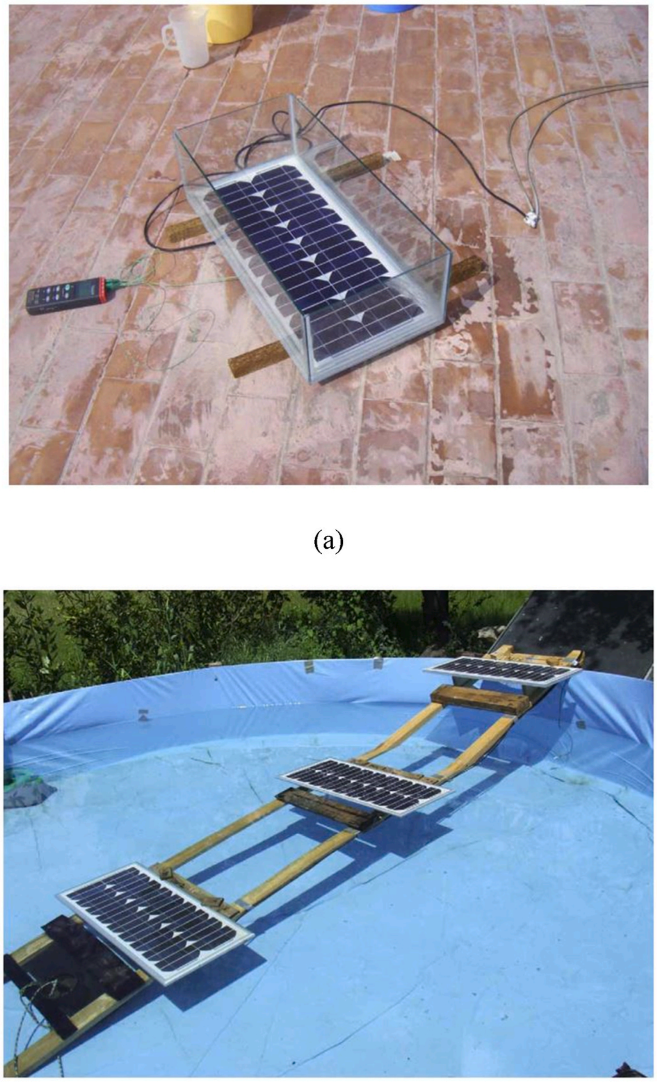
(a) The solar chimney system (b) The hybrid solar chimney and photovoltaic system

Fig. 10. Experimental setups of Ref (Huang et al., 2020).

water and evaluate the power output and efficiency of the panel. Fig. 11 shows their experiments set up in two different cities in Italy: Catania and Pisa. Based on their results, if the panel is submerged in a 5 cm depth of water the power output of the module would be maximum. With increasing the water depth from 5 cm to 15 cm, the power drawn by the panel would decrease. This phenomenon was due to the increase in absorption of light as the water gets deeper. In addition, a 4 cm water depth was reported as a proper depth which cause an increase of 15% efficiency (Lanzafame et al., 2009). From Fig. 12 the variation of the solar spectrum versus different water depths could be observed (Clot et al., 2017). The black plot is the absorption of water on a logarithm scale. Based on the work of Marco Rosa Clot et al. (2017), it can be concluded that even though the second generation amorphous solar cells possess lower efficiency compared to first-generation solar cells, they are quite a good candidate to be used underwater due to their tolerance against partial shading and conversion of light to electricity at a water depth up to 1.5 m. Fig. 13 indicates one of their executive projects which has become operational.

S. Mehrotra et al. (2014) have also investigated the water immersion technique as a passive approach for cooling a 2W polycrystalline silicon solar panel. Fig. 14 shows their experimental work under meteorological conditions of Bhopal in India during 18/04/2014–23/04/2014 from 10:00 a.m. to 5:00 p.m. They have reported that under a 1 cm depth of water, the maximum electrical efficiency of 4.76% was yielded. This achievement was a 17.8% increment compared to the system without cooling. Although in most research papers water was used as the cooling medium where solar panels were submerged, it is not the only option available. Y. Wang et al. (2009) have examined six liquids, which include polar ethanol and glycerin, non-polar benzene and silicon oil, and inorganic distilled water and tap water. The single crystalline solar cells were immersed in these liquids and illuminated under 1000 W/m^2. They came up with the conclusion that non-polar silicone oil had the best performance. Regarding different coolant liquids, F. Al-Amri et al. (2021) have designed a cooling field for a polycrystalline silicon solar panel with a peak efficiency of 11% under Standard Test Conditions (STCs), with the combination of heat pipes and three different liquids such as engine oil, Ethylene Glycol, and water. They have mentioned that owing to higher thermal conductivity and specific heat capacity, water is a better choice than other liquids. Immersing solar cells underwater was done roughly 40 years ago for a different purpose and different context. J. D. Stachiw (1980) studied the performance of solar cells under a water depth of 0.75 up to 29 m for the possibility of powering marine devices. Based on their findings, the efficiency of a solar cell submerged in a certain depth of their experiment would be 5–10 percent of the same solar cell in the atmospheric environment. Nevertheless, they have reported that highly efficient silicon solar cells are still a practical solution for marine applications. The aforementioned reference makes the goal of submerging PV cells clarified. Due to the "shifting of the radiation towards the green and blue side of the spectrum underwater, silicon cells become much less efficient once they are more than a few centimeters below water" (StagnoLuciano, 2014). Hence, maybe floating photovoltaic (FPV) panels on a water reservoir be a viable solution to cool them down without being worried about the optical properties of the liquid type covering the top surface of the panel.

In this section, the efficiency enhancement, as well as the eco-environmental impact of floating solar panels as a feasible solution for cooling a vast solar farm, is discussed. In terms of efficiency, reported by a review paper (Patil Desai Sujay et al., 2017), floating PV panels show over 10% efficiency compared to PV panels installed on land. This is not the only operational advantage that floatovoltaics could bring to us. Concerning the economic aspect, the cost requirement of installing PV panels on the water is about 15% more than installing them on land (Barbuscia, 2018), however, the operational and maintenance costs of floatovoltaics are often lower with respect to the PVs installed on the ground (Ranjbaran et al., 2019). Concerning environmental impact, the establishment of PV panels on water reservoirs such as lakes, canals, dams, and ponds can reduce evaporation by up to 70% (Perera, 2020). In addition, due to the shading effect, algae growth would be limited helping water to get less contaminated (Sharma et al., 2015). For hybrid applications, floating PV panels could be combined with hydropower sites to increase the energy yield, and help manage periods of low water



(a)

(b)

Fig. 11. Experimental apparatus in (a) Catania, and (b) Pisa of Ref (Tina et al., 2012).

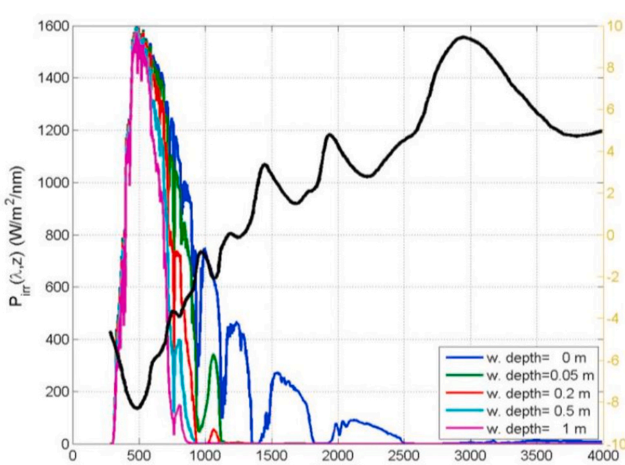


Fig. 12. Variation of the solar spectrum with water depth (Clot et al., 2017).

Fig. 13. PV panels installed at the bottom of a swimming pool in the work of Ref (Clot et al., 2017).

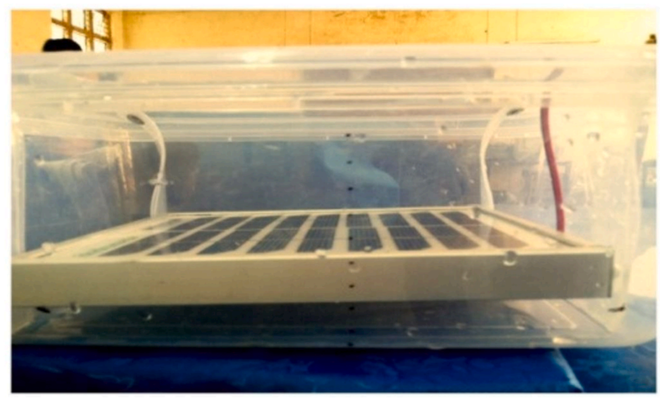


Fig. 14. Experimental work of Ref (Mehrotra et al., 2014).

availability (Kjeldstad et al., 2021). Other added values of the hybrid system could be found in the literature review of N. Lee. et al. (Lee et al., 2020). Fig. 15 depicts a schematic of a hybrid FPV-hydropower system.

2.3. Heat pipe

A heat pipe (HP) is a two-phase heat transfer device where evaporation and condensation occur so that making a large heat transfer possible (Brahim et al., 2014). Coupling solar panels with heat pipes is a passive cooling approach that is mostly recommended in high-latitude areas or the winter season (Zhang et al., 2019). X. Han et al. (2020)

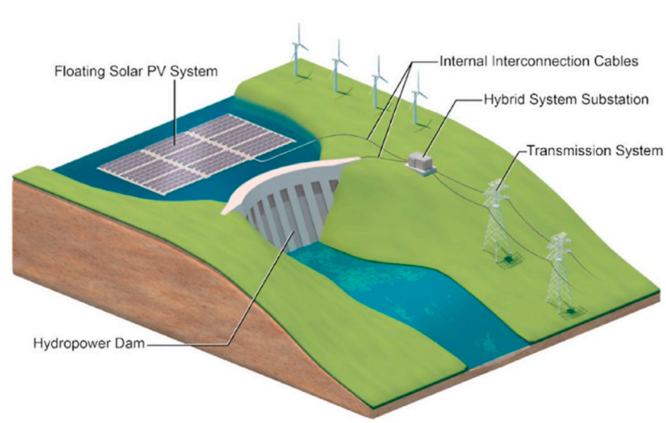


Fig. 15. Schematic of a hybrid FPV-hydropower system (Lee et al., 2020).

proposed a concentrating PVT system that combines the advantage of the nanofluid-based spectral beam splitter (SBS) and HP cooling technologies to raise the PV conversion efficiency. With the use of a heat pipe, at an eight-suns concentration ratio, the average electrical efficiency is 0.7% higher than the case without a heat pipe. Mingke Hu et al. (2016) experimentally studied two different heat pipe PVT systems, namely, wickless heat pipe and wire-meshed heat pipe PVT system. The influence of the inclination angle on both systems has been investigated. They have reported that the wire-meshed heat pipe is not as sensitive as the wickless heat pipe to the inclination angle. The wickless heat pipe PVT system and wire-meshed heat pipe PVT system were recommended at latitudes higher than 20° and lower than 20°, respectively. T. Zhang. et al. (Zhang et al., 2019) have evaluated the geometrical aspects of the heat pipe system used in their experimental and numerical work (Fig. 16). Regarding the working fluid type, they mentioned that water is suitable for temperate climatic regions, while R134a is recommended for cold climatic regions. Another study has also confirmed that a combination of heat pipe with PV is suitable for freezing weather conditions (Modjinou et al., 2019). Yet, the application of heat pipes with a PV system is not limited to the winter months. M. Moradgholi et al. (2014) investigated the assessment of heat pipe with PVT system during both spring and summer. In spring, methanol was chosen as the working fluid of the heat pipe, and the PVT system yielded 5.67% more electrical power than the bare PV system. In summer, acetone was used as working fluid of thermosyphon, and an increment of 7.7% in power output was observed. Fig. 17 shows their experimental setup.

As mentioned at the beginning of the paragraph heat pipe is consisted of an evaporation and condensation section. The excess heat of a PV panel could be absorbed from the evaporation section and released via the condensation section. In order to use the thermal energy of the system, the condensation part is coupled with tap water which the HP-PVT system would be assembled. Therefore, HP-PVT systems are used substantially in domestic regions where electrical and thermal energy are required simultaneously. All the aforementioned papers have investigated the compound of HP-PVT. There are very few studies related to the cooling of PV modules/panels with heat pipes alone. S. Koundinya et al. (2017) experimentally and computationally studied the cooling of PV panels with finned heat pipe technology. Results have shown a maximum decrease of 13.8 K by utilizing this technology. H. Alizadeh et al. (2018) applied pulsating heat pipes (PHPs) for PV cooling. Based on their numerical simulation the PV panel using the PHP showed roughly 18% enhancement in the generation of electrical power. It is worth noting that their simulation was conducted under 1000 W/m^2 heat flux and ambient temperature of 291 K. To sum up, based on our literature review more studies are needed in cooling solar panels using heat pipes alone as a practical cooling approach for solar farms.

2.4. Thermoelectric generator

The thermoelectric generator (TEG) system could act as a cooling system when voltage is applied to the two p and n sides of it (Peltier effect) or could produce electricity if a temperature gradient exists at the two legs (Seebeck effect). In the case of the Peltier effect, TEG has the capability of cooling down a PV module by consuming a fraction of PV power output which would fall in an active cooling category. However, in the case of the Seebeck effect, the TEG could produce supplemental power by absorbing the excess heat of the PV module. Consequently, the PV module is cooled down and more power is produced simultaneously. This could be considered a hybrid technology that would have an advantageous effect on both systems.

Since the TEG system combination with PV cell has two different states regarding Peltier or Seebeck effect, S.-Y. Wu et al. (2018) have studied these two-hybrid systems under different conditions. They have reported that even though the PV-TCS (hybrid PV with thermoelectric as cooling) has lower cell temperature than PV-TGS (hybrid PV with thermoelectric as electricity generator), it also has lower power and efficiency. Wind speed influence on stand-alone PV systems has been more highlighted compared to hybrid systems. The cooling heat sink capacity has a remarkable effect to enhance the performance of both hybrid systems. It is noted worth mentioning that the heat sink was attached below the TEG systems. C. Babu and P. Ponnambalam (Babu and Ponnambalam, 2018) studied the performance of the PV-TEG system by mathematical modeling. They have come up with the conclusion that the hybrid PV-TEG system could produce 5% additional energy and also a 6% increase in overall efficiency. They have also reported that the rise in ambient temperature causes an increment in power for the hybrid PV-TEG system which, however, proved a detrimental influence on the stand-alone PV system.

One of the main challenges in coupling TEG solid state devices to a PV module is the thermal impediment existence between the interfaces due to the microscopic roughness of PV and TEG surfaces. G. Kidegho et al. (2021) have tested the PV-TEG systems with three different thermal interface materials such as graphic sheet, heat spreader, and aluminum foil. They found that the thermal interface materials successfully mitigate the thermal coupling challenges and subsequently improve their overall power output.

The PV-TEG hybrid systems could be combined with heat pipes and result in a heat pipe-based PV-TEG (HP-PV/TEG) system. Fig. 18 taken from the (Makki et al., 2016) well depicts the integration of such a hybrid HP-PV/TEG system. In the theoretical work of (Makki et al.,

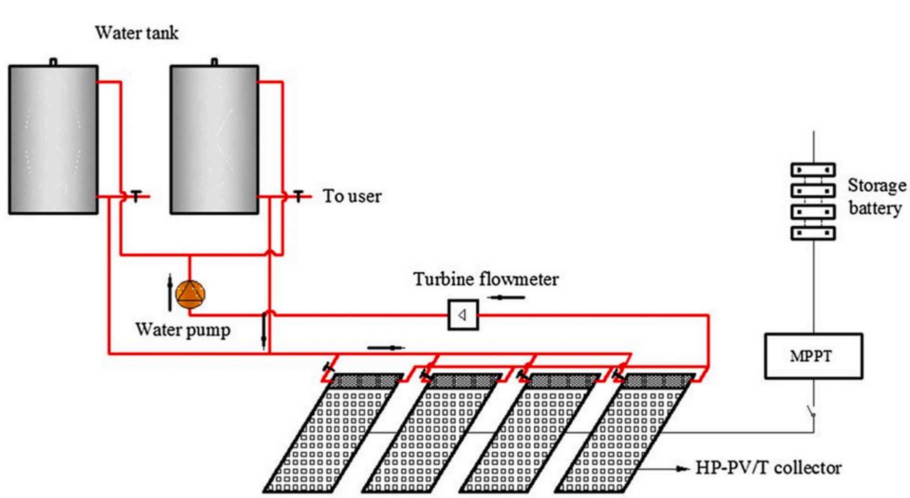


Fig. 16. Schematic diagram of the experimental setup of Ref (Zhang et al., 2019).

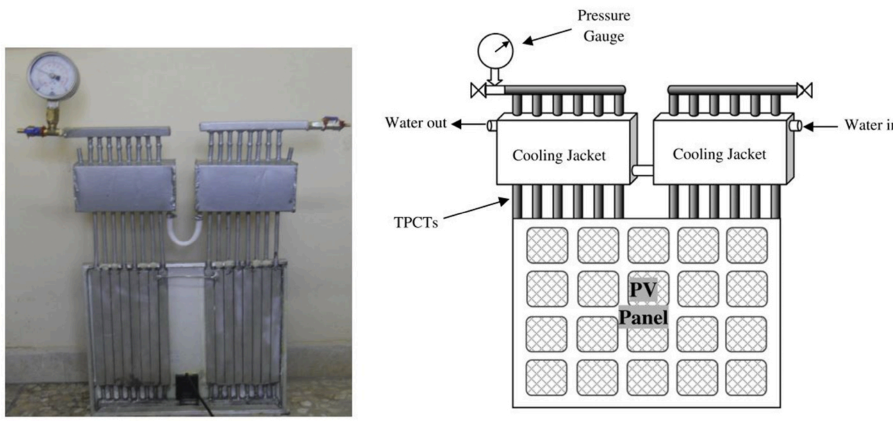


Fig. 17. Experimental setup of Ref (Moradgholi et al., 2014).

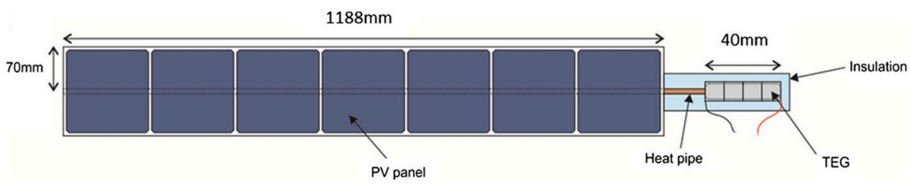


Fig. 18. Top view of heat-piped based PV-TEG system (Makki et al., 2016).

2016), they have studied the hybrid system under different operating conditions of irradiance, wind speed, and ambient temperature. It is observed that in all cases the hybrid system performance excelled over the PV alone system. Since this hybrid cooling technology is passive and has a superior performance compared to the stand-alone PV system, it may have the potential as a practical approach for large-scale photovoltaic grid-connected systems. Nevertheless, experimental studies in this area are required before fully commercializing them.

2.5. Phase change material

Phase-changing materials (PCMs) provide a unique feature by adjusting the temperature in a narrow range of operations (Mahdavi et al., 2021a). Having a high latent heat of fusion during the melting range makes them possible to store the thermal energy as much as possible. Consequently, applying PCMs to PV modules/panels could be a passive feasible course of action. In addition, according to a recent state of art review (Dwivedi et al., 2020), "PCM cooling is the most capable technique". Owing to the previously mentioned benefits of PCMs, combining them with solar modules/panels will avoid two main drawbacks which may happen during the lifetime of a PV system (Klemm et al., 2017):

1 Thermal stresses during the day and night caused by fast temperature changes
2 Formation of solid crust on a PV module caused by water vapor condensation at nights

On account of all the mentioned advantages, there are dozens of published research papers utilizing PCMs with a solar module/panel. Some of those papers are classified as passive techniques, and in the case of PVT combination with PCM (PVT-PCM), they fall into an active classification. The majority of those papers are mentioned in T. Ma et al. (2019), O. Mahian et al. (2021), Hafiz Muhammad Ali (2020), and S.S. Chandel's (Chandel and Agarwal, 2017) review papers. However, here the most up-to-date papers using PCMs with PV systems (PV-PCM) are reported, and also the possibility of utilizing the ideas of enhancing PCMs' thermal conductivity for a solar farm application is discussed. This is a new insight into the PV-PCM efficiency and lifespan treatment.

Huang's research team is considered the founder and pioneer of PV-PCM technology. In 2004, M. J. Huang et al. (2004) proposed the concept of PV-PCM technology by utilizing plate fins to enhance the heat transfer rate (Fig. 19). Their study was conducted both in numerical and experimental. The numerical study was done in parallel to the experimental study helping to observe the thermophysical performance of the PCM, while indoor experiments were done to authenticate the results report. Based on their outputs the fin thickness was an insignificant parameter in the heat transfer rate. However, ambient temperature and

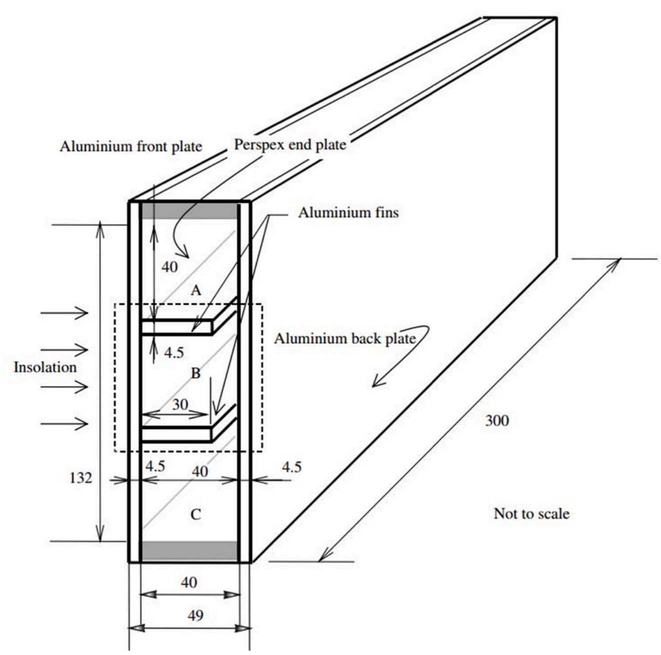


Fig. 19. Schematic diagram of the experimental PV-PCM system of Ref (Huang et al., 2004).

PCM thickness did play a major role. The same research team has done a 3D numerical study in 2007 (Huang and EamesBrian, 2007). They have compared their results with their previous work. Interestingly, the previous 2D numerical simulated case was in good agreement with the new 3D study. Four years later they published a new paper (Huang et al., 2011) in which three different PCMs like waksol A, RT 27, and RT 35 were examined and tested experimentally. They mentioned that extruded aluminum plates were able to maintain the PV module at lower levels during the melting phase transition of PCM. All the foregoing research papers have demonstrated that fins have an essential role in the dissipation of excess heat. Nevertheless, a recent study proved that configurations of fins with PCM were effective at solar radiation intensities higher than 500 W/m^2 (Ezan, 2018).

S. Maiti et al. (2011) experimentally studied the PCM (paraffin wax) role as a passive cooling technique in a PV module with reflectors. The experiments were performed outdoors and indoors. Fig. 20 indicates the outdoor experiment setup of their work. Aluminum lathe turnings were employed inside the PCM to boost the heat transfer rate. Results revealed that using a PCM matrix with a 6 cm thickness, successfully maintained the PV module temperature at 65–68 ◦C for 3 h under indoor conditions, while on contrary without the PCM matrix the temperature rose beyond 90 ◦C within 15 min. In outdoor conditions, the use of a PCM matrix could sustain the PV module operation and enhance the power output to 1.55 times the reference module. N. Savvakis and T. Soutsos (Savvakis and Tsoutsos, 2016) experimentally studied the passive cooling approach of using RT 27 PCM in Mediterranean climate conditions. Their outdoor experimental setup was employed in Chania, Greece. Results showed that compared to the reference PV module, PCM was able to attain 11 ◦C temperature reductions. This was a crucial achievement that justifies the use of PCM. Whereas, in another study done by J. H. C. Hendricks and W. G. J. H. M. van Sark (Hendricks and Van Sark, 2013) in both Malaga and Utrecht, a clear benefit of utilizing PCM based cooling system was not identified. From references (Savvakis and Tsoutsos, 2016) and (Hendricks and Van Sark, 2013) it can be interpreted that the geographical location is a determinant factor in where PCM is a reasonable cooling method or not.

T. Klemm et al. (2017) numerically analyzed the performance of PV-PCM with metallic fiber structure. They have considered three different PCMs RT 44, RT 50, and RT 54. According to their report, a 20 K temperature drop was observed in the peak temperature of the PV module during the daily life cycle. They've also mentioned that PCM selection is contingent upon the latent heat of fusion, the higher the latent heat of fusion, the better system performance will be. In addition, decreasing the porosity from 90% to 80% or 70% serves no interest in heat transfer enhancement. In another numerical study, S. Khanna et al. (2018) analyzed the geometrical optimization of fins and PCM thickness. Their results showed that the suitable depth of PCM thickness for daily average solar irradiance of 3 kWh/m^2 and 5 kWh/m^2 is 2.8 cm and 4.8 cm respectively. The best fin thickness was 2 mm and the best fin length was the one that touches the bottom of the container. Fig. 21 depicts the schematic domain of their numerical study considering the boundary conditions.

An experimental and numerical study was done by V. Sun et al. (2020) in Chiang Mai, Thailand in the summertime. It should be noted that Chiang Mai has a hot climate and the PV module was mounted at a 10° tilted angle. Their goal was to find out an optimum thickness for various kinds of PCMs such as RT 35, 42, 47, and 55 used in their work. Based on their results, the optimum thickness for the aforementioned PCMs were 50, 40, 30, and 20 mm respectively. M. Rajvikram et al. (2019) experimentally studied the cooling of a PV-PCM system in Chennai city of India. The OM 29 PCM was selected as an organic PCM. Their results proved that the conversion efficiency of the PV module with PCM and an aluminum sheet behind it was 24.4% more than the reference module without a cooling system. Fig. 22 indicates their experimental setup.

J. Darkwa et al. (2019) made the PV-PCM system more advanced by adding a TEG. Fig. 23 shows their novel compound system configuration. As its indicated in the picture, the TEG is placed between the monocrystalline PV module and PCM so takes advantage of the temperature difference between the module and PCM to generate electricity. Their indoor experimental setup was tested inside a chamber to assure an insulated experiment and mitigate the affection of any other uncontrollable parameters. Besides their experimental setup, they have developed a numerical model for thermal simulations. An analysis of theoretical PV efficiencies and power output of the three systems named PV, PV-TEG, and PV-TEG-PCM has been done and depicted in Fig. 24. It can be derived from Fig. 24 that on average the PV-TEG-PCM system's power output is higher than the two others. Although this research has comprehensively studied the input variables of designing a PV-TEG-PCM cooling system, further outdoor experimental research is still required to extend the research outcome to an actual operational solar farm panel. Whilst J. Darkwa et al. (2019) employed the TEGs between PV module and PCM, F. Bayrak et al. (2020) mounted them behind the PCM and the compound system was not as efficient as the other cooling systems which were tested in their work. For example, the PV-TEG system compared to PV-PCM-TEG showed higher power output. They have reported that the PCM acted as insulation, hence, hindering the performance of the whole system. Consequently, the selection of PCM type and its combination with TEG is as important as their arrangement in assembly. There is still a huge gap and further research is necessary for this area.

Akshayveer et al. (Kumar et al., 2020b) numerically studied the PCM container shape and its effect on the melting rate of RT 27 PCM. Three different non-rectangular shapes were designed and compared with the reference rectangular container. In comparison to conventional rectangular designs, each of those linear, parabolic, and cubic designs acted better in melting the PCM which decreased the PV temperature and increased the electrical efficiency. If the three PCM enclosures are

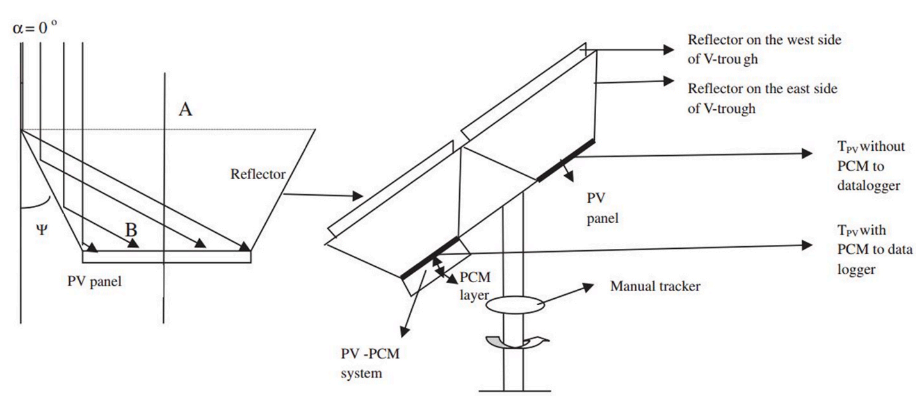


Fig. 20. Outdoor experimental setup of PV-PCM cooling system of Ref (Maiti et al., 2011).

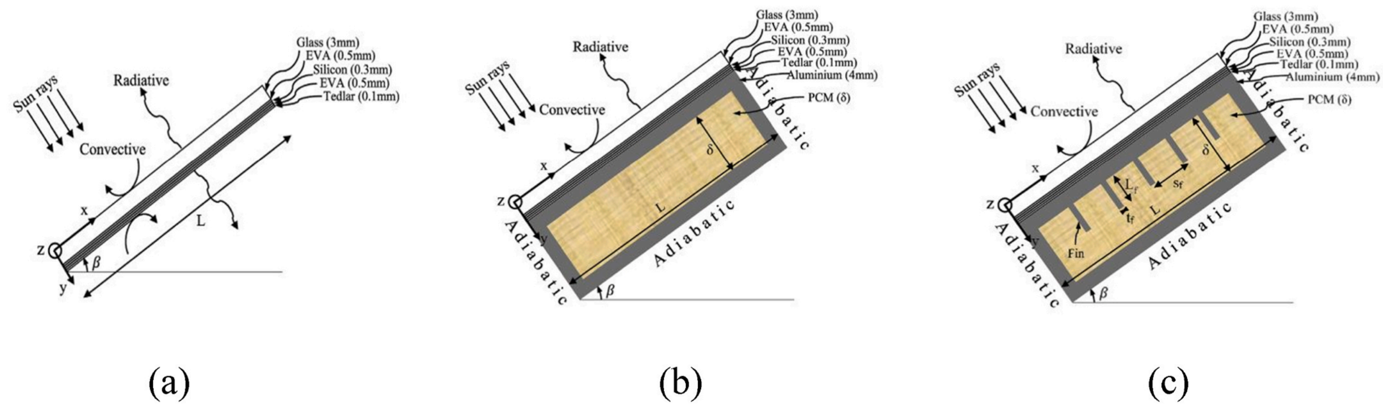


Fig. 21. Three different systems considered in the work of Ref (Khanna et al., 2018).

Fig. 22. Image of the experimental setup of Ref (Rajvikram et al., 2019).

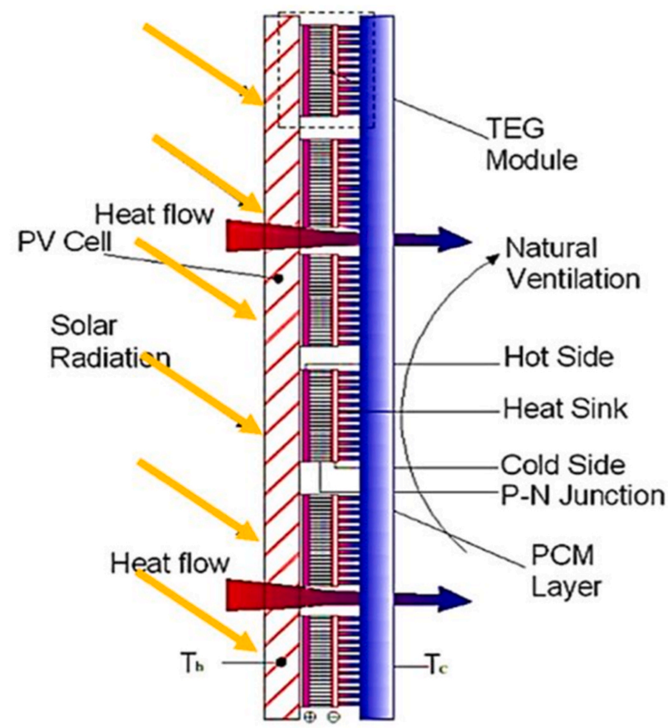
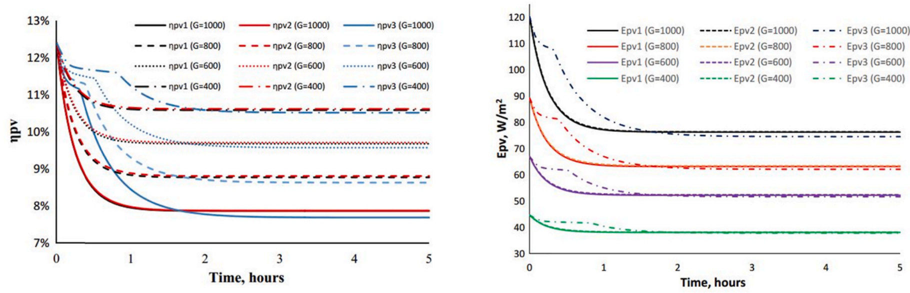


Fig. 23. The physical arrangement of the PV-TEG-PCM system of Ref (Darkwa et al., 2019).

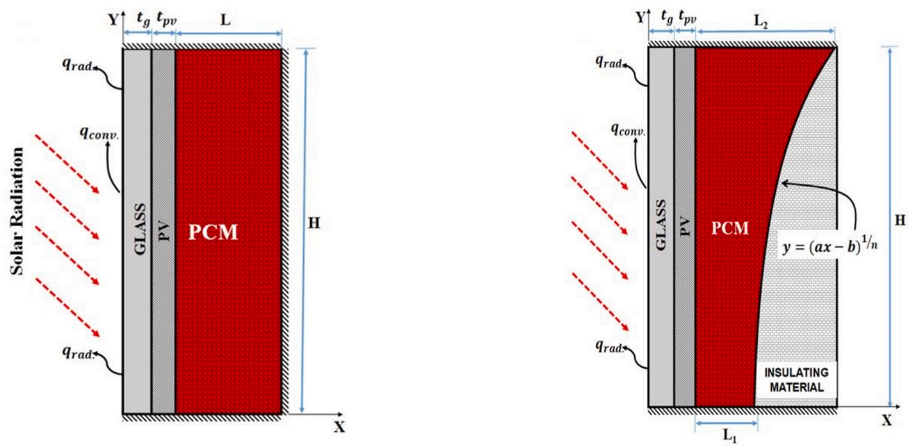
compared with each other, the cubic one has shown superior performance. Fig. 25 (a) shows the schematic view of the PV-PCM system with a conventional PCM enclosure and Fig. 25 (b) with the modified PCM enclosure. Since their research paper was a numerical simulation under constant solar radiation and positioned vertically (without considering various tilt angles) there are still some gaps to generalize their results to a practical case. Hence, an outdoor experimental study is recommended in this area.

An experimental case study of a cooling PV module for extremely hot climates was done by R. Kumar et al. (2020c). The horizontally mounted PV modules were under constant solar radiation exposure (Fig. 26). All experiments were performed in Jalandhar city of India. Three different systems were considered in their study as PV alone, PV-PCM, and PV-PCM with external fins. Their passive cooling system had a slight, yet remarkable difference from the previously mentioned studies. Fins were added outside of the PCM container so that helping the system to faster dissipate the stored heat in the PCM. The rationale behind this engineering design is because simultaneous charging and discharging (SCD) of PCM. On the front side, heat is absorbed from the PV module and transferred to the PCM, and at the bottom side, the PCM is dissipating heat to the ambient. Since the PCM is under SCD condition, the heat promoters should be wisely chosen (Mahdavi et al., 2021b). The reported results of (Kumar et al., 2020c) proved that case 3 with external fins had superior performance in all aspects. They have also mentioned that: "The reduction in the temperature of the PV module is around 22.3 ◦C and 12 ◦C for case 3 and case 2 as compared to without cooling case respectively." In the case of SCD conditions, M. J. Mahdi et al. (2021) have also utilized an external metal foam layer at the bottom of a PV-PCM system to increase the active surface area of heat transfer. Based on their numerical simulation, inclusion of exterior metal foam layer could enhance the melting time up to 32%. The tilt angle has also been considered as a variable input, and results demonstrated that decreasing



(a) (b)

Fig. 24. The results obtained from Ref. (Darkwa et al., 2019): (a) PV efficiency against solar radiation for the three systems, (b) PV power output for the three systems.



(a) (b)

Fig. 25. Schematic diagram showing cross-section of PV-PCM system of (a) conventional container and (b) modified container of Ref (Kumar et al., 2020b).

Fig. 26. Experimental setup used in the work of (Kumar et al., 2020c).

the tilt angle from 90° to 30° increases the melting time by about 18%.

J. Duan (2021) has designed a novel heat sink for a concentrator PV system. It has been reported that embedding a metallic porous structure inside the PCM heat sink could enhance the heat transfer rate significantly, hence, the cooling effect of a PCM-porous heat sink is notably improved compared to a pure PCM heat sink. Fig. 27 indicates the schematic diagram of their numerical work. From Fig. 27 it can be deduced that in the numerical simulation, the PV-PCM-porous system is standing vertically while the solar irradiance is perpendicular to the PV

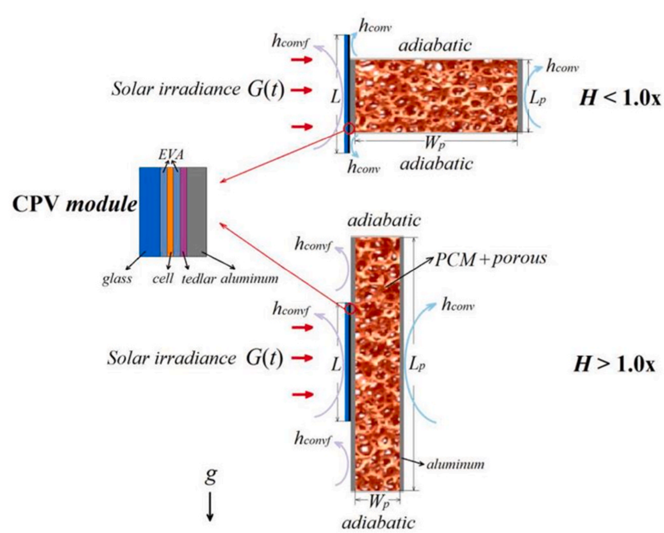


Fig. 27. The schematic diagram of the PV-PCM-porous system used in Ref (Duan, 2021).

module which is contradictory with the real applications where a PV module is positioned horizontally or at a certain tilted angle. The work (Duan, 2021) was not the only case that has made this simplified assumption, in the (Zarma et al., 2019) and (Emam and Ahmed, 2018) research papers could be observed too. Therefore, for future works, it is highly recommended to consider a variable solar irradiance as a function of time-related to a specific geographical location while the PV module is mounted at a certain optimized angle where solar radiation is perpendicular to the plate. Taking reference to (Elsheniti et al., 2020) as an example, M.B. Elsheniti et al. developed a one-dimensional mathematical model to predict the temperature of PV that was in contact with RT 27 PCM. In their numerical approach they have applied a variable solar flux in accordance with Alexandria (a city in Egypt) location at different times, and PV module tilt angle was varied from 0° to 90°. Their simplified mathematical model showed a reasonable deficiency with experimental published data. Hence, they were successful in reducing computational time. They have reported that optimum inclination angles were found for spring, summer, autumn, and winter to be 18°, 17°, 48°, and 41° respectively. Moreover, different PCM thicknesses of 10, 20, 30, and 40 mm were studied during the high-incidence period. Results showed that PCM with 30 mm thickness led to the highest average efficiency of 18%. Lower depths melted rapidly and higher depth was not able to solidify during the day and night.

R. Ahmadi et al. (2021) have done comprehensive experimentation on different cooling methods of a silicon solar cell under laboratory conditions. “Passive”, “active”, and the combination of both were considered in their work. Here, however, only passive methods are discussed. Fig. 28 shows the experimental configurations for passive cooling methods. It can be noted from Fig. 28 that the low thermal conductivity of paraffin was enhanced by embedding a carbon nanotube foam, resulting in a PCM composite. The results were compared in terms of the PV module’s glass temperature and output voltage. From Fig. 29 it can be derived that using PCM could keep the module cool for a long time under constant irradiation and applying PCM-composite will keep the temperature lower for a longer time. By keeping the temperature at lower levels it is expected to voltage drop be hindered which can be observed in Fig. 30.

While almost all of the papers have considered one solid container covering the whole PV module at the back side, S. Nizetic et al. (Sandro et al., 2021) have come up with the idea of attaching small PCM containers. In their experimental study which has been conducted in the Split city of Croatia, they compared three separated systems with each other. One is a reference PV panel, second and third as PV panels cooled by PCM with different configurations. Fig. 31 shows their experimental setup.

Interestingly, the half PCM configuration improved the PV panel performance by 10.7% compared to the reference case. Whereas, the full PCM configuration improved by about 2.5%. Due to the high cost of PCM materials, their novel PCM container design was an important step to commercialize PV panels cooled with PCM. They have reported that their novel design was able to save 47% PCM and 36% aluminum. Since organic PCMs are high-density materials, they were able to reduce the weight of the cooling system significantly. These were all considered as crucial steps in making PCMs applicable to regulate PV panels’ temperature.

Apart from all the advantages which PCMs possess, having a very low thermal conductivity ($\approx 0.1\ W/_{m.K}$) is the main disadvantage (Zhang et al., 2021). Inorganic PCMs have higher thermal conductivity (around $\approx 0.5\ W/_{m.K}$) and a much cheaper price compared to organic PCMs, however, when exposed to metal containers, they will cause corrosion (Ostrý et al., 2020). Thus the encapsulation type of an inorganic PCM should be nonmetallic which will narrow down their practical applications. On the other hand, organic PCMs show good compatibility in contact with metals (Ostrý et al., 2020) which makes them a feasible option for the application of PV panel cooling. As organic PCMs are more common in PV cooling applications, the following, research and methods which are vastly used to enhance their low thermal conductivity are illustrated.

These methods could be categorized into three groups:

1 Using nanoparticles
2 Using extended surfaces
3 Using metallic porous media

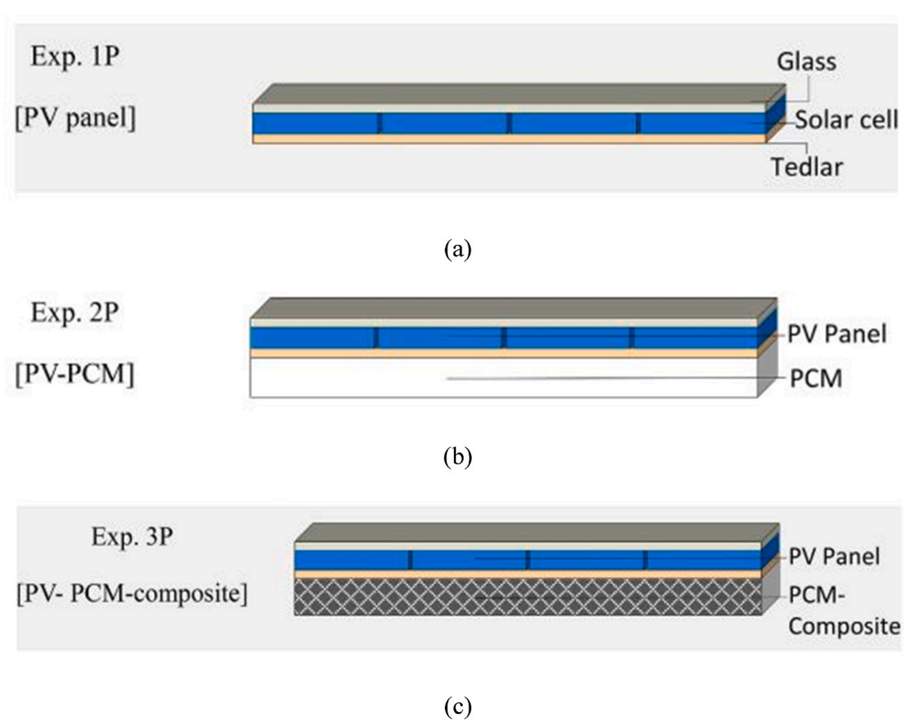


Fig. 28. Passive experimental configurations used in Ref (Ahmadi et al., 2021).

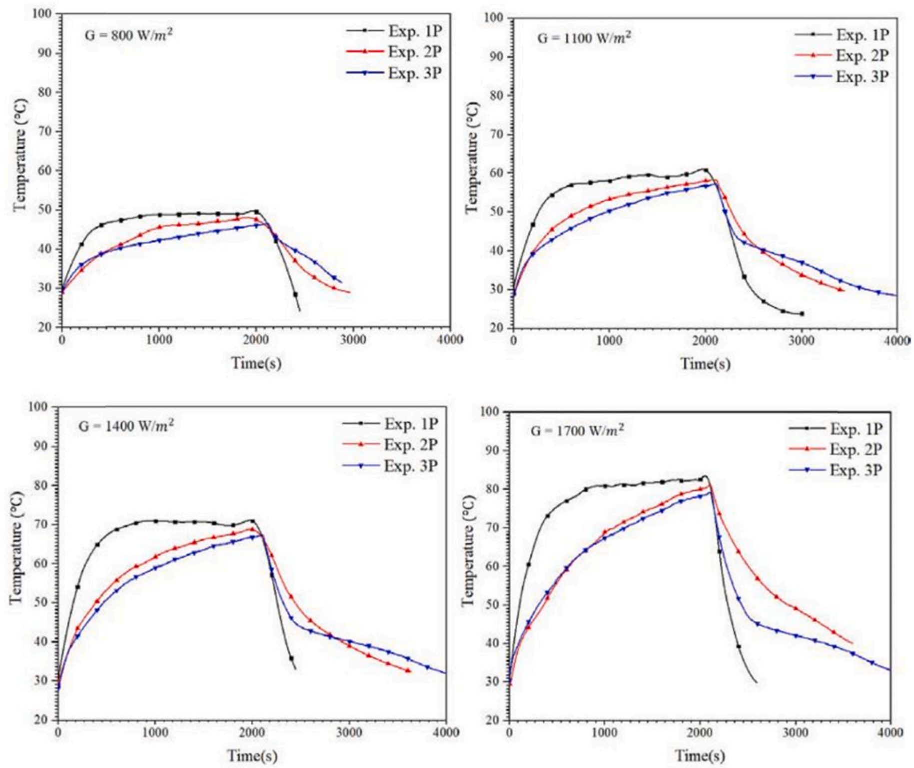


Fig. 29. PV module's glass temperature for passive experiments used in Ref (Ahmadi et al., 2021).

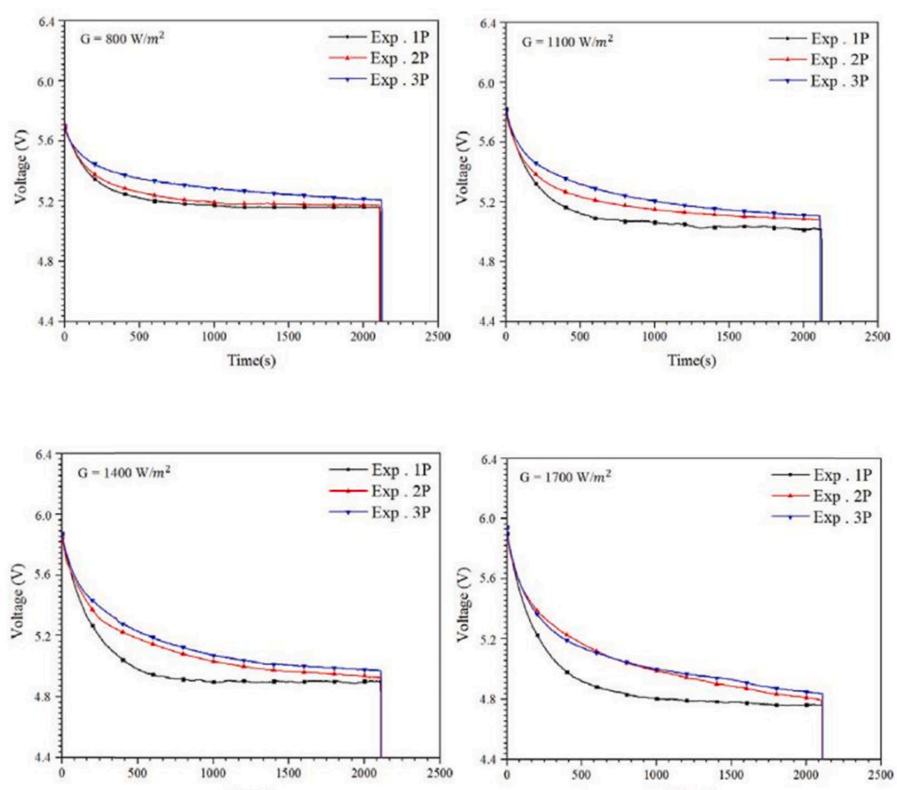


Fig. 30. Open-circuit voltage drop for passive experiments used in Ref (Ahmadi et al., 2021).

Fig. 31. Photo of the experimental setup of Ref (Sandro et al., 2021).

In terms of heat transfer rate, the second and third methods are predominant compared to the use of nanoparticles (Xiong et al., 2020). However, all the abovementioned methods have been applied to boost the heat transfer rate of a PCM in combination with PV modules. These methods are primarily used for PVT-PCM cooling which falls in the active method category. Yet, the idea of switching the active to passive methods by eliminating the thermal collector part was the chief motivation for citing these articles here.

L. Siahkamari et al. (2019) experimentally studied the PVT-PCM system performance under laboratory conditions (T_{amb} = 23 ◦C and constant radiation = 1000 $W/_{m^2}$). The schematic diagram of their experimental work is depicted in Fig. 32. Sheep fat and paraffin wax were used as two different PCMs for their experimental work. Results show that sheep fat was more effective in cooling the PV module compared to paraffin. Adding CuO nanoparticles to sheep fat was able to further decrease the PV module temperature. This led to an increase in power output (Fig. 33).

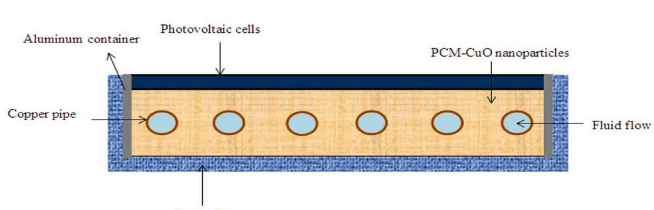


Fig. 32. Schematic diagram of experimental work of Ref (Siahkamari et al., 2019).

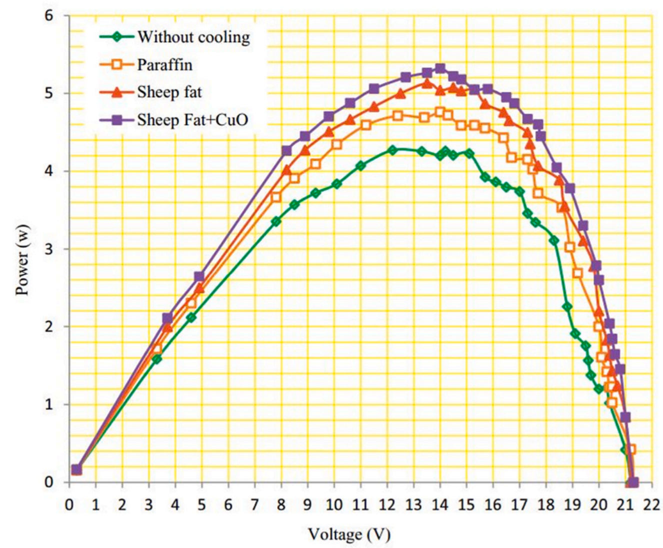
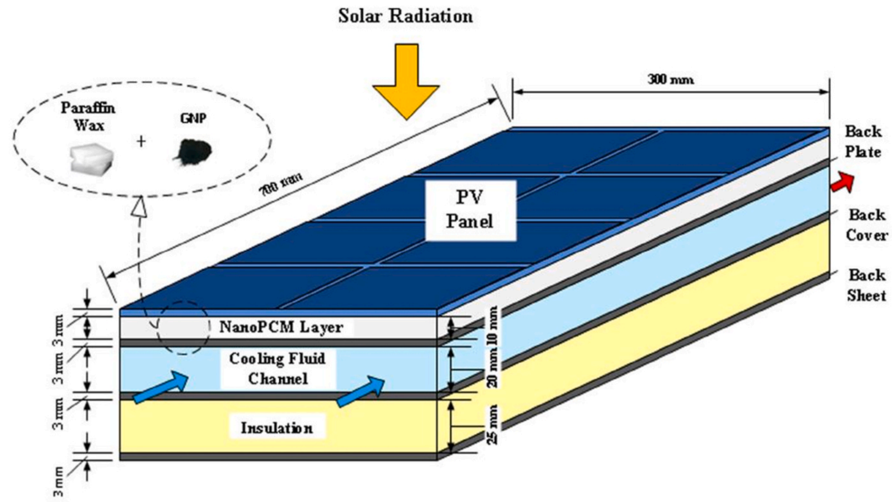


Fig. 33. Output power characteristic curves of PV module at $Q = 6\,mL/_{s}$ (Siahkamari et al., 2019).

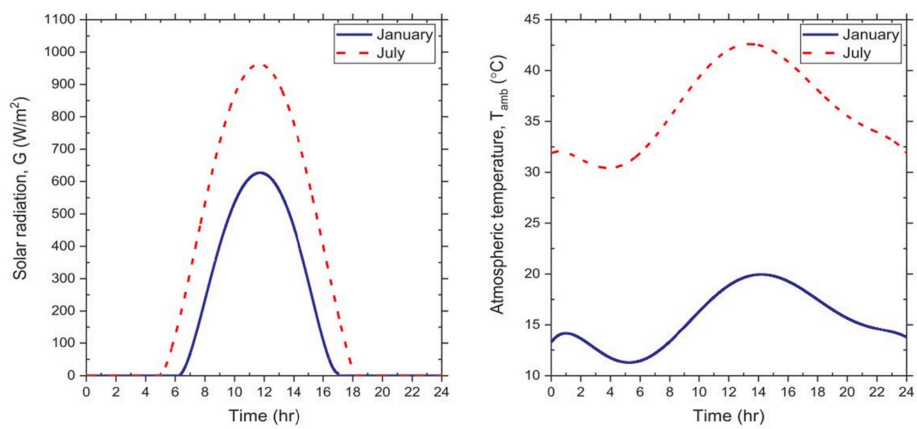
Combining PVT with PCM and the inclusion of nanoparticles within PCM was the main focus of A.S. Abdelrazik et al.'s work (Abdelrazik et al., 2020a). Their numerical analysis was done on two different days in winter and summer at the geographical location of Dhahran, Saudi Arabia. Fig. 34 (a) depicts the schematic diagram of their work and Fig. 34 (b) shows the boundary conditions applied to the domain. They tried to enhance the effective thermal conductivity of the paraffin wax as the PCM used in their study by adding graphene nanoplatelets. Results showed that by adding 10% of nanoparticles to the paraffin the electrical efficiency improved by 6.9% in winter and 22% in summer in comparison with a standalone PV system.

The same research team did another numerical study considering four different types of PCMs with various nanoparticles (Abdelrazik et al., 2020b). The schematic diagram and boundary conditions of their works were the same. Among the nanoparticles, the multi-walled carbon nanotube showed the best performance, while the Calcium chloride hexahydrate and paraffin wax RT 35, respectively, were the best among the four types of PCMs. M. A. Vaziri Rad et al. (2021) experimentally studied the PVT-PCM system in outdoor conditions in Tehran, Iran. As shown in Fig. 35 the PV module was mounted at a tilt angle of 30°. The low thermal conductivity of salt hydrate PCM was improved by inserting aluminum shavings as a metallic porous media. This is a cheap technique to enhance a PCM's thermal conductivity and maybe there is a possibility to apply it to solar farm panels without the active part. Fig. 36 (a) and (b) depict the power output of the PV module during warm and cold months respectively. From Fig. 36 it can be interpreted that utilizing porous media with PCM will enhance the PV module power output significantly. D.M.C. Shastry and U.C. Arunachala (Shastry and Arunachala, 2020) come up with the idea of embedding an aluminum metal matrix honeycomb structure within OM 47 PCM to increase its thermal conductivity. Fig. 37 shows their experimental setup in the outdoor conditions which were conducted in the entire month of March from 8:00 a.m. to 3:00 p.m. Although their results insist on active and passive reports, here, the passive section where no water flows through the serpentine pipes are demonstrated which is shown in Fig. 38. It can be derived from Fig. 38 that incorporation of metal matrix (shown by green squares) decrease the module temperature further. This graph certifies that incorporating a metal matrix with a PCM is a wise approach to enhance the heat dissipation rate. Optimizing its design for a passive alone system, however, requires extra research to be carried out.

The suitability of a PCM for PV cooling strongly relies on a topographical and climatic conditions (Chandel and Agarwal, 2017), hence,



(a)



(b)

Fig. 34. (a) Schematic diagram of work (Abdelrazik et al., 2020a) (b) Boundary condition of work (Abdelrazik et al., 2020a).

Fig. 35. A view of the experimental setup used in Ref (Rad et al., 2021).

it is recommended for areas with high insolations and hot ambient temperatures. For instance according to R. Kumar et al. (2020a) review paper, in Dublin, Ireland the PV-PCM system was not economically viable. However, since the price of a PV-PCM system in Vehari, Pakistan was half, these systems were economical in such environmental conditions.

2.6. *Spectral beam splitter*

According to a recently published review paper, there are two effective approaches to fully utilize solar spectrum (Liang et al., 2021a):

1) Adopting multi-junction cells that convert a broad spectrum range of photons energy into electrical energy. This is possible by the conjunction of various semiconductors with different bandgap energies to be able to fully utilize the incoming sunlight spectrum. Today, with this technology the highest efficiency of conventional single p-n junction solar cells known as the Shockley-Queisser limit has been broken and a 46% electrical efficiency is achieved in a laboratory test. However, multi-junction PV cells are too expensive to be utilized in large-scale applications (Abou-Ziyan et al., 2020).
2) Another solution is using SBS technology to completely utilize sunlight in a full spectrum wavelength range. The advent of this

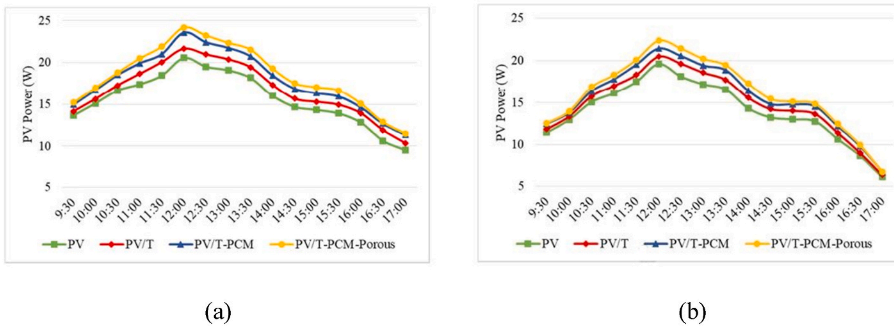


Fig. 36. PV power output in different systems during hours of the day: (a) warm month (b) cold month (Rad et al., 2021).

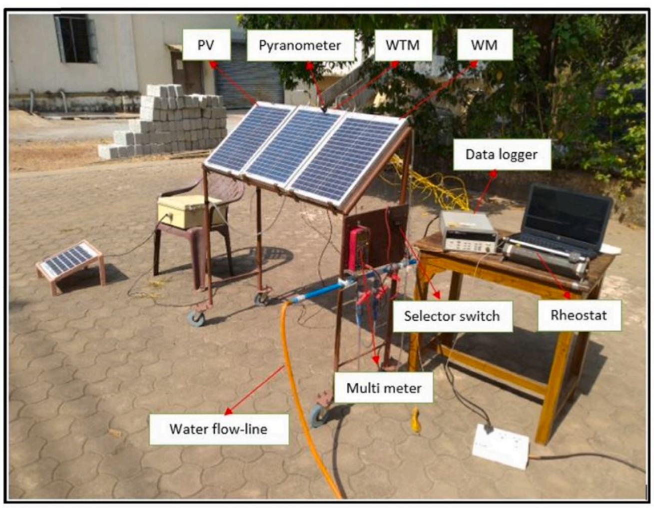


Fig. 37. A view of the experimental setup used in Ref (Shastry and Arunachala, 2020).

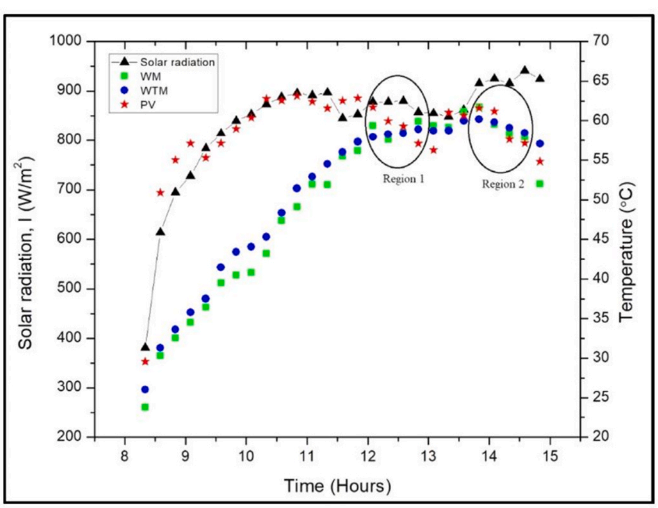


Fig. 38. PV module temperature profiles of different systems without water flow (Shastry and Arunachala, 2020).

technology lies behind the nature of single-junction solar cells. As shown in Fig. 39, single-junction solar cells are capable of utilizing a narrow range of incident sunlight spectrum, the SBS technique will let these devices feed what is useful to them and direct the harmful part of photon energy to a heat sink. According to Huang and

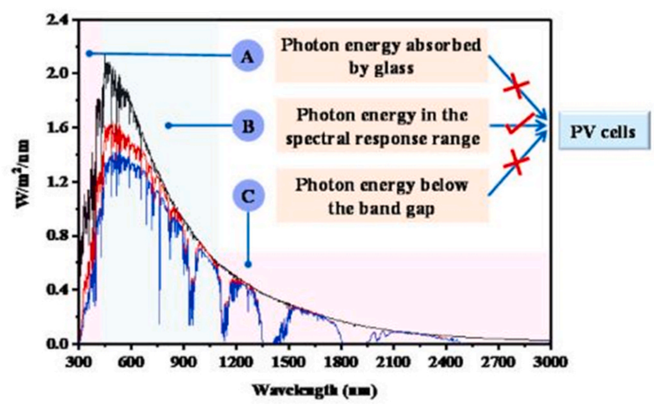
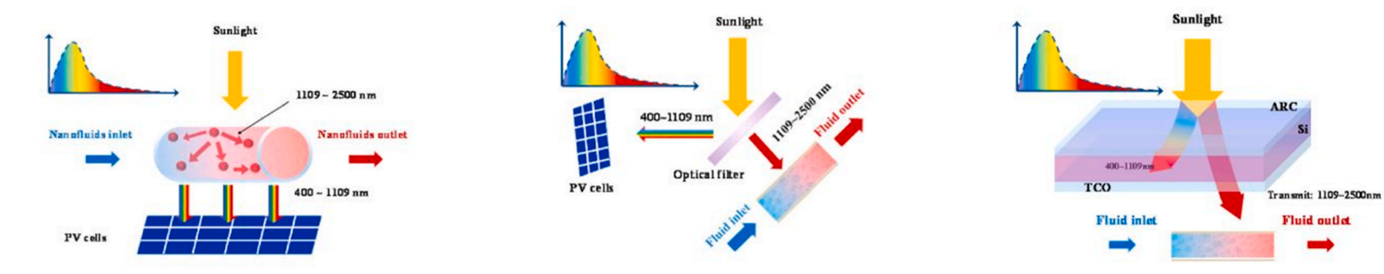


Fig. 39. Solar spectrum distribution diagram which could be converted to a useful form of energy by PV cells (Liang et al., 2021a).

Markides et al. (Huang et al., 2021), the total efficiency limit of SBS PVT collectors is more than 20% higher than that of standalone PV modules and photothermal collectors. Generally, there are three methods available to be able to fully utilize the spectrum of solar energy. These methods are graphically depicted in Fig. 40.

There are dozens of works and research that have been done on various SBS techniques to optimize the cut-off wavelength of the solar spectrum and enhance the overall efficiency of the system. However, none of them have analyzed the applicability of SBS methods in large-scale PV panels. For instance, the utilization of nanofluids-based SBS and nano-film-based SBS is restricted due to the precise optical path requirement, not to mention the expense of their fabrication and instability of nanofluids (Liang et al., 2020). Therefore, semitransparent PV cells-based SBS could play an important role in the passive cooling approach. Since the transmitted long wavelength solar spectrum is not concentrated, the disadvantage of this technique is the production of low-grade thermal energy (Xu et al., 2020). From Fig. 41 it can be derived that with the serrated groove structure at a semitransparent cell's bottom the solar cell can convert wavelength range between 400 and 800 nm to electrical energy and focus 800–2500 nm wavelengths photons on a small spot to provide high-temperature thermal energy (i.e. working fluid) (Liang et al., 2021b). Hence, there is a working fluid that is separated from PV panels with the ability to absorb heat higher than the PV panel operating temperature. In this scenario, the upper bound operation of the thermodynamic cycle of the heat engine would be not limited, therefore, a thermal power plant could be installed parallel to the solar farm panel. The combination of various power plants could be effective in satisfying multi goals such as producing heat, electricity, fresh water, etc. In a very recent study, N.J.Y. Liew et al. (2022) annually analyzed a PV/Concentrated solar power hybrid plant using wavelength selective filters. The wavelength-selective filter was designed to transmit



(a) Nanofluids-based spectral beam splitter (b) Nano-film-based spectral beam splitter (c) Semitransparent PV cell-based spectral beam splitter

Fig. 40. Schematic diagrams of different SBS techniques (Liang et al., 2021a).

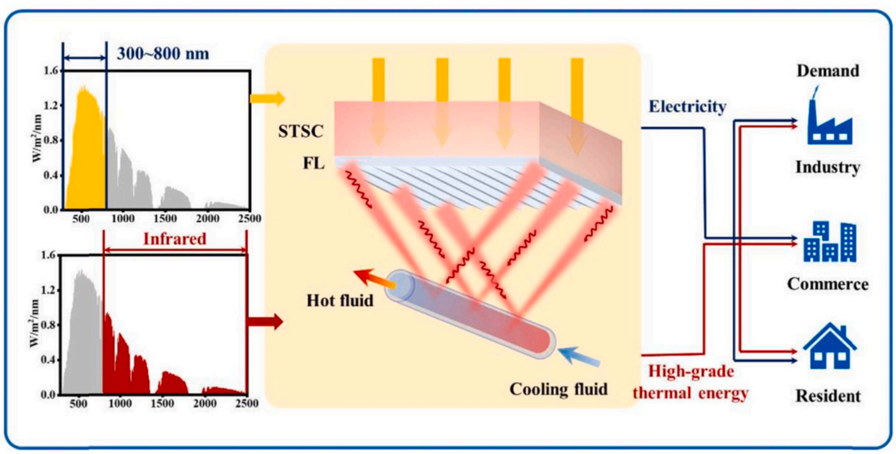


Fig. 41. Schematic and mechanism of novel semitransparent solar cell-based SBS system of work (Liang et al., 2021b).

700–1100 nm (400 nm bandpass width) solar irradiance and to reflect all other spectra. Their results showed that due to the lower operating temperature of the PV station, the hybrid system outperforms the contiguous hybrid plant of solar concentrated and PV systems. Therefore, the annual yield of their coupled system per unit area was 7% higher than the hybrid system which was operated non-compacted. This study ascertains the vital role of the SBS technique in hybrid PV solar power plants. Semitransparent PV cells have also the potential to be combined with various plants such as solar updraft towers and solar distillation systems. In the case of combination with a solar updraft tower, it would be possible to produce more electricity from the vast land of the collector area which is covered by semitransparent solar cells instead of glass or conventional glazing materials. In addition,

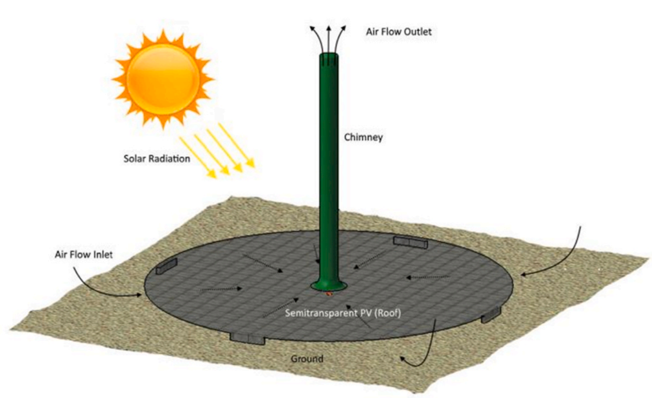


Fig. 42. Schematic diagram of the integrated system studied in Ref (Jamali et al., 2018).

agricultural activities could be carried on under the collector area since semitransparent solar cells will prepare a greenhouse for plants. Despite the aforementioned benefits of such integrated plants, there are just a few studies reported in the pieces of literature. S. Jamali et al. (2018) have studied the integrated solar updraft tower and semitransparent PV system. The integrated system was successful in decreasing the semitransparent PV panel temperature up to 15 ◦C. Fig. 42 shows the schematic diagram of their numerical work. In another study (Jamali et al., 2019), the influence of solar cell packing factor, chimney height, and collector radius was numerically analyzed considering power generation and economic performance of the combined system. Regarding economic performance, the city of Shiraz follows respectively with Yazd, Mashhad, Tehran, and Tabriz having the best fulfillment. The desirable range of packing factor was mentioned to be between 0.3 and 0.5 and for the collector radius and the chimney height the suitable range is $r_{collector} > 120$ m and $h_{chimney} < 250$ m, respectively. Although SBS techniques are an effective passive approach for cooling solar panels, they are still in under developing state and far way ahead of researchers to make them applicable on an industry scale (Liang et al., 2021a).

3. Lessons summary

The extensive studies which have been conducted on cooling PV modules/panels make it vital to prepare this section to summarize all the cited articles in section 2. In Table 2 all the previously discussed papers in the company of their key findings/achievements, type of study, and the environmental conditions are briefly summarized. Moreover, since many case studies have been mentioned in the following Table, for any future work a quick insight into the design parameters with environmental impact and the possibility of combining two or more passive methods could be provided. The following Table could make the

Table 2
The applied passive cooling techniques in different environmental conditions.

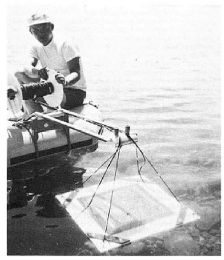
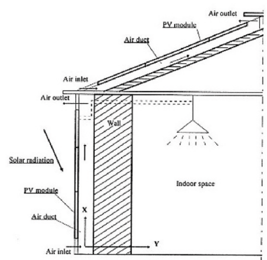
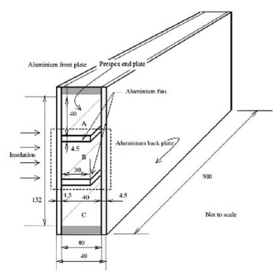
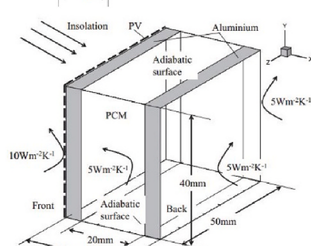
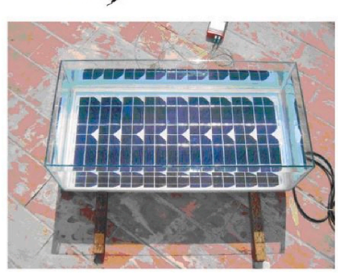
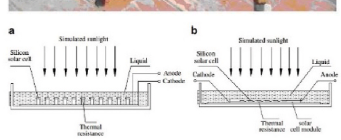
Researcher	Type of Study	Model	Environmental conditions		Findings
			Irradiance (W/m^2)	T_{amb} (◦C)	
J. D. Stachiw (Stachiw, 1980) (1980)	Experimental (Liquid immersion)		**800**	**4–15**	Even at 29 m of water depth, it would be possible to operate a submarine powered by high-efficiency silicon solar cells.
B. J. Brinkworth et al. (Brinkworth et al., 1997) (1997)	Numerical and Experimental (Natural ventilation)		**800**	**25**	The solar cell temperature has been decreased by about 15–20 K.
M. J. Huang et al. (Huang et al., 2004) (2004)	Numerical and Experimental (Phase change material)		**750–1000**	**20**	Under UK weather conditions for the 21st of June, a PCM with a depth of 30 mm could maintain the front surface temperature at 35 ◦*C*.
M. J. Huang et al. (Huang and EamesBrian, 2007) (2007)	Numerical and Experimental (Phase change material)		**750–1000**	**20**	2D model predictions were in good agreement with those of the 3D model.
Lanzafame et al. (Lanzafame et al., 2009) (2009)	Simulation and Experiment (Liquid immersion)		**400–900**	**25–35**	In shallow water depth, a 10–20% increase in efficiency is observed.
Y. Wang et al. (Wang et al., 2009) (2009)	Experimental (Liquid immersion)		**1000**	–	Among six different liquids, including polar ethanol and glycerin, non-polar benzene and silicon oil, and inorganic distilled water and tap water, non-polar silicone oil surpassed others.

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Table 2 (*continued*)

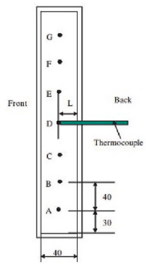
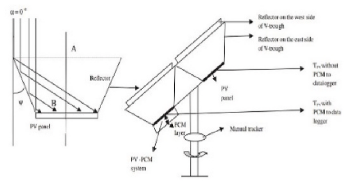
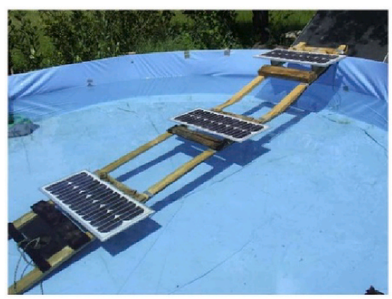
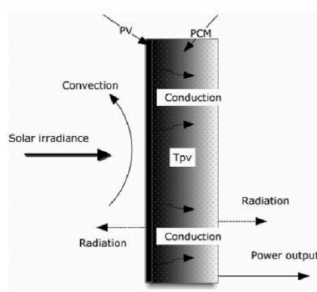
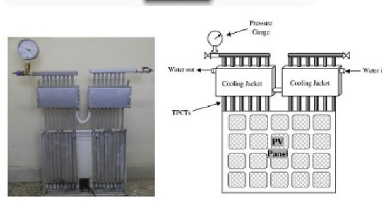
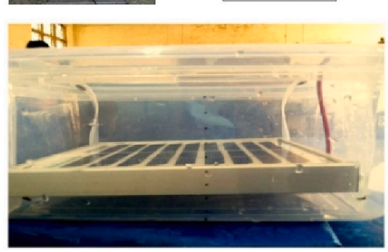
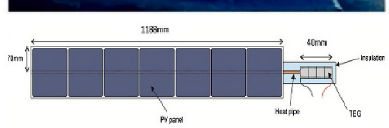
Researcher	Type of Study	Model	Environmental conditions		Findings
			Irradiance (W/m^2)	T_{amb} (◦C)	
M. J. Huang et al. (Huang et al., 2011) (2011)	Experimental (Phase change material)		**750**	**19**	With an internal finned PV-PCM system the temperature was decreased compared to the flat plate PV-PCM system.
S. Maiti et al. (Maiti et al., 2011) (2011)	Numerical and Experimental (Phase change material)		**500–1000**	**28–35**	Employing a 6 cm thick bed of a PCM matrix successfully pegged the module temperature at 65–68 ◦C for 3 h, whereas, in its absence, the temperature rose beyond 90 ◦C within 15 min.
G. M. Tina et al. (Tina et al., 2012) (2012)	Mathematical modeling and Experiment (Liquid immersion)		**805**	**40**	At average irradiance of 805 (W/m^2) and water temperature of 40 ◦*C* the power output of the submerged PV module was higher compared to the case which was out of water.
J. H. C. Hendricks and W. G. J. H. M. van Sark (Hendricks and Van Sark, 2013) (2013)	Numerical (Phase change material)		**0–800**	**12.2–26.3**	The PCM as a cooling approach was not economically justifiable in Utrecht whereas it was a reasonable cooling method in Malaga (Spain)
M. Moradgholi et al. (Moradgholi et al., 2014) (2014)	Experimental (Heat pipe)		**990–1080**	**26.5–36.9**	The attached heat sink dropped the module temperature up to 15 ◦*C*
S. Mehrotra et al. (Mehrotra et al., 2014) (2014)	Experimental (Liquid immersion)		**670–1170**	**33.5–38.4**	Submerging the PV module at a water depth of 1 cm led to a 17.8% increase in electrical efficiency.
A. Makki et al. (Makki et al., 2016) (2016)	Theoretical (TEG and Heat pipe)		**100–1000**	**25–55**	The hybrid system performance excelled over the PV alone system under different operating conditions of irradiance, wind speed, and ambient temperature.

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Table 2 (*continued*)

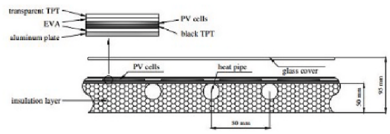
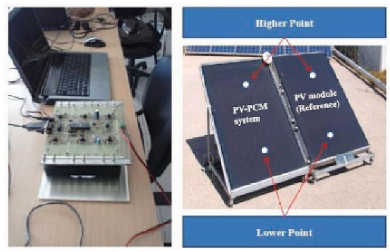
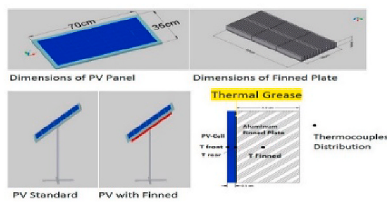
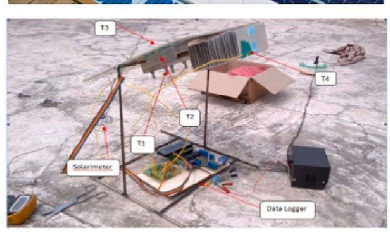
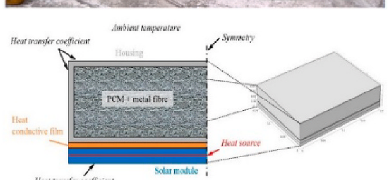
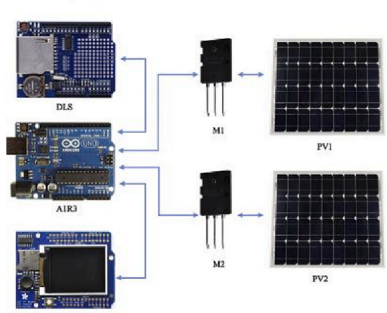
Researcher	Type of Study	Model	Environmental conditions		Findings
			Irradiance (W/m^2)	T_{amb} (◦C)	
Mingke Hu et al. (Hu et al., 2016) (2016)	Experimental (Heat pipe)	 	**650**	**25**	The wire-meshed heat pipe is not as sensitive as the wickless heat pipe to the inclination angle.
N. Savvakis and T. Soutsos (Savvakis and Tsoutsos, 2016) (2016)	Numerical and Experimental (Phase change material)	 	**0–1000**	**12.9–27.6**	PCM was able to attain 11 ◦C temperature reductions.
A. E. Mays et al. (Grubišić-Čabo et al., 2018) (2017)	Experimental (Natural ventilation)	 	**400–850**	–	On average, electrical efficiency and power output were increased by 1.77% and 1.86 W respectively.
Marco Rosa Clot et al. (Clot et al., 2017) (2017)	Experimental (Liquid immersion)		–	–	The optimum energy gained by a submerged PV module will be at a water depth between 1 and 2 cm and a water temperature of 15 ◦C.
S. Koundinya et al. (Koundinya et al., 2017) (2017)	Numerical and Experimental (Heat pipe)	 	**430–519**	–	A 13.8 K drop in the module temperature has been observed.
T. Klemm et al. (Klemm et al., 2017) (2017)	Numerical (Phase change material)	 	**0–800**	**30–45**	A 20 K temperature drop was observed in the peak point of the PV module's daily life cycle.
F. Grubisic-Cabo et al. (Grubišić-Čabo et al., 2018) (2018)	Experimental (Natural ventilation)	 	**300–950**	**12, 32**	The perforated fins proved a superior performance by increasing the electrical efficiency by 2% during peak power.

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Table 2 (*continued*)

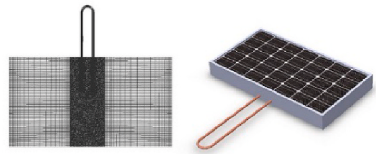
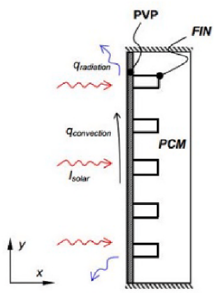
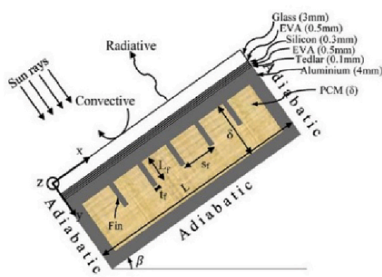
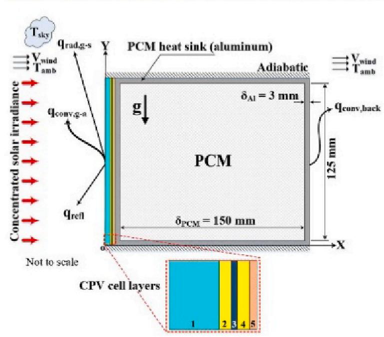
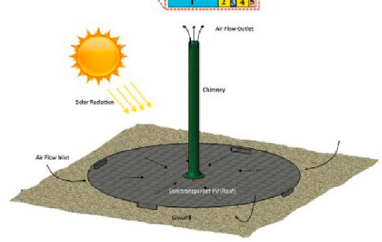
Researcher	Type of Study	Model	Environmental conditions		Findings
			Irradiance (W/m^2)	T_{amb} (◦C)	
H. Alizadeh et al. (Alizadeh et al., 2018) (2018)	Numerical (Heat pipe)		**1000**	**18**	An 18% enhancement in the generation of electrical power was reported.
M. A. Ezan et al. (Ezan, 2018) (2018)	Numerical (Phase change material)		**200–1000**	–	Configurations of fins with PCM were effective at solar radiation intensities higher than 500 W/m2.
S. Khanna et al. (Khanna et al., 2018) (2018)	Numerical (Phase change material)		–	**20**	The suitable depth of PCM thickness for daily average solar irradiance of 3 kWh/m2 and 5 kWh/m2 is 2.8 cm and 4.8 cm respectively.
D. Eryener and H. Kuscu (Eryener and Kuscu, 2018) (2018)	Experimental (Natural Ventilation)		–	–	The hybrid solar updraft tower efficiency increased by about 2% on average compared to a stand-alone PV system.
M. Emam and M. Ahmed (Emam and Ahmed, 2018) (2018)	Numerical (Phase change material)		**400–1000**	**20**	Increasing the number of parallel cavities of the PCM heat sink leads to a substantial reduction in the solar cell temperature, however, increasing the series cavities had an unfavorable effect.
S. Jamali et al. (Jamali et al., 2018) (2018)	Numerical (Natural Ventilation and Semitransparent PV cell)		**300–1300**	–	The integrated system was successful in decreasing the semitransparent PV panel temperature up to 15 ◦*C*.

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Table 2 (*continued*)

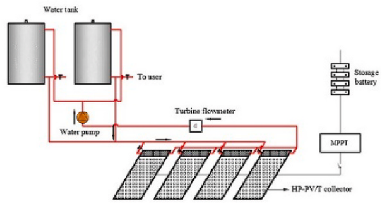
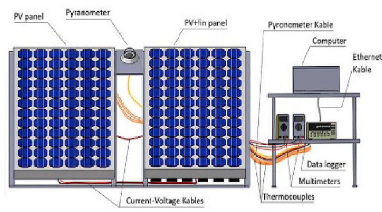
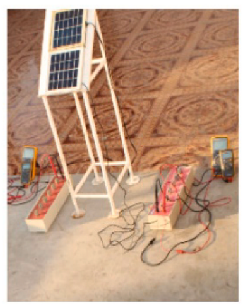
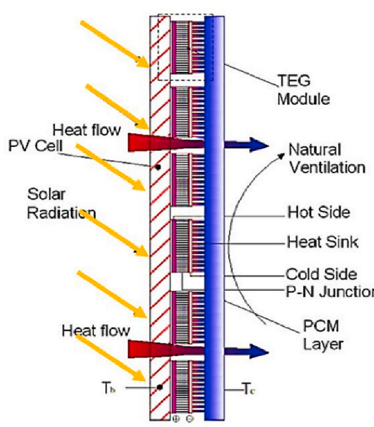
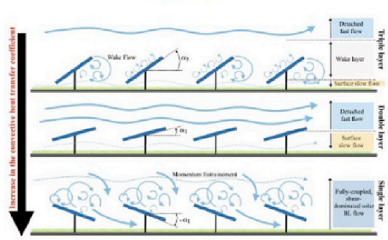
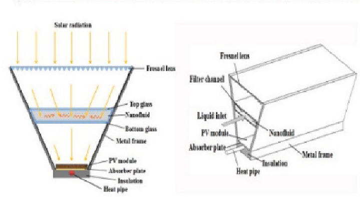
Researcher	Type of Study	Model	Environmental conditions		Findings
			Irradiance (W/m^2)	T_{amb} (◦C)	
Zhang. et al. (Zhang et al., 2019) (2019)	Numerical and Experimental (Heat pipe)		**200–900**	**25–35**	Regarding the working fluid type, they mentioned that water is suitable for mild climatic regions while R134a is suitable for cold climatic regions.
F. Bayrak et al. (Bayrak and Hakan, 2019) (2019)	Experimental (Natural Ventilation)		**500–1100**	–	The use of aluminum fins behind the PV panel successfully maintained the panel's temperature below the maximum allowable limit.
M. Rajvikram et al. (Rajvikram et al., 2019) (2019)	Experimental (Phase change material)		**120–200**	**25–30**	The conversion efficiency of the PV module with PCM and an aluminum sheet behind it was 24.4% more than the reference module without a cooling system.
J. Darkwa et al. (Darkwa et al., 2019) (2019)	Numerical and Experimental (Phase change material)		**400–1000**	**20–39**	The PV-TEG-PCM system's power output was higher than the PV and PV-TEG systems.
A. Glick et al. (Glick et al., 2020) (2020)	Experimental (Natural Ventilation)		–	–	The −30° inclination angle showed the largest heat transfer on the lower surface. Therefore, it was recommended to boost the sub-panel flow through the module's height optimizations or add deflectors to enhance the lifetime and efficiency of PV panels.
X. Han et al. (Han et al., 2020) (2020)	Mathematical modeling (Nanofluid-based SBS and Heat pipe)		**350–850**	**0–40**	With the use of a heat pipe, at an 8-suns concentration ratio, the average electrical efficiency is 0.7% higher than the case without a heat pipe.

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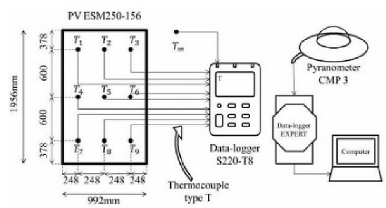
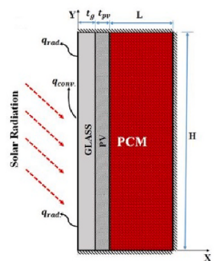
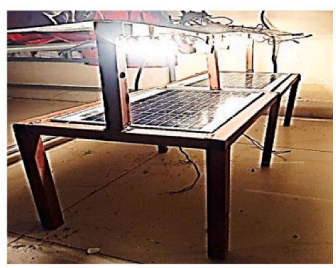
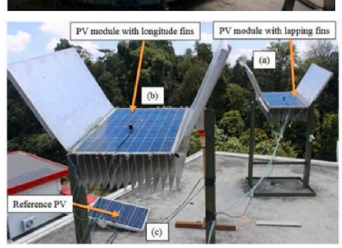
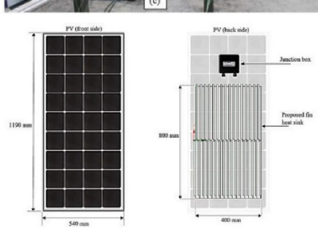
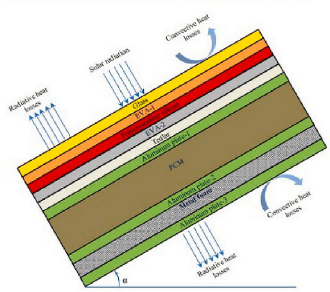
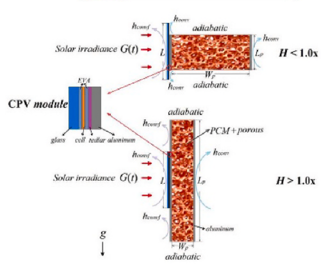
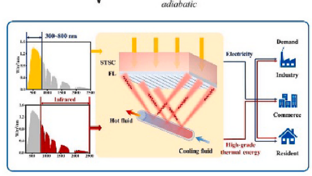
Table 2 (*continued*)

Researcher	Type of Study	Model	Environmental conditions		Findings
			Irradiance (W/m^2)	T_{amb} ($\circ C$)	
V. Sun et al. (Sun et al., 2020) (2020)	Numerical and Experimental (Phase change material)		**200–1000**	**25–40**	With embedding a 50 mm RT42 PCM, a maximum temperature reduction of 13 $_\circ C$ was observed.
Akshayveer et al. (Kumar et al., 2020b) (2020)	Numerical (Phase change material)		**800**	**20**	The encapsulation with cubic profile showed superior performance among others.
R. Kumar et al. (Kumar et al., 2020c) (2020)	Experimental (Phase change material)		**1000**	**20**	Adding fins behind the PCM container box had superior performance.
M.B. Elsheniti et al. (Elsheniti et al., 2020) (2020)	Numerical (Phase change material)	–	**0–750**	**10–30**	The optimum inclination angles were found for spring, summer, autumn, and winter to be 18°, 17°, 48°, and 41° respectively.
M.-H. Huang et al. (Huang et al., 2020) (2020)	Numerical and Experimental (Natural Ventilation)		**850**	–	Covering 50.6% of a collector of a solar chimney will reduce the airflow rate by only 14%, but generates significant electric power output.
A.M. Elbreki et al. (Elbreki et al., 2021) (2021)	Experimental (Natural Ventilation)		**400–1000**	**29–32.5**	A cooling system with lapping fins could be a promising option in Bangi (Malaysia).
Ahmad et al. (Ahmad et al., 2021) (2021)	Numerical (Natural Ventilation)		**400–1200**	**30**	The truncated multi-level fin heat sink design offered a 6.13% lower average temperature compared to the conventional rectangular one.

(*continued on next page*)

Table 2 (*continued*)

Researcher	Type of Study	Model	Environmental conditions		Findings
			Irradiance (W/m^2)	T_{amb} (∘C)	
F. Al-Amri et al. (Al-Amri et al., 2021) (2021)	Experimental (Natural Ventilation, Heat pipe, Phase change material, and Liquid immersion)		**0–600**	**27–40**	The designed heat sink embedded in a PCM achieved a cooler temperature in the first 2 h, however, the heat sink alone system acted better after that. Moreover, the liquid immersion technique successfully eliminated hot spots on the panel.
T. Kjeldstad et al. (Kjeldstad et al., 2021) (2021)	Experimental (Natural Ventilation and floating on water)		–	–	Even when the water temperature is warmer than the air, floating panels on the water have superior performance compared to the panels that were not in direct contact with water. This is because of the efficient heat transport of water compared to air.
M. J. Mahdi et al. (Mahdi et al., 2021) (2021)	Numerical (Phase change material)		**800–1200**	–	The incorporation of a metal foam layer behind a PV-PCM system could enhance the melting time by up to 32%. Moreover, decreasing the tilt angle from 90° to 30° led to the melting time enhancement by 18%.
J. Duan (Duan, 2021) (2021)	Numerical (Phase change material)		**750**	**25**	Embedding a metallic porous structure inside the PCM heat sink enhanced the heat transfer rate significantly.
H. Liang et al. (Liang et al., 2021b) (2021)	Experimental (Semitransparent PV cell-based spectral beam splitter)		–	–	With the serrated groove structure at a semitransparent cell's bottom, the solar cell can convert 400–800 nm wavelength photons to electrical energy and focus 800–2500 nm wavelength photons on a tiny spot to provide high-temperature thermal energy.

(*continued on next page*)

comparison and classification of different passive cooling methods simpler. Since the main focus of the current work is on the performance of the desired cooling technique without considering economic or environmental impact, the S. Nizetic et al. (Nižetić et al., 2017) review paper is recommended for the economic and environmental impact of various cooling techniques. According to the work of reference (Nižetić et al., 2017), the natural ventilation technique has the least environmental impact while cooling with PCM causes the most unfavorable environmental impact. Global warming, acidification, eutrophication, ozone layer depletion, abiotic depletion, human toxicity, and photochemical ozone depletion were the environmental parameters that have been used for comparison. With respect to economic assessment, a 30 kW photovoltaic plant was chosen to study. Based on the outcome the air ventilation cooling approach with aluminum fins was economically a viable option.

Table 2 (*continued*)

Researcher	Type of Study	Model	Environmental conditions		Findings
			Irradiance (W/m^2)	T_{amb} (◦C)	
S. Nizetic et al. (Sandro et al., 2021) (2022)	Experimental (Phase change material)		**100–1100**	**15–32**	Small PCM containers were attached to the backside of a PV panel as a novel approach. Their novel design showed a 10.7% improvement compared to the reference panel, whereas, the conventional full PCM configuration showed only a 2.5% improvement.

4. Conclusion and future development

Cooling PV panels could be categorized into three main groups such as active, passive, and a combination of both. Active cooling methods are effective in residential applications where tap water is available and hot water is in need, or hot air is required for ventilation systems. Passive cooling techniques are cost-effective compared to active methods and also could be applied on larger scales. There are various passive cooling approaches such as natural air ventilation, liquid immersion, use of heat pipes, phase-changing materials, and spectral beam splitters. None of these methods require maintenance costs and among them, the natural air ventilation method is the cheapest one. In the following, each of the passive cooling methods is discussed briefly and the critical challenges that remain unsolved are demonstrated.

(1) Natural air ventilation: Being easy to implement with minimum cost requirement makes this technique the most favorite and effective way of handling PV panels operating temperature. Numerous research has been conducted on cooling PV panels with different fin arrangements and topologies. There are still some gaps remaining in this area such as optimizing the fin arrangement/topology in different geographical locations having variable weather conditions. Up to today most of the studies considered a specific place with stable weather conditions to design extended surfaces (or fins) as benchmarking the performance of the cooling system. However, the cooling system must be able to overcome the harsh conditions at different times of the year. The material type should be also studied so that not add much weight to the system. For instance, porous fins having a wide effective heat transfer area with lower weight could be a better option. With this regard, 3D printing technology could be of great assistance in manufacturing complex fin structures with higher efficiency and effectiveness.

(2) Liquid immersion or floating: As mentioned previously, this method is a viable solution for places with a high level of irradiance and high ambient temperature. Submerging PV panels under the water is frequently used in residential places like pools or ponds where engineers are trying to make benefit from the limited land area. Although by applying this method the PV panels are continuously kept cool, the PV panel power output may drop dramatically with an increase of water depth due to absorption of the solar spectrum. With this regard, some researchers have proposed the idea of floatovoltaic panels where PV panels are floated on the water surface so that the bottom of the PV panels are in contact with cooling fluid and the top surface is above the water. By floating PV panels above the water, the panels are cooled effectively and water evaporation is also decreased by 70% which is very valuable concerning the water crisis. Besides the multi advantages that floating solar farms could have, still, more research is needed about the environmental impact of such enormous devices on water reservoirs.

(3) Heat pipes: Having a relatively low initial investment cost and being technically effective in cooling solar panels have made heat pipes a favorable cooling option. A heat pipe is a two-phase heat transfer process where both evaporation and condensation took place. Most of the research papers have tried coupling heat pipes with PV panels as a heat source for the evaporation section and making the condensation section in contact with water so that providing hot water and making the cyclic operation of the heat pipe possible. In the case of solar farm panels being operative with only the heat pipes cooling system, the condensation section should be able to cool down with the ambient air, hence, still, there is some gap in this area which requires more research to fulfill it.

(4) Thermoelectric generators: Solid-state devices with the ability to produce supplementary electrical energy by utilizing excess heat of PV modules are an exciting solution for increasing the total power output. The potential of TEG systems to be combined with other passive cooling techniques such as heat pipes and spectral beam splitters make them an even a more interesting research topic. Specifically, in desert areas where electricity demand is higher than thermal energy the hybrid HP-PV/TEG systems could play a valuable role.

(5) Phase change materials: The most effective method with a relatively high initial investment cost has become an outstanding option in cooling solar panels and also storing thermal energy. Phase-changing materials are studied and applied to various engineering problems. Yet, is it a viable option in regulating a PV panel temperature in its long time life span? Almost all of the studies considering PV-PCM systems have been investigated for a relatively short time scale and the additional cost of the PCM has not been paid attention to. Therefore, for future research analyzing additional PCM cooling system costs compared to the stand-alone system and evaluating the overall performance of the PV-PCM system in a long life span of the PV panels at larger scales are highly recommended.

(6) Spectral beam splitters: Thermally decoupling the PV and thermal collector brings us a unique feature that can make the systems operate at different temperatures. Achieving a higher operating temperature for the collector system provides the opportunity to establish a thermal power plant beside the solar farm panel, nevertheless, there is little research work that has combined these two plants and analyzed the integrated system thermodynamically. For that reason, further research is needed on applying SBS to PV panels and thermally decoupling the solar farm panel from the heat engine, and taking into account the new integrated plant that has formed. In addition, the possibility of constructing two electrical and thermal power plants with the use of SBS is rarely studied.

Declaration of competing interest

No conflict of interest exists in the submission of this manuscript, and the manuscript is approved by all authors for publication. I would like to declare on behalf of my co-authors that the work described was original research that has not been published previously, and is not under consideration for publication elsewhere, in whole or in part. All the authors listed have approved the manuscript that is enclosed.

Data availability

No data was used for the research described in the article.

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