RESEARCH ARTICLE | DECEMBER 22 2023

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AIP Conf. Proc. 2977, 020021 (2023)
https://doi.org/10.1063/5.0182015

Performance Improvement of the Solar PV System-Based Phase Change Material: A Review

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Abstract. The use of photovoltaic (PV) energy has made great advances in recent years toward satisfying the world's increasing energy demand. Since a large fraction of the solar radiation that falls on photovoltaic cells is converted to heat, there are still significant obstacles to overcome in the design and installation of solar systems. Especially in regions where the average annual temperature is extremely high, it is crucial to maintain a constant temperature for the solar photovoltaics to maximize their effectiveness. Findings indicate that phase change materials (PCMs) have a strong potential for cooling solar cells. In this work, we assess a number of previous studies related to the use of phase change material in photovoltaic modules for temperature control and power increase.

Keywords. photovoltaic, PCMs, solar radiation, PV cooling, efficiency

INTRODUCTION

Energy consumption is a main factor in a nation's economic development. Energy use is expected to grow by 33% in 2030 compared to 2010 [1], [2]. Normally, fuel-fired power plants produce 67% of the nation's electricity, and their dangerous pollution wastes contribute to global warming [3]. Therefore, the included renewable energy sources (RESs) are the finest choice to satisfy the predicted massive rise in energy demand in power systems [4]. One of the widely available, highly efficient, and well-known renewable energy sources is photovoltaic (PV) systems [5]–[8]. The PV was invented for the first time at Bell Labs in 1953, employing semiconductors to turn sunlight into electrical power [9]. Solar energy's main advantage is its simplicity of installation, quietness, cleanliness, and renewable nature. Irradiance, temperature, dust, shading, and the type of PV panel are only a few of the important factors that affect how much power the PV panels generate [10]. The dependence of the PV system on the atmospheric conditions will decrease the efficiency; therefore, to get the highest output power from the PV panel, the PV must operate at a specific point for each irradiance and temperature; this point is known as the maximum power point (MPP). MPP can be obtained in several ways. Conventional and advanced MPP algorithms include perturb and observe, incremental resistance, fuzzy logic, and artificial neural networks (ANN)[11]. A significant amount of the solar radiation falling on photovoltaic cells is converted to heat. The efficiency of a photovoltaic panel decreases as temperature rises, depending on the type of solar cell used. Temperature control is now required to improve solar photovoltaic efficiency, particularly in Iraq, where ambient temperatures are exceptionally high. Reducing the PV panel's temperature in hot ambient conditions will significantly prevent the overheating of PV cells, enhance the output power, and increase the lifespan of the PV panel [12]. The purpose of the current research is to investigate the workings of the PV system, how temperature affects electrical efficiency, and get a better understanding of PV-phase change material (PCM) cooling technology, including its significant successes and ongoing troubles.

4th International Scientific Conference of Alkafeel University (ISCKU 2022)
AIP Conf. Proc. 2977, 020021-1–020021-12; https://doi.org/10.1063/5.0182015
Published by AIP Publishing. 978-0-7354-4776-9/$30.00

PV SYSTEMS OPERATION PRINCIPLES

The conversion of solar energy into electrical energy is based on a phenomenon called the photovoltaic effect. The PV panel is made up of a number of solar cells, which are the basic unit of the system. A solar cell is made up of layers of semiconductor material like crystal silicon, which is the most widespread [13]. The photovoltaic effect depends on incident solar radiation; when semiconductor material is exposed to light, some of the photons are collected by the semiconductor, resulting in a large number of free electrons in it. This is the primary reason for producing electricity due to the photovoltaic effect [14]. **FIGURE 1.** depicts the most commonly used module of a single solar cell, a single diode with a shunt resistance followed by series resistance used to represent the circuit model [15], [16]. The electrical module of PV cells can be represented with five elements, including diode constants (I_0, v_t), photocurrent (I_{ph}), series resistance (R_s), and shunt resistance (R_p). So, the output current of the cell model is stated as follows: [17]

$$I = Ipv - Io\left[\exp\left(\frac{V + IRs}{aVt}\right) - 1\right] - \frac{V + IRs}{Rp} \qquad (1)$$

Where: $$Vt = \frac{Ns.KT}{q} \qquad (2)$$

$$Ipv = (Ipv,n + KI\Delta T)\frac{G}{Gn} \qquad (3)$$

$$Io = \frac{Isc,n + KI\Delta T}{Exp\left(Voc,n + {}^{Kv\Delta T}/_{aVt,n}\right) - 1} \qquad (4)$$

Where : Ipv : represents the solar panel generating current[A], Io : represents the saturation current of the diode [A], Vt : the ideal unit cell thermal voltage [V], a : represents diode quality factor(1~1.5), k : represents Boltzmann's constant(1.381×10-23) [J/K], T : represents kelvin temperature at STC, q : represents charge of the electron(1.602×10-19) [C] , ns : represents number of PV cells connected in series, Rsh : represents cell parallel(shunt) resistance [Ω], Rs : represents cell series resistance [Ω], G : is the irradiation on the device surface (watts per square meters), Gn : is the nominal irradiation, ΔT = T-Tn (T , Tn) represents actual and nominal temperatures [Kelvin], Ipv,n : represents the generated light current under the STC (25 ◦C and 1000 W/m2) [A]

TEMPERATURE EFFECT ON PV SYSTEMS

High ambient temperature (T_{am}) during summer months will cause increasing the PV panel temperature (T_{PV}) [18], [19]. According to the supplier datasheets, the panel efficiency drops by around 0.45% for every 1 ºC increase in (T_{PV}) over the standard test condition (STC), as shown by equation (5) [20] One of the elements that effect on energy conversion is the surface temperature of the solar panel. High surface and ambient temperatures cause panels to overheat, which actually reduces efficiency and power output. The links between the power output, electrical efficiency, and temperatures of PV panels can be determined using equations (5, 6, and 7). [21]

$$\eta PV = [1 - (Tpv - Tstc)] \qquad (5)$$

$$Ppv = Ppv,n \cdot fpv\left(\frac{GT}{GT,STC}\right) \times [1 + \beta r(Tpv - Tpv,STC)] \qquad (6)$$

$$\eta PV = \eta T,STC\left[\gamma \cdot log10(GT) + \left(1 - \beta r \cdot (Tpv - T,STC)\right)\right] \qquad (7)$$

Where: γ : is the coefficient of solar irradiation intensity for PV panel [22], [23] , β_r: is the efficiency of a panel in (%/ºC), and it usually about 0.004 to 0.005/ ºC [24]. As demonstrated in **(Fig. 2)**, when the ambient temperature of the panels is raised over 25 °C, the ($\boldsymbol{V_{OC}}$) greatly decreases and the ($\boldsymbol{I_{SC}}$) significantly increases. This is caused by the saturation current's ($\boldsymbol{I_{sat}}$) exponential dependence on temperature, which leads to increase in ($\boldsymbol{I_{SC}}$) [25]. The ability to generate power is directly influenced by the temperature of the panels, which is controlled by the temperature coefficient. The percentage of temperature coefficient represents the increase in power output when the temperature rises or falls in relation to (STC) of 25°C. In light of everything said above, it is crucial to extract heat from the PV by using appropriate cooling technologies in order to reduce the effects of cell temperature and control the working temperature.

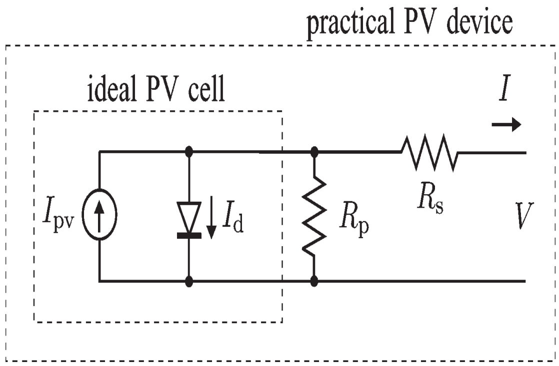

FIGURE 1. Equivalent circuit for one photovoltaic [17]

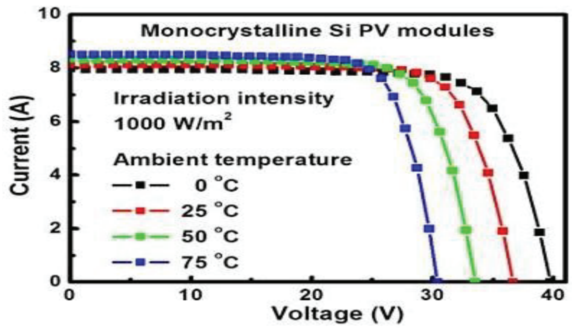

FIGURE 2. Current and voltage characteristics [25].

PV SYSTEMS COOLING PRINCIPLES

Even if the specified working conditions (25 °C and 1000 W/m2) can't be met, the temperature needs to stay as low as possible. Therefore, thermal regulation is essential to maintaining the PV modules' maximum level of efficiency. Thermal regulation can be done through several PV module cooling methods. These cooling methods include using air, liquid, thermoelectric, heat pipes, phase change materials, and a number of other special cooling methods. PV module cooling methods of can be classified as active or passive [26], [27].

Active PV Cooling Techniques

Active methods involve actively removing the heat by cycling air or water through them. A heat-transfer fluid, like air or water, is pumped around the PV panel in order to dissipate the heat that is produced by it. For cooling purposes, pumps or blowers are used in active heat removal systems to continuously circulate thermal transfer fluid across the front and rear of the PV panel [28], [29]. When comparing passive and active systems, it is clear that active heat removal systems are more effective at removing excessive heat from the PV panel, resulting in improved PV panel efficiency. *The main problems with active methods, however, are the high costs of system maintenance and additional power requirements* [30].

Passive PV Cooling Techniques

Using passive cooling methods has many benefits, the most notable being that they do not necessitate any external energy for operation and have either no or extremely minimal maintenance costs. Cause the need of pumps or blowers to circulate the heat transfer fluid through the PV panel is unnecessary in passive cooling systems, as the fluid is cooled through natural mechanisms of heat transfer. When it comes to keeping PV panels cool, a wide range of passive cooling methods have been described. Typical methods of cooling include air cooling and water cooling, with conductive passive cooling being the simplest. [31], [32]

PV SYSTEMS COOLING METHODS

The most popular cooling techniques for achieving PV thermal regulation include using air, hydraulics, forced or natural circulation, and the implementation of phase change material (PCM) [33], [34]. The sections that follow provide more information on PV system thermal regulation techniques.

Air Cooling

The most efficient and cost-effective method of cooling solar panels would be through forced or natural airflow, which are known as passive and active cooling, respectively. Depending on the installation site, forced convection, which is often created by fans or blowers, may be continuous or intermittent [35]. The main disadvantages of this simple PV cooling technology are the poor heat transfer rate in passive mode and the need for additional power, which reduces system efficiency in active mode.

Water Cooling

Water has a better thermal-physical characteristic with a higher specific heat than air, so it can naturally cool PV modules more effectively. Like air cooling, water cooling can either be active or passive. One of the few studies on passive water cooling suggested using steam that would expand in response to solar radiation in a small container for rainwater to push the water to flow over PV modules as a natural method to cool them [36]. Multiple studies on active water cooling have produced numerical models with associated practical testing that represent various aspects of water-cooling technology [37]–[39]. Vera et al. [40] was one of them who produced the multi-objective optimization model of the water-cooling system. His mathematical model shows an energy balance between the PV system and the surrounding environment along with appropriate energy generation, with the possibility to integrate additional PV system layers as needed. This model aids in the prediction of the ideal coolant mass flow rate for achieving maximum efficiency under a given ambient condition. To lower the PV module temperature and increase system efficiency, some researchers recommended immersing the PV module in water up to a particular depth. But just because the water is conductive, it ionizes and reduces electrical efficiency, and after using de-ionized water as an alternative, it will reduce thermal stress. [41]–[44].

Thermoelectric Cooling

The Peltier effect, which asserts that an electric current passing through two conductors will produce either a heating or cooling effect, is the base for thermoelectric cooling (TEC). When two dissimilar materials have a voltage applied to their free ends, a temperature difference is produced. This temperature differential allows Peltier cooling to transfer heat from the warmer to the cooler section. When it comes to cooling electronic components like microprocessors, thermoelectric cooling is a well-known phenomenon. This strategy has also been tested using PV cooling. In their study, Najafi and Woodbury [45] reported on a simulated model of TEC that effectively maintains a low temperature in the PV module while using an economically viable quantity of energy. Cui et al. [46] presented unique thermoelectric cooling facility linked with PCM for cooling concentrator photovoltaic (CPV) systems.

Heat Pipe Cooling

An example of passive cooling system designs. To enhance the rate of thermal transfer between two solid surfaces, heat pipes combine thermal conductivity and phase transition. When a liquid comes into contact with the hot side of the heat pipe, it evaporates due to the temperature difference between the two surfaces. The steam then travels through the heat pipe to the cold point, where it condenses back into a liquid and transfers its latent heat. Heat pipe cooling technology is used in PV cooling, and concentrator PVs (CPV) has seen the most success with this technique.[47]–[50]

Special Cooling Methods

Some of the recent papers discussed non-conventional but still effective strategies for thermal regulation, including using natural vaporization, evaporative cooling for hybrid roof panels, PV thermal regulation through radiative cooling [51]–[54], simple water jet impingement [55], hybrid micro channel water jet impingement [56], and a heat spreader, which is a passive cooling method employed for (CPVs) [57].

PCM-Based Cooling

Researchers are becoming more interested in PCM-based cooling systems because PCM can absorb the extra heat produced by PV panel without the need for a heat transfer fluid or any external energy. PCM store heat energy as latent heat as they go through the process of changing their phase within a small temperature window. High-quality energy sources can be preserved through heat energy storage, particularly in systems in which heat is dissipated as part of the operating cycle processes, such as photovoltaic panels. Long-term uses also require a high-capacity energy storage system. The reduced size and increased heat storage capacity of PCMs make them an attractive option for addressing both of these issues. In comparison to water, concrete, or rock, those materials may absorb energy 5–14 times more for each volume unit. [58]. This section provides a summary of recent literature discussing the areas of current study about PCM's capability for PV cooling, focusing on their limitations, and outlining potential future areas of improvement for this technique.

PV/PCM Working Principles

To lower the panel surface temperature and enhance system performance, PV panels with a PCM for cooling use a hybrid technique in which the PCM and panel are merged into a single unit. A PV panel and a PCM that are enclosed in the proper capsule material and attached to the PV panel's back side make up the combined unit. Particularly during the warm hours when the PV panels' surface temperature is higher than the PCM melting point, the PCM stores the heat that has gathered in the PV panels. The PCM will absorb the extra heat produced by the PV panels without any external energy, keeping their temperature close to the melting point of the PCM, which causes the PCM to start transitioning from a solid form to a liquid form. The PCM keeps soaking up heat from the PV panels until it turns into a liquid. The molten PCM is solidified once the temperature of the panel's surface falls below that of the PCM's melting point. The PCM goes back to its solid form when the extra heat is released into the surrounding space. The PCM solidification process occurs when the solar panels are not receiving any solar radiation during the hours when it is not sunny. Without using any power from the PV panels, the panels are passively cooled and increasing the efficiency of energy conversion [59], [60].

PCMs Classification

Typically, PCMs can be classified into three categories organic chemicals, inorganic compounds, and eutectic mixtures [61]. The melting point, latent heat, and thermal conductivity of these PCM compounds vary, making them useful in a variety of applications. It's important for a PCM to be chemically stable, non-toxic, economical, and corrosion-free [62]. Because of the organic PCMs do not react with the PCM - encased material, no leaking issues, low level of sub cooling, and do not degrade, they are preferred against inorganic PCMs. One major drawback of employing organic PCMs is their low thermal conductivity (0.1-0.2 W/m-K). Lower thermal conductivity requires the employment of heat transfer optimization technologies to provide desired outcomes [63]. The high heat conductivity of inorganic PCMs has not made them a popular choice for study in the PV/PCM field. Due to its toxic properties and sub cooling which it may react with its encapsulation and leak from the containers, inorganic PCM has seen limited application for PV cooling. Solar cells may be damaged when leaked PCM reacts with the PV panel. There has been wide acceptance of using the commercially available organic PCMs for cooling PV panels**.** Low thermal conductivity organic PCMs were shown to be potentially useful in less sunny areas and for operating PV panels at low surface temperatures. While PV systems operating in high solar irradiance conditions can benefit from the superior performance of inorganic PCMs with improved thermal conductivity, such as slat hydrates [64]. It has also been noted drawback of organic PCMs, which have a poor thermal conductivity, may need a capsulation material with a high thermal conductivity, which can be pricey. While inorganic PCMs need a high degree of subcooling [65]. **Table 1** offers a summary of the benefits and drawbacks of the basic PCM kinds.

TABLE 1 Comparison among eutectics and organic and inorganic PCMs. [66]

Types	Eutectics	Organics	Inorganics
Advantages	Large temperature range for phase changes Excellent thermal and chemical stability Large thermal storage capacity Little or none sub-cooling.	No sub-cooling. Good thermal and chemical stabilization. No corrosives Extreme heat fusion Reduced vapor pressure. Not poisonous.	Extreme heat fusion. Cheap. Not burning. Excellent thermal conductivity
Disadvantages	Poor thermal conductivity Leaks while the phase changes.	Poor thermal conductivity Lower in phase change enthalpy. Large volume change during transition	Need sub-cooling Corrosion and high weight Phase separation. Poor thermal stability.

This research has been classified a number of previous studies related to PCM-based procedure to regulate PV panels temperature and focused on advantages and disadvantages of using this type of cooling in PV systems as shown in **Table 2.**

TABLE 2 Practical and theoretical studies related to PCM-based cooling systems.

	Research	Evaluation Method	Pros	Cons
1	Studied a system with external metallic fins. [29]	Used external metallic fins	Increase PV panel's overall efficiency by 12.8% and decrease the peak temperature from 77.5°C to 61 °C	
2	Improved concentrating PV thermoelectric system (CPV-TE) performance [46]	Used PCM in (CPV-TE)	PCMs are a feasible option for the thermal management of the (CPV-TE) system.	
3	Experimental study on the impact of PCM thermal characteristics. [64]	Use five different PCMs with melting temp of 25 ± 4 °C	While PCMs with a high melting point and thermal conductivity perform better at higher temperatures, those with a lower one performs better at lower temperatures.	
4	Presented the first experimental evaluation of PCMs used in integrated photovoltaics.[67]	On the surface of an aluminum box, a solar absorbent substance was used.	Maintain the PV surface working temperature at 25 °C.	
5	A study on a PV/PCM system with a couple of PCMs that have different phase change temps. [68]	Triangle and half circle chambers, and five PCM combinations	Achieve uniform temperature distribution in PV modules due to the newly designed PCM block	
6	Creating 2-D and 3-D models of the PV/PCM system. [69]–[71]	Used aluminum plates, PCM, and internal fins	Dispersion of heat from the front surface. Decrease the duration of thermal regulation	Metal fins increased the system's weight
7	Investigated how a PV/PCM systems in buildings are affected by crystal segregation and convection. [72]	Test the PV/PCM system with three PCMs and fins with different spacing.	To heat a PV system to 42 °C, it would take 250 minutes without a fin. And when using it would reduce the rate of temperature rise	
8	PCMs for thermal control of PVs using differential scanning calorimetry (DSC) and the temperature history method (THM). [73]	Five PCMs of paraffin, eutectic fatty acid mix, and salt hydrate in different forms	Because it has a melting point that is closer to the PV working temperature and a high fusion heat, capric palmitic acids are the ideal choice for PV/PCM systems.	
9	Study microencapsulated PCM (MEPCM) numerically for the summer and winter seasons. [74], [75]	Used (MEPCM) in plastic pouches	The summer and winter seasons showed improvements in PV efficiency of 0.13% and 0.42%, respectively.	
10	A computational and experimental investigation on PCM's ability to lower PV panel peak temp. [76]	Used an algorithm to determine the PV/PCM system's energy balance.	Optimizing system performance requires better heat contact between PV back and PCM. In a PV/PCM system, the excess heat is primarily dissipated during the night.	

TABLE 2 Practical and theoretical studies related to PCM-based cooling systems.

	Research	Evaluation Method	Pros	Cons
11	Study the energy economy of the PV/PCM system for hot and cooler climatic conditions. [77]	Eutectic and salt hydrate PCMs with aluminum fins	Both PCMs increase PV power by 11% and 13% in hot temps and by 4% and 5% in colder climates. PV/PCM hybrids are cost-effective in Vehari, Pakistan.	This system isn't great in cool places like Dublin, Ireland.
12	Investigate the PV/PCM system in Malaysia's hot climate. [78]	PV/PCM system	PV/PCM working temperatures can approach ambient temperature.	
13	PCM effect on the vertical PV system in South Korea's climate. [79]	PV with more PCM thickness	PCM improved energy efficiency by 3%, more heat absorbed, longer duration of PV temperature regulation.	Overall system weight and cost increased.
14	Presented a PV/PCM system's thermal model to anticipate its changing temp profile. [80]	Low melting point (RT-27) PCM (26 °C) was used.	The PV/PCM system's finite difference model successfully estimated module temperature on clear and cloudy days.	
15	The practicality of using PCM in the UAE's hot and dry climate.[81]	Four different PV cell sizes with solid-liquid PCMs	By adding PCMs on cloudy days, reduce the high temp by 5°C, and on sunny days, by 11°C, and boost the panel voltage to 1.7V.	
16	Heat and mass transfer in an impure PCM-based system are described using computational fluid dynamics (CFD).[82]	SP/PCM with cooling fins was used in five different sizes.	Kept the panel temperature below 34.9 °C for an hour and increased the PCM width rather than height to increase performance.	When PCM melts the working temp rises dramatically
17	Experimental research was conducted in the medium climate of Utrecht (Netherlands) and the hot climate of Malaga (Spain).[83]	PV/PCM system with numerical model in Math Works MATLAB 2009a	PV/PCM systems provide the same amount of energy in both medium and hot regions in the summer, but more in the winter for hot regions. Lower heat absorber factor values led to better PV/PCM energy gains.	
18	Studied a PV module combined with a PCM heat storage device in a hot environment.[84]	Used COMSOL Multiphysics	The PV system without PCM had a conversion efficiency of 12%, but with PCM, it was 26%.	
19	PCM was presented in a hybrid (CPV-TE) system.[85]	Hybrid (CPV-TE) system	High-quality cold energy storage increased system efficiency by 30%.	
20	Examine PCM's impact on building integrated concentrator PV systems (BICPV). [86]	new PCM container design for a BICPV module.	PCM boosts efficiency and is more effective at greater solar insolation levels.	

Constraints and Obstacles with PV/PCM Cooling Systems

Most PCMs with a high energy storage density, like paraffin wax, have low heat conductivity. Even when using heat transfer augmentation strategies like employing internal fins or external fins fixed with a PCM container . As was previously said, there is a potential problem with the additional weight of the fins on the PV/PCM system. While salt hydrates have a high thermal conductivity, using them for PV cooling can be difficult due to their subcooling during the time period of PCM solidification. If problems like subcooling and reactivity with PCM capsulation can be fixed, salt hydrates could be a possible alternative to paraffin wax. The PCM container completely encloses the rear of the PV panel, which eliminates any possibility of natural convection. Therefore, it may get hotter than a regular PV panel in the afternoon when the PCM has melted completely because of the poor design of the rear of the PV panel with the PCM. So, a future research topic could be how to build a PCM container that boosts natural convection from the back of the PV panel instead of blocking it. It's also difficult to effectively remove the PCM's heat and recycle it. If the recovered heat is put to good use, the PV/PCM's total efficiency will be improved even further. Therefore, it is important to investigate appropriate heat transfer systems to guarantee effective use of the energy received from the PCM and increase the PV/PCM systems' economization. The PV/PCM system may be 40%–50% heavier than a regular PV panel. As a result of needing a more robust mounting system to support their weight, installing such thick panels can be a costly endeavor. Therefore, less mass of PCM and PCMs with high latent heat would be needed, which are rare. Obtaining PCM with desirable properties like large latent heat, large thermal conductivity, and little subcooling is difficult and costly. since only a few businesses across the world deal with high-quality PCM.

CONCLUSION

The PV panels electrical power conversion efficiency can be increased by around 5% thanks to the PCMs, which can reduce their working temperature by around 20 °C. Choosing a PCM melting point is entirely dependent on the study area's location and temperature. In places with high ambient temperatures and sun radiation, PCMs are more practical and cost-effective. An average of 2.6 kilogram of PCM must be used per square meter of PV panel area in order to lower the temperature by one degree. Such a significant amount of PCM can increase the weight of PV panels up to 40%, making it harder to position and install them. Organic PCMs are preferred for PV systems' thermal management, even with limited thermal conductivity. Inorganic PCMs offer greater economic benefits and longer payback durations because of their cheap cost and high heat conductivity. With a building-integrated design, the PCM-based systems are more economical in situations where heat dissipation from the PV panel is a challenge and there are many chances for heat recycling. It has been established that improving conductivity and heat dissipation with PCMs can enhance PV panel performance. The heat transmission between PV and PCM is believed to be improved by the PCM container's internal or exterior fins, which can reduce the PV panel temperature due to quick heat transfer. PCM combined with some metals, such as graphite, is also considered advantageous for quick heat transfer since the PCM's total thermal conductivity is improved when mixed with metals.

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