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A critical review of photovoltaic panels thermal management: criteria and methods

H. Metwally[1], N. A. Mahmoud[1], W. Aboelsoud[1], M. Ezzat[2]
[1]Power Mechanical Engineering, Ain Shams University, Cairo, Egypt
[2]Power Electrical Engineering, Ain Shams University, Cairo, Egypt

Abstract. In the last few years, several studies have analyzed and discussed previous researchers' efforts. The researcher's activities were performed to classify PV panel cooling systems. The review illustrated the effect of the cooling system on the PV panel's thermal management, PV panel efficiency, and PV panel output power. The study focuses on the review of active, passive, and hybrid cooling system applications. The effects of different PCM materials and PCM containers on the PV panel passive cooling system are investigated experimentally and numerically. PCM material simulation is difficult, so the study analyses the available simulation methods and their advantages and disadvantages. The PV panels' active cooling system is very sufficient in both thermal management and energy efficiency. The review also summarizes each cooling technique's advantages and disadvantages for optimum model design and material selection. The study discovered that combining two or more cooling systems increases system efficiency by transferring energy from one to the other.

Keywords. PV panels, passive cooling, active cooling, hybrid cooling.

1. Introduction

Government investment goals support renewable power since electrical power generation is the most expensive energy transition. The energy future is the integration of renewable energy and traditional energy sources [1]. Many countries are taking steps to reduce CO2 emissions and increase renewable energy resources [2]. Photovoltaic panels, which come in several varieties, including flat type (PV), are one of the most efficient renewable sources of energy [3] or concentrated type (CPV) [4]. Photovoltaic panels (PV) provide 0.015 percent of the world's overall electricity generation [5]. Sun radiation energy (G) is captured by a semiconductor-retaining fabric that creates an electron supply for electrical current. Applying a small resistance to the PV panel output generates a maximum short-circuit current (I). On its surface, the PV panel absorbs solar irradiation flux and converts it into heat.

Figure 1 shows that the PV panel temperature affects power generation. Numerical relationships show that PV working temperatures typically rely on environmental conditions [6]. PV is kept operating at low temperatures via a variety of techniques. Passive, active, and hybrid cooling systems transfer temperature from the back of the PV panel [7]. Radiation, convection, and all other types of heat transfer are used to transfer the heat lost from the PV panel. The use of phase change material (PCM) behind the PV panel is necessary for passive cooling systems to remove heat effectively. If not, an active cooling system must drive air or water onto the front or rear of the PV panel surface in order to remove heat from the system.

Meanwhile, hybrid cooling systems are developing a system that combines the benefits of passive and active cooling processes. Because of their low operating costs and high efficiency, passive cooling systems are the most commonly used cooling technique. Phase-change material took much attention because of its immense heat storage capacity. A latent heat storage system is preferable to sensible heat storage in PV panel temperature control applications. Also, high storage density, based on phase change material enthalpy, maximizes the passive cooling system's cooling effect. The active cooling system has been developed in the last few years. Active cooling depends on fluid motion for additional forced convection in the front or the back of the PV panel. Other active cooling systems use a device or system that enhances the total power generation, such as a thermoelectric generator (TEG). Thermoelectric generator (TEG) theory depends on transferring PV panel energy and fluid flow temperature into a steady electrical current (I). The hybrid cooling system is a system that was created by combining phase change material (PCM) and a thermoelectric generator (TEG). Hybrid cooling system applications significantly enhance the PV panel temperature control and the PV panel power generation systems.

The hybrid cooling system's overall performance is always higher than the passive and active cooling systems' performances when compared separately [7]. The temperature of the PV panel is used as the heat source for the TEG in some applications of the hybrid cooling system. The PCM temperature is used as the TEG heat source in other hybrid cooling systems.

The review is focused on the review of active, passive, and hybrid cooling system applications. The review also summarizes each cooling technique's advantages and disadvantages for optimum model design and material selection, as seen in Figure 2. In the last few years, several studies have analyzed and discussed previous researchers' efforts. The researcher's activities were performed to classify cooling systems, investigate used materials, conduct experimental studies, and perform numerical simulations of active, passive, and hybrid cooling systems.

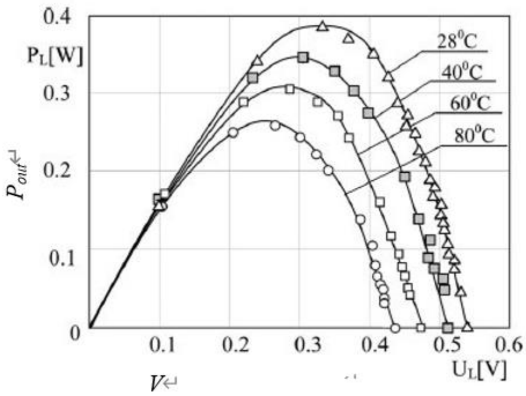

Figure 1. The effect of PV panel temperature on the power output [6]

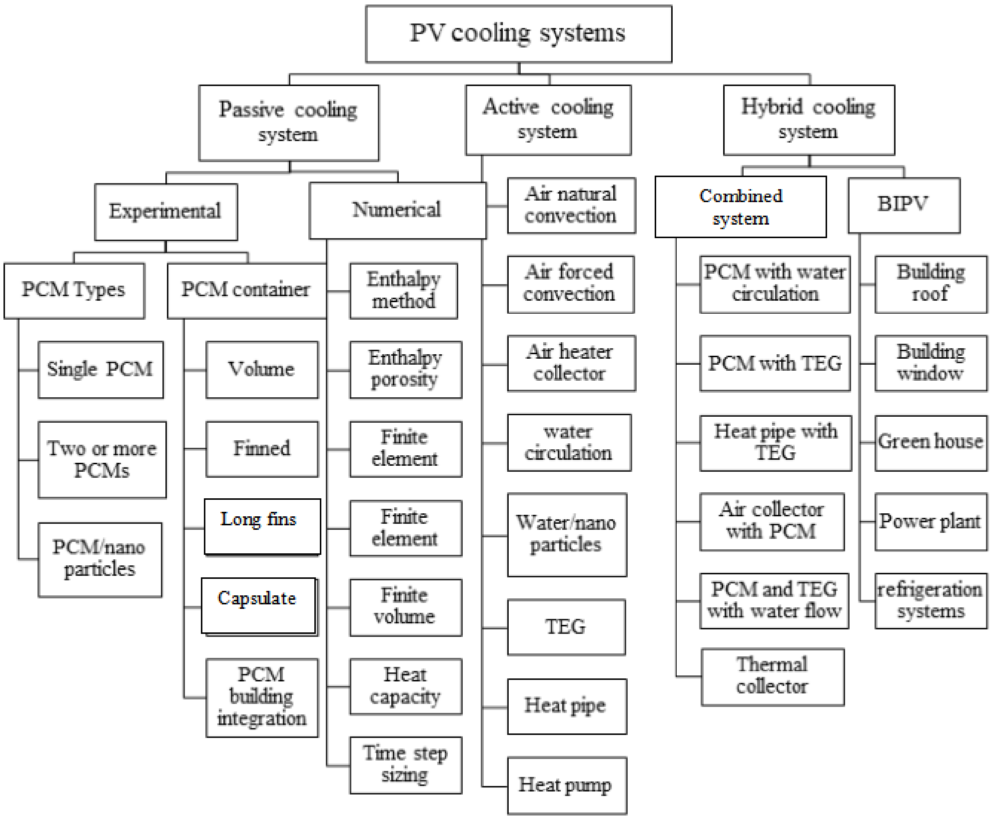

Figure 2. The PV cooling systems summary

2. Discussion

In the last few years, several studies have analyzed and discussed previous researchers' efforts regarding PV panels. The researcher's activities were performed to classify cooling systems, investigate used materials, conduct experimental studies, and perform numerical simulations of active, passive, and hybrid cooling systems.

2.1. Passive cooling system

In the past decade, PCM has been a promising photovoltaic cell cooling technique to cool PV panels and store thermal energy. PCM criteria were studied from many perspectives, such as thermal, physical, chemical, environmental, and economical. Ali et al. [8] analyzed the PV cooling systems depending on the PCM as a passive cooling device. He also concluded that the PV panel's efficiency increased by 20% as a result of the cooling system's inclusion of PCM. In the summer compared to the winter, the PV cooling mechanism was more effective when PCM was used. Additionally, the rear of the PV panel's heat conduction was increased by adding finned PCM containers. Tao et al. [9] analyzed the technology overview and material selection of the hybrid PV+PCM systems. Their findings revealed that the most affected factor is the energy balance between the PV cells and the PCM in different phases. PCM thermal conductivity is a significant thermal property that has received little attention. Waqas et al. [10] presented significant criteria for passive cooling systems, such as development, performance evaluation, PCM selection, heat transfer, and simulation application. Developing a PV+PCM system can reduce the PV panel's temperature up to 20 °C when the electrical efficiency is increased to 5%. The passive cooling system faces technical difficulties due to the cost and availability of suitable PCMs. Otherwise, future work must focus on improving PCM heat transfer problems.

In their analysis of PCM-based PV panel cooling techniques, which included PVT systems, Chandel and Agarwal [11] focused on the practicality of the technology. According to the findings, depending on the melting temperature and geographic location, PCM was not a viable cooling option. A potential medium for regulating the temperature of PV panels is PCM with a melting temperature greater than 30 °C. Ma et al. [12] found that using PCM in PV panel temperature control was not economical if used only to enhance PV panel efficiency. The combination of PCM and PVT maximizes overall system efficiency. Because of their high cost, toxicity, corrosiveness, flammability, and difficulty in disposal, the disadvantages could not be avoided [13]. Otherwise, increasing system thermal conductivity with additional PCM fins. The passive cooling system fails to work after the latent heat of PCMs is exhausted. The most promising cooling system is the combination of PCM and fluid-forced convection [14].

Meanwhile, the application of passive cooling systems in electronic components and power batteries has yielded promising temperature control results. PCM's application has many advantages: compactness, high efficiency, high heat transfer, no electricity needed, isothermal heat removal, noiseless, passive heat exchange, no maintenance cost, and simplicity instead of the traditional forced convection methods. In addition, selecting a suitable PCM for a cooling system based on physical and thermal properties is critical in the following section on optimizing different PCM materials and their effect on PV panel thermal management and efficiency.

2.1.1. Effect of PCM properties

PCM thermo-fluid properties are significant in the cooling process, so researchers studied many types of PCMs. The impact of employing pure (white petroleum jelly) and combination PCM (white petroleum jelly, copper, and graphite) on the thermal behavior and electrical performance of a PV panel was investigated experimentally by Hachem et al [15]. The experimental study was provided in both cases, with and without copper and graphite molecule additions. Figure 3 shows the experimental prototype. When using Pure PCM, results showed that the PV panel's temperature decreased by 6.5 °C and the electrical efficiency increased by 3%. Otherwise, when using PCM with additions, electrical efficiency increased by 5.8 percent [15].

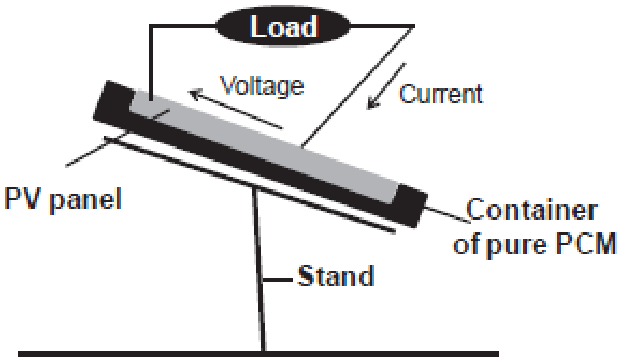

Figure 3. Experimental prototype of PV panel cooling with PCM, [15]

Another PCM type (Paraffin wax 35) was studied experimentally to evaluate the PV+PCM system and the PV+PCM-T system's thermal regulation [16]. Results indicated that the PV panel temperature was reduced by 23 °C when using the PCM cooling technique, and the electrical efficiency increased by 5.18%. Another advantage is that the water was heated up to 41.6 °C, which means 1253 kJ/day more power is used [16]. Hence, the addition of PCM to the PVT system indicated an electrical power output increment of 11.1% when using PCM [17]. Novel PCM with nanoparticles [18] was investigated in the PV panel cooling system, improving the PV panel's electrical efficiency by 25%, as seen in Figure 4. The selection of the appropriate PCM increased the power output by 8%–11% [19].

Aneli et al. [20] looked at how two varieties of PCM, RT28 and RT35, affected the temperature of the PV panel in various weather scenarios. The results of this investigation show that PV+PCM units outperform traditional PV modules, particularly during the warmest months. Utilizing RT28 and RT35 revealed an increase in the peak power of the energy generated of 10% and 3.5%, respectively. Also, when using PCM combined with a nanofluid PV cooling system, the system average thermal energy output was 42% higher than the system without PCM [21]. Arshad et al. [22] investigated the size of Cu nanoparticles and discovered that the 0.01 volume fraction nanocomposite PCM has the highest thermal storage capacity. Yadav et al. [23] investigated the thermal control of a 100-watt PV panel with myristic acid PCM and carbon nanoparticles, employing a steady-state heat rejection rate.

Many experiments were carried out in order to find the best PCM for the passive cooling process. The effects of paraffin wax, stearic acid, and natural zeolite on the energy efficiency of PV thermal systems were examined by Kandilli and Uzel [24]. According to the assessments, the typical energy efficiencies for paraffin, natural zeolite, stearic acid, and conventional PVT systems, respectively, were estimated to be 33%, 40%, 37%, and 32%. Shastry and Arunachala [25] investigated the effect of the OM-47 PCM, which enhanced thermal management by 11.1%. Hassan et al. [26] and Qasim et al. [27] investigated the use of RT-35HC to improve cooling systems.They concluded that the cooling system was enhanced by 23.9% and 13.3%, respectively. Moreover, the CPV panel's implementation of mineral oil with graphene fillers decreased the CPV panel by 40 oC [28]. Figure 5 shows the experiment held by different PCM materials (organic RT50 and inorganic C48). The results indicated that the PCM allowed power generation up to 30% of the maximum power values in the unglazed case. In the glazed case, the power generation was enhanced by 25% with a 12% thermal improvement [29]. Meanwhile, the PCM cavity construction affects the heat transfer rate. So, in the next paragraph, we will analyse the different PCM cavity constructions.

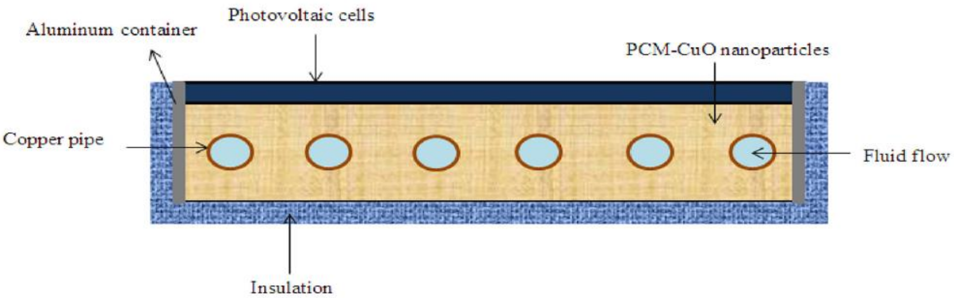

Figure 4. Novel phase change material (PCM) in a PV module combined with a thermal cooling system (water flow) [18]

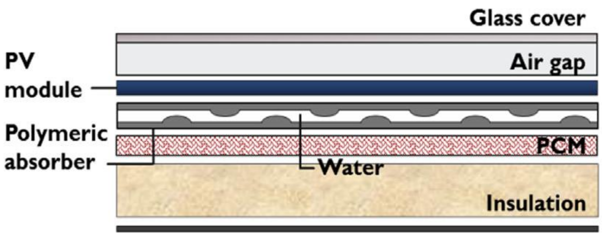

Figure 5. Plat and tube thermal absorber using water flow and PCM absorbs heat from fluid flow [29]

2.1.2. Effect of PCM physical model

In another investigation performed in the UAE, the PV passive cooling process was investigated to determine its energy-saving and system efficiency throughout the year. The cooling effect of PCM was minimal due to unmalting at low temperatures and non-solidification at high temperatures, but annual PV electrical generation increased by 5.9 percent [30].

Meanwhile, Klugmann-Radziemska and Wciso-Kucharek [31] tested a mixed system of water and two separate PCMs to improve electrical parameters and decrease PV panel temperature. The passive cooling system on CPV was studied and subjected to a solar radiation strength of 670 W/m2. Simultaneously, the device was able to keep the average CPV cell temperature around 6 °C lower than usual. Another finding was that for CPV/PCM systems with horizontal aluminium fins, the average temperature of PV cells was approximately 3 °C lower than the CPV/PCM system's temperature without fins and could be sustained for more than 5 hours [32]. A solar tracking CPV+PCM-T cooling system was also investigated to determine the passive cooling effects. The results found that the CPV+PCM-T cooling system increased the average electrical generation by 10%, thermal efficiency by 5%, and overall energy efficiency by 15% compared to the CPV-T with thermal cooling [33].

Furthermore, paraffin wax RT42 was assessed with indoor experience using a light source of 1000 W/m2 to improve the BICPV system's performance through thermal regulation. Results showed a 7.7% improvement in electrical efficiency and an average 3.8°C decrease in module central temperature [34]. CPV+PCM cooling systems were also investigated in severely hot ambient temperatures. Otherwise, the evaluated CPV temperature was decreased by 28 °C [35]. In addition, the application of a water jacket around CPV+PCM increased the electrical efficiency to 17.7% [36]. While the simulation method is affecting the simulation results for the PCM properties through the cooling process, So, identifying each mathematical and numerical method is performed in the next paragraph.

2.1.3. PCM mathematical and numerical modeling

Mathematical, computational, and thermodynamic studies of passive cooling systems were reviewed and compared with different PCMs to find the most precise model [37]. Future research areas and thermodynamic studies of solar systems were focused on numerical simulations. Numerical simulations have many methods; each method was used for modelling a separate application, as seen in Table 1.

Also, solving mathematical modelling problems is too complicated, and it is impossible to achieve an exact analytical solution when numerical modelling is used to approximate the problem's solution. Tangsiriratana et al. [52] developed various mathematical correlations depending on environmental and numerical parameters to evaluate the electrical efficiency and the PV panel power output. A numerical assessment of the PV+PCM system revealed that the high melting temperature PCM works best in the summer. Furthermore, since the PCM cannot melt on cold days, it could limit heat transmission throughout the winter. The biggest year-round improvement in power output, according to Zhao et al. [38], was 2.46 % in comparison to the reference PV system. Furthermore, Zhao et al. [39] found that the PV efficiency might decline by 0.65 percent for every 1 Celsius increase in PV temperature. They demonstrated how the use of PCM may lower the temperature of PV by 24.9 °C, increasing power generation by up to 11.02 %. In order to apply the stability of desert sand as a thermal storage medium, Khanna et al. [55] constructed numerical modelling of desert sand PCM with thermal water pipe. Their findings demonstrated the feasibility of desert sand as a thermal storage medium for use in thermal and photovoltaic systems.Furthermore, Zhao et al. [39] found that the PV efficiency might decline by 0.65 percent for every 1 Celsius increase in PV temperature. They demonstrated how the use of PCM may lower the temperature of PV by 24.9 °C, increasing power generation by up to 11.02 %. In order to apply the stability of desert sand as a thermal storage medium, Khanna et al. [55] constructed numerical modelling of desert sand PCM with thermal water pipe. Their findings demonstrated the feasibility of desert sand as a thermal storage medium for use in thermal and photovoltaic systems. On the other hand, Khanna et al. [40] investigated the electrical efficiency of PV+PCM under various wind, azimuth angle, wind direction, wind velocity, PCM melting temperature, and ambient temperature conditions and discovered an overall improvement of 9.7%.

In order to apply the stability of desert sand as a thermal storage medium, Khanna et al. [55] constructed numerical modelling of desert sand PCM with thermal water pipe. Their findings demonstrated the feasibility of desert sand as a thermal storage medium for use in thermal and photovoltaic systems. Additionally, Khanna et al. [55] investigated numerically the optimization of a photovoltaic system with fin-fitted phase-change material under various operating conditions for optimal power augmentation. They came to the conclusion that, for fin widths of 0.5 mm, 1 mm, 2 mm, and 4 mm, respectively, the power output rose from 125 W/m^2 to 137 W/m^2, 140 W/m^2, 142 W/m^2, and 143 W/m^2. By creating a system with four different PCM heat sink designs, series and parallel PCM cavities were compared for heat rejection maximisation, and it was shown that employing more cavities in parallel generated a more stable heat sink [56]. Figure 6 shows a PV-T system with PCM materials as a porous medium, which improves energy efficiency by 16.7% [57]. Nehari et al. [60] developed a PV cooling system with a backside fin model with PCM material to improve electrical efficiency. Technically speaking, it was determined that the use of a PCM material was suitable because it decreased the operating temperature of a PV panel by up to 10.26 °C and boosted efficiency by up to 3.73 %. Many of the numerical simulations caused significant errors because they neglected PCM convective and irradiative heat transfer [58], [59], and [60].

Table 1. Summary of PCM numerical simulation methods

Method	Advantage	Disadvantage
Enthalpy method [39], [41]	The temperature distribution and the experimental results correlate well. useful for estimating temperature in phase change scenarios.	Simulating PCM operated in accordance with its physical characteristics. Not good for estimating temperature for convection/diffusion processes.
Enthalpy porosity [22], [42], [43]	Rapid convergence, high accuracy.	Sensible and latent enthalpy were described as content enthalpy, which was measured.
Finite difference [44], [45], [46]	high precision, consistency, and quick convergence.	The discretization of the continuous problem domain. Only discrete points were taken into account for the dependent variables. By simulating derivatives as differences, PDEs are transformed from conservation assertions to the algebraic equation.
Finite element [47], [48], [49]	Widely used for structural mesh.	Not used for unstructured mesh.
Finite volume [50], [51]	Represent the PDE in algebraic equation forms. They were used for the unstructured mesh.	
Heat capacity [52], [53]	Temperature function during the melting process.	
The implicit finite difference [54]	Stable and convergent.	Usually used for one-dimensional simulation

Emam et al. [61] simulated a CPV+PCM system with various inclination angles of -45°, 90°, and +45°, as shown in Figure 7. The PCM liquid fraction was rectifying at a different position. The contours of the results showed that the best position for the PV cooling process was 45°.Figure 8 represents a numerical calculation of the PV+PCM cooling system temperature under convection and conduction heat transfer. Results showed an improvement in PV panel temperature under different conditions [62]. A global numerical simulation of PV+PCM system energy output improved it by 6% over a standard output power production rate [53].A system composed of an impure PCM in the back of a solar panel with fins was modelled with a 12.6% overall temperature drop [63].Also, encapsulated paraffin wax was analysed in a ventilation duct with a maximum 18% decrease in PV temperature [64]. The PCM layer melting temperature and module thickness were simulated in the PV-T system. Results showed a maximum efficiency at the PCM layer thickness of 3.4 cm with a 40 C melting temperature [65]. Table 2 illustrates PCM theoretical and mathematical simulation and provides researchers' efforts in the last decade with valuable expertise to save time and experiment design costs. Meanwhile, the simulation is dependent on the numerical process. The simulation time step is very important in the numerical simulation.

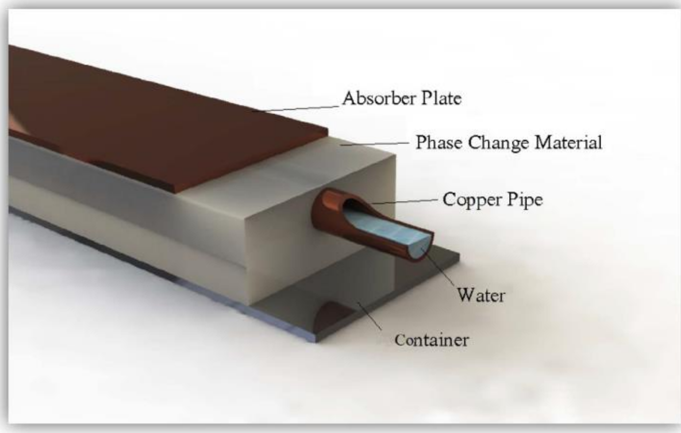

Figure 6. Mousavi investigation model using a combination of PCM and thermal water-cooling system [57]

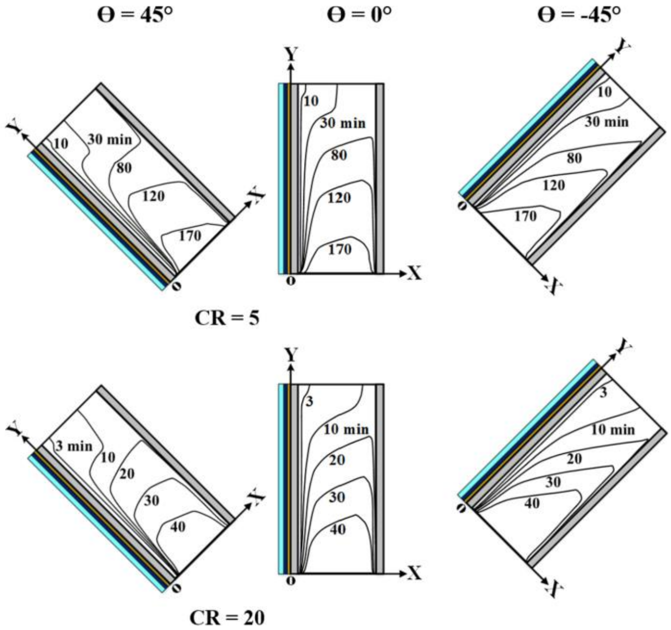

Figure 7. The effect of the PV panel inclined angle on PCM liquid fraction and cooling process [61]

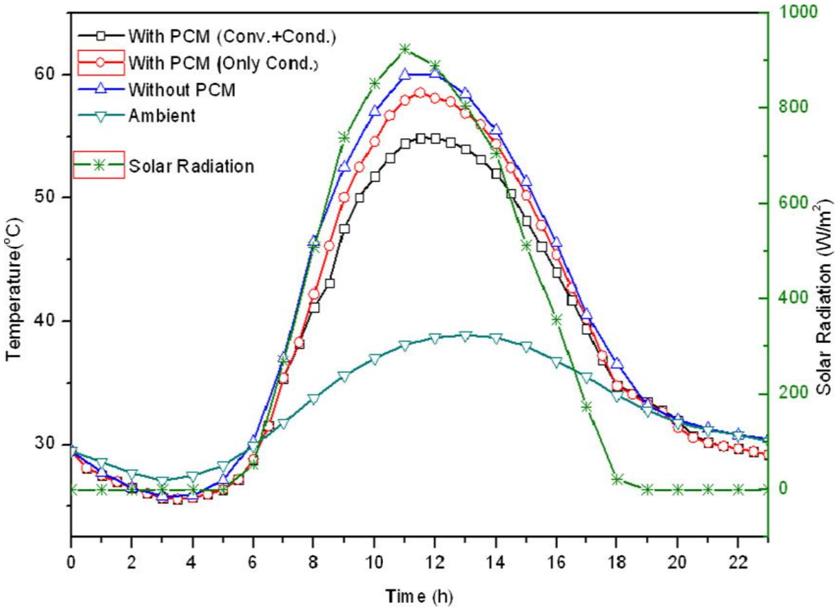

Figure 8. The effect of natural convection inside melted PCM on the rate of heat transfer [62]

Table 2. Summary of the numerical simulation model, software, and errors

References	Simulation model	Software	Dimension	Validation Ref.	Accuracy
Lu et al. [32]	enthalpy-porosity	Fluent	3-D	[32]	±1 °C
Zhao et al. [38]	conductivity method	MATLAB R2018a	1-D	[38]	±0.5%
Zhao et al. [39]	thermal resistance	MATLAB R2018a	1-D	--	--
Smith et al. [53]	enthalpy method	--	1-D	[5]	---
Khanna et al. [55]	Solidification/Melting	ANSYS Fluent 17.1	2-D	[50]	±0.5%
Emam and Ahmed [56]	Solidification/Melting	ANSYS Fluent 17.2	2-D	[5], [47], [66], [67]	±2 °C
Mousavi et al. [57]	Finite volume method	ANSYS Fluent/CFX	3-D	--	9%
Ma et al.[58], [59]	Solidification/Melting	ANSYS Fluent 17.0	1-D	MATLAB Model	±1.5 °C
Nehari et al. [60]	enthalpy-porosity	Fluent 6.3	2-D	[68]	--
Emam et al. [61]	Finite volume method	ANSYS Fluent 16.2	1-D	[5], [66], [68]	±1.2%
Kant et al. [62]	Finite element	Comsol	2-D	[69], [70]	---
Biwole et al. [63]	Finite element	---	2-D	[70]	±4 °C
Zukowski [64]	Effective heat capacity	TES_MZ	3-D	experimental data	12%
Khanna et al. [71]	Solidification/Melting	ANSYS Fluent 17.1	2-D	[63]	±1.5 °C
Al-Hmoud et al.[72]	Solidification/Melting	ANSYS Fluent v19.1	3-D	--	--
Arıcı et al. [73]	Finite difference	TRNSYS	1-D	[74]	1.0%
Yu et al. [75]	Finite volume method	Fluent	3-D	[76]	1 K
Nouira and Sammouda [77]	conductivity method	COMSOL	3-D	[69]	±2 °C
Liu et al. [78]	k–epsilon turbulence	ANSYS Fluent 14.0	3-D	[79]	---
Malvi et al. [80]	Finite difference	---	1-D	---	---
Lamberg et al. [81]	Effective heat capacity	FEMLAB	3-D	[82]	±2 °C

2.1.4. Effect of time step on the melting process

A number of flow phases, including unstable, buoyancy-driven, incompressible laminar, and natural convection effects, are involved in the intricate process of PCM melting [41]. The time step needs to be small enough to allow for the computational capture of the physical parameters. To guarantee acceptable accuracy and avoid oscillation node temperature instability, some numerical studies take into account the time step optimization selected at a time step of 0.1s [38]. Additionally, when the simulation time step shrank, the PV panel temperature stabilized and dropped, limiting the change to less than 0.1 percent [40]. Table 3, extracted from the review, showed the time step size of the PCM melting numerical simulation. Finally, PCM's coolant performance is an excellent technique for temperature control of PV panels and increased power generation. Several studies on thermal control and hybrid systems have been published to increase PV panels' thermal performance.

Table 3. Summary of time step references

Reference	Time step (s)	Calculation time (h)	Dimension
Zhao et al. [38]	0.1	24	1D
Khanna et al.[40]	0.1	4.5	2D
Khan and Khan [41]	0.1	1.3	3D
Smith et al [53]	3600	8760	1D
Emam and Ahmed [56]	0.1	4	2D
Nehari et al.[60]	0.01 to 100	4	2D
Kant et al.[62]	5	24	2D
Kamkari et al.[67]	2	9	3D
Nouira and Sammouda [77]	0.01 to 100	24	2D
Malvi et al.[80]	1	24	1D
Rabie et al.[83]	0.2	2	2D
Darkwa et al. [84]	60	5	2D
Motiei et al. [85]	300	24	2D
Maatallah et al. [86]	300	24	2D
Rucevskis et al. [87]	5	24	3D
Li et al. [88]	0.005	0.11	2D
Paper [89]	60	24	2D
Brent et al. [90]	10	0.3	2D

2.2. Active cooling systems

Active cooling processes increase overall efficiency by using the available thermal energy in energy conversion processes such as thermal processing, electrical power generation, and refrigeration.

2.2.1. Thermal cooling system

Thermal cooling system theory is the use of a fluid flow to absorb excess heat. The excess heat is transferred from the PV panel to fluid flow by conduction and convection. Various researchers are evaluating water-based PV-T and PV+PCM system performance using different absorber designs. Water was the standard fluid used in a liquid-based PV-T system. However, significant work was reported on PV panel electrical efficiency improvement. The PV-T system is the best-suited system for increasing electrical efficiency [91]. Preet et al. [92] concentrated research on several cooling technologies related to the water-based photovoltaic-thermal system and PV+PCM system. The aim was to find a new design of cooling arrangements to improve PV-T system performance. The PV-T cooling system's effectiveness was confirmed by various experimental, numerical, and theoretical analyses.

The economic and environmental implications of thermal cooling strategies were researched by Nieti et al. [93]. The collected findings showed that water base cooling approaches increased PV panel performance the most, and that this performance varied from around 10% to 20% on average. Abdelrazik et al. [94] analyzed the design of the thermally active cooling systems. Results indicated that cooling from the PV's top and bottom sides was an excellent cooling technique. The best liquid channels were honeycomb channels, and nanofluid in the cooling process was more efficient than traditional water. Hassan et al. [26] clarified the variable concentrations of nanoparticles and the volume of (graphene/water) nanofluid in the PV-T+PCM system. The best flow criteria were a 0.1% graphene concentration and a water flow rate of 40 LPM for PV, a temperature decrease of 23.9 °C, and an overall efficiency enhancement of 12%.

Furthermore, the PV-T-PCM system with water circulation only enhanced thermal efficiency by 6% [95]. Maatallah et al. [86] carried out another experiment to compare PV-T+PCM systems with and without water thermal cooling. The findings showed thermal, electrical, and overall system efficiency increments of 26.87%, 17.33%, and 40.59%, respectively. Javidan and Moghadam [96] demonstrated an experiment using a multi-nozzle jet impingement cooling (JIC) system with water as the coolant, which reduced the operating temperature by 30° C. Also, the application of forced air as coolant fluid in CPVs with fins increased power output by 27% [48]. Simulation and experiments were used to validate the required design parameters of solar air heaters [97-101]. The PV-T system efficiency enhancement dedicated from the review is shown in Table 4. Another active cooling method is the use of thermal collectors, which are used to transfer extra heat released from PV panels to heating water.

Table 4. Summary of PV Thermal cooling system efficiency

References	PCM	Fluid Type	η enhance. (%)	T_{sur} enhance (°C)
Hassan et al. [26]	RT-35HC	Water / graphene	12	23.9
Arcuri et al. [49]	N/A	Water / Air	5.75 / 5.13	15
Su et al. [65]	N/A	Air	10.7	13
Malvi et al. [80]	Paraffin wax	Water	9	20
Maatallah et al. [86]	Paraffin wax	Water	11.26	16
Xu et al. [95]	Fatty acid	Water	6	15
Kazemian et al. [109]	Paraffin wax	Water/ ethylene glycol	12	13
Hossain et al. [110]	Lauric acid	water	12.19	8
Baygi and Sadrameli [111]	Polyethylene-glycol	water	8	15
Kazemian et al. [112]	Paraffin wax	Water/ ethylene- glycol	4.22	10
Preet et al. [92]	Paraffin wax	water	15	30
Zhou et al. [113]	N/A	water	7.2	10
Liu et al. [114]	Microencapsul-ated slurry	N/A	11.4	N/A
Lin and Ma [115]	N/A	Air	18	N/A
Lin et al. [116]	SP21E, RT18HC,	Air	18	N/A
Browne et al. [117]	Palmitic acid	water	20	5
Browne et al. [118]	Mixture	Air	3.5	13
Lin et al. [119]	S22, SP24E	Air	8.31	20
Rubbi et al. [120]	N/A	MXene/ palm oil	15.44	20
Sathyamurthy et al. [121]	N/A	Water/ CNT/Al2O3	15.2	13.7
Lebbi et al. [122]	N/A	Air	5.7	12
Jha et al. [123]	N/A	Air	13	6
Sivaram et al. [124]	N/A	Air	11	12
Salameh et al. [125]	N/A	water	8	15

2.2.2. Thermal collector and heat pump

PV panels have been implemented in various ways over the last few years, using various technologies. Ruuskanen et al. [102] connected the PV panel with the ground-source heat pump to control the energy forecast, saving domestic water heating costs by 53%. Also, Dannemand et al. [103] investigated the combination of a PV panel thermal collector with a heat pump and storage tank (Figure 9), which increased the system's output power by 55%. Sakellariou and

Axaopoulos [104] presented a renewable power fraction index to indicate the overall energy performance of PV panels and ground heat pump systems. Emmi et al. research's [105] demonstrated the viability of using solar energy directly to generate household hot water and provide heat for heat pumps. The comparison of the two system designs, with photovoltaic and thermal panels and with solar thermal collectors, revealed that photovoltaic technology had the potential for a meaningful increase in heat pump efficiency. Bhardwaj et al. integrated the PCM material in an indirect dryer system, which decreased the process time by 37.50% and increased the energy efficiency by 9.8%. [106 – 108].

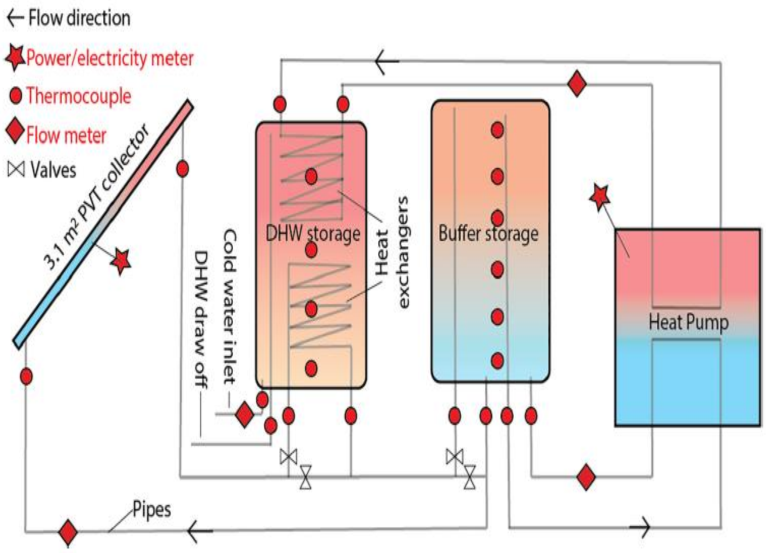

Figure 9. Schematic diagram of PV panel with the heat pump source increasing system efficiency [103]

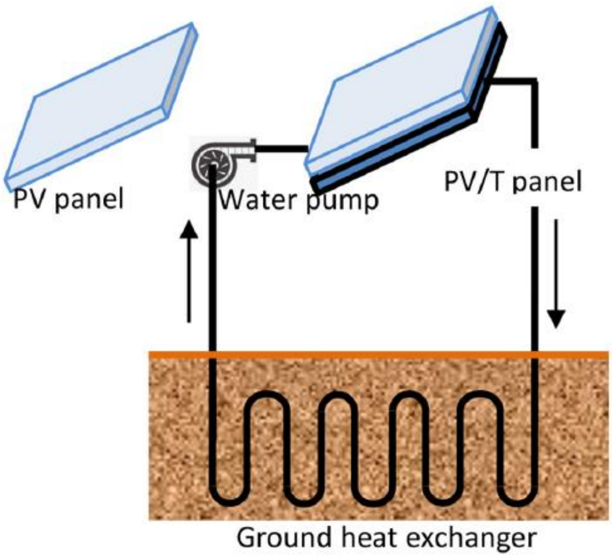

Figure 10. PV panel water thermal cooling with a ground heat exchanger [126]

Alkayiem and Reda [126] and Ruoping et al. [127] integrated the PV panel water thermal cooling with a ground heat exchanger and compared the simulation results with experiment implementation as shown in Figure 10. According to the results, the integrated heat exchanger was able to lower the PV surface temperature by about 8° C during the day and increase it by about 3° C above the necessary temperature, where condensation occurs at night. The thermoelectric generator is another active cooling device that converts heat to electricity (TEG). The effect of TEG on PV panel temperature will be analyzed in the paragraph after, which will also improve system performance as a whole.

2.2.3. Thermoelectric generator cooling system

The active cooling solution that makes use of extra heat from the PV panel is called thermoelectric power generation (TEG), and it is the most promising. P-type and n-type semiconductor columns with the same square cross-section are placed between two metallic interconnectors to form the basis of the TEG. The Seebeck effect, which asserts that a temperature difference between two dissimilar semiconductors causes a voltage differential between the two substances, is the basis for how a TEG device operates. Additionally, the output power rose as the temperature gap between the hot and cold sides widened. The high PV temperature is used by the TEG to generate energy from surplus heat. Ambient temperature and tilt angle are two crucial factors that affect a PV-TEG system's performance [128-29].

To achieve more compatible and effective system integration, Karami et al. [130] and Kohan et al. [131] explored a PV-TEG system with altering system parameters including material characteristics, multiple TEG couplings, cross-sectional area, and length. They showed that a number of significant physical and geometrical features of the integrated device had a significant impact on its overall output power. To produce a more harmonious and effective integration of TEG and PV, the material characteristics, number of TEG couplings, cross-sectional area, length, and other system parameters were calculated in an ideal range. Consequently. The tool has the advantage of functioning effectively, particularly in two situations: combining with solar collectors and in space. According to their findings, the PV-TEG system application increased electricity generation by

TEG is additionally silent and ecologically benign because it has no moving parts. Many applications produce electricity from TEG at night using PCM latent heat [132]. A standard CPV-T+TEG system and a CPV+TEG with PCM are created by integrating the TEG device into the CPV+TEG system. Instead of CPV+TEG without PCM, the CPV+TEG+PCM system integration controls large electrical power augmentation up to 49.5 percent [133]. According to simulation, system efficiency exceeded 40% [134–135].

For efficiency testing, Sark [136] built a PV+TEG system by simply mounting a TEG converter on the back of a PV panel. Figure 11 depicts a system that uses water at room temperature as a heat sink and PV temperature as a heat source. Using the PV+TEG+W system, efficiency was improved by 8–23%. Additionally, employing a nanofluid as a heat sink [137] increased total efficiency by 1.3–1.8%. A PV-TEG system with nanofluid is shown in Figure 12. A system created by Lertsatitthanakorn et al. [138] that utilised cold air as a TEG heat sink demonstrated an improvement in thermal efficiency with increased airflow. They concluded that the greatest total efficiency of the TEG solar collector was 72.2 %, an improvement in electrical efficiency of 5.7 %. Figure 13 displays

A heat pipe PV-TEG hybrid system was simulated by Makki et al. [140], and the outcomes are depicted in Figure 14 as a 2.5 percent increase in PV efficiency. Gu et al. [141] built a mathematical model of a PV-TEG system using the thermal resistance theory and found that the addition of TEG boosted energy output by 2.85 percent. A PV module and several TEGs were coupled by Fathabadi [142] to directly convert solar heat and radiation into electricity. A unique solar-powered PV/thermoelectric hybrid power source was the end product. The following is an outline of the innovations and contributions of that research work: Solar heat and radiation are immediately converted into electric power by the PV/thermoelectric hybrid power source.A heat pipe PV-TEG hybrid system was simulated by Makki et al. [140], and the outcomes are depicted in Figure 14 as a 2.5 percent increase in PV efficiency. Gu et al. [141] built a mathematical model of a PV-TEG system using the thermal resistance theory and found that the addition of TEG boosted energy output by 2.85 percent. A PV module and several TEGs were coupled by Fathabadi [142] to directly convert solar heat and radiation into electricity. A unique solar-powered PV/thermoelectric hybrid power source was the end product. The following is an outline of the innovations and contributions of that research work: Solar heat and radiation are immediately converted into electric power by the PV/thermoelectric hybrid power source. Table 5 shows the different research objectives of TEG applications and the diversity of the TEG heat source and heat sink.

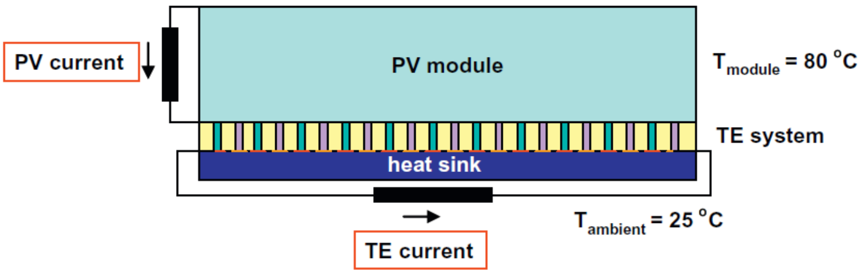

Figure 11. PV-TEG cooling system using water as TEG heat sink [136]

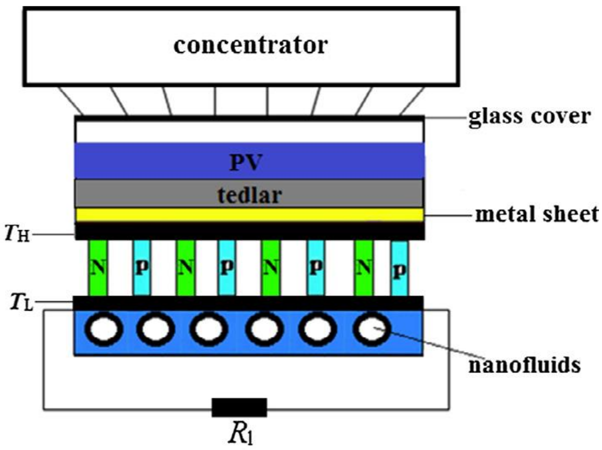

Figure 12. Schematic diagram of PV-TEG cooling system using water with nanoparticles as TEG heat sink [137]

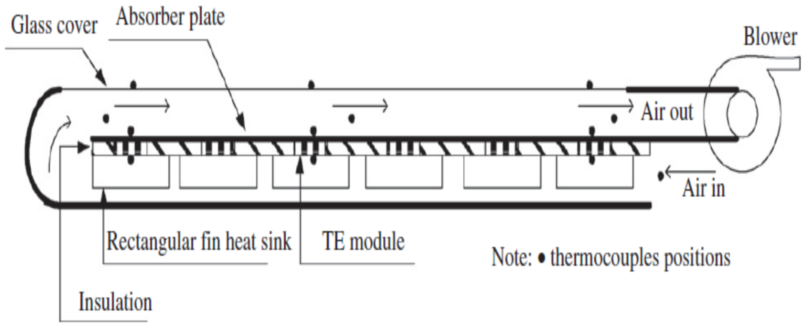

Figure 13. TEG solar air collector using cold air as TEG heat sink and PV panel temperature to heat airflow [138]

Table 5. Summary of TEG cooling system performance

References	Research objective	TEG heat source	TEG model.	TEG heat sink.	Study type
Motiei et al. [85], [143]	System efficiency enhancement	PV	HT6-12-40	PCM	Numerical
Mishu et al. [144]	thermal management	PV	GM250-71-14-16	Pin-fins	Experiment
Indira et al. [145]	tracking system effect	PV	equation	Pin-fins	Numerical
Ko et al. [146]	PCM layer thickness	PV	equation	PCM	Numerical
Ruzaimi et al. [147]	TEG array configuration	PV	manufactured	Air natural convection	Experiment
Metwally et al. [148]	System efficiency enhancement	PV	1261G-7L31-04CQ	Cooling water	Numerical
Nazer et al.[149]	Thermal management	PCM	manufactured	Natural convection	Experiment / Numerical
Greppi and Fabbri [150]	Thermal management	PV	manufactured	Pin-fins	Numerical
Ji et al. [151]	Power output estimation	PV	equation	Cooling water	Experiment / Numerical
He et al. [152]	Thermal management	CPV	manufactured	Cooling water	Experiment
Chem et al. [153]	Different geometries of organic semiconductors	OPV	manufactured	Air natural convection	Experiment
Ben et al. [154]	Electrical efficiency enhancement	CPV	manufactured	Cooling water	Experiment
Zeneli et al. [155]	TEG performance evaluation	Heat source	manufactured	Heat pipe	Experiment / Numerical
Zheng et al. [156]	Enhance TEG energy conversion	Heat source	manufactured	Water film	Experiment / Numerical
Pires et al. [157]	System efficiency enhancement	PV	TEC1-12708	Water heating panel	Experiment
Shittu et al. [158]	System efficiency enhancement	Heat pipe	Bismuth telluride	Cooling water	Experiment
Salari et al. [159]	Thermal efficiency parameters	PV	equation	Water heating	Numerical
Shatar et al. [160]	TEG configuration	PV	SP1848–27145	Air natural convection	Experiment
Birol et al. [161]	Exergy efficiency enhancement	PCM	manufactured	Heat pipe	Experiment

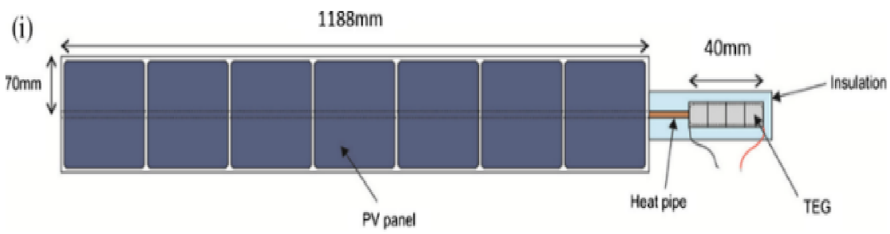

Figure 14. HP-PV-TEG cooling system using Heat pipe as TEG heat source [140]

2.3. Hybrid cooling system

Passive cooling systems and active cooling systems enhance the PV panel's thermal efficiency, electrical output, and overall system performance. Many hybrid cooling systems were studied to maximise the overall system performance in various industries [162]. Motiei et al. [85], [143], designed and simulated a hybrid PV+TEG+PCM system using the PCM as a TEG heat sink. They found that the system's best performance was at the PCM layer thickness of 45mm and 50mm [84], as shown in Figure 15.

Additionally, as shown in Figure 16, Cui et al. [163] examined and modelled a hybrid PV+PCM+TEG employing PCM as a TEG heat source. Temperature stability was a benefit of PCM as a heat source. The water channel was used as a TEG heat sink when it was at room temperature. The efficiency of the PV panels was increased by the hybrid cooling system by 1%. Additionally, Luo et alsimulation .'s of a BIPV-TEG hybrid system [164] used cold airflow and heat pipes as a TEG heat sink. According to their findings, as shown in Figure 17, overall system efficiency increased by nearly 70%.

Integration of a PV panel in a different application aims to save power and enhance the energy performance of the system. Many renewable energy resources (PV and wind) were combined to maximize electrical power output. Sinha and Chandel [165] analyzed and optimized the techniques to design and develop PV/wind hybrid energy systems for the last 25 years. Ghorbani et al. [166] integrated a device, including PVT collectors, an ejector cooling cycle, and PCM storage, as seen in Figure 18. Results showed that the thermal energy efficiency improved by 8.6% and the electrical energy efficiency decreased by 4.1%. Hu and Yue [167] showed that integrating the PV panel with two refrigerant systems enhanced the coefficient of performance by 41%. Babayan et al. [168] studied a new PV-T system with a PCM and proton exchange membrane (PEM). The proposed system aimed to generate hydrogen in a hydrogen fueling station, as shown in Figure 19. Results showed that the PV-T system hydrogen output with PCM was enhanced by 5.32 percent.

Meanwhile, Ren et al. [169] investigated a hybrid PV-T solar air heater using PCM with rotary desiccant cooling systems for residential applications, as seen in Figure 20. When the regeneration temperature was reduced from 70 °C to 60 °C during the simulation days, the solar thermal power output increased from 82.6% to 100.0%. Alinejad et al. [170] simulated the FPV integration into the greenhouse's roof horizontally and vertically and found a reduction in the electrical demand by 45.5%, as seen in Figure 21. Neelam et al. [171] looked into the advancements of CPV integration in power plants that used direct steam generation. In addition, Mehrpooya et al. [172] developed a mathematical model of CPV panels and a biodiesel production plant combination, raising the energy efficiency to 60.83%. Meanwhile, Lazzarin and Noro [173] coupled glazed PVT to ground-source heat pumps. The collector's thermal efficiency was boosted by using glazed PVT, and ground coupling permits high electrical efficiency without running the risk of cell breakage from overheating.

Different cooling systems were used in the PV panel thermal management. Each cooling system has a different effect on the overall system efficiency. Table 6 summarizes the effects of various PV panel cooling media on panel temperature and system efficiency.

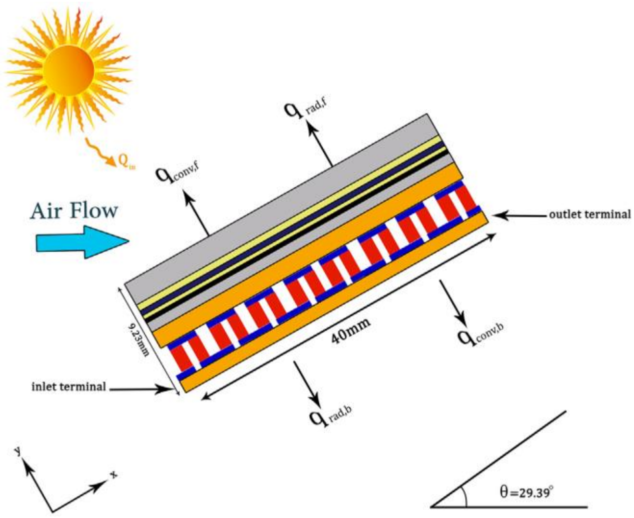

Figure 15. PV+TEG+PCM module using PCM as TEG heat sink [85], [143]

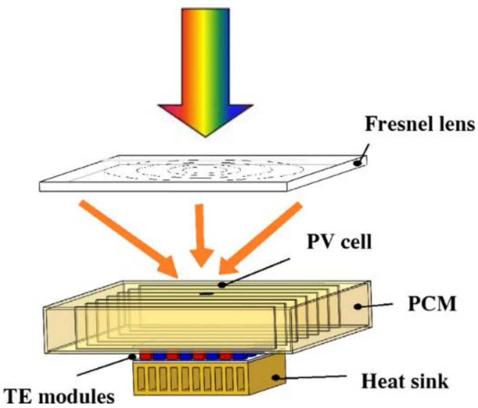

Figure 16. PV+PCM+TEG model using PCM as TEG heat source [163]

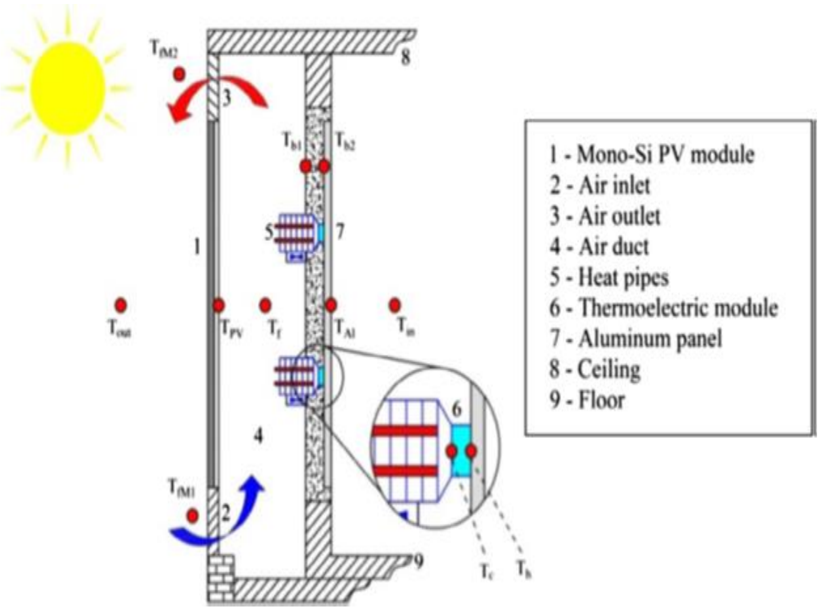

Figure 17. BIPV+TEG wall system [164]

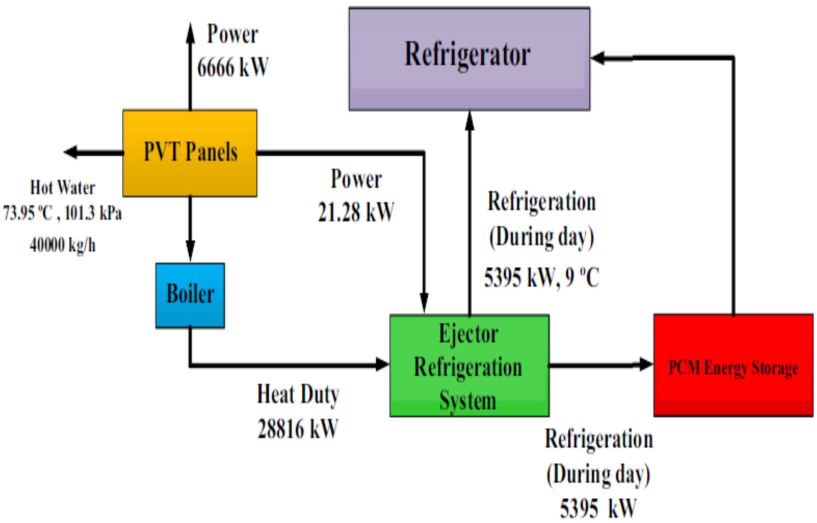

Figure 18. The hybrid cooling system combination of PV panels in refrigerant circuits [166]

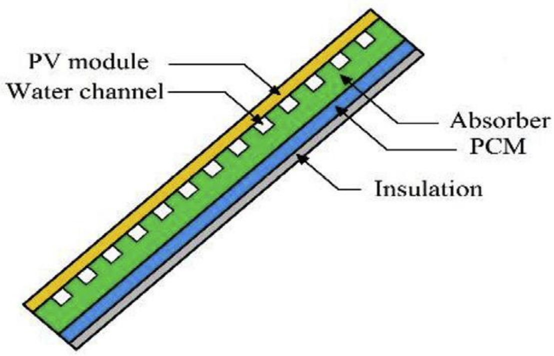

Figure 19. Hydrogen production schematic from PCM stored heat [168]

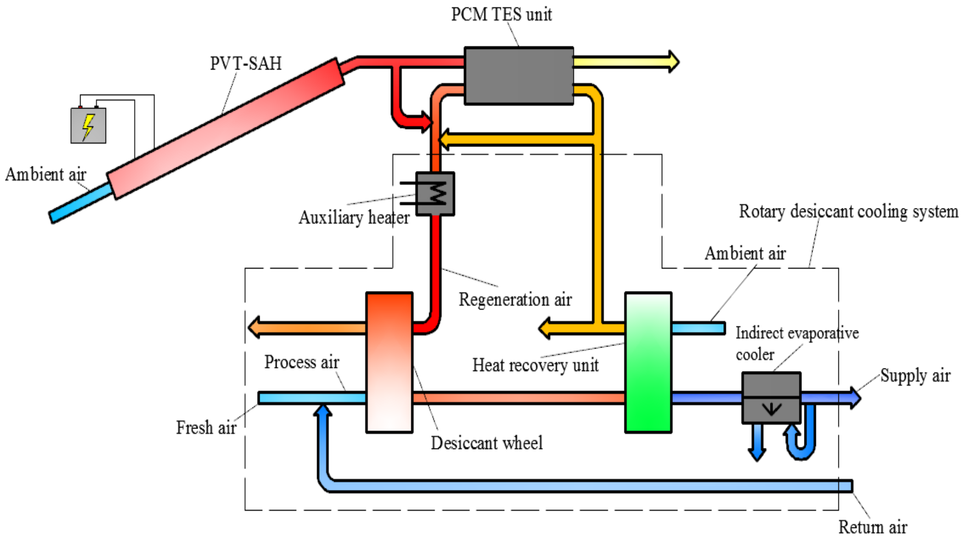

Figure 20. The schematic diagram for the PVT-SAH system [169]

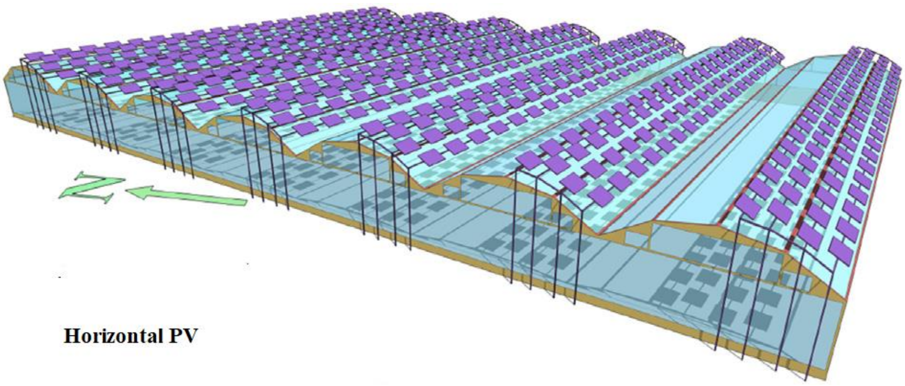

Figure 21. Integration of horizontal PV panel with greenhouse [170]

Table 6. Summary of different PV panel cooling systems

PV panels cooling media	PV panel Temperature drop (ºC)	Overall system efficiency (%)
Air-only [122]	5.7	12
PCM only [15]	6.5	5.8
PCM + Air[118]	3.5	13
Water only[125]	8	15
Water + heat pump [104]	N/A	55
Water + heat exchanger [127]	22	N/A
Water + nanoparticles. [120]	15	13
PCM + Water [80]	9	20
PCM + Water + nanoparticles [109]	12	13
TEG + Water [136]	N/A	23
PCM + TEG + Air [149]	22.7	60
PCM+ TEG+ Water [163]	N/A	30
BIPV [166]	N/A	8.6

3. Conclusion

The current review discussed and reported the photovoltaic panel's thermal management using passive, active, and hybrid cooling systems. Also summarized are the causes of high PV operating temperatures and their effects on system performance. The purpose of the present review article is to describe various cooling methods. Multiple researchers reported the methodology to improve the photovoltaic panel's efficiency. Many researchers established various experimental, numerical, and theoretical analyses to evaluate and optimize the PV, PCM, and TEG systems' performances. Various factors and parameters are affecting the selection of cooling systems.

PCM's thermal and physical properties—melting temperature, thermal conductivity, container geometry, and availability—are significant variables affecting the PV panel's power generation efficiency. The addition of nanoparticles to PCM improves overall thermal conductivity and the PV panel's efficiency. The finned PCM layer reduces the temperature of the PV panel by about 6 °C less than the un-fined layer. The optimum PCM layer thickness is 3.5 to 5 cm. PCM melting temperature also affects the yearly ideal operating temperature when using low melting temperatures in winter and high melting temperatures in summer. Thermal conductivity and latent heat control processes in PCMPCM applications maintain temperature stability below 65 °C while avoiding PV temperature fluctuations. Time step is a significant element in the numerical assessment of PCM.

Meanwhile, the passive cooling system reduces the PV panel's temperature without using absorbed thermal energy. Thus, active cooling systems offer methods to increase overall system thermal efficiency. The PVT system's performance depends on the fluid temperature, fluid flow rate, and fluid channel geometry and sizes. Air cooling PV panel performance is less than liquid cooling because of high thermal conductivity and high viscosity. Water is the most common fluid employed in the liquid-based PVT system, while the addition of nanofluids improved system efficiency. The PVT system is best suited for roof utilization. The PVT system is a sufficient technology that meets the demand for hot water for domestic and industrial usage. Otherwise, using additional devices for power generation also enhances the overall efficiency of power generation using TEG. The TEG module is connecting to the PV panel's backside. The PV-TEG established a temperature drop in the PV panels of about 8 °C, and the PV panel efficiency improved by 8% to 23%.

4. Future Vision

Raising the efficiency of PV panels through research is a promising field. Many studies are performed in the field of active cooling systems to raise the total system efficiency. The researcher will try to find more TEG material and high-performance semiconductors for PV panel assembly in the coming years.

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