EXPERIMENTAL INVESTIGATION OF A PHOTOVOLTAIC THERMAL SYSTEM WITH PHASE CHANGE MATERIAL

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ABSTRACT

EXPERIMENTAL INVESTIGATION OF A PHOTOVOLTAIC THERMAL SYSTEM WITH PHASE CHANGE MATERIAL

Among environmentally friendly energy sources, solar energy is one of the most widely used. Photovoltaic systems convert sunlight into electrical energy, forming the primary means of utilizing this energy source. However, the efficiency of PV systems decreases with rising temperatures. This study investigates the integration of phase change materials and water-cooled photovoltaic-thermal systems to enhance PV panel performance.

The study consists of two stages, and both experiments were conducted in Antalya. In the first stage, the performance of PV panels integrated with PCMs having melting points of 25°C and 35°C was compared with standard PV panels. Results indicate that PCM integration improves thermal management and increases electrical efficiency. The PV-PCM35 system demonstrated a 21.3°C reduction in panel temperature under high-temperature conditions, leading to an average efficiency increase of 2.16%, with a maximum recorded increase of 3.72%.

In the second stage, the performance of a water-cooled PV/T system integrated with PCM was compared to traditional PV systems. Findings reveal that the PV/T-PCM system provides significant improvements in electrical efficiency. The water-cooling mechanism effectively dissipates heat, maintaining lower panel temperatures and enhancing efficiency. The PV/T-PCM system achieved a maximum electrical efficiency increase of 3.79% and a thermal efficiency increase of 62.74%. These results demonstrate the potential of PV/T-PCM systems to produce more efficient energy in hot regions, particularly in areas with high temperatures such as Antalya.

ÖZET

BİR FOTOVOLTAİK ISIL SİSTEMİN FAZ DEĞİŞTİREN MALZEME İLE DENEYSEL İNCELENMESİ

Çevre dostu enerji kaynakları arasında güneş enerjisi en yaygın kullanılanlardan biridir. Fotovoltaik sistemler, güneş ışığını elektrik enerjisine dönüştürerek bu enerji kaynağını kullanmanın temel yolunu oluşturur. Ancak, PV sistemlerin verimliliği, sıcaklık artışlarıyla azalır. Bu çalışma, PV panellerin performansını artırmak için faz değiştiren malzemeler ve su soğutmalı fotovoltaik termal sistemlerin entegrasyonunu araştırmaktadır.

Çalışma iki aşamadan oluşmaktadır ve her iki deney de Antalya'da gerçekleştirilmiştir. İlk aşamada, erime noktaları 25°C ve 35°C olan faz değiştiren malzemelerle entegre edilmiş PV panellerin performansı, standart PV panellerle karşılaştırılmıştır. Sonuçlar, faz değiştiren malzeme entegrasyonunun termal yönetimi iyileştirdiğini ve elektriksel verimliliği artırdığını göstermektedir. PV-PCM35 sistemi, yüksek sıcaklık koşullarında panel sıcaklığını 21.3°C oranında düşürerek, ortalama %2.16 ve maksimum %3.72 oranında verimlilik artışı sağlamıştır.

İkinci aşamada, faz değiştiren malzeme ile entegre edilmiş su soğutmalı bir PV/T sistemin performansı, geleneksel PV sistemlerle karşılaştırılmıştır. Bulgular, PV/T-PCM sisteminin elektriksel verimlilikte önemli iyileştirmeler sağladığını ortaya koymaktadır. Su soğutma mekanizması, ısıyı etkili bir şekilde dağıtarak panel sıcaklıklarının düşük kalmasını sağlamış ve verimliliği artırmıştır. PV/T-PCM sistemi, maksimum elektriksel verimlilikte %3.79 ve termal verimlilikte %62.74 artış göstermiştir. Bu sonuçlar, PV/T-PCM sistemlerinin özellikle Antalya gibi yüksek sıcaklıklara sahip bölgelerde daha verimli enerji üretme potansiyeline sahip olduğunu göstermektedir.

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Abbreviations

PCM	Phase change material
PV	Photovoltaic panel
PV-PCM25	Photovoltaic panel with phase change material, melting at 25°C
PV-PCM35	Photovoltaic panel with phase change material, melting at 35°C
PV/T	Photovoltaic thermal system
PV/T-PCM	Phovoltaic thermal system with phase change material

CHAPTER 1

INTRODUCTION

1.1. Problem Statement

To optimize the efficiency of the photovoltaic panel, it is imperative to mitigate the temperature increase during operation. Moreover, high temperatures can negatively impact various parts of the photovoltaic system, including thermal stress, which may lead to system breakdowns. Figure 1 shows the PV module temperature in summer in Antalya. In warmest and dry regions, the PV modules can gain the temperatures as high as 75°C, cousing to a 25% decrease in their efficiency (Dida et al. 2021). To solve this problem, cooling methods are applied. This temperature optimization could significantly enhance the efficiency and longevity of solar panels, potentially leading to more widespread adoption of solar energy.

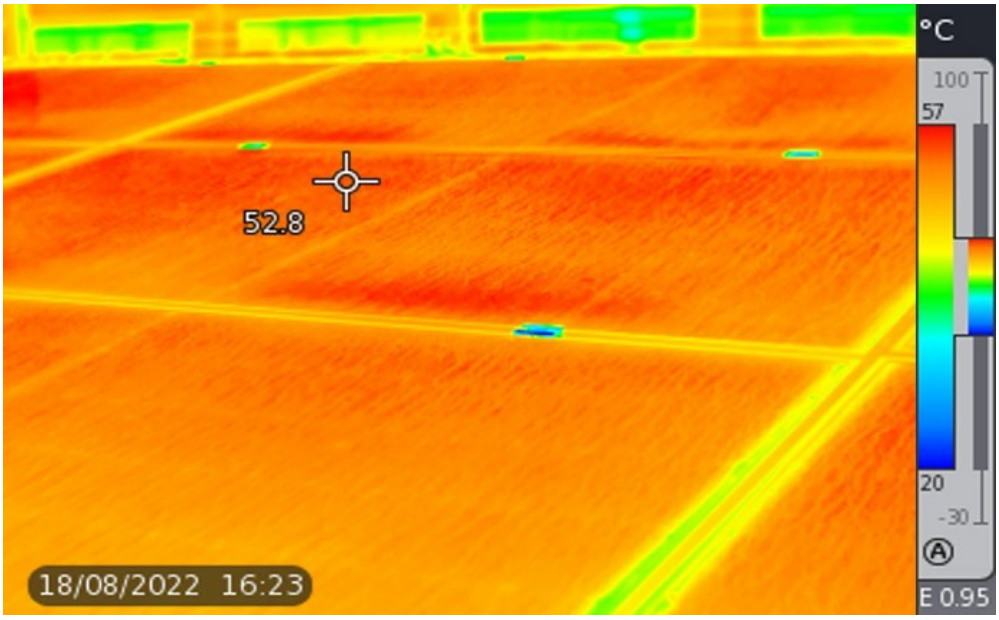


Figure 1 Thermal image of PV.

PV/T solar systems can be more efficient by utilizing heat removal from PV cells for other practical applications. In these systems, the temperature is reduced by circulating fluid through the bottom of the panels. This process not only lowers the surface temperature of the panels but also heats the coolant, contributing to thermal energy generation. As a result, both electricity and thermal energy are produced. A diverse array of cooling techniques, encompassing liquid based, air based, and phase change material based approaches, has been implemented in hybrid photovoltaic thermal systems to optimize both electrical performance and thermal energy recovery.

An effective approach to improving the efficiency of PV and PV/T systems is the integration of phase change materials. Combining PVTs and PCMs significantly lowers PV surface temperature and stores heat (Fayaz et al. 2019). The PV/T-PCM system combines active and passive cooling to obtain heat for valuable purposes while producing electricity in the same system, ultimately increasing the lifespan of the PV system.

1.2. Aim and scope of this thesis

Generally, PV/T-PCM system experiments that combine water heating systems with photovoltaic cooling have been conducted in European countries. Considering the weather conditions in Antalya, a suitable phase change material will be selected, and the system will be evaluated accordingly.

In summary, the novelty and motivations can be written as follows:

1. Comparison of PCMs with Different Melting Points:

Novelty: The study compares the suitability of PCMs with different melting points (RT25 and RT35) for optimizing thermal management of PV panels in the hot climate conditions of Antalya.

Motivation: This research aims to enhance energy efficiency through effective temperature management and determine which PCM configuration is more efficient, thereby contributing to sustainable energy solutions.

2. PV/T-PCM System Implementation and Comparison with PV Systems:

Novelty: The investigation aimed to evaluate a hybrid photovoltaic-thermal system augmented with phase change material, comparing its efficacy against conventional PV configurations.

Motivation: This comparison aims to evaluate the advantages of the PV/T-PCM system in terms of energy efficiency and cooling performance, thereby providing insights into improving solar energy technologies.

1.3. Thesis Outline

The presented thesis is arranged into six chapters, as explained below:

In Chapter Two, the literature studies on photovoltaic panels and photovoltaic thermal (PV/T) systems are presented. This chapter discusses the principles of photovoltaic technology, the effects of temperature on panel efficiency, and various thermal management techniques aimed at enhancing energy output.

In Chapter Three, general information about phase change materials (PCM) is provided. This chapter examines the fundamental properties of phase change materials, with particular emphasis on their capacity to absorb and release thermal energy during phase transitions. This characteristic is crucial for the efficient thermal management of photovoltaic systems.

In Chapter Four, the methodology of the thesis is described in detail. This chapter outlines the experimental approach taken, including the materials used, the measurement methods, and the devices employed in the study. Furthermore, the experimental procedures are systematically discussed.

In Chapter Five, the test results are presented, comparing the thermal performance of different configurations, such as PV-only, PV/PCM, and PV/T-PCM systems. The chapter includes data visualizations, including graphs and tables, to illustrate findings related to temperature reduction and efficiency enhancements.

In Chapter Six, the conclusion presents a summary of the key findings.

CHAPTER 2

PHOTOVOLTAIC MATERIALS AND TECHNOLOGY

2.1. Semiconductors

A photovoltaic solar cell is a semiconductor structure device that converts lightsolar energy into electrical energy. The classification of materials into conductors, insulators, and semiconductors based on the amount of electrons present in their outermost orbit. Conductors are materials characterized by a high density of free electrons in their conduction band. These free electrons can move freely within the material, allowing it to easily carry electric current. Most metals are good conductors. A material which does not easily release electrons is called an insulator. There are very few free electrons in an insulator. If the outermost shell of an atom contains 4 electrons, the material is classified as a semiconductor.

2.2. p-n junction

A solar cell operates on the basis of photoelectric effect, coupled with the functioning of the p-n junction. The n-type material contains a high concentration of free negative charge carriers that are can move freely in the material. In contrast, the p-type material has an abundance of free positive charge carriers (holes), which allow for the movement of charge (Abou Jieb and Hossain 2022). A pn junction diode is shown at the top of Figure 2. When the p- and n-type materials are combined, in the n-type side free electrons start to move toward p-type side and fill the holes. Similarly, the positive charges in the p-doped side diffuse toward the n-doped side. This results in the n-part of the p-n junction to become positive ion rich area, while the p-side to become negative ion rich area.

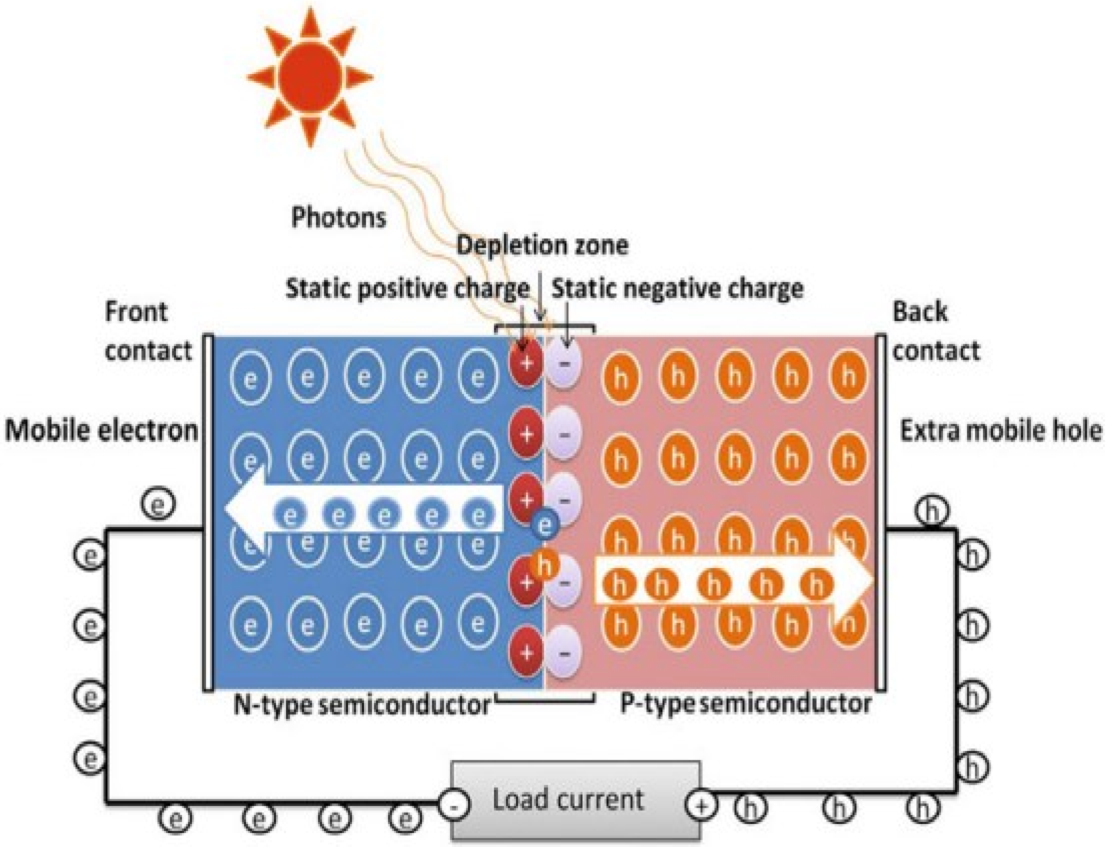


Figure 2 PN Junction Theory.

(Source: Anand, Shukla, and Sharma 2022)

2.3. Photovoltaic effect

The photovoltaic effect, discovered by Alexandre-Edmond Becquerel in 1839, serves as the foundation for converting light into electrical energy (Kumavat, Sonar, and Dalal 2017) . When light strikes a photovoltaic cell, it provides energy to excite electrons within the material, causing them to move. This movement begins as electrons are transported from the p-type layer to the n-type layer by passing through the depletion region, driven by the electric field created within the cell. When an external electrical load is connected, electrons flow from the n-type layer to the load via the external circuit and subsequently return to the p-type layer (Abou Jieb and Hossain 2022).

2.4. PV cell characteristics

The I-V curve serves as a fundamental tool for evaluating the performance of solar panels. It delineates the correlation between current (I) and voltage (V), thus playing a crucial role in determining the solar panel's maximum power point.The resulting current–voltage characteristic is shown exemplarily in Figure 3.

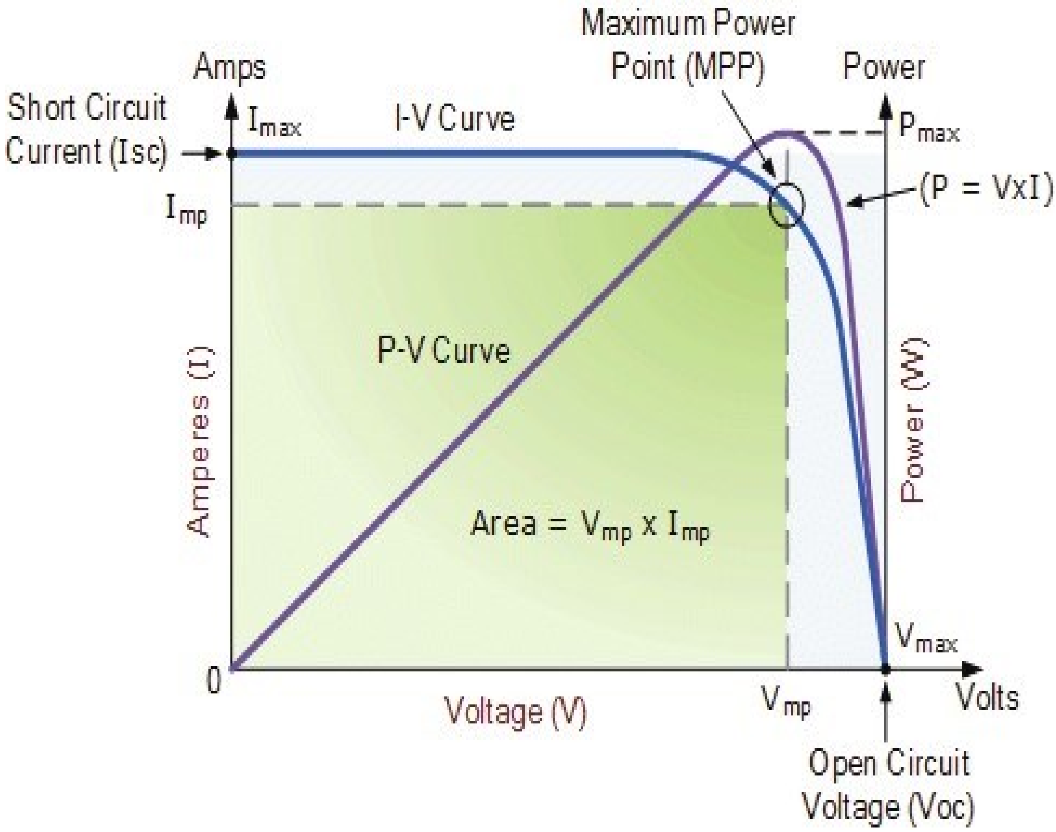


Figure 3 Current–voltage characteristics of a solar cell.
(Source: Afghan, Neamah, and Husi 2017)

The point on the I-V curve that corresponds to the highest generated power is referred to as the maximum power point. It allowed to determine I–V curves and the following parameters, V_{OC} , I_{SC} , V_{MP}, I_{MP} , FF and η. The maximum power Pmax can be written as,

$$P_{max} = I_{MP}V_{MP} \tag{2.1}$$

The fill factor (FF), as defined bu equation (2.2) (Singh et al. 2021) serves as an essential indicator of a PV panel's overall performance. Solar panels typically achieve a fill factor (FF) value of 80%.

$$FF = \frac{V_{MP} \times I_{MP}}{V_{OC} \times I_{SC}} \tag{2.2}$$

The efficiency of a solar cell is determined by comparing the electrical power generated at the maximum power point to the total incident light energy falling on the cell surface under specific irradiance conditions equation (2.3):

$$\eta = \frac{I_{SC}V_{OC}FF}{P_{in}} \tag{2.3}$$

where P_{in} is power of incident light under STC. The cell efficiency is determined under standard test conditions. Under standard test conditions (STC), the efficiency of solar cells is evaluated with specific parameters: an irradiance of 1000 W/m² incident perpendicular to the surface, a cell temperature of 25°C, and an AM 1.5 solar spectrum as specified in IEC 60904–3 (Winter 2020). These conditions are widely accepted for testing and benchmarking the performance of photovoltaic cells, providing a consistent reference for comparing different cell technologies.

2.5. Types of Solar Cells

Photovoltaic cells are classified into four primary generations: the first, second, third, and fourth generations (Pastuszak and Węgierek 2022a; Kant and Singh 2022). This classification reflects the continuous advancements in solar technology, focusing on optimizing energy conversion efficiency, reducing production costs, and incorporating more sustainable materials. Solar cell structures differ in size and material composition, which significantly impacts the efficiency of converting sunlight into electricity. The four generations of solar photovoltaic cells are illustrated in Figure 4.

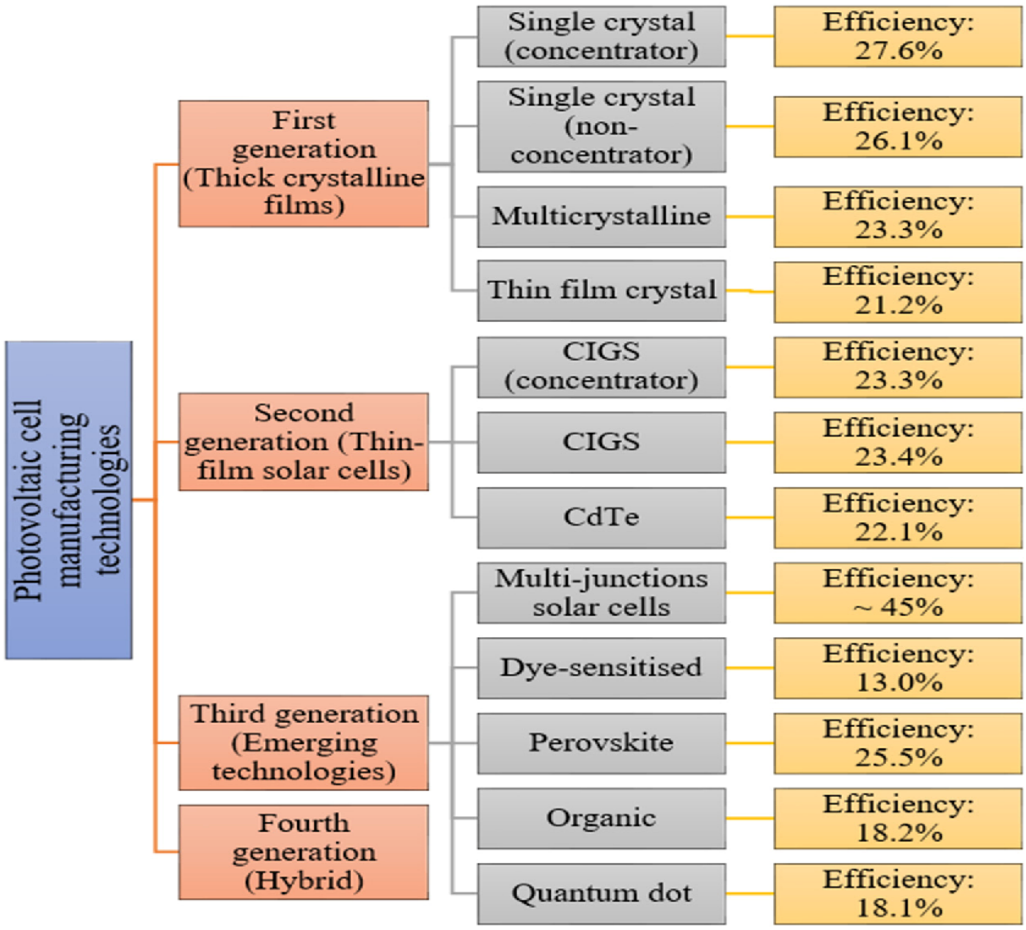


Figure 4 The classification of the four generations of solar photovoltaic cells (Source: Pastuszak and Węgierek 2022b).

2.5.1. First Generation Solar Cells

First-generation solar cells are fabricated using either monocrystalline or polycrystalline silicon wafers. These two types of cells are illustrated in Figure 5. Monocrystalline silicon cells feature an orderly crystalline structure and typically exhibit a dark gray appearance. The monocrystalline silicon cell is constructed from a single silicon crystal, while the polycrystalline silicon cell consists of multiple crystalline grains.

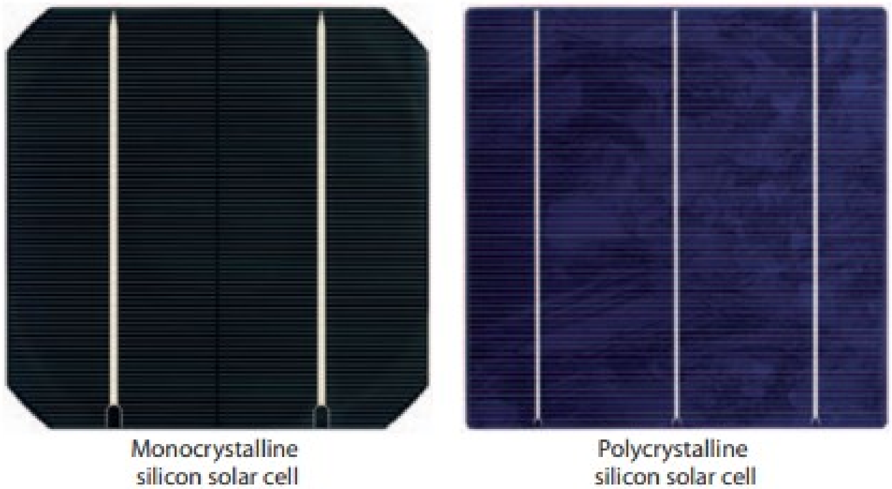


Figure 5 Photographs of monocrystalline and polycrystalline solar cells
(Source: Saga 2010)

The primary advantage of monocrystalline cells lies in their high efficiency, with the current laboratory efficiency record reaching 27.6%, as indicated in Figure 4. Monocrystalline silicon is produced through a process known as the Czochralski process, (Nayeripour, Mansouri, and Waffenschmidt 2020). Multicrystalline cells are more cost-effective to produce than monocrystalline cells, primarily because their manufacturing process is less complex. Solar panels made from polycrystalline silicon exhibit lower efficiency compared to those made from monocrystalline silicon due to the reduced purity of the silicon material.

2.5.2. Second Generation Solar Cells

Second-generation solar cells, also known as thin-film solar cells, consist of ultra-thin layers measuring only a few micrometers in thickness. Second generations solar cells are more flexible, lighter than first-generation PV panels due to their low thickness (Efaz1 et al. 2021). An example of a thin-film solar cell is shown in Figure 6.

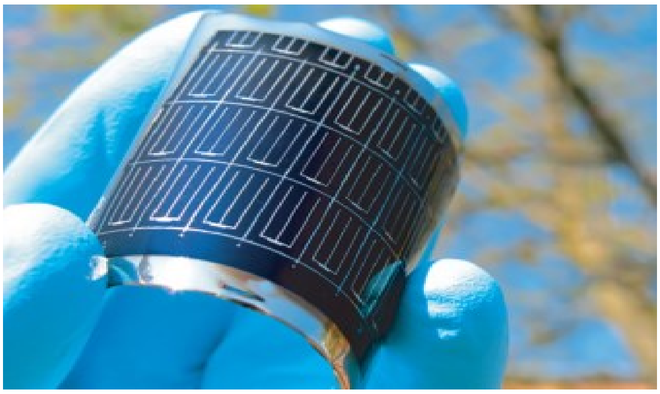


Figure 6 Thin film solar cell.
(Source: Ramanujam et al. 2020)

While these solar cells exhibit lower efficiency compared to their first-generation counterparts, they offer a more economically viable manufacturing process. Thin film solar cells exhibit a lower efficiency degradation with increasing temperature. The second-generation solar cell materials comprise CdTe, a-Si, CIGS and micro-amorphous silicon (Tiwari 2023).

Amorphous silicon (a-Si) solar cells utilize silicon in an amorphous, non-crystalline structure, characterized by atoms arranged in a random pattern rather than in a regular lattice. The production process of amorphous silicon photovoltaic cells is conducted at relatively low temperatures. These solar cells can be produced at relatively lower temperatures, which significantly decreases manufacturing expenses and allows for the creation of cost-effective, flexible substrates (S. Sharma, Jain, and Sharma 2015).

Cadmium Telluride (CdTe) is a compound used in photovoltaic cells that consists of cadmium and telluride. CdTe has a direct band gap of 1.45 eV and possesses a high absorption coefficient, surpassing $5\text{x}10^{15}/\text{cm}$, enabling the absorption of photons within a few micrometers of its absorber layer (Aghaei 2012). However, a notable drawback of CdTe solar cells is the toxicity associated with cadmium, a heavy metal integral to their production process (Machín and Márquez 2024).

CIGS solar cells, consisting of copper, indium, gallium, and selenium, deliver higher average efficiencies compared to CdTe solar cells. Some CIGS cells have reached efficiencies of up to 22.8%, positioning them as a competitive alternative to crystalline silicon-based solar cells (Sarah, Roland, and Ephraim 2020).

2.5.3. Third Generation Solar Cells

Third-generation solar cell technologies encompass a range of advanced systems, including dye-sensitized, perovskite, quantum dot, and organic solar cells (Ahmad, Naqvi, and Jaffri 2021). These novel approaches seek to enhance efficiency and reduce manufacturing expenses through innovative energy conversion mechanisms. Nevertheless, these technologies remain in the research and development phase, with widespread commercial adoption yet to be realized.

2.5.4. Fourth Generation Solar Cells

Fourth-generation solar cells are also referred to as hybrid solar cells due to their ability to combine inorganic materials with organic materials. The photovoltaic cells in question amalgamate the merits of their predecessors, such as cost-efficiency, pliability, and augmented durability, while integrating advanced materials, including nanomaterials, metal oxides, graphene, and carbon nanotubes, to further enhance their operational performance and structural robustness (Iqbal et al. 2022).

Current research efforts are focused on constructing these solar cells with multiple layers of semiconductor materials, each layer designed to absorb different wavelengths of light, thereby increasing overall efficiency.

2.6. Overheating of solar cells

Temperature exerts a significant influence on the efficiency of solar cells and various performance parameters, including the maximum power point, short-circuit current, and open-circuit voltage. When exposed to sunlight, photovoltaic cells convert a portion of the solar energy into electrical energy through the photovoltaic effect, while the remaining energy is absorbed as heat. This heat accumulation increases the cell temperature, which adversely impacts the energy conversion efficiency and subsequently lowers the maximum power output that solar cells can produce. This decline in power output is evident in various performance curves, such as those illustrated in Figure 7, which demonstrate how increased cell temperatures correlate with decreased maximum power output.

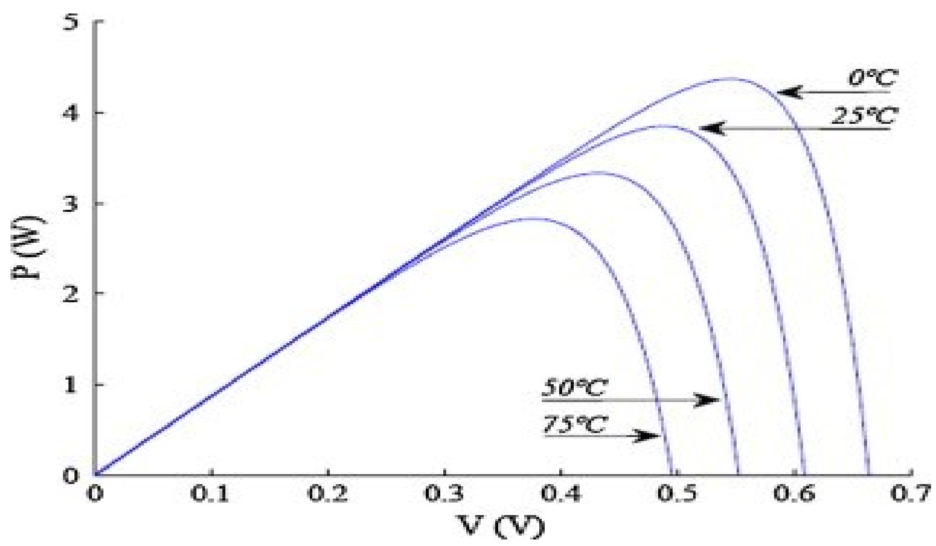


Figure 7 P-V curves for various temperature.

(Source: Moharram et al. 2013)

The primary impact of increasing cell temperature is observed in the open-circuit voltage (V_{OC}), which decreases linearly with rising cell temperature, leading to a drop in overall cell efficiency. Figure 8a shows the characteristics under an irradiation intensity of 1000 W/m², while Figure 8b presents the same under an irradiation intensity of 800 W/m². As illustrated in Figure 8, the short-circuit current (I_{sc}) shows a slight increase with the rise in cell temperature. However, the reduction in open circuit voltage (V_{OC}) is considerably more pronounced than the marginal increase in Isc, resulting in a net decline in power output. The variations in V_{OC} and I_{sc} with temperature and irradiation levels underline the critical role of environmental conditions in determining PV module efficiency. These findings emphasize the necessity of developing advanced materials and cooling systems to mitigate the negative effects of temperature on photovoltaic performance.The temperature dependence of V_{OC} is given by

$$V_{OC} = V_{OC,25°C}[1 + \beta(T - 25°C)] \quad \textbf{(2.4)}$$

where β is the open circuit voltage temperature coefficient.

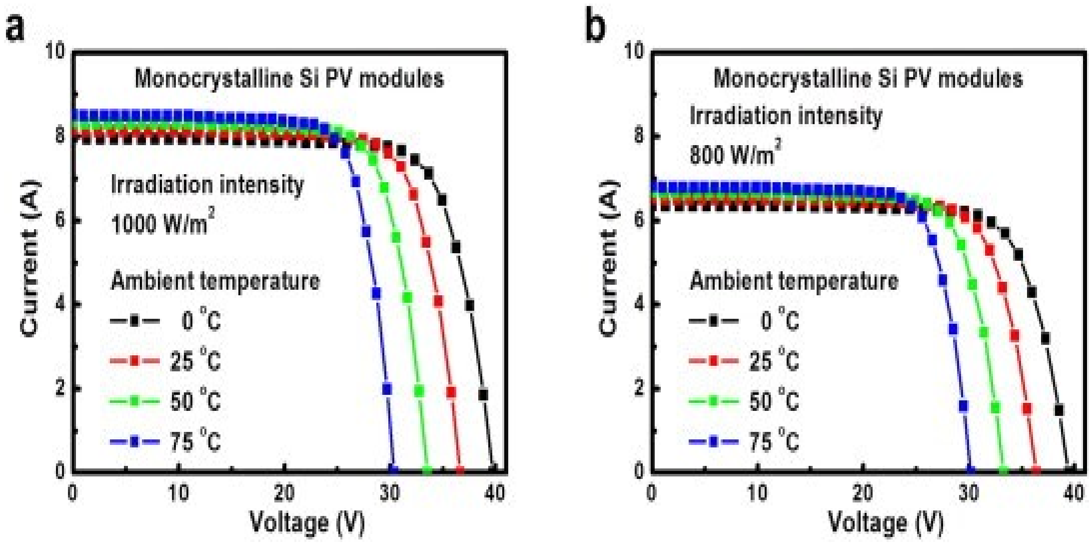


Figure 8 Current-Voltage (I-V) Characteristics at Different Ambient Temperatures and Irradiation Levels.

(Source: Jiang et al. 2012)

Figure 9 presents the variation in electrical efficiency with temperature, indicating a decline in efficiency as the temperature of the photovoltaic module rises (Hasanuzzaman et al. 2016).

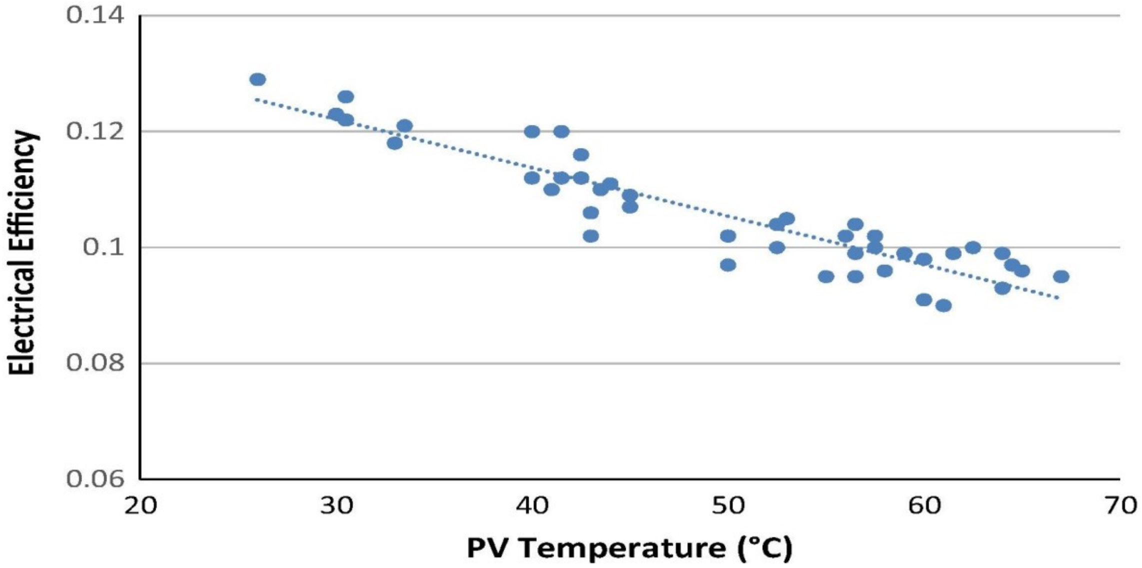


Figure 9 Temperature Impact on the Electrical Efficiency of a PV Module.
(Source: Hasanuzzaman et al. 2016)

2.7. Solar panel cooling method

Photovoltaic panels are highly sensitive to temperature variations, which can significantly impact their efficiency and longevity. Research indicates that a 10°C elevation in panel temperature can lead to a twofold increase in the degradation rate (Abd-Elhady et al. 2025). To mitigate the adverse effects of elevated temperatures and maintain optimal operational conditions, it is imperative to implement effective cooling strategies that facilitate the dissipation of accumulated thermal energy (Sheik et al. 2022). Various methods using different materials are employed in solar panel cooling technologies to manage heat. An illustrative diagram detailing the classification of these cooling methods is provided in Figure 10.

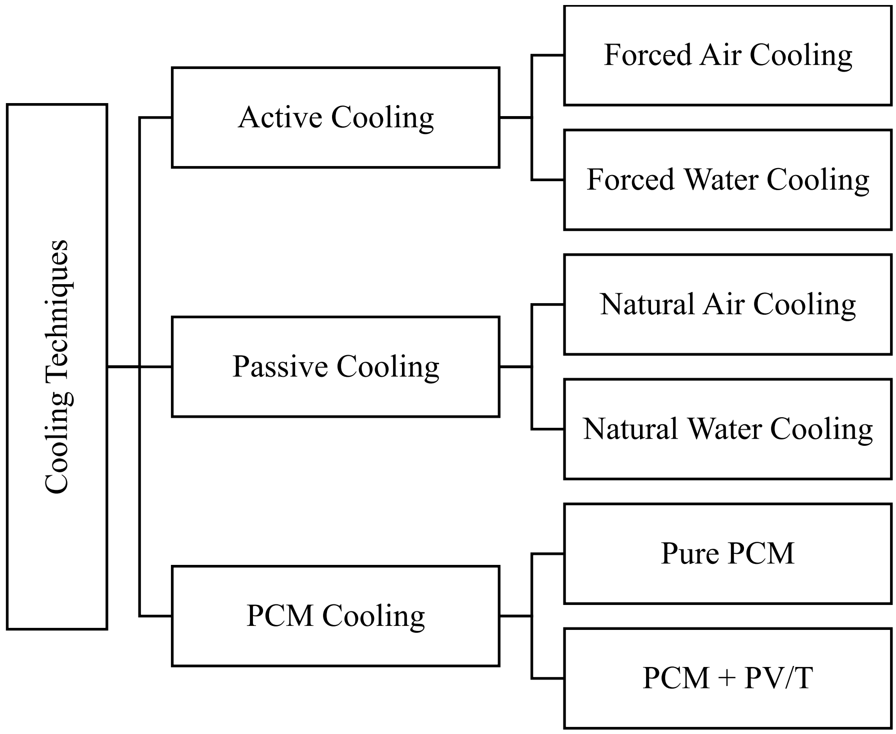


Figure 10 Classification of PV cooling techniques.
(Source: Raju et al. 2024)

Active cooling methods, such as forced air and water circulation, are effective in achieving high heat transfer rates; however, they often involve increased energy consumption, higher initial costs, and system complexity (Maleki et al. 2020). Passive cooling approaches, utilizing natural air or water circulation, offer low-cost and energy-free solutions, easy to integrate but their performance is significantly influenced by environmental factors, such as wind direction and speed (Shukla et al. 2017). Phase change materials offer several advantages, including high heat transfer rates, increased heat absorption due to latent heating, and isothermal heat removal, making them highly efficient for thermal management (Zare and Mikkonen 2023). Additionally, PCMs operate without electricity, require no maintenance, and are silent in operation, contributing to energy savings and environmental benefits. However, the use of PCMs is associated with several drawbacks, including their relatively high cost, potential safety concerns such as toxicity, fire risks, and corrosive properties, as well as environmental challenges related to their disposal at the end of their lifecycle (A. Hasan et al. 2017).

2.8. Photovoltaic Thermal System

Photovoltaic thermal (PV/T) systems integrate photovoltaic and solar-thermal technologies into a single device, enabling the simultaneous generation of electricity and thermal energy from solar radiation. PV/T system integrates a conventional solar photovoltaic panel with a thermal collector attached to its rear side. This configuration is designed to warm up domestic water or air for ventilation purposes.The schematic representation of a PV/T system is shown in Figure 11.

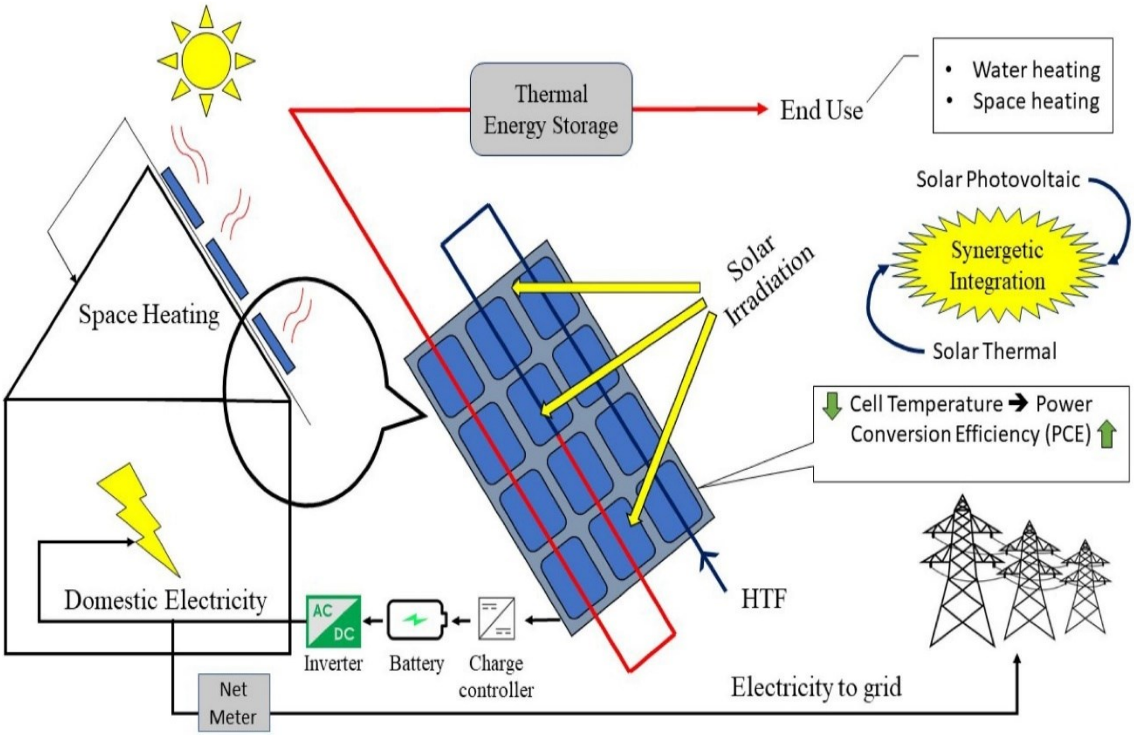


Figure 11 Schematic representation of a PV/T system.
(Source: Verma et al. 2022)

PV/T systems can be analyzed from several technical aspects, including the type of photovoltaic modules, thermal absorber design, working fluid selection, and circulation methods (Kostic and Aleksić 2020; Salameh et al. 2021). The diagram below (Figure 12) categorizes the key design parameters into three categories: the type of collector, the type of coolant, and the type of PV material.

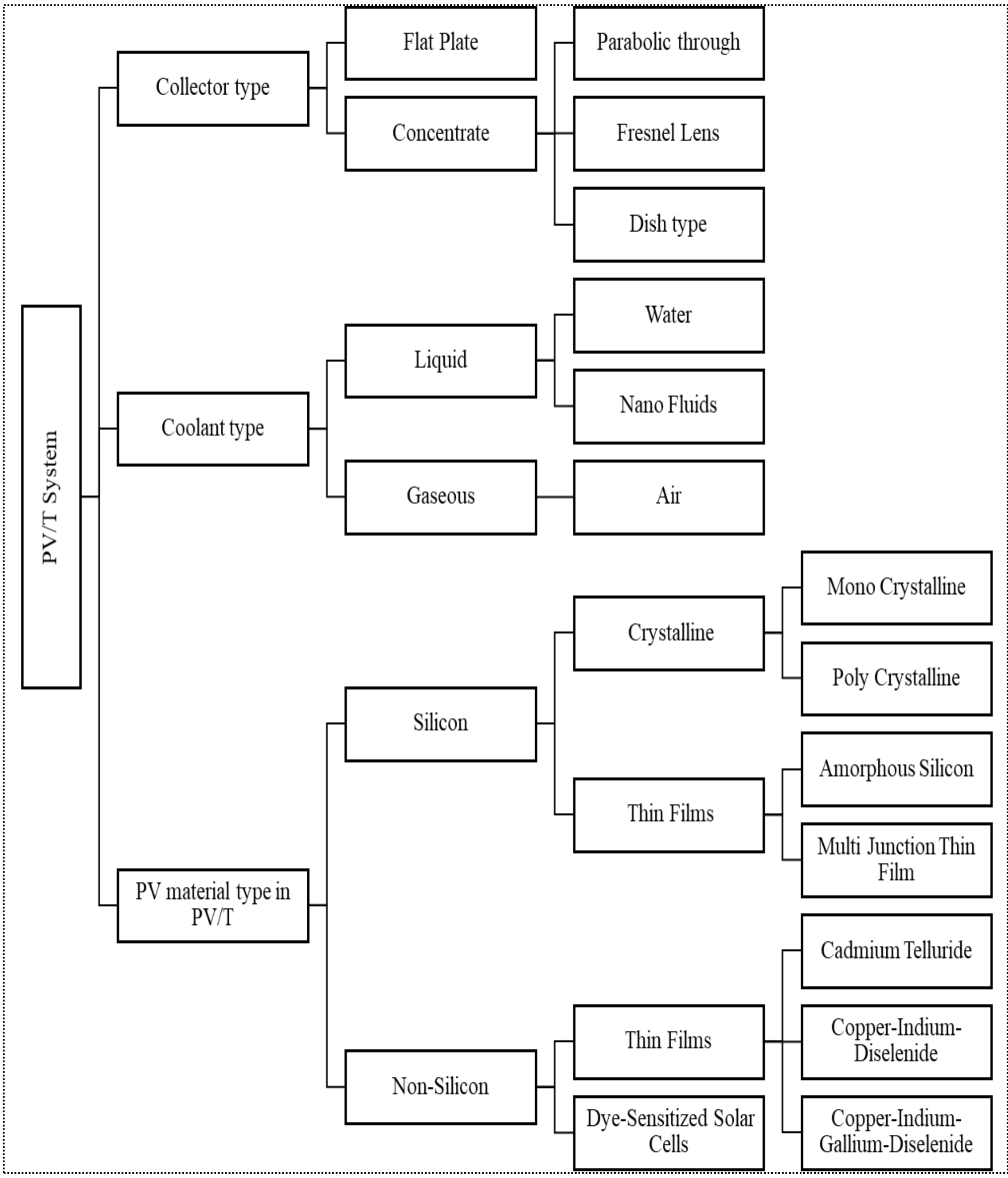


Figure 12 Design of PV/T collectors.
(Source: Babu and Ponnambalam 2017)

The choice of collector type, such as flat plate or concentrated systems, directly impacts system efficiency (Daneshazarian et al. 2018; Pang et al. 2020). The material used for photovoltaic cells also plays a crucial role, with options including silicon-based materials, thin films, and non-silicon alternatives like dye-sensitized solar cells. A well-designed thermal absorber can effectively dissipate the heat accumulated by photovoltaic modules during their operation. (Va and Sekhar 2021). The selection of the working fluid in PV/T systems is a critical factor influencing the heat transfer efficiency. Different fluids, such as water, nanofluid offer varying thermal properties that significantly impact the overall performance of the system (Sardarabadi et al. 2017; Sathyamurthy et al. 2021). The efficiency and thermal regulation of photovoltaic thermal systems are heavily influenced by mass flow rates (Pang et al. 2019).

Lastly, the integration of hybrid collectors, which combine photovoltaic and thermal functionalities, represents an innovative approach to enhance overall energy capture and utilization (Wu et al. 2017). Each of these factors must be carefully considered to optimize PV/T system design for maximum efficiency in harnessing solar energy.

PV/T technology produces the additional benefits (Al-Waeli et al. 2017; Madhi,Aljabair, and Imran 2024; Pathak et al. 2022). PV/T systems produce both electricity and heat, enabling a more comprehensive utilization of solar energy resources. By integrating photovoltaic and thermal systems, overall efficiency is significantly increased compared to having separate systems. Additionally, PV/T systems require less physical space than standalone photovoltaic and thermal installations, making them particularly suitable for applications where available area is limited. Furthermore, PV/T systems reduce thermal degradation, thereby increasing the lifespan of the photovoltaic panel.

2.8.1. Using air in PV/T systems

The theory of PV/T air was stated by Kern and Russel (Kern and Russell 1978). The photovoltaic cells in this system are cooled through the utilization of air as the operational fluid medium. Based on the configuration of the air channels, four primary types can be distinguished (Chow 2010): channels positioned above the PV cells, channels located below the PV cells, PV cells situated between single-pass channels, and the double-pass configuration.

This method presents both advantages and disadvantages that are important to consider (Kumar and Rosen 2011; M. A. Hasan and Sumathy 2010).

Advantages of using air in PV/T systems:

- No freezing or boiling occurs in the collector fluid.
- No damage occurs in case of leakage.
- Lower maintenance requirements due to the absence of specialized heat transfer fluids.
- Reduced risk of corrosion compared to liquid-based systems.
- Simpler installation process due to the compact and lightweight design.
- Lower risk of high-pressure issues, as air systems operate at lower pressures.
- Generally, a more cost-effective solution in terms of materials and maintenance.

Disadvantages of using air in PV/T systems:

- Low heat capacity and low conductivity, resulting in low heat transfer efficiency.
- Low density, leading to high volume requirements for heat transfer.
- Significant heat losses due to air leakage.
- Slower heat recovery compared to liquid systems.
- Limited effectiveness in extremely low temperatures due to decreased air density.

2.8.2. Using water in PV/T systems

These systems use water as the heat transfer fluid, circulating it through tubes connected to the PV panels. Water is widely accessible, inexpensive, and has good heat transmission properties, which makes it a popular choice in this field. The thermal energy collected through water can be effectively employed for domestic hot water production, offering an efficient solution for fulfilling household heating demands. Figure 13 shows the schematic layout of the system, where photovoltaic laminates are connected to an absorber surface, and water tubes are used to remove heat from the PV module. The circulation of water is facilitated by pumps, which enhance the cooling process and boost the overall efficiency of the system.

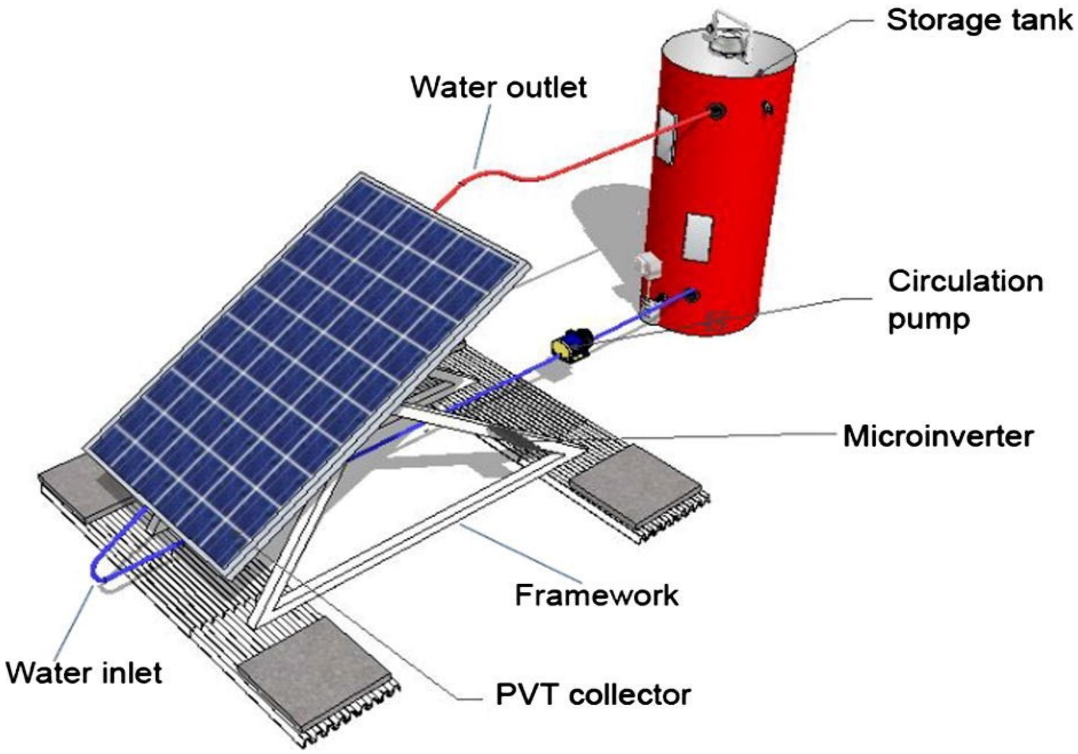


Figure 13 PVT system configuration.
(Source: Aste et al. 2016)

The schematic representation of the water-based PV-T collector is provided in Figure 14. This system incorporates an anti-reflective, toughened glass cover to minimize reflection losses. Furthermore, ethyl vinyl acetate (EVA) layers positioned above and below the photovoltaic cells enhance durability. A Tedlar back sheet further augments the system's resilience and longevity. Beneath the photovoltaic cells, a heat-conducting absorber plate efficiently transfers thermal energy to a fluid-carrying pipe.

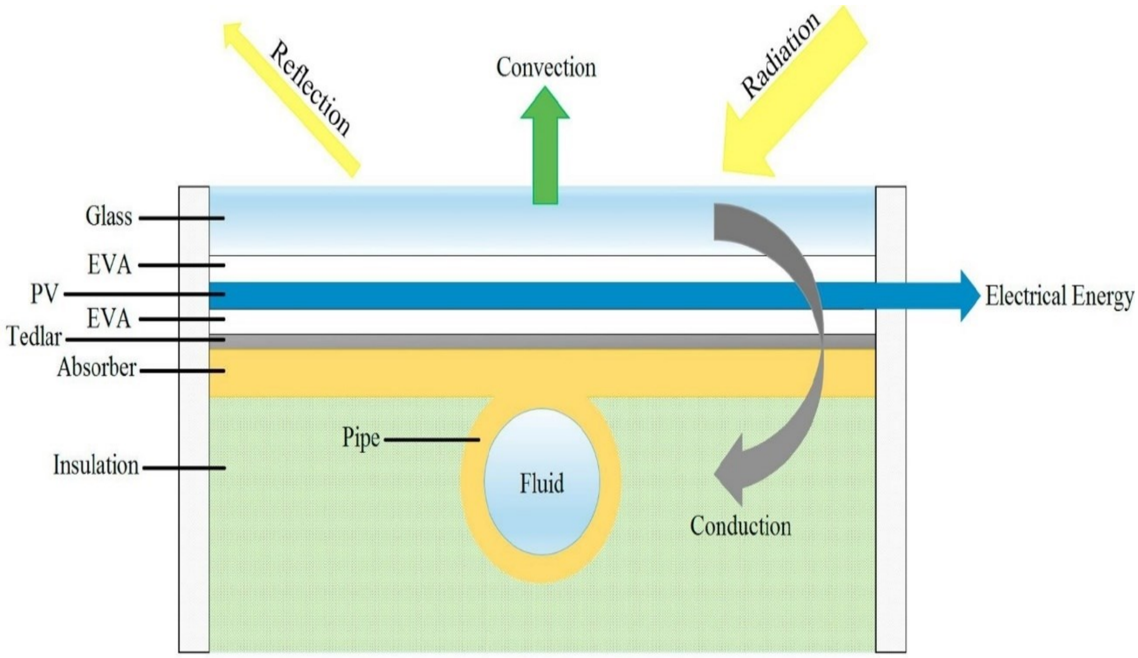


Figure 14 Diagram of the Photovoltaic Thermal Collector System.
(Source: Hosseinzadeh et al. 2018)

This method presents both advantages and disadvantages that are important to consider (Jia, Alva, and Fang 2019; Islam et al. 2016).

Advantages of Water-Cooled PVT Systems:

- High heat capacity enables more efficient heat transfer.
- Excellent thermal conductivity facilitates faster energy transfer
- The system can transport significant heat in a smaller volume, saving space.
- Water offers efficient cooling performance even under elevated temperatures, making the system more effective in extreme heat conditions.
- Reduced heat loss risk compared to air-based systems, as water systems are less prone to leakage.

Disadvantages of Water-Cooled PVT Systems:

- Freezing and boiling risks: Water can freeze at low temperatures or evaporate at high temperatures, risking system damage.

- Leakage-related damage can result in significant costs, as water can harm the components it comes into contact with.
- Corrosion susceptibility, particularly in metal parts subjected to prolonged water exposure.
- More complex installation complexity, due to the need for integrating water pipes, pumps, and additional components.
- High-pressure issues; water-based systems require robust and durable materials to withstand elevated pressures

2.8.3. Using PCM in PV/T systems

The incorporation of phase change material (PCM) in photovoltaic thermal (PVT) systems typically entails its utilization in conjunction with water, both serving as coolant substances. Water-based PVT systems incorporate PCM to manage temperature by capturing excess thermal energy. The incorporation of a PCM layer enables the solar cell to capture waste heat, resulting in enhanced efficiency. Figure 15 presents the schematic diagram of the PV/T system with PCM.

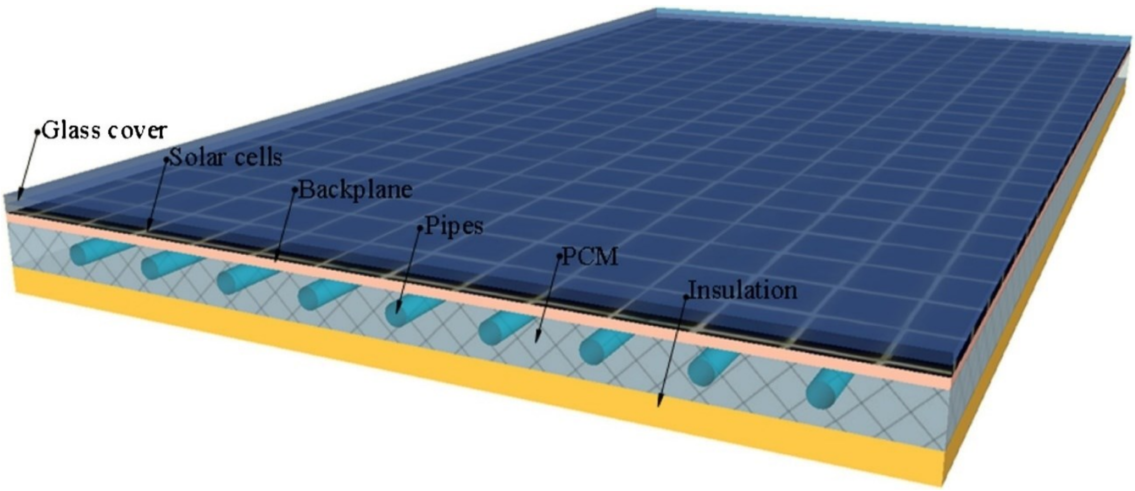


Figure 15 Schematic representation of the PV/T sytem with phase change material. (Source: Su et al. 2017)

(Maatallah, Zachariah, and Al-Amri 2019) examined the performance of an integrated photovoltaic/thermal (PV/T) system combined with a phase change material (PCM) and water module, as illustrated in Figure 16. The findings revealed that this combined approach improved the overall system efficiency by 40.59% and increased its thermal efficiency by 26.87%. The electrical energy output was approximately 17.33% higher compared to traditional PV modules. The study also demonstrated that the water-based PV-T/PCM system achieved superior lifecycle conversion efficiency, surpassing conventional PV panels by about 27%.

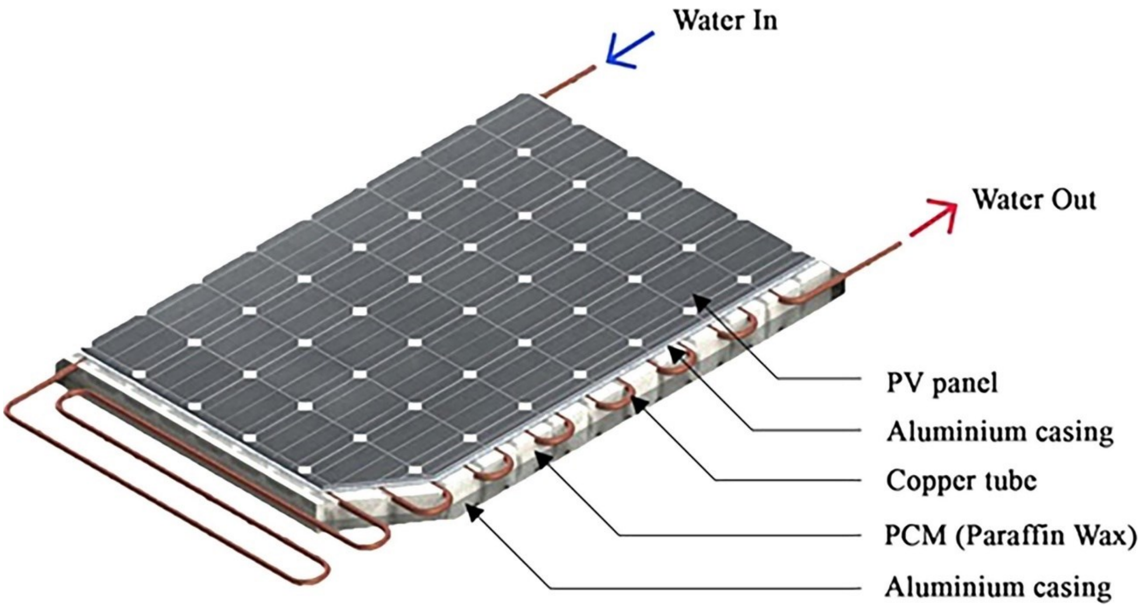


Figure 16 Water-based PVT system.
(Source: Maatallah, Zachariah, and Al-Amri 2019)

(Browne, Norton, and McCormack 2016) conducted a comparative analysis of the performance between standard PV/T modules and those incorporating phase change materials (PCM), as illustrated in Figure 17. The results demonstrated that the PV/T module with PCM integration achieved a water temperature 5.5 °C higher than that of the standard PV/T module.

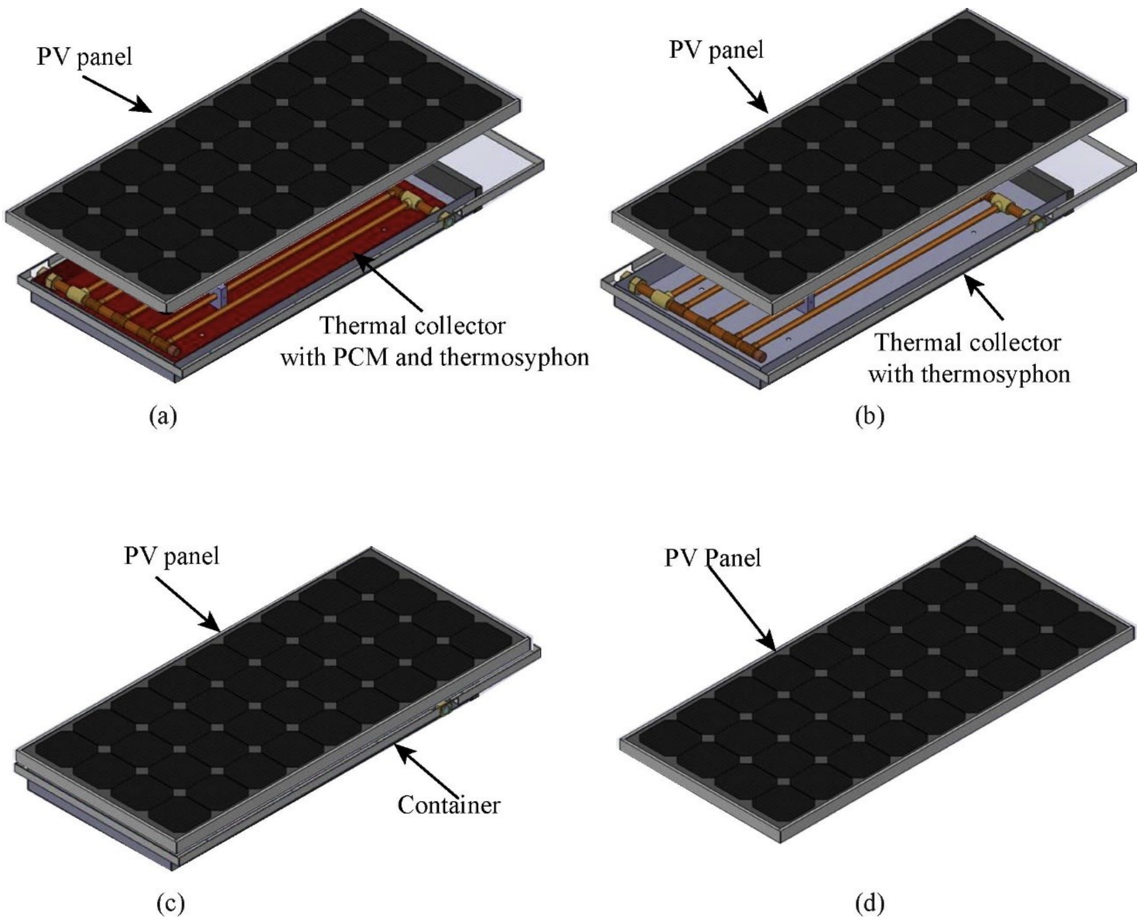


Figure 17 Overview of the Systems in the Experiment
(Source: Browne, Norton, and McCormack 2016).

(Chakraborty, Kumar Yadav, and Bajpai 2021) revealed that incorporating phase change material (PCM) into photovoltaic modules (PV/T-PCM) led to a 1.55% boost in electrical efficiency and a temperature reduction of 10 °C in the module when compared to the standard SPV module.

(Chaichan et al. 2021) investigated the effect of phase change materials on improving the performance of photovoltaic-thermal (PV/T) systems, with a focus on the influence of melting point variations. Figure 18 presents a schematic diagram showing the cross-section of the PV/T system. Under simulated summer conditions in Iraq, the use of phase change materials significantly reduced the temperature of photovoltaic cells, thereby enhancing the overall system performance. The study reported peak electrical and thermal efficiencies of 13.7% and 39.0%, respectively.

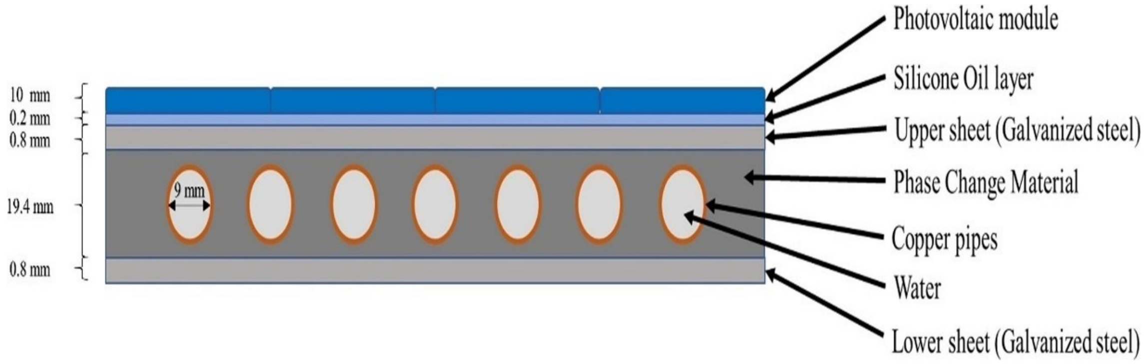


Figure 18 Cross-sectional schematic of the PVT system used
(Source: Chaichan et al. 2021).

CHAPTER 3

THERMAL ENERGY STORAGE

Several energy storage systems have been developed to store energy for later use. These systems are capable of storing energy in different forms, including mechanical, electrical, and thermal energy. Thermal energy storage is the process of storing heat energy for a certain period and retrieving it when needed. This technology is used effectively to store heat energy obtained from various sources such as solar energy, industrial waste heat. Thermal energy storage can be categorized into three main types: sensible heat storage, latent heat storage, and thermochemical energy storage (Sadeghi 2022).

3.1. Sensible heat storage systems

Sensible heat refers to the energy stored or released when a material's temperature is increased or decreased without a change in phase. The quantity of thermal energy stored is contingent upon the specific heat capacity of the material, the magnitude of temperature change, and the amount of storage material. The quantity of energy stored is calculated following the Eq. (3.1):

$$Q = mc_p\Delta T \tag{3.1}$$

where, Q is the quantity of heat stored (J), m is the mass of storage material (kg), c_p is the specific heat of the storage material (J/kg K), and ΔT is the temperature change (K).

3.2. Latent heat storage systems

Latent heat storage systems function by utilizing the thermal energy absorbed or released when the storage phase change material transitions between physical states. During a phase transition, the temperature of the substance does not change. Figure 19 illustrates the temperature-energy relationship of melting and solidification processes.

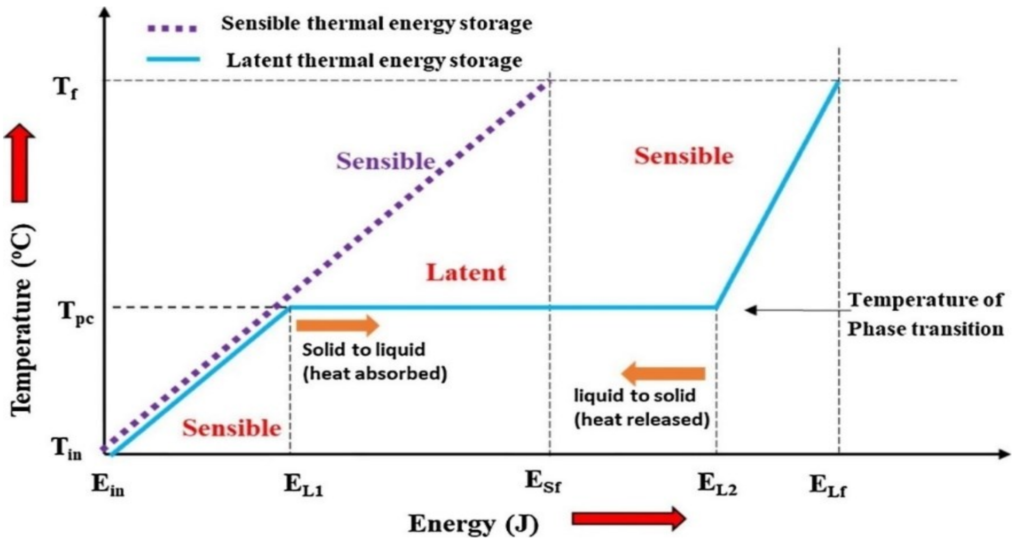


Figure 19 Phase transition profile of phase change material.
(Source: Reddy, Mudgal, and Mallick 2018)

The heat storage capacity is then given by (Douvi et al. 2021):

$$Q_{latent} = m[c_{ps}(T_m - T_i) + f\Delta q + c_{pl}(T_i - T_m)] \quad \textbf{(3.2)}$$

where, Q_{latent} is latent heat storage capacity (J), T_m is melting temperature (K), m is mass of the material (kg), c_{ps} is specific heat of solid phase J/(kg.K), c_{pl} is specific heat of liquid phase J/(kg.K), f is melt fraction, Δq is latent heat of fusion (J/kg).

Phase change can occur in various forms, including solid-to-solid, solid-to-liquid, solid-to-gas, liquid-to-gas, and the reverse. During solid-to-solid phase transitions, energy is stored as the substance changes from one crystal structure to another. These transformations generally involve smaller changes in latent heat and volume compared to transitions between solid and liquid states. Solid-gas transitions have very high latent heat of phase transition, but their large volumetric expansion make the system complex and impractical. The most commonly used type of phase change material in this application is represented by solid-liquid phase change materials. This preference is attributed to their widespread availability and the minimal volume change they undergo, particularly in comparison to liquid-vapor phase change materials (Fernandes et al. 2012).

3.3. Classification of phase change materials

PCMs are classified into three groups: organic, inorganic, and eutectic (Banerjee et al. 2022) .

3.3.1. Organic PCMs

Organic materials are further described as paraffin and nonparaffin. Nonparaffin PCMs include fatty acids, alcohol, etc. In commercial applications, paraffin is the most commonly used organic TES material (Alva, Lin, and Fang 2018).

The primary advantages of organic PCMs are their non-corrosive nature and chemical stability, as well as their minimal or absent subcooling properties. The principal disadvantage of most organic PCMs is their low thermal conductivity (R. K. Sharma et al. 2015). Organic phase change materials possess advantageous characteristics, including low corrosion rates and superior thermal and chemical stability. Nonetheless, these materials are characterized by reduced thermal conductivity in comparison to alternative substances.

3.3.2. Inorganic PCMs

Inorganic PCMs consist of metals, salts, and salt hydrates, as well as metal alloys. Compared to organic alternatives, they offer higher thermal conductivity and a greater latent heat of fusion (Wong-Pinto, Milian, and Ushak 2020). However, inorganic phase change materials exhibit corrosive behavior toward most metals and are susceptible to decomposition and subcooling, which can negatively impact their phase change properties (Junaid et al. 2021).

3.3.3. Eutectic PCMs

A eutectic phase change material is composed of a specific mixture of organic and inorganic components. This unique composition enables the creation of numerous permutations, which can be engineered to suit particular applications.

3.4. Properties of PCMs

A comprehensive examination of extant literature reveals five pivotal factors to consider in PCM selection: thermophysical properties, kinetic behavior, chemical compatibility, economic viability, and environmental impact (Yang, Huang, and Zhou 2020; Zeng, Liu, and Shukla 2017; Alva et al. 2017; Soares et al. 2013; Preet 2021) .

Thermophysical properties:

- High latent heat of fusion
- High thermal conductivity
- Small volume change on phase transformation
- Phase transition temperature suitable for the operating range

Chemical properties:

- Chemical stability.
- Complete reversible freeze/melt cycle
- Compatibility with construction materials
- Non-corrosive
- Non-toxic
- Not flammable

Kinetic properties:

- No supercooling
- Long term thermal stability

Economic properties:

- Cost effective
- Abundant

Environment properties:

- Easy recycling

3.5. PCM selection criteria for PVT

When it comes to using Phase Change Materials (PCMs) for managing the temperature of Photovoltaics (PV), it's important to consider certain criteria for selecting the right PCM. The major selection criteria include appropriate melting temperature, latent heat of fusion, and high thermal conductivity.

(Waqas and Jie 2018) highlighted that optimal benefits can be obtained when the PCM's melting point is chosen to create a 10°C to 12°C gap between the melting point and the average lowest ambient temperature during the hottest summer month. A mathematical model by (Ma, Zhao, and Li 2018) recommends that the PCM melting temperature should be 5°C above the ambient temperature.

Table 1 displays the monthly average temperature data recorded in Antalya between 1930 and 2023 by the Turkish State Meteorological Service (MGM). During the summer months, temperatures tend to be higher than other seasons. From the table, it is observed that the average temperature in summer is 27.4 degrees.

Table 1 Average temperatures in Antalya.
(Source: Turkish State Meteorological Service 2024)

Month	Maximum Temperature	Minimum Temperature	Average Temperature	Average Maximum Temperature	Average Minimum Temperature
January	23.9	-4.3	10	14.9	6
February	26.7	-4.6	10.7	15.6	6.4
March	28.6	-1.6	12.9	18	8.1
April	36.4	1.6	16.4	21.4	11.3
May	41.7	4.6	20.6	25.7	15.3
June	44.8	7.1	25.3	30.7	19.7
July	45	11.1	28.6	34.2	22.8
August	44.6	14.8	28.4	34.1	22.8
September	42.5	13.6	25.3	31.2	19.5
October	41.2	10.3	20.6	26.6	15.3
November	33	0	15.5	21.3	10.9
December	25.4	-1.9	11.7	16.7	7.7

In this study, both PCM with a melting temperature of 25 °C and PCM with a melting temperature of 35 °C were selected for testing. PCM melting at 25 °C and PCM melting at 35 °C were integrated into the PV system. Initially, the performance of both PCM types was observed and evaluated. Subsequently, the PCM melting at 35 °C was integrated into the PV/T system.

CHAPTER 4

MATERIALS AND METHODS

4.1. System Design

In this study, experiments were conducted on four distinct systems: a conventional PV module, a PV-PCM system using RT25, a PV-PCM system using RT35, and a PV/T-PCM system. The layer configurations for each system are outlined in Figure 20.

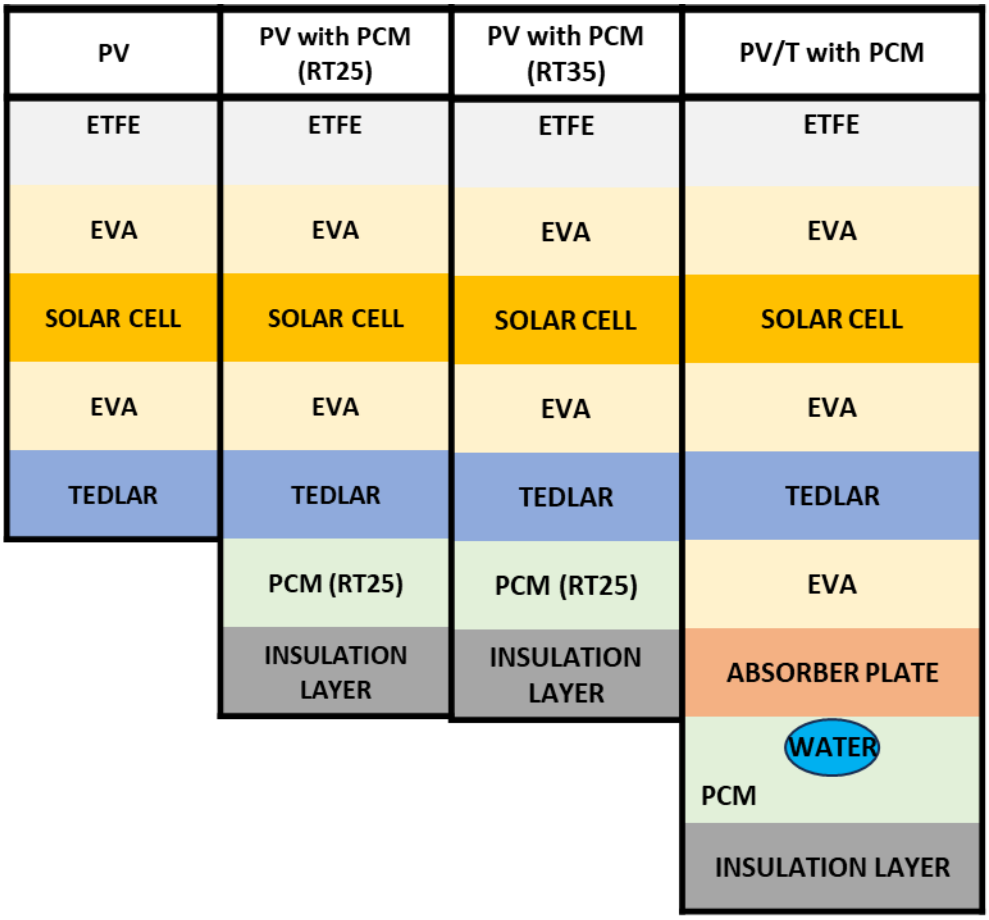


Figure 20 The specifications of four different experimental configurations.

4.1.1. PV

Each system comprises a 55-Watt photovoltaic module with dimensions of 780 mm × 450 mm. The detailed specifications are provided in Table 2.

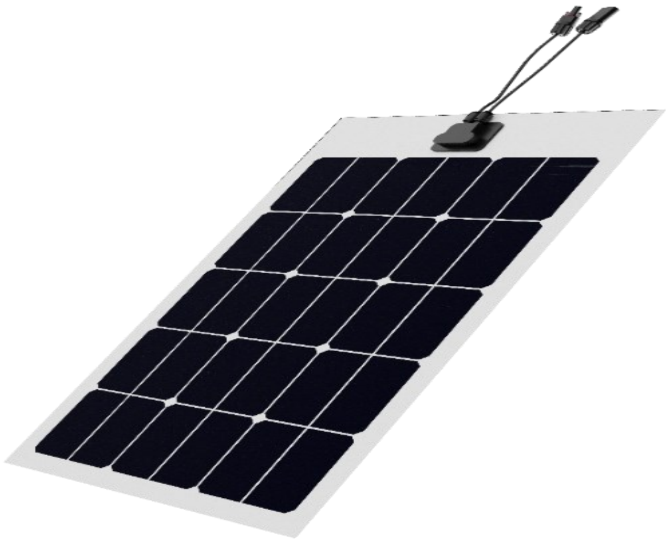


Figure 21 PV.

Table 2 Specifications of photovoltaic panel.

Specifications	Properties
Peak Power (P_{max})	55
Maximum Power Voltage (V_{mp})	18.48
Maximum Power Current (I_{mp})	2.98
Open Circuit Voltage (V_{oc})	21.6
Short Circuit Current (I_{sc})	3.19
Standard testing temperature	25°C
Standard testing solar irradiation	1000 W/m²
Standard testing air mass	1.5

The PV module comprises five layers: ETFE (ethylene tetrafluoroethylene), a backsheet layer, two layers of ethylene vinyl acetate (EVA), and silicon cells. To address the issue of weight associated with PCM and PVT systems, the PV panel was manufactured using ETFE, which significantly reduced its weight.The ETFE layer provides high light transmittance (≥90%) and lightweight properties, allowing effective sunlight penetration while protecting the underlying components. Additionally, the ETFE layer's surface is laminated with a mesh cloth at high temperatures to form a pyramid structure. Directly beneath the ETFE layer, the silicon cells are encapsulated with two layers of ethylene vinyl acetate (EVA). These EVA layers contribute to adhesion, cushioning, and environmental resilience, crucial for the module's longevity and performance. Completing the module's structure, a backsheet layer acts as a robust shield against environmental factors like moisture and mechanical stress, further improving the module's reliability.

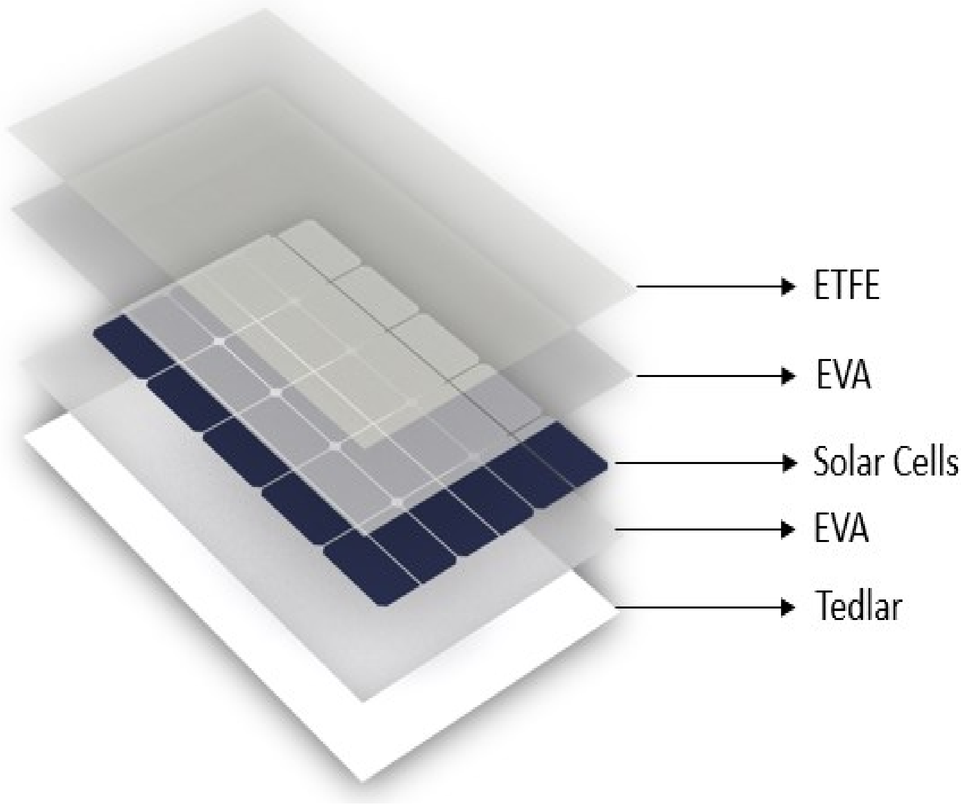


Figure 22 Components of PV.

In summary, the strategic incorporation of ETFE, combined with series-connected IBC silicon cells encapsulated in EVA and a durable backsheet, enhances light absorption, durability, and overall performance of the PV module, making it suitable for a broad range of photovoltaic applications.

The electrical connections have been repositioned to the front surface of the panel to facilitate enhanced integration of PCM on the rear side. This design modification simplifies the installation process for both PV-PCM and PV/T-PCM configurations, while also mitigating potential leakage-related concerns.

Table 3 Thermophysical properties of the materials used in PV panel.
(Source: Maadi et al. 2019; Das et al. 2020)

Layers	Thickness (mm)	Density (kg/m3)	Thermal Conductivity (W/mK)	Specific heat capacity (J/kgK)
ETFE	0.1	1700	0.24	1172
EVA	0.4	960	0.35	2090
Solar Cell	0.15	2330	100	700
Backsheet	0.31	1200	0.2	1250

4.1.2 PV-PCM

This study investigates two distinct paraffins with different melting points: one at 25°C and the other at 35°C. Both paraffins were evaluated through experimental setups to assess their performance in PV-PCM applications. Figure 23 illustrates the structural layout of the PV-PCM system. During the experiments, PCM layers with a thickness of 3 cm were utilized. The thermophysical properties of the paraffins are presented in Table 4, and the paraffins were sourced from Rubitherm.

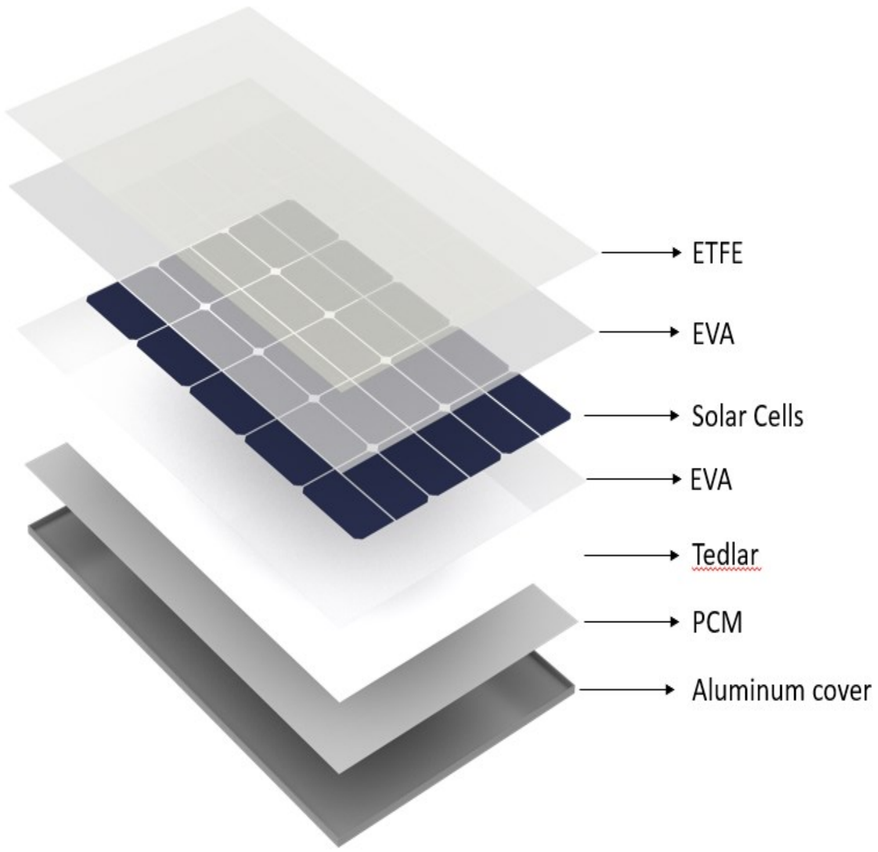


Figure 23 Components of PV-PCM.

Table 4 Paraffin thermophyscial characteristics.
(Source: Rubitherm GmbH 2024)

Properties	RT35	RT25
Melting point temperature (°C)	35	25
Heat storage capacity (kj/kg)	160	180
Liquid state density at (kg/m³)	770 (at 45°C)	760 (at 40°C)
Solid state density (kg/m³)	860 (at 15°C)	840 (at 15°C)
Thermal conductivity (W/m.K)	0.2	0.2
Flash point (°C)	165	140

Figure 24 illustrates the fabrication process of two distinct PV-PCM modules, designed to evaluate the performance of phase change materials with melting points of 25°C and 35°C. Initially, as shown in Figure 24a, an aluminum sheet is adhered to the photovoltaic panel using silicone sealant, forming a base for the subsequent integration of the PCM. In Figure 24b, the PCM is applied to the panel's surface, where it helps absorb excess heat and regulate the module's temperature. A flat aluminum sheet is then placed over the PCM, as depicted in Figure 24c, to provide structural support and prevent leakage, ensuring the stability and effective heat distribution. Finally, as illustrated in Figure 24d, a Bizofol ABA bubble aluminum insulation layer is applied to enhance the module's thermal resistance, thereby improving its overall efficiency and durability under operational conditions.

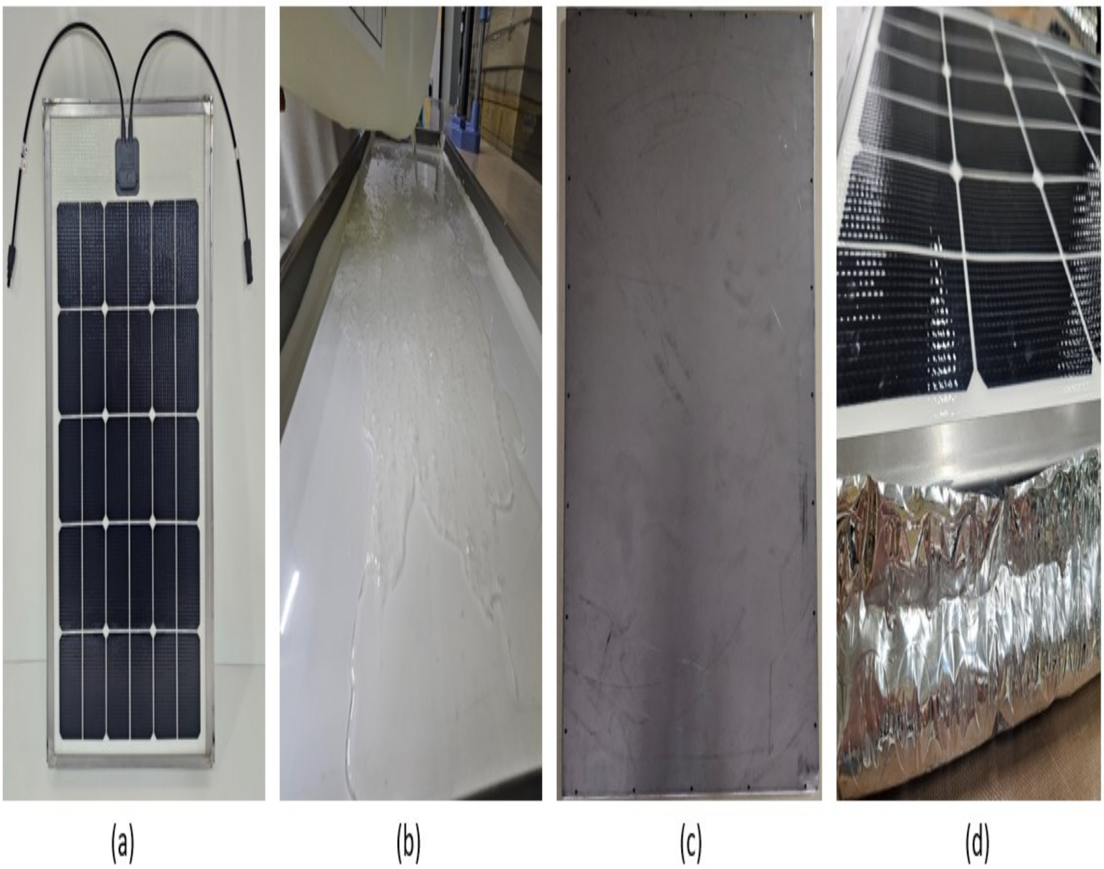


Figure 24 Manufacturing process of PV-PCM.

4.1.3. PV/T-PCM

Figure 25 shows the structure of the PV/T-PCM systems.

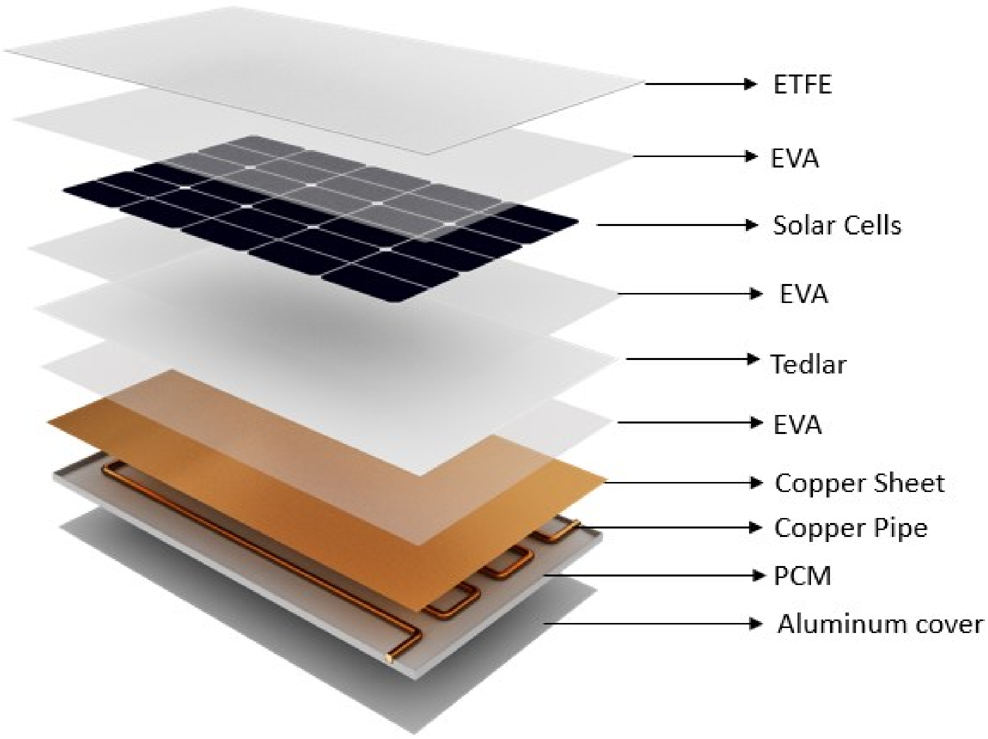


Figure 25 Components of PV/T-PCM.

In the PV/T design, EVA was added beneath the Tedlar layer to create an effective bond between the Tedlar and the thermal absorber copper sheet, which measures 780 mm × 450 mm and has a thickness of 0.5 mm. EVA lamination significantly reduces the thermal resistance between the PV layer and the thermal absorber while also eliminating potential issues such as adhesive thickness. This configuration enhances the module's durability while also improving thermal conductivity. The EVA layer, with its high adhesive strength, establishes a strong connection between the Tedlar and the copper sheet, optimizing heat transfer.

For this experimental investigation, copper pipes were chosen due to their superior heat conduction properties. These pipes were attached to the back of the panel. Each pipe measures 4527mm in length, with a diameter of 12.7mm and a thickness of 1 mm. The distance between the two neighboring sections of the copper pipe loop was maintained at 53 mm. Following these preparations, the PCM was applied to the back side of the panel, completing the assembly process, as shown in Figure 26. The PCM material used was Rubitherm RT35, which features a melting range of 32℃–38℃ and a latent heat with storage capacity of 160 kJ/kg, specific heat capacity 2 kJ/kg.K, thermal conductivity, 0.2 W/m.K.

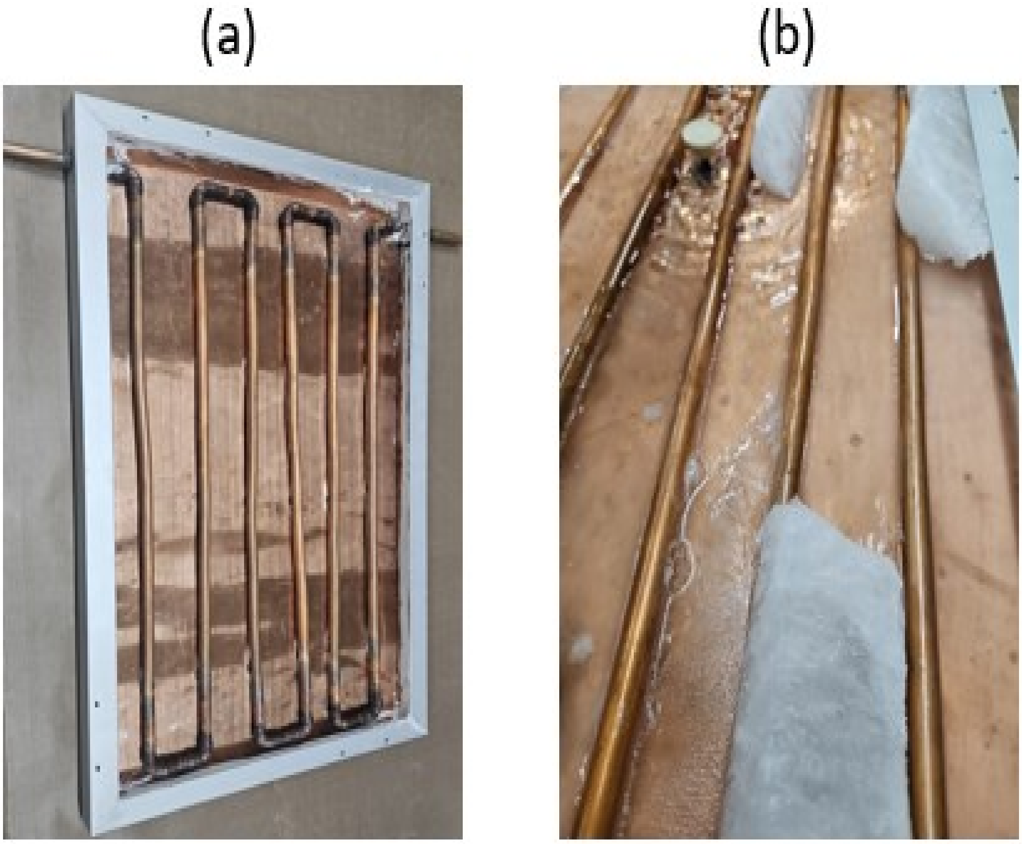


Figure 26 (a) Fixing copper pipes (b) Pouring PCM.

A 24V pump with a maximum flow rate of 0.9lt/dk is utilized to circulate the fluid throughout the panels in the PV/T-PCM system.

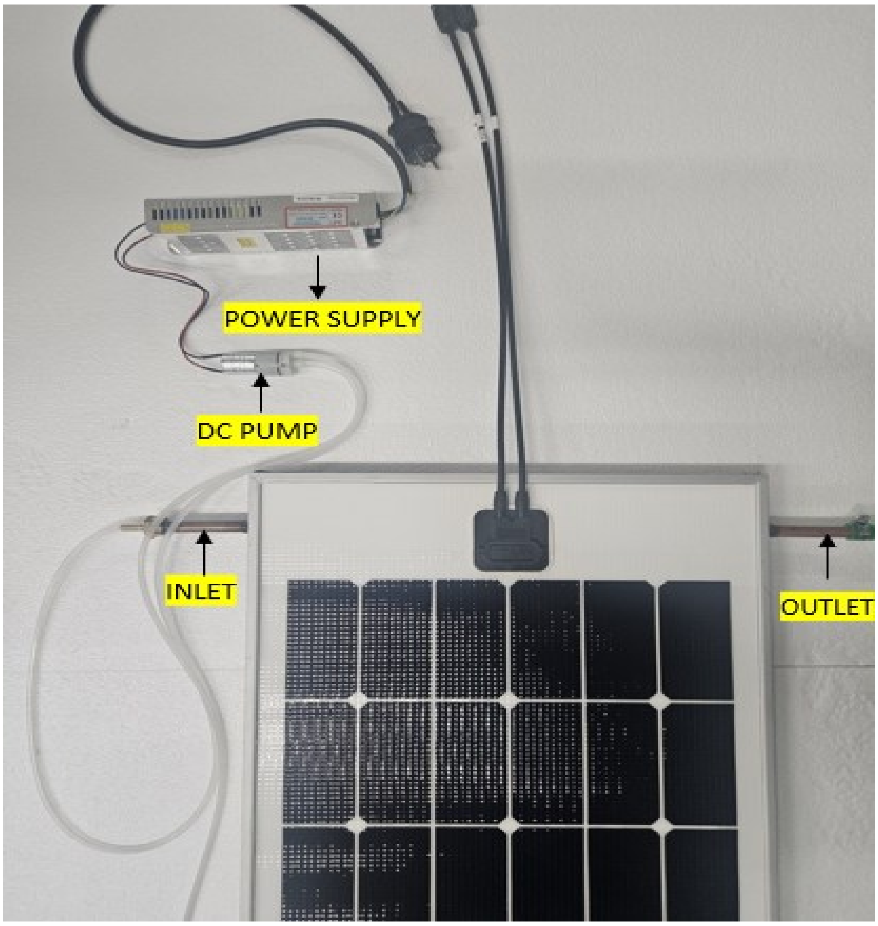


Figure 27 PV/T.

4.2.Experimental set up

The experiments were conducted in two distinct phases. In the first phase, the performance of photovoltaic (PV) panels integrated with phase change materials (PCMs) that melt at 25°C (RT25) and 35°C (RT35) was evaluated. The tested configurations included PV-PCM35 and PV-PCM25, and their performance was evaluated against standard PV panels without PCM. In the second phase, the performance of the water-cooled photovoltaic-thermal system integrated with PCM was assessed relative to the standard PV system.

Figure 28 Picture of the first phase of experimentation.

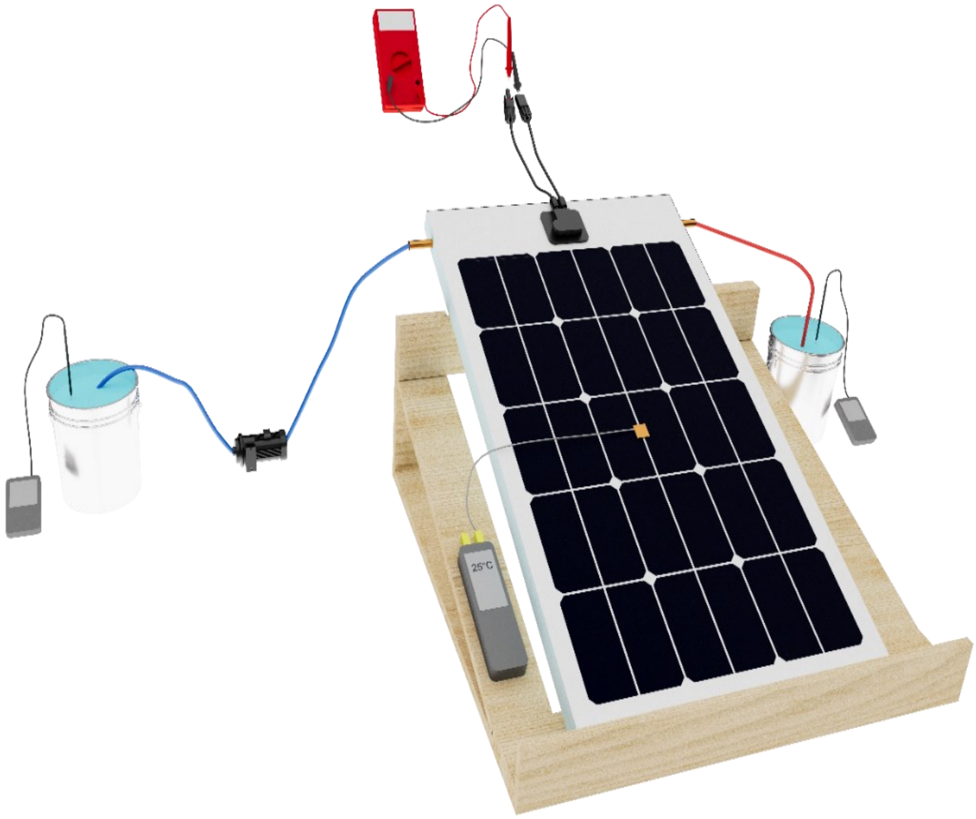


Figure 29 Picture of second phase of experimentation.

4.2.1. Test location

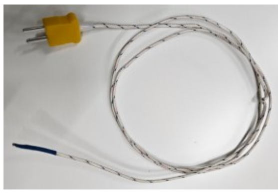
The experimental setup, shown in Figure 30, was constructed using a wooden frame to achieve a 20-degree tilt for the panels. This design ensures that the panels are positioned at the desired angle for optimal performance testing. The wooden frame provides a stable base for the panels, allowing for consistent testing conditions during the experiments conducted in Antalya, Turkey, at the geographic coordinates of 36°53′N, 30°42′E.

Figure 30 Experimental Setup with 20-Degree Tilt Angle for Photovoltaic Modules.

4.2.2. Experimental Measurements

During the experiments, several variables were monitored, including the surrounding air temperature, the temperature of the PV module, the intensity of solar radiation, the current at short circuit, the voltage at open circuit, and the temperature of the water. These various measurements are crucial for comprehending the thermal and electrical characteristics of the photovoltaic module, as well as how weather conditions affect its performance. Comprehensive information regarding the experimental apparatus utilized in the investigation is presented in Table 5.

Table 5 Experimental device information.

Name of equipment	Equipment types	Measuring Range	Pictures
Solarirradiance meter	200R	100 – 1250 W/m2	
Temperature sensor	200R	-30°C to +125°C	
Thermocouple	K-type	-50°C +250°C	
Data acquisition	DT-3891G	-200 to +1372°C	
PT100	KIMO 310	-200 to +600°C	
Voltmeter	UT 89X	600mV - 1000V	
Ammater	UT 89X	60µA - 20A	

4.2.3. Uncertainty analysis

Experimental errors may arise from various sources, including human errors, instrumentation setup, measurement device inaccuracies, and environmental factors (Hassan and Abo-Elfadl 2017). The measurement error for the equipment utilized in the experiment is detailed in Table 6, as specified in the technical documentation provided by the manufacturers.

The uncertainty in experimental results was calculated using Equation (4.1):

$$W_R = \left(\frac{\partial R}{\partial x_1} w_1\right)^2 + \left(\frac{\partial R}{\partial x_2} w_2\right)^2 + \cdots + \left(\frac{\partial R}{\partial x_n} w_n\right)^2 \qquad \textbf{(4.1)}$$

Table 6 Uncertainty analysis

Sensor Type	Measurement Error
Ammeter	±(0.5% + 2)
Voltmeter	±(0.8% + 2)
Solar irradiance meter	1
Thermocouple	0.1
PT100	0.1

4.2.4. Calculation of systems performance

The efficiency of a photovoltaic (PV) module is defined as the ratio between the electrical energy produced and the total energy incident on its effective surface area. This relationship can be mathematically expressed in equation (4.2):

$$\eta_{el} = \frac{P_{out}}{P_{in}} = \frac{V_{OC} \times I_{SC} \times FF}{G \times A} \quad \textbf{(4.2)}$$

where G denotes the solar irradiance reaching the PV panel, and A represents the panel's surface area.

The formula for determining the degree of electrical efficiency improvement is as follows (Akrouch et al. 2023) :

$$\eta\% = \frac{\eta\%(Cooled\ PV) - \eta\%(Standard\ PV)}{\eta\%(Standard\ PV)} \quad \textbf{(4.3)}$$

The thermal performance equation specific to PV/T systems can be found in reference (Kazem 2019):

$$\eta_{th}\% = \frac{\dot{m}c_p(T_o - T_{i)}}{G \times A} \times 100 \quad \textbf{(4.4)}$$

where A represents the collector area, $\dot{m}$ is the mass flow rate, c_p is the specific heat (J/kg.K) and T_o and T_i are outlet and inlet fluid temperature, respectively.

The total efficiency of the system is expressed as the sum of electrical and thermal efficiencies, given by:

$$\eta_{(PV/T-PCM)} = \eta_{electrical} + \eta_{thermal} \quad \textbf{(4.5)}$$

CHAPTER 5

RESULTS AND DISCUSSIONS

This study examined the integration of photovoltaic (PV) panels with phase change materials (PCMs) in two phases. In the first phase, the performance of PV panels integrated with PCMs that melt at 25°C (RT25) and 35°C (RT35) was analyzed and compared to standard PV panels. In the second phase, the efficiency of the water-cooled photovoltaic-thermal (PVT) system integrated with PCM was evaluated against that of the conventional PV system. The results obtained are presented in the following graphs.

5.1. First phase of experimentation

Initial experiments were conducted between July and August of 2024. Figure 31 shows the ambient temperature and solar radiation data for 9 August 2024. The observed solar radiation intensity reached its zenith at 962 W/m² during the specified period, accompanied by ambient temperature readings ranging from 32°C to 41°C.

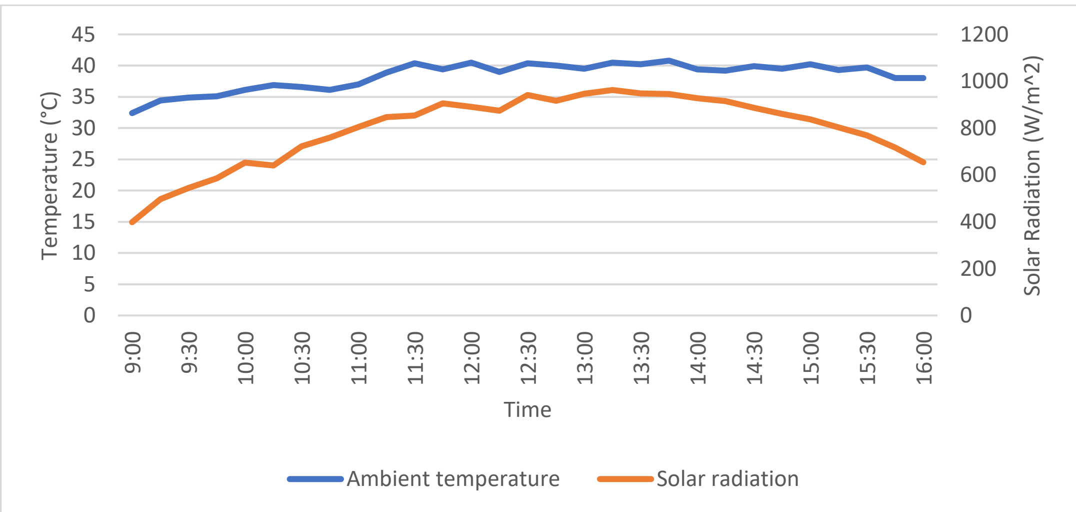


Figure 31 Ambient temperature, solar radiation.

5.1.1. Surface temperatures

Figure 32 presents the ambient temperature, reference module panel temperature, and the temperatures of PV-PCM35 and PV-PCM25 systems over the period from 9:00 to 16:00 on August 9, 2024. The results show that the standard PV panel reached the highest temperatures throughout the day, exceeding 70°C, especially during midday. These elevated temperatures lead to thermal losses in PV panels, resulting in reduced efficiency. In contrast, PV panels integrated with PCMs operated at lower temperatures compared to the standard panel, providing effective cooling.

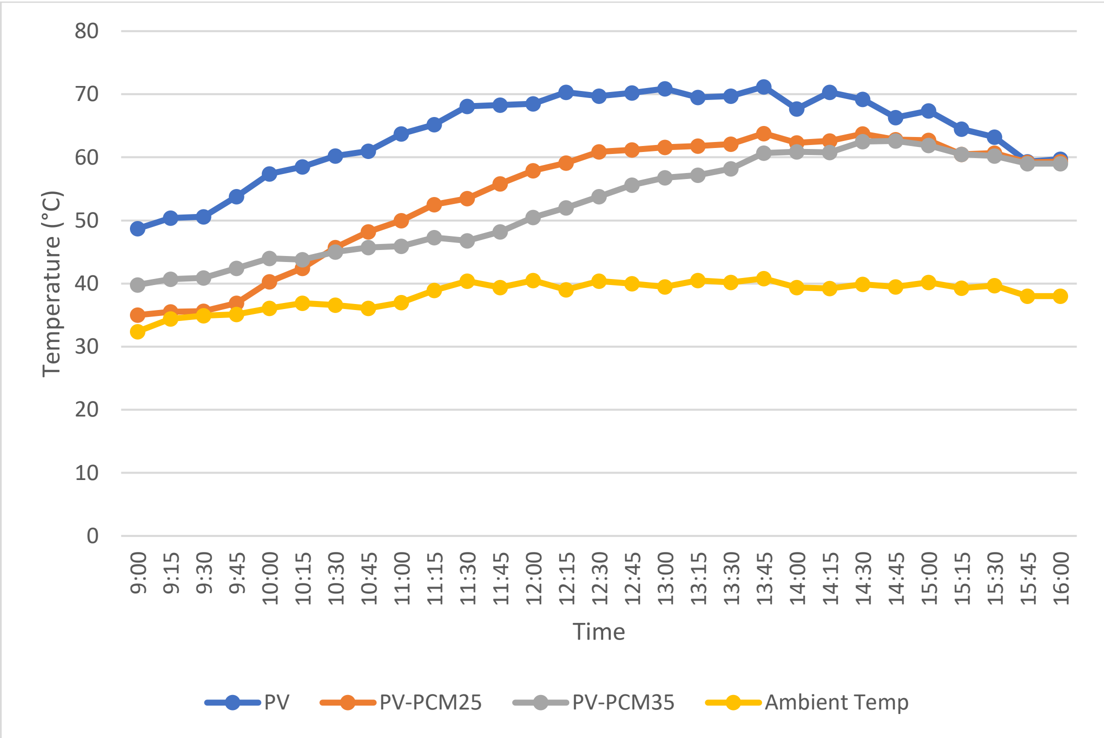


Figure 32 Variation of temperature of PV, PV-PCM25 and PV-PCM35 systems with the time.

The findings indicate that the conventional PV panel's temperature peaked at 71.2°C around 13:45, then steadily declined to 59.7°C by the experiment's conclusion, with an average temperature of 63.9°C throughout the day. In contrast, the PV-PCM35 system peaked at 62.5°C and decreased to 59°C, with a daily average of 52.5°C, while the PV-PCM25 system reached up to 63.8°C and ended at 59.3°C, with a daily average of 54.3°C. The data reveals that the PV-PCM35 configuration exhibited an 11.4°C decrease in average temperature compared to the standard PV panel, while the PV-PCM25 system demonstrated a 9.7°C reduction. Additionally, the greatest temperature variance between the conventional PV panel and the PV-PCM35 was observed to be 21.3°C at 11:30, indicating a peak temperature reduction of 31.28%. At 10:00, the PV panel and PV-PCM25 exhibited the most significant temperature contrast of 17.1°C, indicating a peak temperature reduction of 29.79%.

The PV-PCM25 system incorporated a phase change material with a 25°C melting point, which effectively constrained temperature escalation from the early stages of the day. This PCM, characterized by its low melting temperature, swiftly transitioned phases, demonstrating efficient heat absorption capabilities. However, because of this low melting point, the material lost its heat storage capacity as midday approached, diminishing the cooling effect and causing the temperature of PV-PCM25 to rise close to that of the standard PV panel in the afternoon. Conversely, in the PV-PCM35 system, the PCM with a melting point of 35°C absorbed heat for a longer period and transitioned to phase change at a higher temperature, allowing the panel to maintain more stable temperatures, especially around midday, providing more effective thermal regulation. The extended cooling effect offered by PV-PCM35 enabled better thermal management, particularly during the peak midday heat. The results highlight the crucial importance of PCM melting temperature in enhancing PV panel thermal regulation, demonstrating the effectiveness of PCM integration in reducing PV panel temperatures and mitigating efficiency losses due to thermal effects during peak irradiance hours.

5.1.2. Output voltage

Figure 33 presents the distribution of open circuit voltage measured during the experimental period, which extended from 09:00 to 16:00. The peak voltage did not coincide with the highest solar irradiance. The output voltage started to decrease despite the increase in solar radiation.

An examination of the figure reveals a consistent inverse relationship between the PV panel's voltage and solar radiation levels throughout the day. Starting from the morning, as radiation rises, the open-circuit voltage (Voc) of the standard PV panel steadily declines. This illustrates how higher radiation levels and increasing temperatures contribute to a gradual reduction in voltage over time.

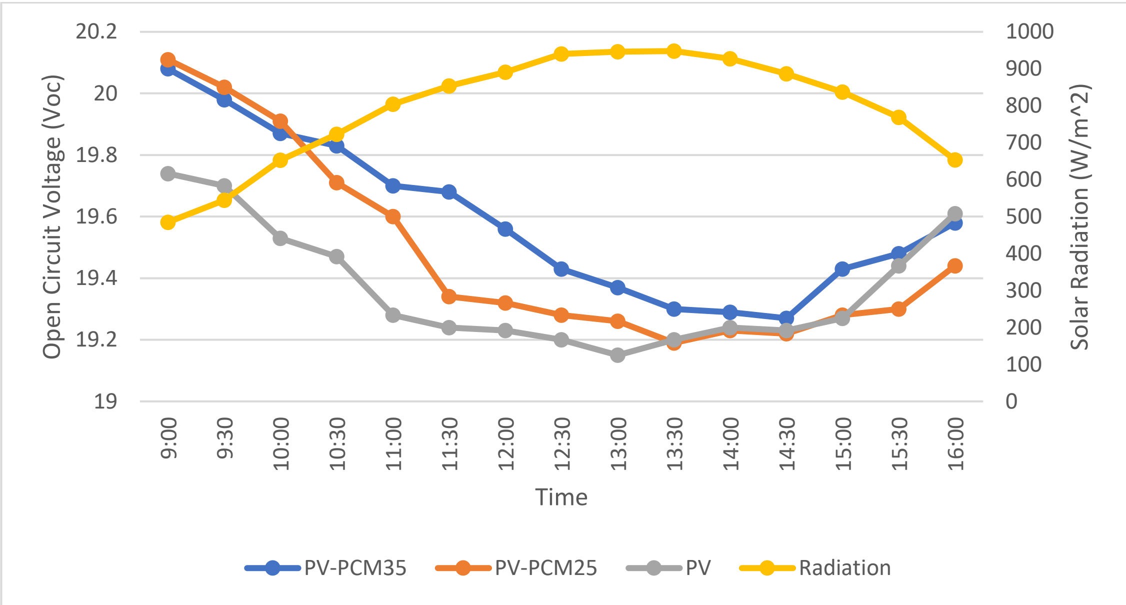


Figure 33 Impact of Solar Radiation on Open Circuit Voltage (Voc).

The maximum output voltage difference between the PV panel and the PV-PCM35 configuration was measured as 0.44 V at 11:30, resulting in a maximum increase of 2.29% in PV voltage. Similarly, the maximum output voltage difference between the PV panel and the PV-PCM25 configuration was 0.38V at 10:00, indicating a maximum increase of 1.95% in PV voltage.

On average, the PV panel recorded a voltage of 19.34 V, while the PV-PCM35 recorded 19.56 V and the PV-PCM25 recorded 19.44 V. This represents a 0.22 V difference between the standard PV panel and the cooled configurations, translating into a 1% improvement in voltage for the cooled panels.

5.1.3. Short circuit current

Figure 34 presents the distribution of current measured during the experimental period, which extended from 09:00 to 16:00. The results indicate a clear correlation between increasing solar radiation and a rise in current.

The maximum measured current value was recorded at 13:30, reaching 3.04 A, with solar radiation of 948 W/m². In contrast, the minimum current value was noted at 09:00 PM, measuring 1.56A, with solar radiation of 485 W/m².

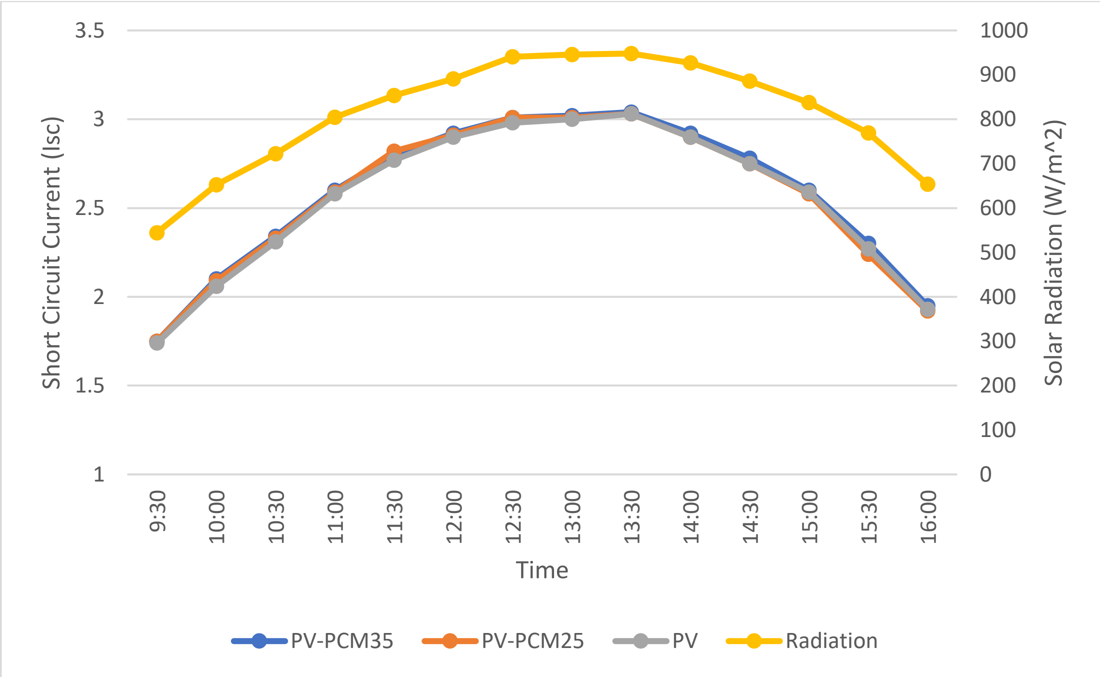


Figure 34 Impact of Solar Radiation on short circuit current (Isc).

Based on the Figure 34, it appears that the temperature of the panel has minimal impact on the short-circuit current (Isc). While the short-circuit current increases with rising solar radiation across all panel types, there is no significant difference in the rate of increase between the standard PV panel and the PCM-containing panels (PV-PCM35 and PV-PCM25).

5.1.4. Power output

Figure 35 illustrates the output power comparison of PV, PV-PCM25 and PV-PCM35 modules. It is clear that as the solar irradiance increases, the power output of the PV modules increases proportionally. The experimental results revealed that the PV-PCM35 panel exhibited a mean power enhancement of 0.8 W in comparison to the conventional PV panel. The peak differential in power output was recorded at 1.45 W. This indicates that the electrical power of the PV-PCM35 configuration is approximately 3.28% higher than that of the conventional PV panel. The PV-PCM25 panel demonstrated a notable improvement in performance, with an average power increase of 0.34 W and a peak power output differential of 1.10 W. These findings indicate that the PV-PCM25 configuration achieved an electrical power enhancement of around 3.40% relative to the standard PV panel.

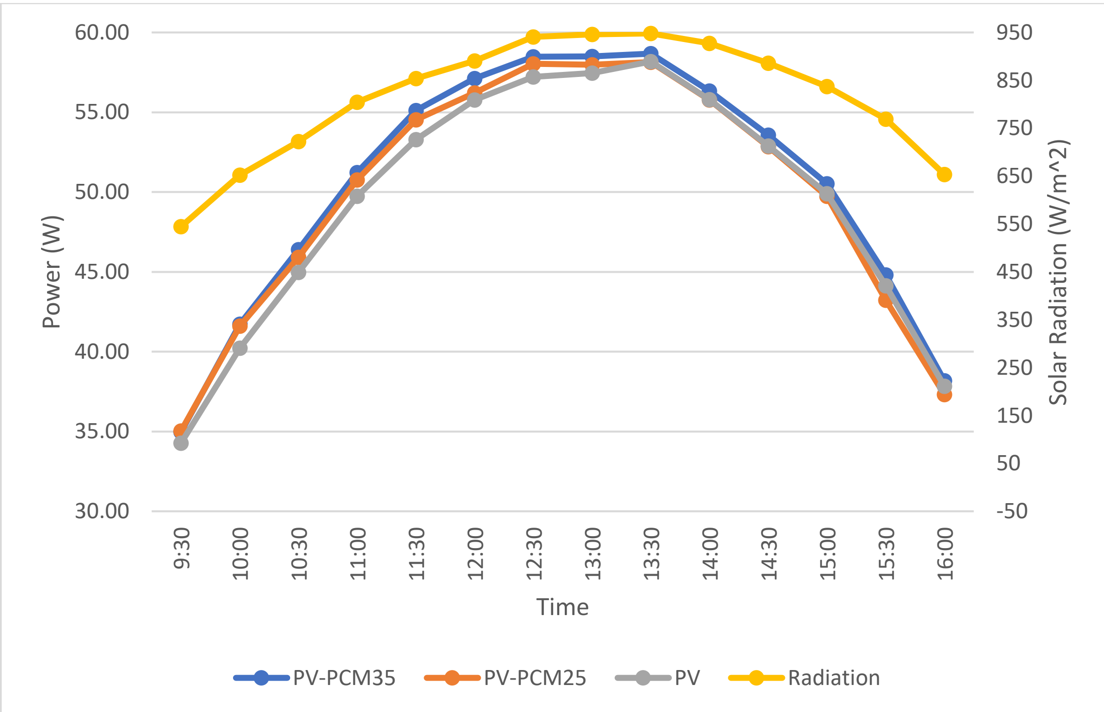


Figure 35 Impact of solar radiation on power.

5.1.5. Electrical efficiency

Figure 36 illustrates the electrical efficiency comparison between the PV, PV-PCM25 and PV-PCM35 modules. The maximum efficiencies were recorded in the morning.

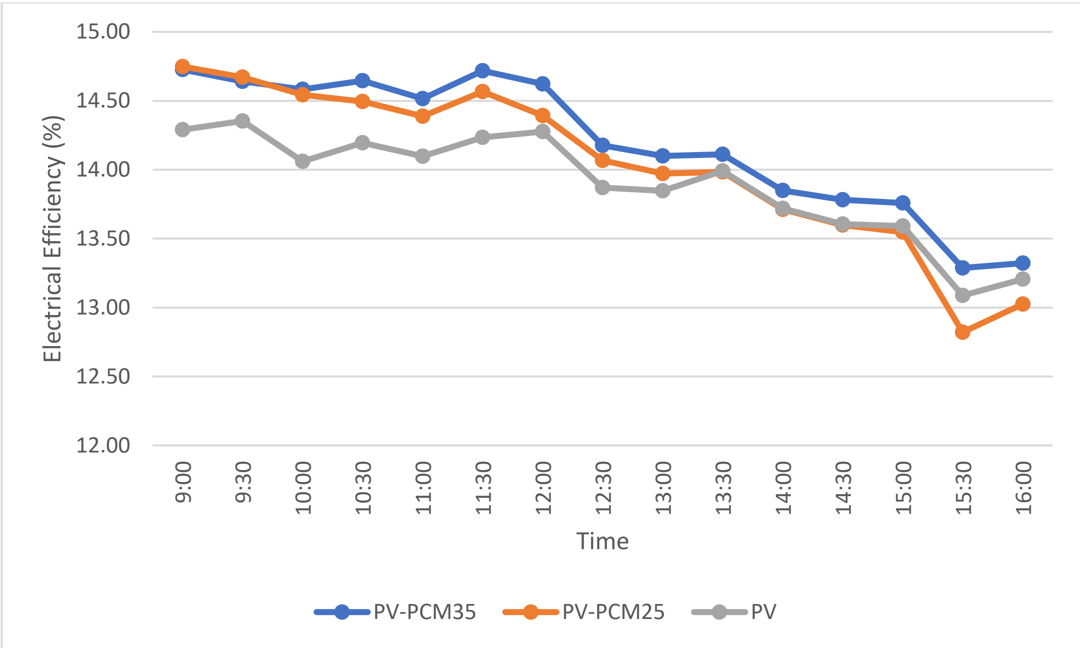


Figure 36 Impact of time on electrical efficiency.

The PV system demonstrated an average electrical efficiency of 13.89%, whereas the PV-PCM35 system exhibited an electrical efficiency of 14.19%. This represents a mean improvement of 2.16% in electrical efficiency for the PV-PCM35 system compared to the standard PV system. Furthermore, the maximum electrical efficiency of the PV-PCM35 system was 3.72% higher than that of the conventional PV panel. Similarly, the PV-PCM25 system achieved an electrical efficiency of 14.04%, representing an average increase of 1.01% in electrical efficiency, with its maximum electrical efficiency being 3.43% higher than that of the conventional PV panel.

5.2. Second phase of experimentation

The second phase of experimentation was conducted at the same location between 19 September 2024 and 2 October 2024.

5.2.1. Surface Temperatures

Figure 37 shows the ambient temperature, PV temperature, and the temperature variations of PV/T-PCM systems measured between 9:00 and 16:00 on 2 October 2024.

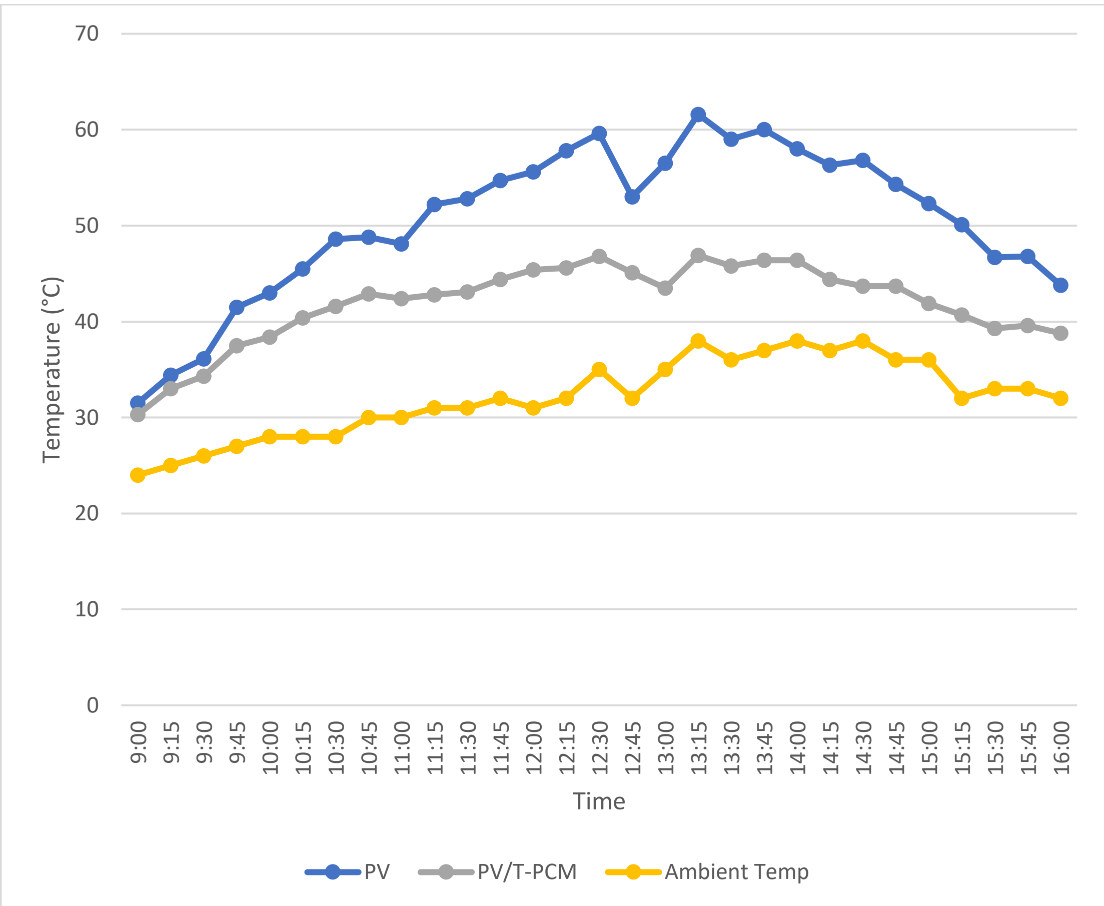


Figure 37 Temperature of PV and PV/T-PCM.

The Figure 37 highlights the increase in cell temperature relative to the ambient temperature. An average temperature decrease of 8.63°C was noticed between the PV and the PV/T-PCM. The largest temperature difference recorded between the PV panel and PV/T-PCM was measured to be 14.7°C at 13:15. This technique causes 23.86% maximum decrease in PV panel temperature.

5.2.2. Output voltage

At 13:15, the highest voltage differential observed between the PV panel and PV/T-PCM was recorded as 0.47V. This approach results in a maximum voltage enhancement of 2.35% for the PV system.

The data collected shows that the PV/T-PCM system recorded a mean voltage of 20.58V, while the PV system registered a slightly lower average of 20.30V. This translates into a difference of 0.28V, representing 1.36% improvement in PV/T-PCM.

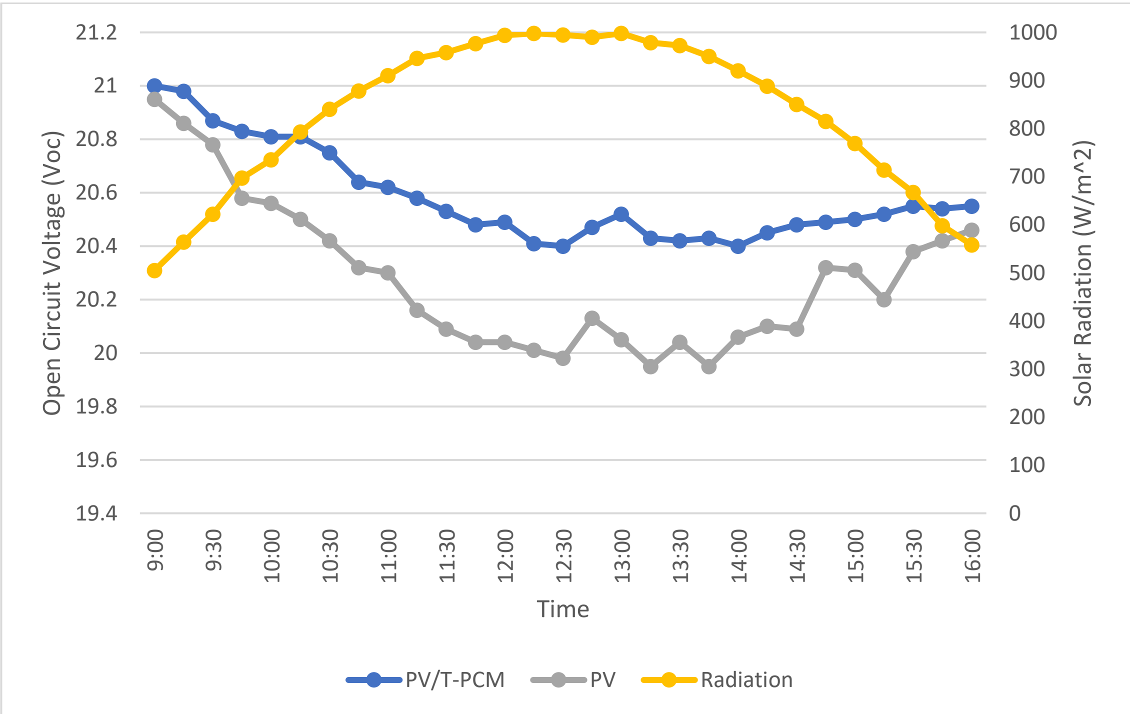


Figure 38 Impact of solar radiation on open circuit voltage (Voc).

5.2.3. Short circuit current

Figure 39 presents the distribution of current measured during the experimental period, which extended from 09:00 to 16:00. The results demonstrate a significant correlation between increased solar radiation and an elevation in current.

The maximum measured current value was recorded at 12:15, reaching 3.1 A, with solar radiation of 998 W/m². In contrast, the minimum current value was noted at 09:00 ,measuring 1.58A, with solar radiation of 505W/m².

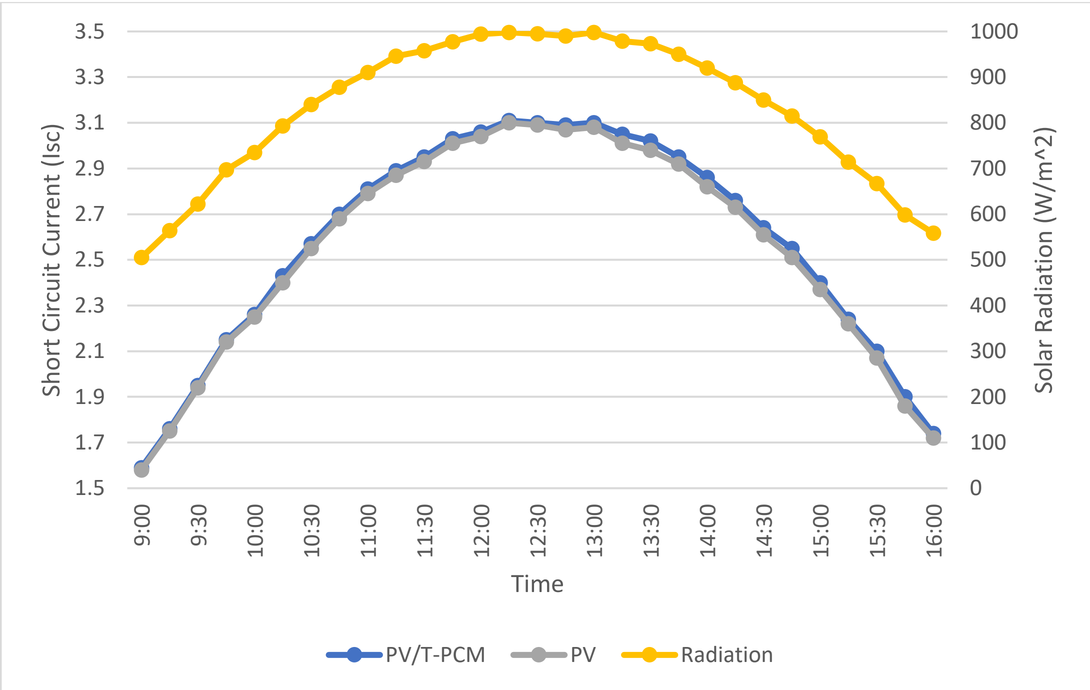


Figure 39 Impact of solar radiation on short circuit current (Isc) for PV and PV/T-PCM.

5.2.4 Power Output

Figure 40 presents a comparison of power output between PV modules and PV/T-PCM35 modules. It is clear that as the global solar irradiance intensity increases, the power output of the PV modules rises proportionally. The maximum output power of the PV/T-PCM system was recorded as 50.89 W at 13:00, while the minimum output power was 26.7 W at 09:00. The difference in peak power output was measured as 1.81 W. This indicates that the electrical power generated by water-based PV/T collectors is approximately 3.77% higher compared to conventional PV panels. On average, the PV/T system produces 1.05 W more electricity than standard PV systems.

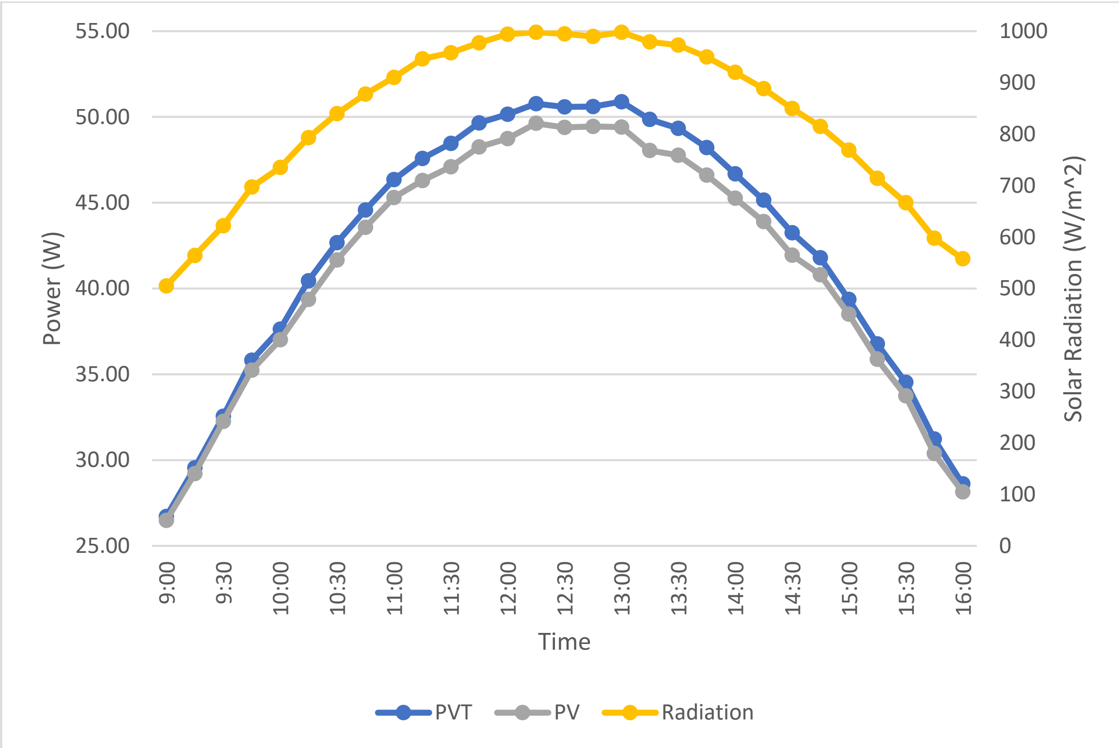


Figure 40 Impact of solar radiation on power.

5.2.5 Electrical efficiency

Figure 41 presents a comparison of the electrical efficiency between PV modules and PV/T-PCM35 modules. The highest efficiencies were observed during the morning hours.

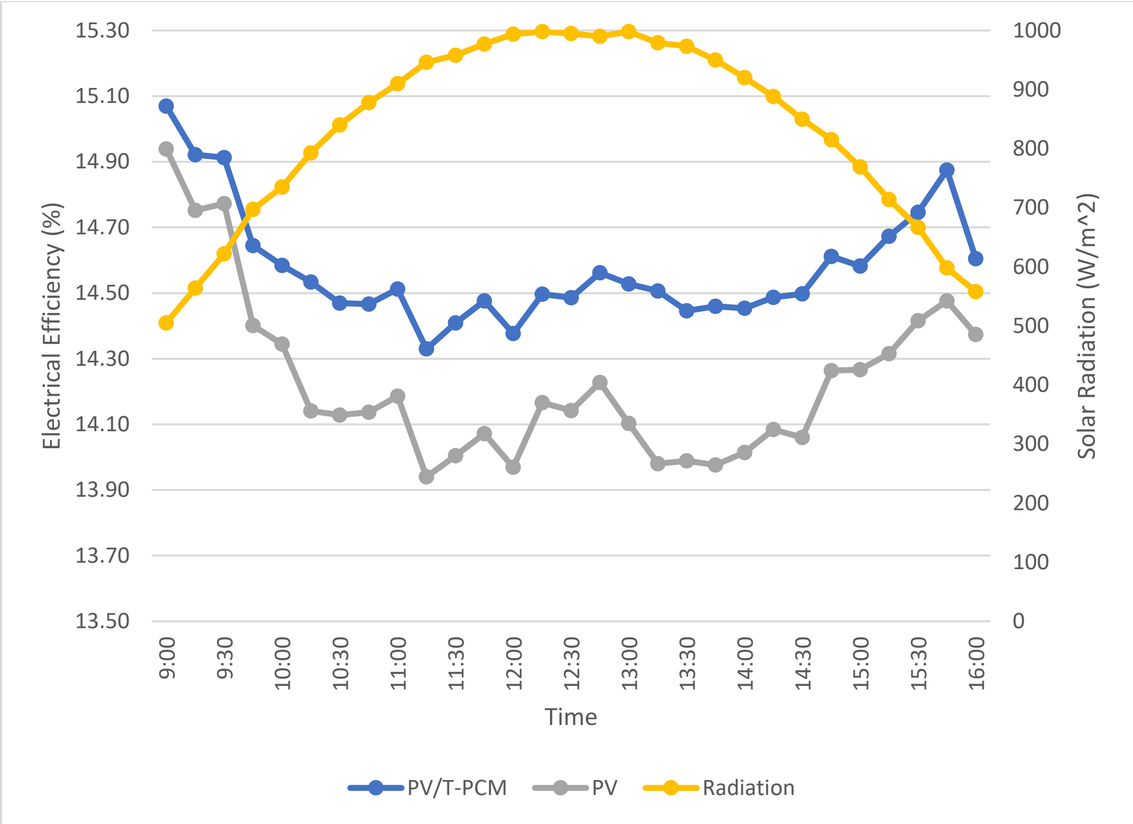


Figure 41 Electrical efficiency.

The PV system demonstrated an average electrical efficiency of 14.23%. In contrast, the PV/T-PCM system exhibited an electrical efficiency of 14.58%, indicating a mean improvement of 2.46% in electrical performance for the PV/T-PCM configuration. Moreover, water-based PV/T collectors demonstrated a 3.79% higher peak electrical efficiency compared to traditional PV panels.

5.2.6. Thermal efficiency

Figure 42 depicts the daily fluctuations in thermal power and fluid temperature. The thermal gradient between the collector's inlet and outlet reached its zenith at 3.5°C, coinciding with peak solar irradiance. The average temperature disparity observed was 2.4°C.

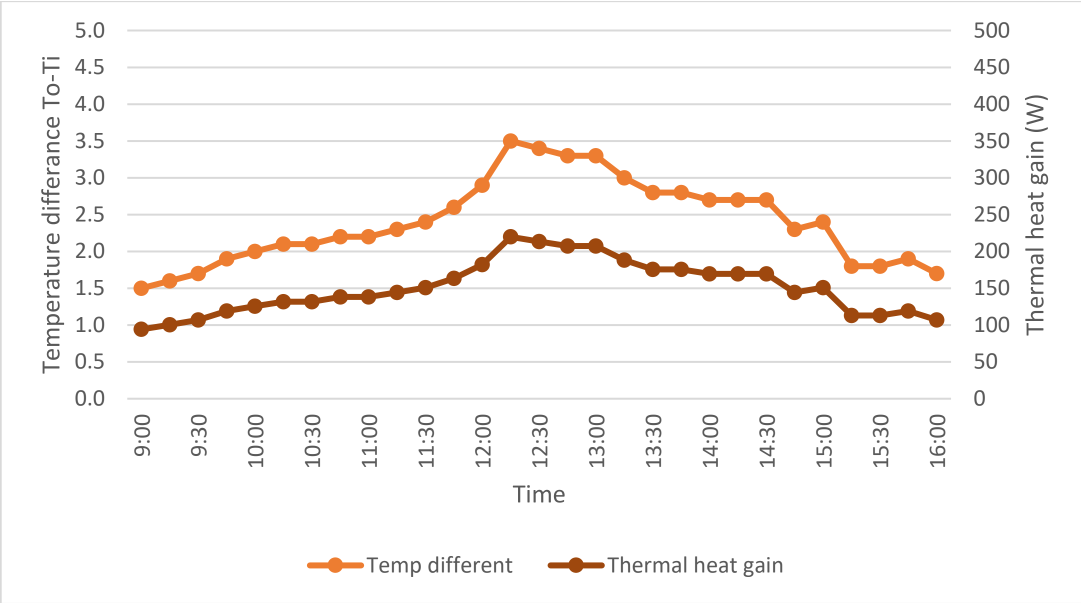


Figure 42 Inlet and outlet temperature difference and heat gain over time.

The maximum thermal energy obtained was 220 Watts at 12:15, with an average of 151 Watts in the PVT system. The system achieved a maximum thermal efficiency of 62.74%, while the average efficiency was measured at 51.55%.

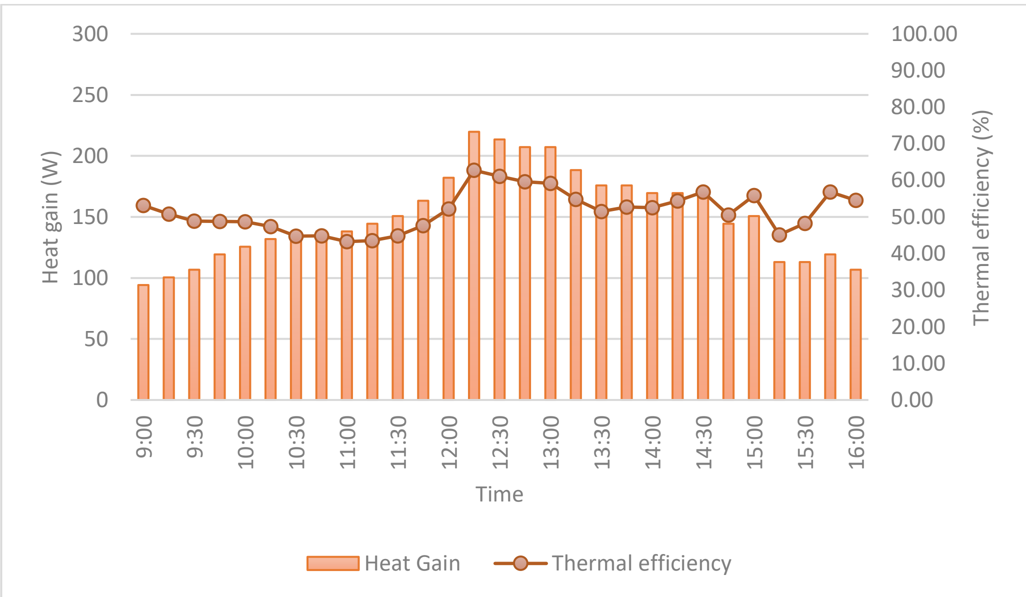


Figure 43 Thermal analysis of PV/T system.

5.2.7. Overall efficiency

Figure 44 illustrates the net power of the PVT system, calculated by subtracting the power consumed by the pump from the combined electrical and thermal power. The variations in power over time reflect the influence of solar radiation and environmental conditions, offering insights into the system's efficiency. The highest net power is observed at midday, when solar radiation reaches its peak.

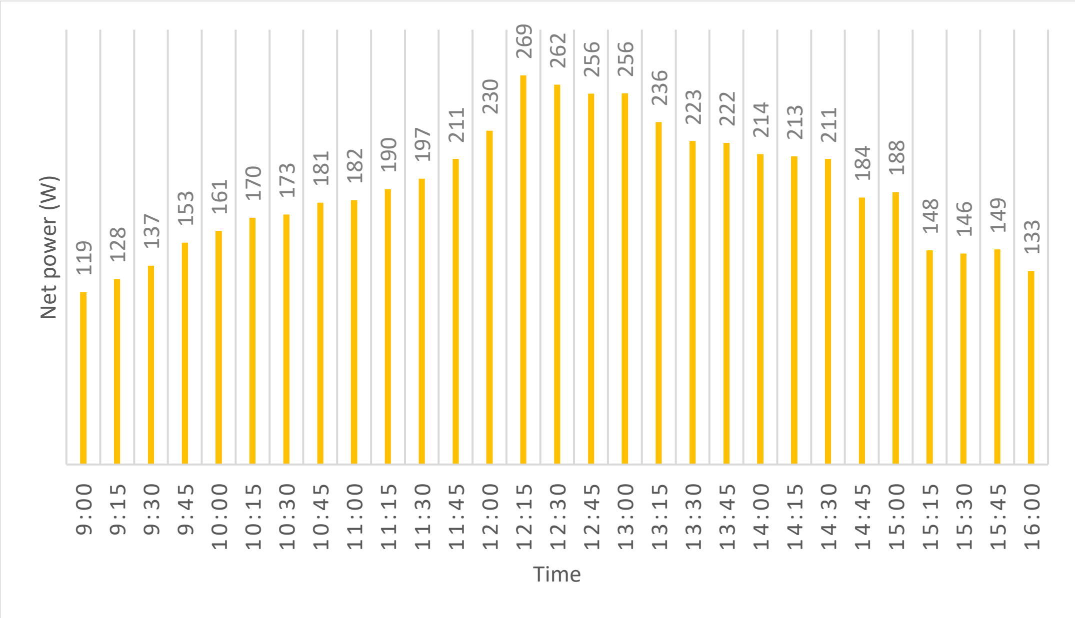


Figure 44 Hourly Variation in Net Power of the PVT System.

Figure 45 illustrates the overall efficiency of the PV/T-PCM system throughout the day. The efficiency is calculated by summing the total electrical and thermal power produced by the system and then dividing by the total incident solar energy and the area of the panel. The highest efficiency of 77.23% was observed at 12:15 PM, which coincides with the peak solar radiation. This time period shows the optimal performance of the system, reflecting the maximum energy conversion efficiency achieved by the combined electrical and thermal output.

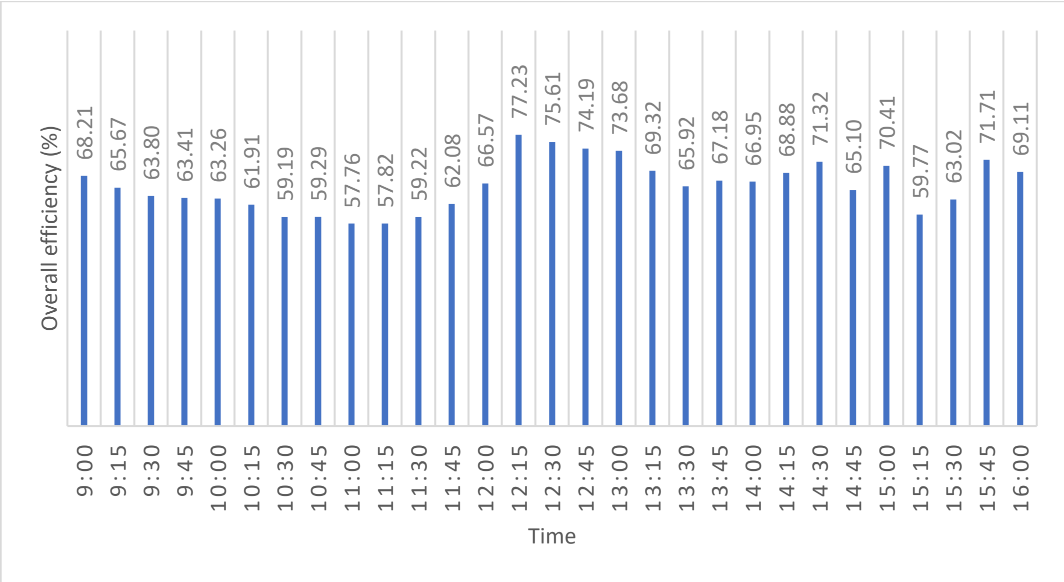


Figure 45 Overall Efficiency in the PV/T-PCM System.

The PV/T-PCM system's daily average efficiency, combining both electrical and thermal contributions, is presented in Figure 46. The recorded daily mean efficiencies for electrical, thermal, and total energy outputs are 14.58%, 51.55%, and 66.13%, respectively. It is seen that the overall efficiency of the PV/T-PCM system is higher than PV system by 51.9%

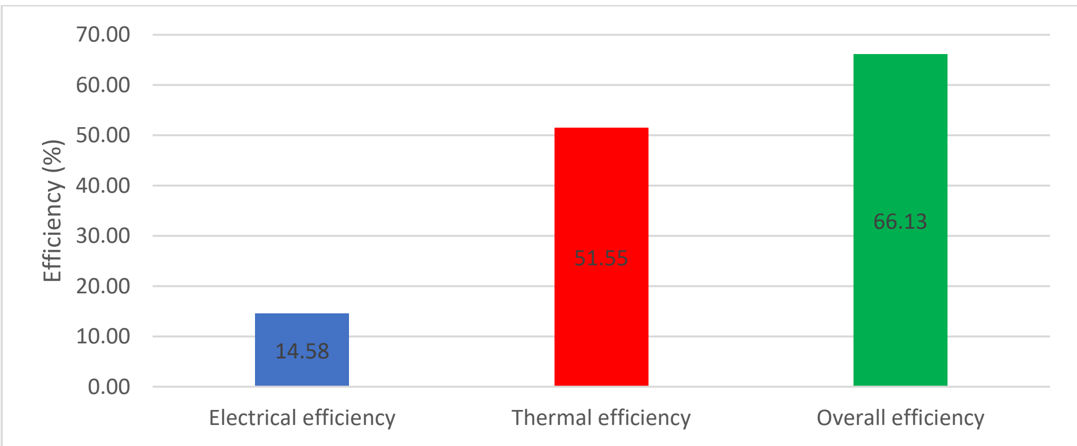


Figure 46 Daily mean of thermal, electrical and overall energy efficiencies of PV/T-PCM.

CHAPTER 6

CONCLUSION

This study investigated the performance of photovoltaic (PV) panels integrated with phase change materials (PCMs) in two distinct phases. In the first phase, the performance of PV panels integrated with PCMs that melt at 25°C (PV-PCM25) and 35°C (PV-PCM35) was evaluated in comparison to conventional PV panels. The findings from this phase demonstrate significant differences in performance. The PV-PCM25 panel, characterized by its lower melting temperature, showed superior thermal regulation capabilities during the initial hours of the day. However, as ambient temperatures rose, its effectiveness diminished. Conversely, the PV-PCM35 panel performed effectively throughout the day, especially under higher ambient temperatures. It achieved a maximum temperature reduction of 21.3°C, compared to the 17.1°C reduction of PV-PCM25. On average, the PV-PCM35 panel provided a temperature reduction of 11.4°C, leading to improvements in both power output and efficiency.

The electrical efficiency of PV-PCM35 showed an average of 14.19%, representing a 2.16% increase over standard PV panels, with a maximum efficiency gain of 3.72%. In comparison, PV-PCM25 demonstrated a 1.01% average efficiency increase, with a maximum gain of 3.43%. These findings underscore the importance of selecting a PCM based on environmental conditions. In hot climates like Antalya, where temperatures remain high throughout the day, the PCM with a 35°C melting point (PV-PCM35) proves to be more effective for thermal regulation and overall system performance.

In the second phase of the study, the performance of a water-cooled photovoltaic-thermal (PV/T) system integrated with PCM was evaluated against a conventional PV system. Results demonstrated that the PV/T system outperformed the conventional PV system in both electrical and thermal efficiencies. The water-cooling mechanism ensured effective thermal regulation, preventing overheating and improving overall performance. The PV/T system showed a 2.46% average increase in electrical efficiency, with a maximum gain of 3.79%, alongside a remarkable 62.74% improvement in thermal efficiency. These results highlight the dual-benefit nature of the system, making it a promising solution for enhancing both electrical and thermal performance in PV applications.

In conclusion, this study demonstrates that while PCM with a 25°C melting point provides benefits in the early part of the day, PCM with a 35°C melting point offers superior overall performance in hot climates. Moreover, integrating PCM with a PV/T system enhances both electrical and thermal efficiencies, emphasizing the potential of such systems for sustainable energy solutions in high-temperature regions.

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