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# Passive and Active Techniques for Cooling Photovoltaic Cell using PCM: An Investigation of Recent Advances

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**ABSTRACT**

Photovoltaic (PV) technology is one of many renewable energy sources, which converts solar energy directly received into electricity. In recent years, PV has advanced quickly as researchers try to make it more effective. 80% of the solar radiation that hits PV cells is absorbed, but only 12–18% of that energy is converted into electricity, with a maximum conversion rate of 24%. This indicates that a significant amount of sunlight is lost irretrievably. when a significant portion of the solar energy that is absorbed but not used by the photovoltaic process is converted to heat, which causes PV cells' operating temperature to increase above their design temperature, Consequently, the cell's effectiveness declines as a result of this increase. The crystalline silicon-based PV cells' efficiency drops by 0.5% for each Celsius increase in temperature of operating. When operating temperature of cell exceeds design temperature, open-circuit voltage decreases significantly while the closed-circuit current slightly increases. Research has shown that PCMs can be applied in a variety of ways to enhance performance of PV cells, including as a coating applied directly onto the surface of the modules, as a heat exchanger in contact with module's back, or as an integrated component within the module itself. One recent advancement in the area of PCM-based cooling of PV modules is the development of hybrid cooling systems that combine PCMs with other cooling methods, such as air or water cooling. These hybrid systems have been shown to significantly improve the temperature stability and efficiency of PV modules compared to single PCM-based systems. PCMs have unique thermal properties that make them suitable for use in cooling systems because they can store and release thermal energy when phase transitions occur due to their high latent heat capacities. Recommendations for the use of phase change materials in Photovoltaic cooling, continue to research and develop new phase change material-based cooling systems that are more stable, have higher thermal conductivity and are effective in a wider range of temperatures.

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## 1. Introduction

Regular consolidation of population in a country is mostly subject to the country' and sequentially the improvement is governed by access to energy as well as energy depletion. A deeply rooted relationship has been observed between energy use and higher living organization. A country that uses more energy expenditures per capita can achieve the qualifying realization in every sector in the world compared to the least energy-consuming countries [1]. It means the countries that consume more energy have a higher standard of living for individuals, and higher energy consumption means more use of traditional energy sources.

The excessive use of traditional fossil fuels at a disturbing rate caused a crisis of energy and related environmental issues of climate change, harmful greenhouse gas emissions, and the destruction of ozone layer, which endangers human security and the future of the planet [2]. Therefore, finding alternatives to provide clean energy and solve these issues was necessary.

Photovoltaic technology (PV), An innovation that produces electricity from direct solar radiation, is just one of the numerous renewable energy sources. This technology becoming increasingly popular, especially in regions that receive high sun radiation. PV has progressed swiftly in recent years, with researchers working to improve its effectiveness as well as affordability in a variety of locations around the world. This contributed in the rapid reduction of reliance on fossil fuels, the main source of electricity generation [3]. All types of clean energy sources derive their primary energy from solar radiation [4].

Renewable energy sources are not limited to solar energy, but there is water and wave energy, wind energy, biofuels, Tides, and Geothermal energy is also used to generate electricity. However, in terms of energy production, photovoltaic systems outperform alternative sources in a variety of industries [5].

The direct application of the photoelectric phenomenon is photovoltaic (PV) energy. Edmund Becquerel discovered this phenomenon at 1839, and the first photovoltaic device using semiconductors was developed in Bell Lab at 1954 [6].

Scientific investigation and industrial utilization of PV technology, which simply transforms sunlight and photon energies to electricity by semiconductors, have advanced significantly, and it is still on track to increase efficiency and lower costs. In 1961, Shockley and Queisser proposed a 30% theoretical conversion efficiency limit to the AM1.5 solar spectrum. It was then revised with a calculation that was 33.7% more precise and had a bandgap of 1.34 eV [7].

80% of the solar radiation that hits photovoltaic cells is absorbed, but only 12–18% of that energy is converted into electricity, with a maximum conversion rate of 24%. This indicates that a significant amount of sunlight is lost irretrievably. when the photovoltaic process converts a sizable portion of the solar energy that is absorbed but not used into heat, which causes the photovoltaic cells' operating temperature to increase above design temperature, this increase causes a decrease in cell efficiency [8].

The efficiency of crystalline silicon-based PV cells drops by 0.5% of each Celsius increase in operating temperature [9,10]. The studies indicated that both the voltage and the cell's productivity are significantly impacted by the rise in operating temperature. whenever the design temperature of a cell is exceeded by its operating temperature, the closed-circuit current rises slightly while the open-circuit voltage significantly decreases [3]. The majority of PV cells are installed in arid and desert regions, which implies that they are exposed to severe weather conditions, temperatures that are particularly high and a lot of UV radiation. This suggests an increase in the detrimental effects on the operational life and effectiveness of cells. So, numerous cooling techniques have been suggested, on which the investigators have been working to lower operating temperatures and raise the cell's efficiency. Passive and active cooling techniques for photovoltaic cells are the two main categories [11]. Photovoltaic cells are cooled to generate more electrical energy and lengthen cell life. where scientists created a variety of cooling systems to lower photovoltaic cells' operating temperatures [12,13].

One of the fundamental problems of using phase change materials is their low thermal conductivity, which can limit their cooling effectiveness. Another challenge is the high cost and lack of stable operational design of phase change materials, which has limited their use in photovoltaic/thermal (PVT) systems. However, researchers have made improvements by combining PCMs, fins and nanofluids.

This paper's goal is to demonstrate that using PCMs as heat sinks for photovoltaic panels can regulate and reduce the temperature of the panels, leading to increased efficiency and extended life of solar cells. and determine the benefit of adding nanomaterials and fins to PCMs that can enhance their specific thermal capacity and thermal conductivity.

### *1.1 Photovoltaic Technology*

Certain semiconductor materials, such as silicon, are used to construct photovoltaic cells, which shows what is known as bulk photovoltaic effect, a specific characteristic [14]. In essence, a photovoltaic cell is a high-tech method of converting sunlight into electricity. Direct current electrical energy can be applied this way, converted to AC energy, and then used or stored for future use [15]. Photovoltaic modules, which combine photovoltaic cells to increase capacity, are highly reliable, long-lasting, and low-noise devices. Solar cell fuel is the sun which is the resource required to run photovoltaic systems, and it is free and inexhaustible energy. Photovoltaic cells are divided into two types according to the material from which they are made: organic cells and inorganic cells [16].

Solar cells are also divided according to manufacturing technology into three generations: The first generation is the cells that are made of crystalline silicon such as (Mono and Polo). The second generation (Thin Film) such as Amorphous Silicium and Copper Indium Diselenide. Third-generation nanotechnology-based cells such as Super tandem and Intermediate [17]. The efficiency of solar cells has greatly improved from 1980 until 2022. The highest recorded research cell efficiency is 47.1% of a four-junction cell as shown in Figure 1 [18].

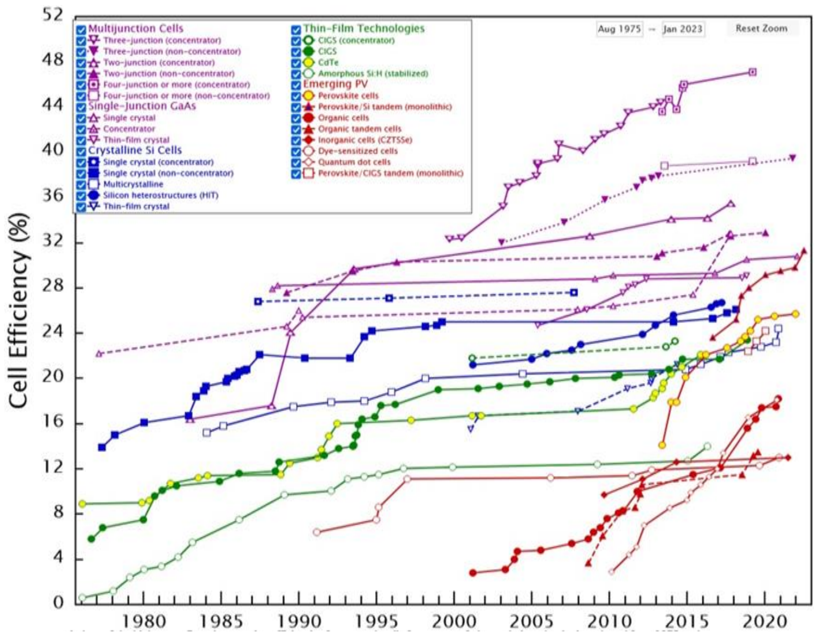


**Fig. 1.** Interactive Version of its Research Cell Efficiency Chart for a Range of PV Technologies by NREL

### *1.2 Why We Need a Photovoltaic System*

Photovoltaic systems are needed to provide electricity to people who are difficult to reach by the grid due to their location in inaccessible places or who consume very little energy. These systems consist of photovoltaic modules, charge controllers, storage systems and voltage isolators [19]. They are used in home electrification, especially in building integrated photovoltaic (BIPV) systems [20]. Digital technologies such as the Internet of Things (IoT), Artificial Intelligence (AI) and edge computing are being adopted to make these systems more efficient. Photovoltaic systems are reliable, clean sources of electricity that can suit a variety of applications. They can also be deployed in urban centres to supply critical loads, such as video surveillance systems, and help avoid economic losses and loss of life due to the inoperability of the electrical power grid. In addition, photovoltaic systems play an important role in improving the energy efficiency of buildings and can be used in zero-energy buildings.

### *1.3 Working Principle*

Essentially, a solar cell is a junction or diode between two semiconductors with atomic lattice impurities that either provide up electrons (the donor) or hold them (the acceptor) [21]. As the photons of light that fall on the semiconductor material excite the electrons associated with the semiconductor material and the electrons become more energetic and have more freedom to move. This is referred to as photoelectricity. Albert Einstein found that ultraviolet or blue light causes electrons to escape, when light strikes a material, the kinetic energy of photons usually excites the electrons into higher states of energy within the material, however, electrons that are excited quickly return to their stable state. To avoid this in a photovoltaic panel, The electrode of the external circuit is composed of both P and N-type semiconductors. In a solar cell, two semiconductors are combined to form a P-N junction. To achieve this crossover, a material like silicone is typically combined with various chemicals. When antimony is added to silicon, a semiconductor of the N-type is formed, whereas silicon with boron produces a P-type semiconductor. Before electrons return to a stable state, a material of the P-type pulls the charged electrons in the junction (depletion layer) and feeds them to the external circuit. leads. A current D.C. is generated in the presence of an external circuit with a load as shown in Figure 2 [22].

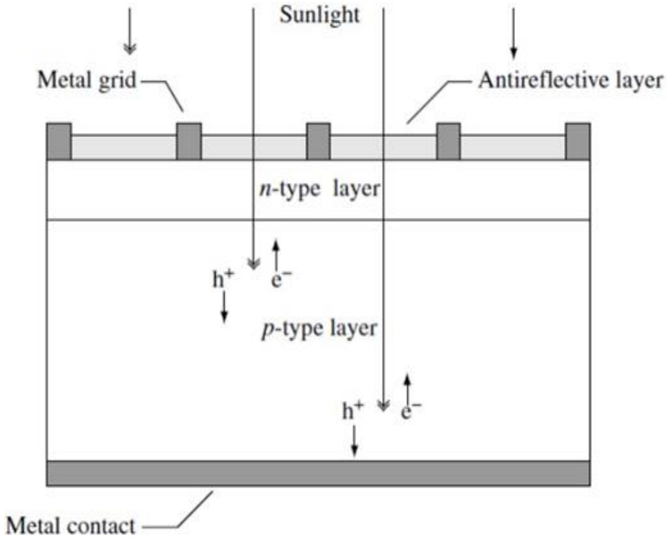



**Fig. 2.** A PV cell's general structure

### *1.4 Factors Influencing PV Cell Performance*

(i) Solar irradiance

The amount of received irradiation determines how much power a PV cell will generate. The radiation from the sun varies all through the entire day and typically reaches its maximum around noon. For a module, the highest solar irradiation levels occur when the surface is pointed directly at the sun. To produce the best rates of electricity generation, the PV cell inclination angle must be determined by geographic location. For tracking the ideal path perpendicular to the sunlight's rays and absorbing the greatest amount of solar radiation, photovoltaic cells are able to be mounted on a solar tracker [23].

(ii) Temperature

The operating temperature of PV cells is one of the most significant variables affecting their output. Wind velocity, surroundings temperature, sunlight, and other elements influence this temperature. As the temperature and amount of sunlight increase, so do cell temperatures. Due to their fundamental characteristics, semiconductors are a crucial part of photovoltaic (PV) cells, and an increase in temperature will cause a decrease in efficiency. The primary cause of efficiency loss is the linear decrease in the voltage in open circuits that happens as cell temperature rises. According to the conducted literature review, the efficiency of crystalline cells decreases by about 0.5% for every 1 C increase in cell temperature. Different thermal management strategies have been created with the intention of keeping the cells' temperature as low as possible to prevent efficacy loss [24].

(iii) Accumulation of dust

Dust or dirt has an effect on the PV cell's output rate, which can lessen the amount of sunlight received by partially blocking solar radiation. The productivity of the cell decreases by about 7% when there is dust on the surface. In this case, washing the cell surface improved the generation rate in the cell by an average of 32.27%, according to the findings of a study done in Lebanon [25].

(iv) Solar cell material

The PV cell's construction and manufacturing depend heavily on its material. A variety of materials, such as silicon, indium phosphide, copper indium diselenide, and others, can be used to create PV cells. The majority of commercial PV cells are made of silicon, which is the most advanced material for making them. Since there has been a significant investment in R&D projects aimed at improving solar cell efficiency, it is anticipated that the conversion rate of crystalline cells, which currently account for the largest market shares, will soon be improved [26].

(v) Shading

The output of the solar cells is significantly decreased by the shadowing effect. Due to the cells' series connection, shade condition has an impact on both the current within the cells and the panel as a whole. According to studies on how shading affects solar cells, a 2% shaded photovoltaic cell would produce up to 70% less power, illustrating the significant impact of blocking on a photovoltaic cell's efficiency [27].

(vi) Cooling techniques

As we mentioned earlier, the majority of PV cells are installed in places with challenging weather conditions, especially extreme temperatures, and Ultraviolet rays, which harm the reliability and lifespan of PV modules as well as their efficiency. Researchers have proposed and created a number of cooling technologies to reduce operating temperatures and improve the efficacy of photovoltaic units as shown in Figure 3.

Systems that use materials that phase change (PCM), natural air ventilation, heat pipes, and thermal fins are examples for systems of passive cooling. Active cooling techniques, on the other hand, rely on pumps or fans that require external power sources. Examples include forced air ventilation, water spraying on the front or back of the photovoltaic cell, and forced water circulation [28].

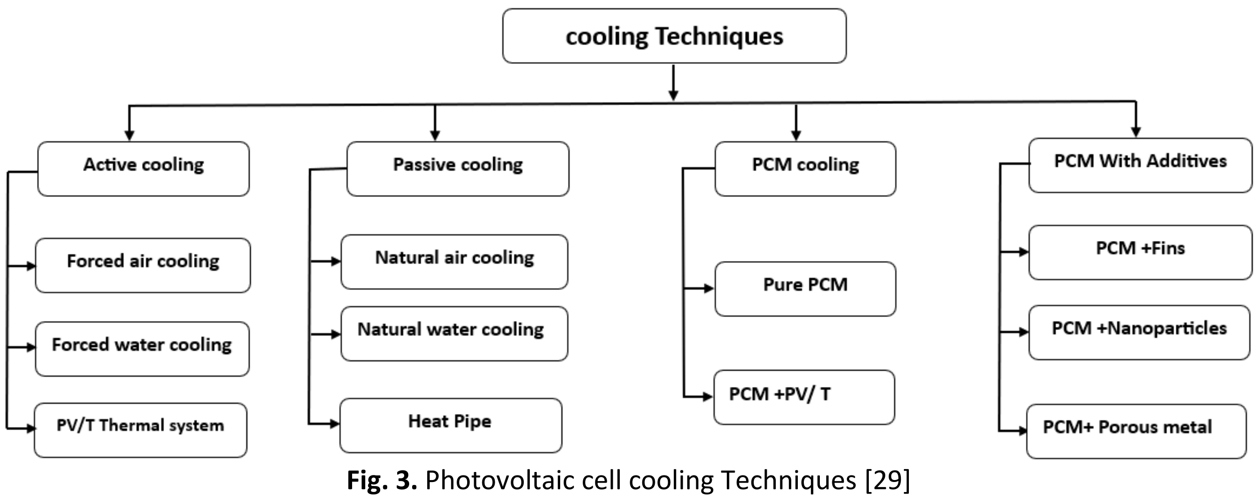



**Fig. 3.** Photovoltaic cell cooling Techniques [29]

### *1.5 PCM in PV Cooling Applications*

PCM-based cooling technologies have been widely studied for cooling photovoltaic (PV) modules. These techniques include integrating the PCM behind the PV module, using thermal additives filled into the PCM, or using thermal collectors placed behind the PV module or inside the PCM enclosure. PCM selection is critical to improving cooling system efficiency. Different types of PCM were investigated, such as organic, inorganic, eutectic, and commercial PCM. Commercial PCM and organic PCM are found to be the best options due to their improved chemical aspects. The PCM selection process can be based on the melting temperature method, which simplifies calculations. Integrating PCM into PV cooling systems reduces the temperature of PV cells and increases the overall efficiency of PV panels [30,31].

## **2. Literature Review**

### *2.1 Passive Cooling*

The use of phase change materials (PCMs) in cooling photovoltaics has gained interest in recent research. Various studies have investigated the cooling effect of PCMs on photovoltaic (PV) panels and its impact on PV performance. Experiments conducted at various sites have shown that PCMs can effectively reduce the temperature of PV panels, leading to improved efficiency and power generation. Different types of PCMs, such as silica, carbon black nanoparticles dispersed in PCM, soy wax, paraffin, and beeswax, have been tested for cooling purposes, the cooling properties in PCM on PV the cells have been investigated through experimentation Xu *et al.,* [32]. Under no wind, 1000 W/m2 irradiance, and 7.31 °C ambient temperature, PCM can successfully decrease the PV cell's temperature. In 300 minutes, the PCM can reduce the average temperature of the PV cells' top and back surfaces by 33.94 °C and 36.51 °C, respectively. The average PV cell's output power increased by 1.35 W, and its energy production efficiency increased by 1.63%. PV cells using PCM cooled from its peak temperature to ambient temperature to stay for 480 minutes as opposed to just 60 minutes for the cell without PCM. To keep cell temperatures near ambient, Badi *et al.,* [33] used PCM-OM37P. At Renewable Energy and Energy Efficiency Centre (REEEC) in University of Tabuk, on display was the enhanced GCL-P6/60265W PV cell efficiency as shown in Figure 4. Using PCM to cool the photovoltaic cell during peak hours has resulted in the lowest drop voltage of 0.6V. This is equivalent to cooling at a 5–6 °C temperature. The roughly 3% power improvement percentage (PIP) between conventional and PCM-cooled PV cells is due to the different operating voltages between the two types of cells. The PIP value was overestimated as a result of PV string configuration, which takes the average value of the two PV cells' electrical current during operation.


**Fig. 4.** (a) There are PCM collections with PCM-OM37P content, (b) the positions of both thermocouples rear and front

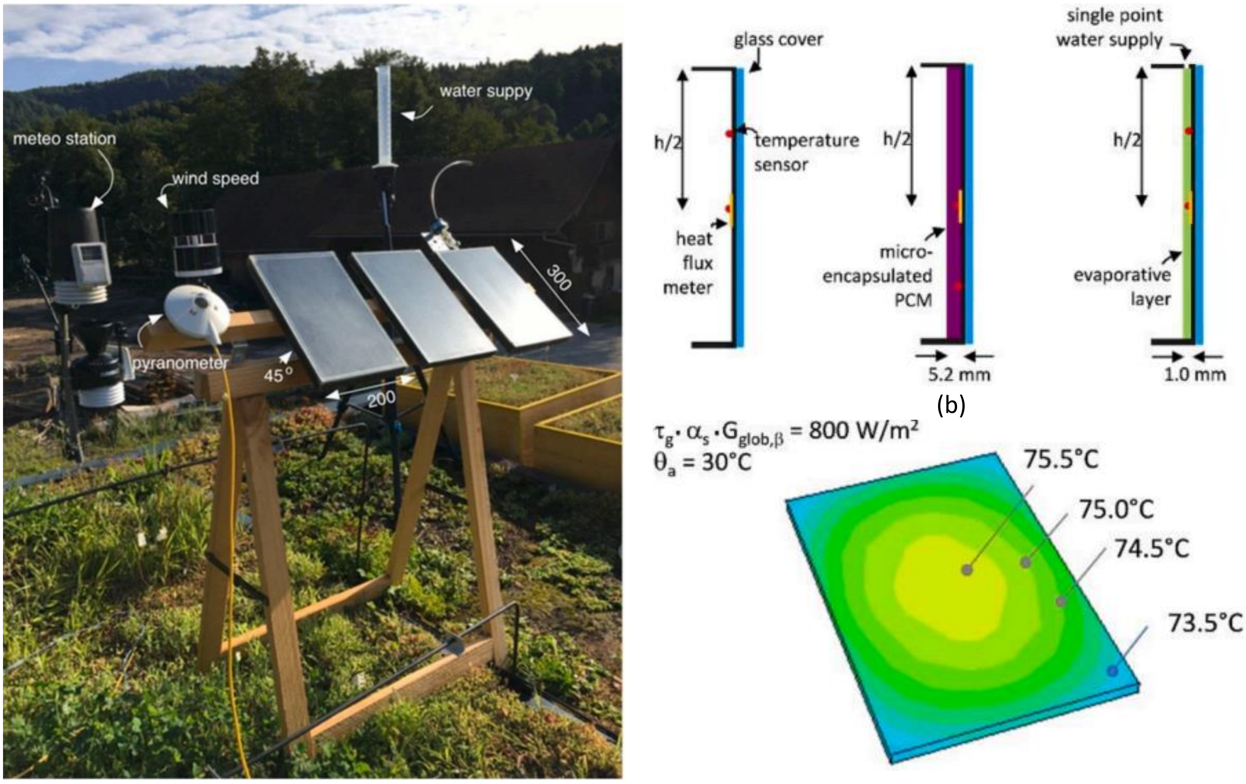
To boost the production of electricity in PV/T (photovoltaic/thermal) collectors, Shakibi *et al.,* [34] combined a nanoparticle-based PCM layer with finned collectors as a capacitor. To ascertain how the nanophase change material layer affects the system's efficiency as mentioned, investigated the distribution of temperature within the layer of phase-change material in its solid and melted states. Following that, a large amount of data is collected and used to train and find the best network using a deep learning model. The gilt-edged network is then optimized using LINMAP, TOPSIS, Shannon entropy decision makings, Grey Wolf Optimization (GWO), Bat algorithm (BA), Particle swarm optimization (PSO), and Biogeography-based optimization (BBO).

Greatest thermal efficiency is obtained when the speed of wind is lower than 2 m/s and DNI exceeds 950 W/m$^2$.

For cell thermal management, incorporates the work of Sheik *et al.,* [35] a standard PV cell, cooling of a photovoltaic cell with PCM, and a PV cell cooling with nanoscale PCM (NPCM). The PCM, Polyethene Glycol (PEG) 1000, had a point of melting between 33 and 39 °C. Alumina as well as nanoparticles of silica were used as the PCM's input materials.

When applying a PV-PCM, PV-Alumina a nanomaterial with a phase change (ANPCM), and PV-Silica nanomaterial of the phase change (SNPCM) cooling system, the electrical efficiency is increased by 4.82, 8.1, and 7.17%, and the electrical output is increased in 5.12, 8.4, and 7.29%, respectively. The temperature decreases by 17.15% when compared to uncooled cells. There are a pair of choices in Arkar *et al.,* [36] work: Micro-encapsulated Material of Phase Change (PCM), which only conducts heat, and macro-encapsulated Material of Phase Change, which also conducts heat but uses convection. Evaporative cooling was compared to the effectiveness of the free cooling with Phase Change Material. Using in-situ experiments, As shown in Figure 5, the thermal response of simulated photovoltaic panels (vPV) was evaluated. A layer of 5.2 mm thick micro-encapsulated phase change material was applied to one vPV, while an evaporated layer was applied to another. The necessary thermal characteristics of Phase Change Material were discovered to offer in three chosen environments (Stockholm, Ljubljana, and Athens), passive cooling achieved the same efficiency as an evaporation cooling process.

Free cooling of photovoltaic cells using phase change material may be as effective as cooling by evaporation in both the hottest and coldest observed environments when the thermal conductivity of the phase change material is higher than 1.8 W/mK for micro-encapsulated phase change material and higher than 1.2 W/mK for macro-encapsulated phase change material and the latent heat capacity is greater than 250 kJ/kg. For specified ranges of thermal characteristics, evaporative cooling in a cooler environment will be more efficient than passive cooling. If the thermal conductivity of the PCM layer is less than 0.4 W/mK and the latent heat capacity is less than 150 kJ/kg in such an environment, the additional heat transfer resistance of the phase change material layer causes PV cell heating to increase.




(a) (c)

**Fig. 5.** (a) An experimental stand in vPV cells; (b) A schematic showing the location of the thermocouples as well as heat flux sensors on vPV cells, and (c) Boundary conditions and a 3-D numerical model of the steady-state temperature demonstrating the minimal impact of edge thermal crossings

Duan [37] Look into the use of a brand-new phase change material (PCM) and a porous metal foam heat sink for CPV systems that require concentrator cooling. determine the effect of the PCM-porous method on improving the electrical efficiency of CPV components for more efficient cooling techniques, which can improve their overall performance and electric productivity. uses mathematical and geometric models to simulate the PCM-CPV system, then verifies the mesh convergence and simulation process to guarantee the accuracy of the simulation results, as shown in Figure 6. The effects of PCM-porous systems with different porosities (= 100%, 90%, 80%) and heights (H = 3.0x, 2.0x, 1.0x, 0.5x) on improving the electrical efficiency of CPV modules are studied numerically. The PCM-porous method's porosity and heights are the main variables that impact the cooling effect on the CPV panels. The PCM-porous approach might boost the electrical performance of CPV modules. By increasing the height (H) of a PCM-porous cavity from 0.5x to 1.0x, efficiency and power output could rise by up to 50%. However, when the height is increased from 1.0x to 2.0x, there is little difference in electric efficiency. Going from 2.0x to 3.0x height slightly reduces the electric efficiency when the porosity is less than 100%.

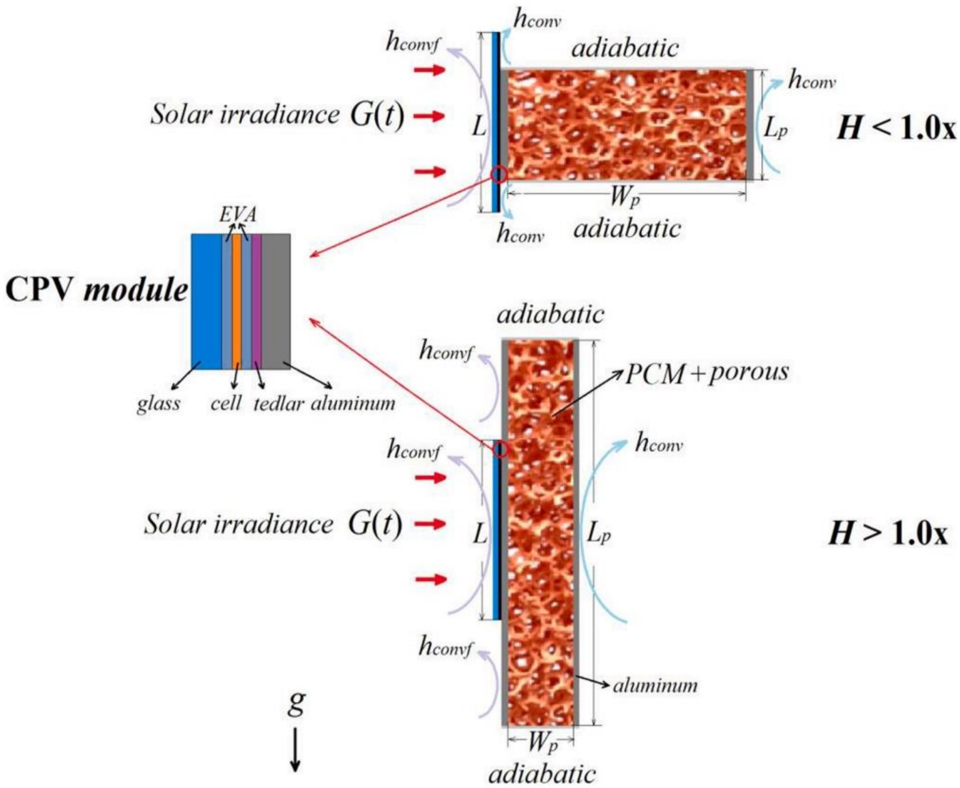



**Fig. 6.** PCM-porous systems schematic

To regulate a PV system's temperature, Sharaf *et al.,* [38] used an aluminium metal foam (AMF) with PCM passive cooling technique. Two modules are used in the outdoor experiments: PV unaltered and PV combined with AMF integrated into PCM (referred to as PCM/PV/AMF) as shown in Figure 7.

Data on the PCM temperature and the distribution of PV panel surface temperatures during the winter, the voltage in open circuit, and the power output generated were collected.

The PV-PCM/AFM system produced power which was 1.85%, 3.38%, and 4.14% greater than compared to conventional photovoltaic in January, February, and December, respectively. The photovoltaic surface temperature was also 4.0%, 7.4%, and 13.2% less than conventional photovoltaic of traditional PV, respectively.

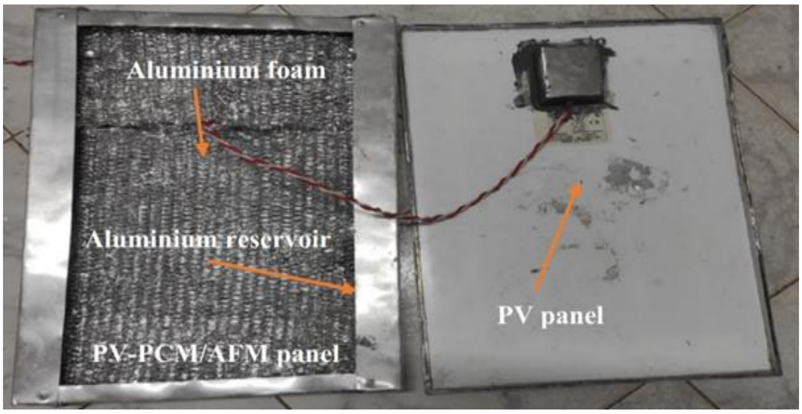



**Fig. 7.** A photograph showing the improved PV-PCM/AFM module

Conducted tests in Coimbatore, Tamilnadu in February by Kumar *et al.,* [39], where the photovoltaic panel, the PCM, the cell's angle, and the experiment's duration were set. For two continuous hours, they recorded the speed of the wind, the temperature, current production, and voltage each 15 minutes. The panel was also connected in series with a variable resistance load to measure its output voltage and current. The voltmeter and ampere meter were both connected in parallel with the loads and the panel, respectively. Every time the resistive load was changed, the current-voltage curve was measured, and the peak power point was determined. The file includes references to other research studies that utilized comparable methods and more information on this work method more information on this way of work.

When used as usual, PV panels' electrical performance increased by average of 2.8%, and when used as a mixed phase change material, it increased by an average of 4.3% as shown in Figure 8.

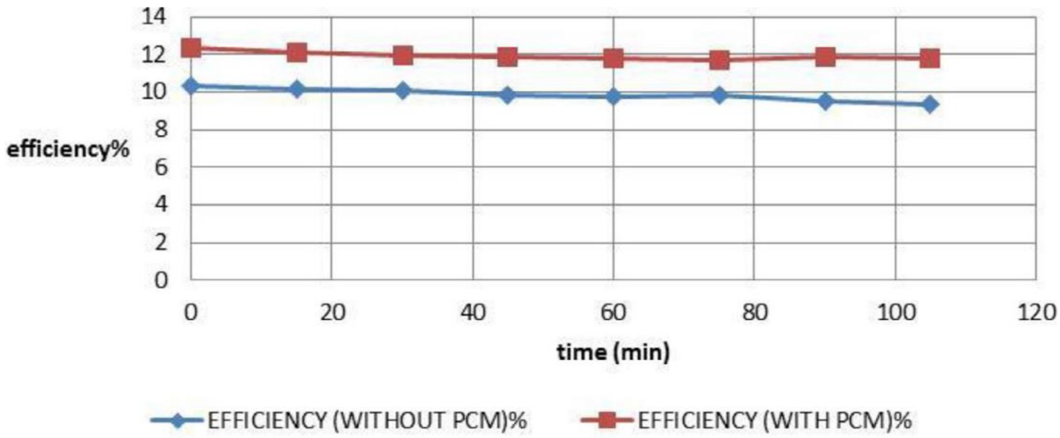



**Fig. 8.** Efficiency variation for the reference as well as improved cases using mixed PCM as an indicator of time

Bayrak *et al.,* [40] experimented with various cooling techniques, including PCM, TE, as well as aluminium fins, to compare the output, temperature, and performance of PV panels. PV panel output power and surface temperatures were measured under various cooling conditions, and the results were analyzed to ascertain which cooling technique was most efficient at lowering surface temperatures and raising output power. $CaCl_2.6H_2O$ is one of the PCMs most frequently used in photovoltaic cooling, and the other has a melting temperature greater than the surface of the photovoltaic panel. utilizing various layouts for the aluminium fins and various TE material counts [6,8,11]. The findings demonstrated that TE alone can achieve resistance to load of thermal electricity (TE) cooling to maximum power. The study also discovered that using the wrong type of material for phase change (PCM) can insulate solar panels, raising panel temperatures and reducing output power. The study also compared the efficiency of various cooling techniques in lowering surface temperatures and raising output power. When it came to lowering surface temperatures and boosting output power, the researchers discovered that using PCM, TE, as well as aluminium fins all had a beneficial effect. However, the results varied depending on the particular cooling technique employed.

Utilizing the software TRNSYS, work is focused on experimental as well as simulations of heat extraction from a PV cell as shown in Figure 9 [41]. A PCM- RT28HC was added to a modified Canadian Solar CS6P-M PV cell. A PV cell's temperatures with and with no PCM were measured and contrasted. The TRNSYS software was used to simulate both PV cells, and the outcomes were compared to simulations and actual experimental data.

The PV cell without PCM's surface reached a difference in temperature of 35.6 C over the course of one day, which was higher than that of cell with phase change material. Output of PV-PCM panels for the town of Ljubljana raised by 7.3% over the course of a year, according to the simulation results.

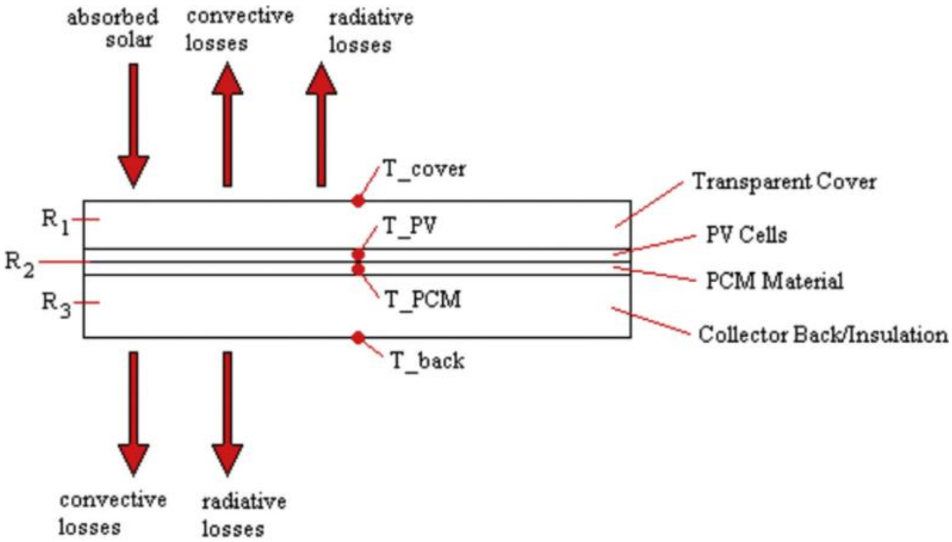



**Fig. 9.** PV-PCM cell configuration

### *2.2 Active Cooling*

The assessment in Gad's *et al.,* [42] work is based on 4E approaches: exergetic, economic, energetic, and environmental. Through the use of MATLAB software, an entire transient mathematical structure is built and solved numerically. Utilizing two PCMs (x nbv1 and SP15-gel, respectively), hybrid cooling system's effectiveness during the winter and the summer has been investigated. Information is based on weather in Egypt. Utilizing hybrid nanoparticles, Performance-wise, the HP-PCM system for cooling outperforms traditional solar cell cooling. Additionally, the energy efficiency of photovoltaic cells is greater compared to that of PCM. Compared to conventional PV cells, cell's operating temperature compared to conventional PV cells, operating temperature in the PV cell decreased by 20.9 °C and 18.3 °C, respectively, while the efficiency of the cell rose by 11.5% and 9%. In comparison to the conventional cell systems utilizing SP31 and SP15-gel, which achieve daily energy efficiencies of 8.77% and 7.84%, the suggested cooling method using hybrid nanoparticles achieves the greatest daily efficiency of energy, about 56.45% and 54.45%, respectively. Said *et al.,* [43] introduces and carefully assesses a hybrid of both active and passive mist cooling. Based on their availability, sustainability, and stability in nature, coconut husk and paraffin wax were selected as the PCM and passive cooling materials, respectively. First, coconut husk and paraffin wax are combined and applied to the back for the cell. When the ambient temperature is 41.59 °C and the average irradiance is 752 $W/m^2$, the average temperature of the cell's surface can rise to 62.57 °C, with a maximum of 67.37 °C. When the ambient temperature is 41.59 °C and the average irradiance is 752 $W/m^2$, the average temperature of the cell's surface can rise to 62.57 °C, with a maximum of 67.37 °C. The back surface of the PV cell thickens, increasing the temperatures on the front and back surfaces by 2.07% and 0.33%, respectively.

Using mixed cooling and heat storage systems, a hybrid method is created to maximize the energy derived from sunlight [44]. The suggested system combines Nanofluids as an operational fluid as well as a PCM to heat storage by a small device. In addition to using phase change material (paraffin wax RT35) as a cooling fluid, it also looks at the effects of using a nanofluid technology ($Al_2O_3$-water) as a coolant. Coolant systems are evaluated for pure water as well as pure water with the addition of PCM, starting with pure water flow rates of 0.8, 1.2, and 1.6 l/min. The effects of using Nanofluid ($Al_2O_3$-water) at the weight percentages (0.05, 0.1, 0.2, 0.3, and 0.4) % as well as adding PCM at various weight fractions to the cooling Nanofluid circulation system on the performance of the photovoltaic module are then investigated.

The coolant Nanofluid ($Al_2O_3$-water) and paraffin wax RT35 should be combined at a dosage of 0.4% weight fraction and a flow rate of 1.6 l/min for the cooling mechanism to function optimally. It results in a decrease in photovoltaic temperature of 8.39 and 12.11 °C on average and the highest value throughout the entire day, respectively, when compared to the reference PV cell. Additionally, it results in an increase in photovoltaic module-generated electricity by 25.33% and 37.81%, respectively, with the highest value throughout the day.

In an indoor solar simulator with radiation ranging from 800 to 1700 W/m$^2$ (regular to concentrated), all tests are carried out [45]. Although PCM is used as a passive coolant system, it is inserted into a special heat-conductive foam (PS-CNT foam) to prevent malfunction caused by its poor thermal conductivity as shown in Figure 10.

The electrical productivity can be improved by up to 14.0% while PV-cell temperature can be decreased by up to 6.8% using PCM composite. Separately, the active cooling is evaluated by 0.3 to 1 litre per minute water flow through the cooling block mounted below the PVT. Because of effective thermal energy as well as power generation harvesting, efficiency of the active cooling technique is significantly higher than that of passive PVT systems.

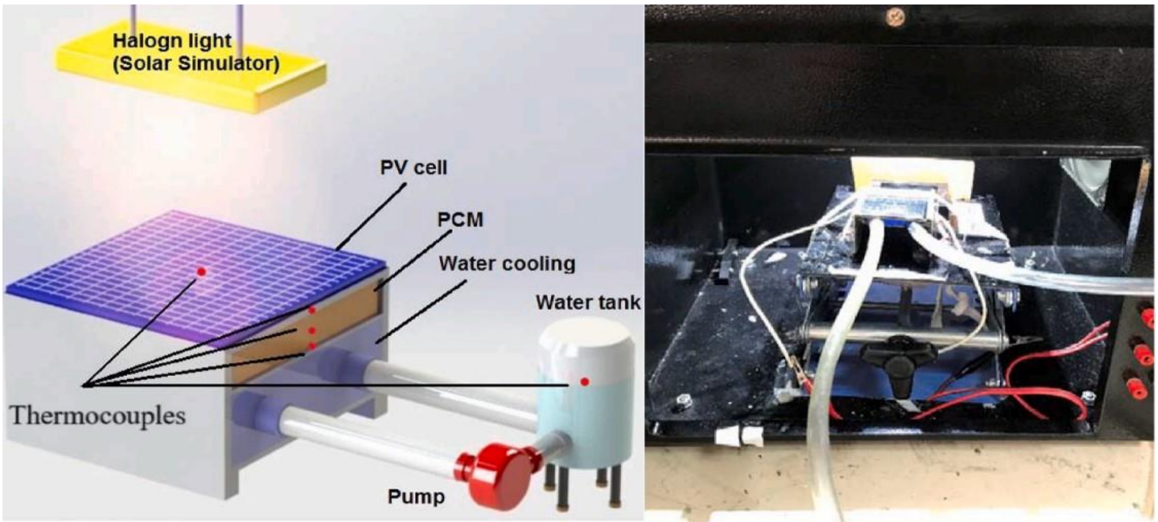



**Fig. 10.** PVT active cooling experimental test facility

In this work, Darkwa *et al.,* [46] develops a numerical model for thermal simulations of integrated PV/ PCM / TEG systems and uses it to evaluate system's power output and efficiency. To determine the model's dependability for upcoming projects, experimental data is used to validate it. Comparing system's performance to that of standard PV as well as PV/TEG devices and analyzing various cooling tactics as shown in Figure 11.

During the first 1.5 hours, the combined PV/TEG/PCM system produced approximately 9.5% more energy than standard photovoltaic as well as PV/TEG systems. Performance was enhanced as a result of the PCM layer's assistance in reducing the temperature gradient across the TEG. Different cooling strategies had varying effects on the system's performance, with forced convection modes of cooling being more effective than natural convection modes. To further enhance the system's thermal performance, future research should focus on system optimization, future research should focus on improving conductivity, thickness, and phase shift temperature of PCM layer. Further research is required to assess integrated PV/TEG/PCM system's long-term reliability and stability under various environmental conditions. Finally, to achieve the best thermal performance of the PV/TEG/PCM system, a 50 mm thick PCM layer with a thermal conductivity of 5 W/mK and a changing stage temperature of 40-45 °C was used.

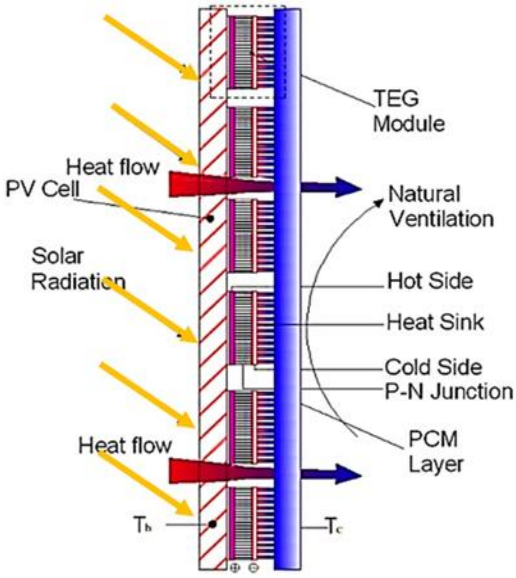



**Fig. 11.** PV-TEG-PCM system's physical arrangement

Use of a novel PCM material, sheep fat, for potential PV thermal management efficiency by Siahkamari *et al.,* [47]. The article also makes reference to an investigation into various techniques for utilizing PCMs within PV/T and photovoltaic systems to enhance performance, demonstrating that doing so is an effective way to cool solar panels. In chamber during the back of photovoltaic cell, copper microchannel tubes flowing through cold water cold water passing by them are used to postpone the PCM material's melting. as shown in Figure 12. The experiments began with sheep fat. Second, CuO nanoparticles (0.004 (w/v)) have been added to improve the cooling efficiency of the sheep fat. Nanoparticles of CuO (0.004 (w/v)) were added to improve the cooling efficiency of sheep fat. The results of the traditional PCM layout with paraffin wax were compared to those of pure sheep fat and sheep fat+CuO nanoparticles. Although both PCM (paraffin wax and sheep fat) can improve the cooling efficiency of the PV module under consideration, sheep fat is more effective. Furthermore, comparing the greatest electrical energy generated to paraffin wax cooling cell and no-cooling cell using sheep fat+CuO nanoparticles reveals increases in highest electrical power produced of 5.3% to 12% and 24.6% to 26.2%, respectively.

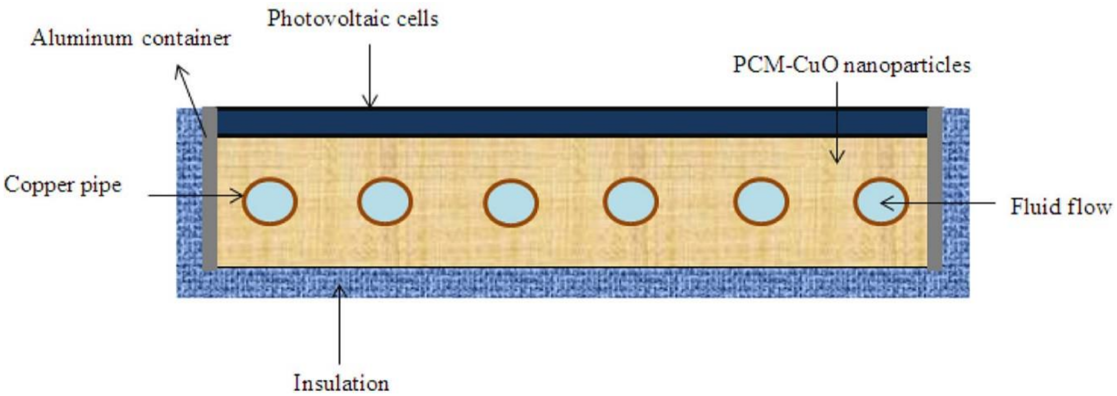



**Fig. 12.** PV cell cross-section with PCM-CuO nanoparticles surrounding the copper microchannel tubes

Nasef *et al.,* [48] developed and simulated a solar photovoltaic (CPV) system's thermal control using a mix of both passive and active cooling systems as shown in Figure 13. A closed-circuit water-cooled technology and PCM thermal storage are combined in developed design.

A two-dimensional model of the CPV multiple layers in a combined system of cooling was created. When compared to conventional direct PCM-PV and water-cooling separate systems, the proposed system achieves a 60% reduction in CPV average temperature. The cell the temperature is still below 78 °C in the presence of 10 concentration ratios (CR) and 0.01 m/s HTF speed. Furthermore, the maximum temperature of the PCM remains below the decline temperature limit. When nanofluid is used as an HTF enhancer, CPV efficiency increases by 2.7%, and the PV's maximum temperature and PCM melting time both decrease by 4 °C and 12%, respectively.

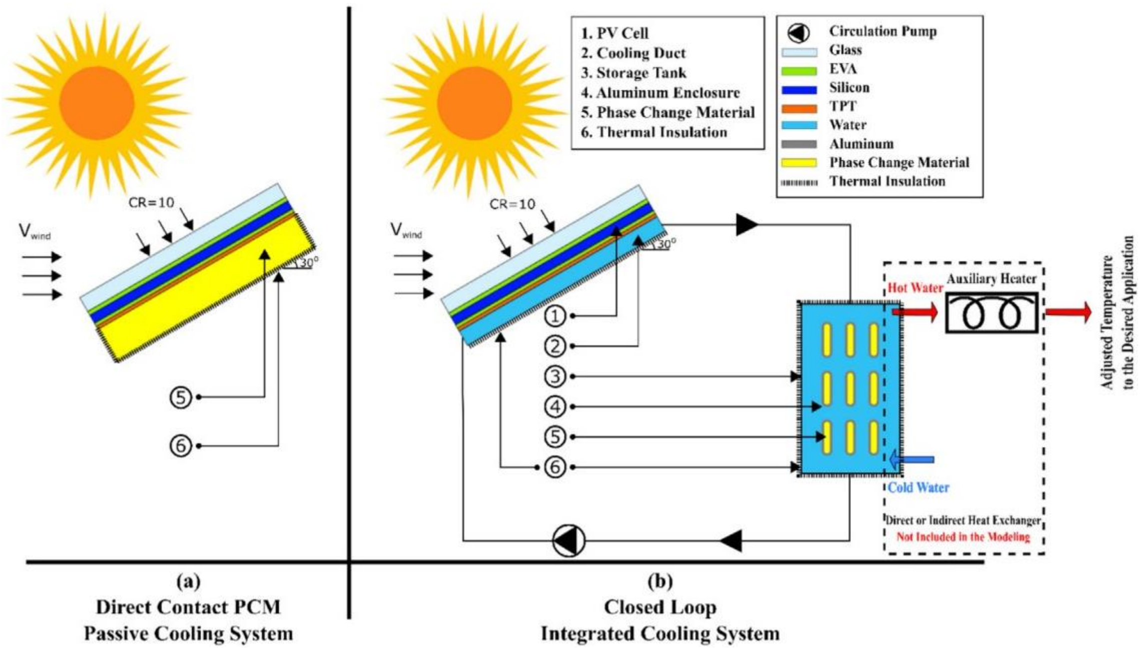



**Fig. 13.** Physical Models for Systems with Indirect PCM-Water Loop and Direct Contact PCM

The reason for cooling photovoltaic cells with phase change materials (PCMs) is to improve the efficiency of photovoltaic panels by reducing their temperature. The use of PCMs as a cooling medium has been explored in several studies. PCMs have the ability to store and release thermal energy, making them suitable for cooling PV panels. Different types of PCMs, such as nanofluids, air, and nano-enhanced PCMs, have been investigated for their cooling properties. Experiments conducted at various sites have shown that PCMs can effectively reduce the temperature of PV panels, leading to an increase in their electrical efficiency. It has been observed that the cooling effect of PCM modules on PV panels reduces the average temperature of the panels and increases their efficiency in power generation. Using PCM-based cooling systems can help maintain low module temperatures and maximize the conversion efficiency of PV panels.

## 3. Conclusions

Phase change materials (PCMs) have been subject of extensive research recent years with goal of creating more effective cooling solutions for photovoltaic (PV) modules. Due to its high the latent heat capacities and capacity to store and release thermal energy during phase transitions, PCMs have special thermal properties that make them suitable for use in cooling systems.

According to research, PCMs can be used in a number of ways to improve performance of photovoltaic cells, including as a coating that is directly applied to the modules' surfaces, a heat exchanger that is in contact with the modules' backs, or an integrated part of the module itself.

One recent advancement in field of PCM-based cooling for photovoltaic cells is hybrid cooling systems development that combines PCMs with other cooling methods, such as air or water cooling. These hybrid systems have been shown to significantly improve the temperature stability and efficiency of PV modules compared to single PCM-based systems.

Inorganic salts are one type of PCM that has shown promise in cooling PV modules due to their high melting points and thermal stability. PV cell cooling systems that are both passive as well as active can use PCMs like paraffin wax, also, can be incorporated into building materials or coatings, or used in standalone cooling systems. Choice of Phase change materials depends on specific application requirements, such as the temperature for a phase change and thermal stability.

However, researchers have also shown that the use of these types of materials can have negative environmental and social impacts if not properly managed.

There is still much research that needs to be done in the field of PCM-based cooling for PV modules, particularly in optimizing the selection and application of PCMs, as well as in developing more efficient and cost-effective hybrid cooling systems. However, the potential benefits of using PCM-based cooling for PV modules are clear, and future work in this field has potential to significantly improve the effectiveness and functionality of photovoltaic systems.

Overall, cooling photovoltaic panels using PCMs can have number of benefits: They absorb a significant amount of thermal energy when they change from a solid to a liquid or from a liquid to a gas. Preventing the cells from overheating. Improve the PV cell’s performance and prolong its lifespan. Can be applied to passive as well as active cooling systems. The use of PCMs in cooling photovoltaic cells can help reduce energy consumption and provide renewable energy sources. PCMs have a high thermal conductivity, a sharp point of melting, and a high volumetric thermal latent storage capacity. It is also non-flammable and sustainable. The use of PCMs may also be able to lessen the problem of erratic energy supply. PCMs can help balance the supply and demand of energy, particularly as renewable energy sources become more prevalent. Zero costs for maintenance.

However, there are also some limitations or disadvantages to consider when using PCMs: The installation cost is high. It can be challenging to stop incongruent melted and separation of phases during cycling, which can cause a sizable loss of the latent heat enthalpy. When the PCM has undergone several cycles, this can be especially problematic. The selection of phase change material is based on requirements for the particular application, such as the necessary phase change temperature and thermal stability. This may restrict the variety of PCMs that can be used for PV cooling. The effectiveness of PCM-based cooling systems can be impacted by factors such as external temperature and insulation.

Based on the available research, some recommendations for the use of PCMs in PV cooling include:

(i) Choose a PCM that has a suitable phase change temperature for the specific application and is stable over multiple cycles.
(ii) Incorporate the PCM into an effective cooling system that takes into account external temperatures, insulation and other relevant factors.
(iii) Consider the cost-effectiveness of using PCM-based cooling systems compared to traditional air or liquid cooling systems.
(iv) Continue to research and develop new PCM-based cooling systems that are more stable, have higher thermal conductivity and are effective in a wider range of temperatures.
(v) Overall, use of phase change materials in cooling of photovoltaic cells has the potential to provide significant benefits in terms of improved energy efficiency and sustainability. Specific application requirements and technological limitations should, however, be carefully taken into account.

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