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Enhancing Photovoltaic Cell Performance Using Heat Sink and Composite Phase

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بسم الله الرحمن الرحيم

Dedication

To those who instilled in me a love of knowledge and supported me every step of the way...

To my dear father and my precious mother, without your prayers, sacrifices, and faith in me, I would never have reached this day... Thank you from the bottom of my heart for your patience, generosity, and unconditional love.

To my brothers and sisters, who have been a source of support, strength, and motivation for me...

To my esteemed teachers, and to all those who have supported me with a word, advice, or prayer...

To my friends and colleagues from my university studies, who have made these years of study unforgettable...

I dedicate the fruits of my labors to all of you, for you are the true partners in this success.

Aouiche wail

Dedication

This work is the culmination of a long journey, rich in challenges, learning, and hope…

I dedicate it, with all my love and gratitude:

To my beloved parents, pillars of my life, whose silent prayers and daily sacrifices have illuminated my path. May God protect you and reward you for everything.

To my family, a source of affection, strength, and comfort, in easy days as well as in times of uncertainty.

To my teachers and supervisors, for their intellectual and human generosity, who awakened in me a passion for knowledge.

To my sincere friends, companions on my journey and with whom I have shared unforgettable memories.

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Please accept my deepest gratitude and sincere respect.

Abstract

The generation of electricity through photovoltaic (PV) systems is among the fastest-growing renewable energy solutions. However, in hot and arid environments, such as the Saharan region, the performance of PV panels is significantly reduced due to heat accumulation, high solar irradiance, and elevated ambient temperatures. To mitigate this thermal degradation, various passive cooling techniques have been explored, including the integration of phase change materials (PCMs). In this study, we numerically evaluate the cooling effect of a Propolis-based natural PCM on the thermal and electrical performance of PV modules. A 2D transient simulation was conducted using ANSYS Fluent, under climatic conditions representative of El-Oued, Algeria. The objective is to improve the energy yield of the PV module by reducing its surface temperature using an eco-friendly thermal regulation layer. Results demonstrated that Propolis effectively lowers the module temperature during peak irradiance and enhances electrical efficiency, confirming its potential as a sustainable alternative to synthetic PCMs.

Keywords: Photovoltaic panels, passive cooling, Propolis, phase change material, CFD simulation, Saharan climate.

Résumé :

La production d'électricité à partir de systèmes photovoltaïques (PV) figure parmi les solutions d’énergie renouvelable les plus dynamiques et en pleine expansion. Cependant, dans les environnements chauds et arides tels que la région saharienne, les performances des panneaux photovoltaïques sont considérablement réduites en raison de l'accumulation de chaleur, de l'irradiation solaire élevée et des températures ambiantes élevées. Pour atténuer cette dégradation thermique, diverses techniques de refroidissement passif ont été explorées, notamment l’intégration de matériaux à changement de phase (MCP). Dans cette étude, nous évaluons numériquement l'effet de refroidissement d’un MCP naturel à base de propolis sur les performances thermiques et électriques des modules PV. Une simulation transitoire en 2D a été réalisée à l’aide du logiciel ANSYS Fluent, dans des conditions climatiques représentatives de la ville d’El-Oued (Algérie). L’objectif est d’améliorer le rendement énergétique du module PV en réduisant sa température de surface grâce à une couche de régulation thermique écologique. Les résultats ont montré que la propolis réduit efficacement la température du module pendant les périodes de forte irradiation et améliore le rendement électrique, confirmant ainsi son potentiel en tant qu’alternative durable aux MCP synthétiques.

Mots-clés : Panneaux photovoltaïques, refroidissement passif, propolis, matériau à changement de phase, simulation CFD, climat saharien.

ملخص:

تُعدّ إنتاجية الكهرباء من الأنظمة الكهروضوئية (PV) من بين أسرع حلول الطاقة المتجددة نموًا وانتشارًا. ومع ذلك، فإن أداء الألواح الشمسية يتأثر سلبًا في المناطق الحارة والجافة مثل المناطق الصحراوية، وذلك بسبب تراكم الحرارة، وشدة الإشعاع الشمسي، وارتفاع درجات الحرارة المحيطة. ولمعالجة هذا التدهور الحراري، تم استكشاف العديد من تقنيات التبريد السلبي، بما في ذلك دمج المواد متغيرة الطور (PCM). في هذه الدراسة، تم تقييم التأثير التبريدي لمادة متغيرة الطور طبيعية مستخلصة من صمغ النحل (البروبوليس) على الأداء الحراري والكهربائي للوحدات الكهروضوئية، وذلك باستخدام محاكاة عددية ثنائية الأبعاد غير مستقرة تمت عبر برنامج ANSYS Fluent، في ظل ظروف مناخية مماثلة لولاية الوادي – الجزائر. ويهدف هذا العمل إلى تحسين إنتاج الطاقة للوحدة الكهروضوئية من خلال تقليل درجة حرارة سطحها باستخدام طبقة تنظيم حراري صديقة للبيئة. وقد أظهرت النتائج أن صمغ النحل يساهم بفعالية في خفض درجة حرارة الوحدة خلال ساعات الذروة الشمسية، مما يؤدي إلى تحسين الكفاءة الكهربائية، ويؤكد إمكاناته كبديل مستدام للمواد الصناعية متغيرة الطور.

الكلمات المفتاحية: الألواح الكهروضوئية، التبريد السلبي، صمغ النحل، المواد متغيرة الطور، المحاكاة العددية، المناخ الصحراوي.

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- **PV :** Photovoltaic
- **PCM :** Phase Change Material
- **CPCM :** Composite Phase Change Material
- **HS :** Heat Sink
- **TES :** Thermal Energy Storage
- **HTF :** Heat Transfer Fluid
- **LHTES :** Latent Heat Thermal Energy Storage
- **SH :** Sensible Heat
- **LH :** Latent Heat
- **T :** Temperature
- **I :** Solar Irradiance
- **PCE :** Power Conversion Efficiency
- **STC :** Standard Test Conditions
- **k :** Thermal Conductivity
- **h :** Heat Transfer Coefficient
- **q :** Heat Flux
- **ΔT :** Temperature Difference
- **η :** Efficiency
- **σ :** Stefan–Boltzmann Constant
- **ε :** Emissivity

General Introduction

General Introduction:

In the face of rapidly increasing global energy demand, societies around the world are confronted with the urgent need to secure reliable, affordable, and environmentally sustainable energy sources. Conventional fossil fuels, which have long dominated the global energy mix, are now associated with several pressing challenges, including resource depletion, greenhouse gas emissions, and their substantial role in driving climate change. These challenges have intensified the search for alternative and renewable energy resources that can ensure both energy security and environmental protection. Among the available options, solar energy stands out as one of the most promising and sustainable solutions, owing to its abundance, renewability, and the remarkable technological advancements that have made it increasingly cost-competitive.

Photovoltaic (PV) technology, which directly converts sunlight into electricity, has gained significant attention due to its versatility, scalability, and declining installation costs. From powering small-scale household devices to supplying large-scale solar farms, PV systems have demonstrated their potential as a cornerstone of the global transition toward clean energy. Nevertheless, the performance and long-term reliability of PV modules remain critical issues that directly influence their contribution to the energy sector. A major obstacle lies in the thermal behavior of photovoltaic cells: as solar panels operate under direct sunlight, their temperature often rises well above ambient levels, leading to a notable decrease in energy conversion efficiency. Studies have shown that for every degree Celsius increase in cell temperature, the efficiency of a typical silicon-based PV cell decreases by approximately 0.4–0.5% [International Renewable Energy Agency, 2022]. This phenomenon not only limits the energy output but also accelerates material degradation, reducing the overall lifespan of the system.

To address this challenge, researchers have proposed various thermal management techniques, ranging from passive air cooling and active water-based systems to advanced approaches such as phase change materials (PCMs) and hybrid cooling designs. While these methods have shown promising results, each is associated with specific limitations. Air cooling, for instance, is simple but often insufficient under high solar radiation. Water cooling, though effective, requires additional infrastructure and raises concerns about water scarcity in arid regions. PCMs, on the other hand, provide excellent thermal buffering capabilities but suffer from limited heat transfer rates and long-term stability issues. These limitations highlight the urgent need for innovative solutions that can combine efficiency, sustainability, and cost-effectiveness in improving PV thermal performance.

In light of this, the present study focuses on exploring the potential of integrating heat sinks with composite phase change materials (CPCMs) as a hybrid thermal management system. By combining the high thermal conductivity of heat sinks with the latent heat storage capacity of CPCMs, this approach aims to enhance heat dissipation and maintain photovoltaic cells at lower operating temperatures. The research adopts an experimental framework coupled with comprehensive thermal evaluation to investigate the effectiveness of this integrated solution. Ultimately, the study seeks to contribute to the development of advanced cooling strategies that can extend the operational lifespan, improve the conversion efficiency, and promote the widespread adoption of photovoltaic systems in the global energy landscape.

Chapter I:

Bibliographic Study

Introduction Chapter I

The increasing global demand for clean and sustainable energy sources has placed photovoltaic (PV) technology at the forefront of renewable energy research. Photovoltaic cells, which directly convert solar radiation into electricity, are widely recognized for their environmental benefits, reliability, and scalability. However, despite their potential, PV systems still face significant limitations, particularly the issue of performance degradation under high operating temperatures. When solar cells are exposed to prolonged sunlight, the generated heat leads to reduced electrical efficiency, accelerated material fatigue, and shortened operational lifespan.

In this context, a bibliographic study provides the necessary foundation for understanding the progress achieved so far in improving PV cell performance. It allows the identification of scientific approaches, theoretical models, and technological solutions proposed by previous researchers. By analyzing these contributions, it becomes possible to highlight the strengths and limitations of different methods, identify research gaps, and build a solid framework for the present study.

The purpose of this bibliographic review is therefore twofold: first, to examine the state of the art regarding PV cell performance enhancement, with particular emphasis on thermal management strategies; and second, to explore the combined use of heat sinks and composite phase change materials as innovative solutions to address the thermal challenges faced by PV systems. This review will serve as the cornerstone for defining the research problem, objectives, and methodological choices of the current work.

I Overview of solar energy and its importance

I.1. Overview of solar energy

The sun constituted a source of power for several ancient civilizations since the dawn of history. Different cultures and peoples approached the sun from various perspectives; some worshipped it and others relied on its energy for agricultural and thermal purposes. During the Neolithic Age that spanned from 5000 BC to 2000 BC, the Stonehenge monument was constructed with an alignment with the sun. It was used as a worshipping space that allowed the sunlight during winter to enter to the inside [1]. Historical records show that the ancient Egyptian civilization used extensively the solar energy to heat their shelters. They constructed their houses with thermal techniques so that they store the sun heat along the daytime; then, the walls released the heat during the night. This thermal aspect helped the house-keepers to enjoy warm nights. Then, by the 3rd century BC, the Romans and the Greeks used mirrors as tools to reflect the sunlight. The burning mirrors lightened torches which were used for religious ceremonies in both civilizations.

Later, in the mid-18th century, Horace Benedict de Saussure (1740-1799), a Swiss physicist, invented the first solar energy collector, named hot box. Then, by the 19th century, the industrial revolution stirred up innovative ideas and projects amongst engineers and scientists. Their inventions were economically and industrially oriented. To illustrate with, W. Adams invented the sun collector that is an oven with octagonal reflectors made from glass mirrors. The latter concentrated the sunlight to a box to allow the cooking of the food inside the pot. The Swedish-American John Ericsson (1803-1889) invented the Sterling engine that used solar energy collected by a reflector. Besides, the discovery of the photovoltaic effect constituted a turning point to the manufacturing of the solar energy equipment and industry as a whole. Etymologically, the term photovoltaic is composed of two Greek words: phos and volt, which mean light and the electro-motive force unit. Historically speaking, Alexandre-Edmond Becquerel (1820-1891) -a French physicistinvented the photovoltaic cell when he was only 19 years old. Conducting his experiments at his father’s laboratory, Becquerel illuminated silver chloride that he put inside an acidic solution. He noticed voltage on the platinum electrodes [2].

Solar energy is generated when sunlight is converted into electricity. Sunlight is composed of photons, which are units of light energy. When sunlight reaches the earth, that energy can be captured via solar panels and transformed into usable energy in the form of electricity. When sunlight hits a solar panel, the photons are absorbed by the panel's photovoltaic cells, which convert the energy into electricity. The electricity is then sent to an inverter, and then on to power homes and businesses.

For best access to the sun's rays, solar panels are usually mounted on rooftops or on the ground, and they can be deployed on individual homes and small businesses or in large-scale commercial installations, usually on significant acreage. In any scenario, each solar panel is connected to a grid or battery system that can store excess energy for use when the sun is not shining.

While all renewable energy sectors have been growing, the solar energy sector has experienced particularly rapid expansion. Solar energy has seen an average annual growth rate of 33% over the past decade—making it the fastest-growing source of electricity in the world—and this trend is expected to continue. This growth rate is due to a range of factors. First, the cost of solar panels has steadily decreased, which means that it is becoming more cost-effective for consumers and businesses to invest in solar energy. Second, government incentives and policies, such as tax credits and renewable energy mandates, have made solar energy a more attractive source of electricity. And finally, shifting preferences have led many consumers to opt for clean renewable energy like solar over more polluting energy sources [3].

I .2. The importance of solar energy

The Sun is an extremely powerful energy source, and sunlight is by far the largest source of energy received by Earth, but its intensity at Earth's surface is actually quite low. This is essentially because of the enormous radial spreading of radiation from the distant Sun. A relatively minor additional loss is due to Earth's atmosphere and clouds, which absorb or scatter as much as 54 percent of the incoming sunlight. The sunlight that reaches the ground consists of nearly 50 percent visible light, 45 percent infrared radiation, and smaller amounts of ultraviolet and other forms of electromagnetic radiation.

Solar energy drives and affects countless natural processes on Earth. For example, photosynthesis by plants, algae, and cyanobacteria relies on energy from the Sun, and it is nearly impossible to overstate the importance of that process in the maintenance of life on Earth. If photosynthesis ceased, there would soon be little food or other organic matter on Earth. Most organisms would disappear, and in time, Earth's atmosphere would become nearly devoid of gaseous oxygen. Solar energy is also essential for the evaporation of water in the water cycle, land and water temperatures, and the formation of wind, all of which are major factors in the climate patterns that shape life on Earth.

The potential for solar energy to be harnessed as solar power is enormous, since about 200,000 times the world's total daily electric-generating capacity is received by Earth every day in the form of solar energy. Unfortunately, though solar energy itself is free, the high cost of its collection, conversion, and storage still limits its exploitation in many places. Solar radiation can be converted either into thermal energy (heat) or into electrical energy, though the former is easier to accomplish [4].

Solar energy is produced by the sunrays and may be transformed into electricity or heat. The sun's energy is always accessible to us for free, and because to technological advancements, we can now use even more of it. The growing cost of energy is one of today's biggest concerning problems. As Earth's resources are being exhausted, energy prices are rising. Fortunately, technology has made new natural resources available, including solar energy. Despite the fact that energy consumption is increasing, there are things that every homeowner can do to cut expenses and benefit the environment [5]. Some of the benefits people get from the solar energy are shown in Figure 1.

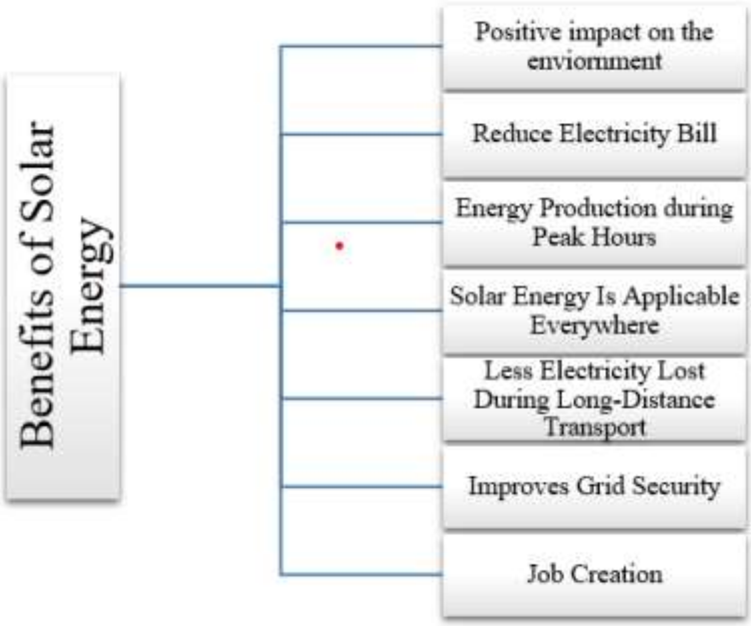

Figure (I) 1: Depicts the Benefits of Using Solar Energy [6].

Solar costs should be cut in half by 2030 according to the solar industry's extremely defined costreduction roadmaps. Higher-efficiency modules are already being developed; they can provide 1.5 times as much power as currently available, comparably sized modules thanks to a technique known as tandem silicon cells. These will have a significant effect moving forward. Additionally, there are industrial advances in the works that will lower the quantities of pricey components required in the creation of solar cells, including silicon and silver, as well as breakthroughs like bifacial modules, which enable panels to absorb solar energy from both sides. The best way to incorporate solar energy into our homes, places of work, and power systems is the other significant breakthrough. Better power electronics and more extensive usage of inexpensive digital technology are the results of this. The continuing change of the energy sector is being driven by urgent requirements and appealing prospects as shown in Figure 2 [5].

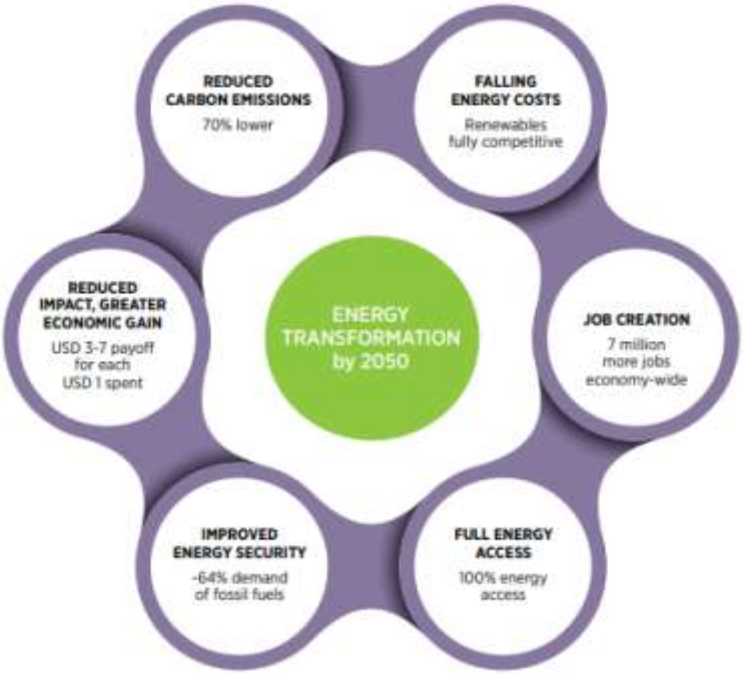

Figure (I) 2: Representing the Current Energy Change Which is Being Driven by Urgent Requirements and Appealing Prospects [7].

I.2. Problem of overheating in PV panels and its impact on efficiency

I.2.1. Problem of overheating in PV panels

Heat can “severely reduce” the ability of solar panels to produce power, according to CED Greentech, a solar equipment supplier in the United States.

Depending on where they're installed, hot temperatures can reduce the output efficiency of solar panels by 10%-25%, the company says.

According to the American renewable energy website EnergySage, solar panels are tested at 25°C (77°F) and generally have a temperature range of between 15°C and 35°C. Solar cells – the electronic devices that convert sunlight into electricity that are connected together to build solar panels – produce solar power most efficiently within this range.

But solar panels can get as hot as 65°C (149°F), EnergySage says. This can affect the efficiency of solar cells.

The impact of heat on solar panels is to do with the laws of thermodynamics - the science of heat and how it affects things.

The electricity generated by solar panels comes from a flow of particles called electrons inside the electrical circuit, explains news site Euronews.

When temperatures soar, these electrons can bounce around too much – and this reduces voltage, or the amount of electricity generated.

Too much heat also reduces the efficiency of the solar panel, by 0.5 percentage points for every degree Celsius rise in temperature.

Solar panels aren't the only energy system impacted by high temperatures.

Nuclear power plants and other types of thermal plants – which convert heat into electricity – can also be affected.

According to an expert interviewed by Fortune magazine, all types of thermal power plants – whether coal-fired, gas-fired or nuclear – need huge amounts of water to keep them cool.

In France, the heatwave cut electricity output from two nuclear power plants when the hot temperatures warmed water in the nearby Rhône River used to cool nuclear reactors, Fortune notes [8].

The hot spot effect within the realm of solar panels denotes the occurrence of concentrated overheating on the surface of an individual solar cell. This occurrence is usually triggered by the uneven distribution of sunlight across the solar panel, a scenario that arises when a specific section of the panel is shaded or receives less sunlight in comparison to the surrounding areas.

The hot spot effect can cause solar panels to overheat locally, reducing their efficiency and potentially causing damage. Details are as follows:

1.Efficiency degradation: When hot spots occur in solar panels, the local temperature rises, which usually leads to a decrease in the performance of the solar cell as the temperature rises. At high temperatures, the electronic conductivity of the photovoltaic cell is weakened, thus affecting the cell's power generation efficiency.

2. Thermal Expansion and Contraction: Solar panels are subject to solarisation and thermal expansion due to prolonged exposure to sunlight. This surface thermal expansion and contraction may cause fatigue and stress in the panel material, which increases the risk of cracks or other structural problems in the panel.

3. Component Damage: Hot spots may cause damage to electronic components inside the solar panel from high temperatures, such as battery connectors, wires, etc. Damage to these components may degrade the overall performance of the panel.

4. Lifespan affected by thermal stress: When exposed to high temperatures for extended periods of time, solar panels may be subjected to frequent thermal stress. This thermal stress may shorten the life of the panel, thereby reducing its reliability in a solar power system.

Causes of the hot spot effect may include shadowing, module defects, or uneven aging of the cell, which results in localised uneven light, overheating certain areas. Specific causes are listed below:

1. Partial Cell Aging:Over time, individual solar cells within a panel may age differently due to various factors like uneven exposure to sunlight, leading to an imbalance in cell performance. This can contribute to the formation of hot spots as some cells degrade faster than others, affecting the overall efficiency of the solar panel.

2. Mismatched Panels in Series:In solar panel installations where panels are connected in series, a mismatch in panel specifications or conditions can lead to uneven power production. This

imbalance can cause certain panels to operate at lower currents, making them susceptible to hot spot formation, particularly during periods of high solar irradiance.

3. Faulty Bypass Diodes:Bypass diodes are crucial components that help mitigate the impact of shading on solar panels. If these diodes fail to function properly due to manufacturing defects or wear and tear, it can result in ineffective shading mitigation, promoting the occurrence of hot spots in the shaded areas of the panel.

4. Inadequate Ventilation:Poor ventilation around solar panels can contribute to heat buildup, especially in warmer climates. Inadequate airflow can hinder the dissipation of heat generated during energy conversion, exacerbating the hot spot effect. Proper design considerations for ventilation are essential to maintain optimal operating temperatures.

5. Installation Errors: Errors during the installation process, such as improper tilt or orientation, can impact the uniformity of sunlight exposure across the solar panel array. This non-uniform exposure may lead to localized overheating, emphasizing the importance of precise installation practices to prevent hot spot formation.

6. Shadow masking: One of the primary reasons for hotspots on solar panels is shading. When a portion of the panel is shaded, a significant reverse bias voltage can develop across the shaded cells due to the series connection of cells. This can lead to heat accumulation, temperature rise, and the formation of hotspots. Additionally, shading can reduce the overall efficiency of the panel because the shaded cells cannot generate electricity at the same rate as the rest of the panel. Another factor contributing to hotspots is the accumulation of dirt and debris. Dirt and dust on the panel's surface can block some of the incoming sunlight, resulting in reduced performance and increased temperatures. Debris can also disrupt the panel's heat dissipation and airflow [9].

I.2.2. Temperature rise in photovoltaic panels and its impact on efficiency

Represents how much the power of the board decreases when the temperature rises. It is noted that the efficiency of the board decreased between 4.2% and 10.08% when the temperature rose from 35 C0 to 49 C0. This is explained by the fact that most solar photovoltaic cells are affected by high temperatures, which leads to a noticeable deterioration in their performance and a decrease in energy production. This is consistent with the results of several previous research (Govindasamy & Kumar, 2023), (Maka & O'Donovan, 2022), (Sun. et al, 2022) [10].

The primary function of solar panels is to absorb solar radiation and convert it into electricity. The efficiency of the solar panel, influenced by climatic and environmental conditions, can vary, with temperature being a key factor. Among the three elements of a solar panel, the photovoltaic cell plays a crucial role and is particularly sensitive to temperature. A significant drop in solar cell performance is a characteristic of high temperatures. Efficiency is the amount of energy a system produces in proportion to the amount it receives. In the case of solar panels, the energy entering the system is determined by the intensity, angle and spectrum of sunlight. The electricity generated by the solar panel is treated as the output. The efficiency of solar panels is determined by several factors.

They can be divided into three basic categories:

1- environmental factor.

2- operational factors such as shading and dirt.

3- design factors.

The intensity of the sun or sunlight is determined by weather conditions, latitude, and time of year. There is a close correlation between temperature coefficient and performance at high temperatures for the same cell technologies.

Indeed, many studies have demonstrated the existence of such a correlation and have used it for this purpose. The temperature coefficient plays a crucial role in performance indicators, serving as one of the key parameters of cells. The resulting ratios show how efficiency decreases as the temperature increases. It was found that there is an expected decrease of 0.42% for each temperature increase above 25C0 (see Thermal properties of the solar panel Table 2) [10].

I.3. Existing cooling methods and their limitations

I.3.1 Existing cooling methods

Managing the temperature of solar cells is essential for optimizing their performance. Implementing effective cooling strategies, such as incorporating cooling systems or heat sinks, helps dissipate excess heat and mitigates efficiency losses caused by temperature increase. By maintaining lower operating temperatures, the band gap and open-circuit voltage can be preserved, ensuring that the solar cell operates at its highest potential and achieves maximum energy conversion efficiency. We can model the current-voltage relationship of semiconductors diodes with Eq. (1), the Shockley diode equation:

Equation 01: $$ID = Is\left(\frac{VD}{e\,nV\,T} - 1\right)$$

The absorbed heat raises the cells temperature up to 70ºC and every degree gained affects the electrical conversion efficiency of the cell with approximately 0.5%, at temperatures exceeding 25ºC. This is the reason why cooling methods (Fig. 2) for PV panels, are so important [11].

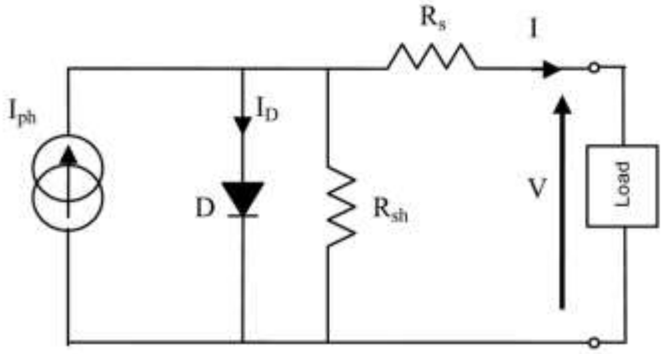

Figure (I) 3: Solar cell electrical equivalent circuit [12].

The main equation (Sangram and Saini, 2016) for analyzing the solar cell with single-diode model is derived from the Shockley equation:

Equation 02: $$\boldsymbol{I = Iph - Is\left[exp\left(\frac{V+IRs}{nVT}\right) - 1\right] - \frac{V + IRs}{Rsh}}$$

where:

I_D: is the diode current;

I_S: is the reverse bias saturation current;

Iph: is the photo-generated current;

V: is the voltage across the solar cell;

V_D: is the voltage across the diode;

V_T : is the thermal voltage;

N: is the ideality factor (quality factor or emission coefficient);

R_S: is the series resistance, which is associated with the resistance of the solar cell material and contacts;

Rsh: is the shunt resistance, which is associated with current that flows through the solar cell but does not contribute to power production [11];

In the Eq. (2) VT can also be written as follow:

Equation 03: $$V_T = \frac{kT}{q}$$

Where:

k : Is the Boltzmann constant?

T : is the absolute temperature of the P-N junction;

q : is the elementary charge;

Effective cooling techniques are essential for solar panels to maintain peak performance and counteract the adverse impacts of overheating. Various cooling methods are employed to achieve this. Here are several widely adopted cooling techniques for solar panels.

3.3 Water cooling

On the other hand, active water cooling for PV required a mechanical or electrical devices to actively reduce the temperature of PV modules. This may include circulating water or other fluids through a heat exchanger. They are useful in hot climates or highpower output systems and provide greater cooling efficiency and control over operating temperature than passive cooling methods.

Irwan et al, carried an indoor experiment in order to investigate the effect of water flowing at the surface in cooling the PV panel. Results showed that a decrease in PV temperature by 5–23 ◦C increases the output power of the PV panel by 9–22%.

On the other hand, Moradgholi et al. experimentally investigated the effect of heat pipes in cooling PV panels, and the module used in his experimental study is represented in Figure 6. Results showed an increase of 5.67% in power when using methanol as a working fluid in spring and an increase of 7.7% in power when using acetone as a working fluid in summer [13].

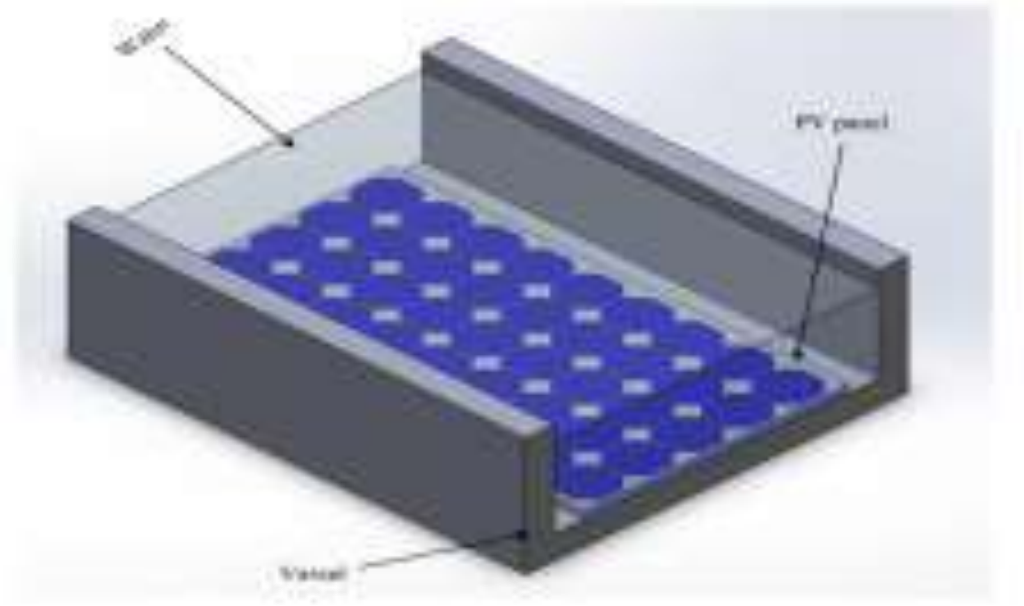

Figure (I) 4: PV panel immersed in water [14].

I.3.3. Nanofluids cooling

Nanofluids have high heat transfer properties due to their higher thermal conductivity compared to common liquids. These properties allow these materials to be successfully used to cool PV panels efficiently. The nanofluids efficiently remove significant waste heat, resulting in lower PV surface temperatures. [15] It has also been shown that this type of fluid can be considered a spectral filter for PV cells because it selectively absorbs the incident infrared radiation Ali [16]. The nanofluids flow through various channels, usually microchannels, which are placed in the back of the PV panel.

Nguyen et al (2005) conducted numerical investigations on the performance of a high heat output microprocessor with water and ethylene glycol based aluminium oxide nanoparticles and reported that the addition of nanoparticles considerably results in the increasing of heat transfer coefficient and decrement in the maximum junction temperature. It was observed that the heat transfer coefficient increases by 53% with 7.5vol% of nanoparticles to the water for the given heat input of 150W and the maximum junction temperature decreases from 65.8°C to 58.4°C. Similarly, the same effect was observed in case of ethylene glycol based nanofluids with decrement in the maximum junction temperature from 82.9°C to 67°C. Nguyen et al (2007) investigated the performance of distilled water based aluminium oxide through the closed liquid cooling system of a microprocessor. He reported that the heat transfer coefficient was augmented by 40% with 6.5% of particle volume concentration and observed a decrement in the temperature of the heated component than the base fluid. He also reported the effect of nanoparticle size on the heat transfer behaviour by comparing 36nm and 47nm sized particles. He also concludes that the smaller size nanoparticles of 36nm augment a high heat exchange between the nanoparticle and the liquid phase due to high number of particles and high heat transfer area and hence resulted in a high heat transfer coefficient as compared with the large sized nanoparticles [17].

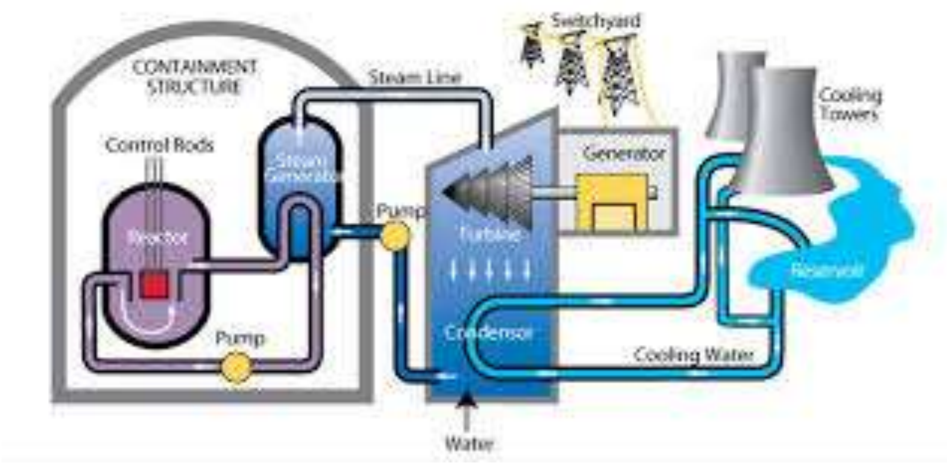

Figure (I) 5: Nanofluids in Electronics Cooling Applications [18].

I.4. Objectives of the study

The primary objective of this study is to investigate and evaluate efficient cooling techniques for photovoltaic (PV) panels to mitigate the problem of overheating and enhance their overall efficiency. The specific objectives include:

1. **Analyzing the Impact of Overheating** – To assess how excessive temperatures affect the performance and energy conversion efficiency of PV panels.
2. **Reviewing Existing Cooling Methods** – To examine current cooling techniques used in PV systems, their advantages, and their limitations.
3. **Developing an Improved Cooling Solution** – To propose and analyze a more effective cooling method that enhances heat dissipation while maintaining cost-effectiveness.
4. **Experimental Validation** – To conduct simulations and/or experimental tests to compare the proposed cooling method with existing solutions.

5. **Optimizing Performance and Sustainability** – To explore how the suggested cooling approach contributes to improving the long-term efficiency, durability, and sustainability of PV systems.

This study aims to provide a practical solution that enhances PV panel efficiency while considering economic and environmental factors.

Chapter Ⅱ: Literature Review

Introduction Chapter II

The literature review constitutes a critical foundation for the present study, as it provides an overview of the current state of knowledge regarding photovoltaic (PV) systems and the challenges affecting their performance. By examining previous research, this chapter aims to identify the main factors influencing PV efficiency, with particular attention to thermal effects that lead to performance degradation. Furthermore, it explores the range of solutions proposed in the literature, from conventional cooling methods such as heat sinks to more advanced thermal management strategies including composite phase change materials. Through this review, the study seeks to highlight both the achievements and limitations of earlier works, thereby establishing the research gap and justifying the need for investigating the combined use of heat sinks and composite PCMs to enhance PV cell performance.

II.1. Fundamental principles of photovoltaic technology

PV panels face challenges, particularly overheating, which significantly reduces their efficiency. This chapter explores the fundamental principles of PV technology, including its working mechanism, key influencing factors, and the impact of temperature on performance, with a focus on potential solutions to enhance efficiency.

II.1.1 Solar Photovoltaic Technology Basics

Solar cells, also called photovoltaic cells, convert sunlight directly into electricity.

Photovoltaics (often shortened as PV) gets its name from the process of converting light (photons) to electricity (voltage), which is called the *photovoltaic effect*. This phenomenon was first exploited in 1954 by scientists at Bell Laboratories who created a working solar cell made from silicon that generated an electric current when exposed to sunlight. Solar cells were soon being used to power space satellites and smaller items such as calculators and watches. Today, electricity from solar cells has become cost competitive in many regions and photovoltaic systems are being deployed at large scales to help power the electric grid. [19]

Figure (II) 1: Solar Photovoltaic Technology Basics. [19]

II.1.2 Silicon Solar Cells

A silicon solar cell is a photovoltaic cell made of silicon semiconductor material. It is the most common type of solar cell available in the market.

The silicon solar cells are combined and confined in a solar panel to absorb energy from the sunlight and convert it into electrical energy.

These cells are easily available in the market and are widely used due to their cost-effective pricing. They have a lifespan of over 25 years and can function without requiring high maintenance. Due to these benefits, they play a crucial role in the solar panel market [20].

II.1.3 Thin-Film Solar Cells

it is essential to understand what a thin-film is. A thin film is a material created ab initio by the random nucleation and growth processes of individually condensing / reacting atomic / ionic / molecular species on a substrate. The structural, chemical, metallurgical and physical properties of such a mate-rial are strongly dependent on a large number of deposition parameters and may also be thickness dependent.

Thin-films may encompass a considerable thickness range, varying from a few nanometers to tens of micro-meters and thus are best defined in terms of the birth processes rather than by thickness. One may obtain a thin material (not a thin-film) by a number of other methods (normally called thick-film techniques) such as by thin-ning a bulk material, or by depositing clusters of microscopic species in such processes as screen-printing, electrophoresis, slurry spray, plasma gun, ablation, etc. A thick film can indeed be very thin, limited by the size of the depositing clusters, and its properties may also be sensitive to the various deposition parameters. Being sim-pler, cheaper and having relatively much larger throughput or rate of deposition, thick-film techniques are of considerable interest for viable TFSC technologies [21].

II.1.4 Solar Cells

A third type of photovoltaic technology is named after the elements that compose them. III-V solar cells are mainly constructed from elements in Group III—e.g., gallium and indium—and Group V—e.g., arsenic and antimony—of the periodic table. These solar cells are generally much more expensive to manufacture than other technologies. But they convert sunlight into electricity at much higher efficiencies. Because of this, these solar cells are often used on satellites, unmanned aerial vehicles, and other applications that require a high ratio of power-to-weight.

II.1.5 Next-Generation Solar Cells

Solar cell researchers at NREL and elsewhere are also pursuing many new photovoltaic technologies—such as solar cells made from organic materials, quantum dots, and hybrid organic-inorganic materials (also known as perovskites). These next-generation technologies may offer lower costs, greater ease of manufacture, or other benefits. Further research will see if these promises can be realized [22].

II.2. Effect of temperature on PV performance

II.2.1 Effect of Temperature on The Performance of Photovoltaic Module

Like all other semiconductor devices, solar cells are sensitive to temperature. Increase in temperature reduce the band gap of a semiconductor, thereby affecting most of the semiconductor material parameters. The decrease in the band gap of a semiconductor with increasing temperature can be viewed as increasing the energy of the electron in the material. Lower energy is therefore needed to break the bond in the bond model of a semiconductor. Therefore, increase in temperature reduce the band gap in a solar cell, the parameter most affected by an increase in temperature is the open-circuit voltage. Thus, this reduced the output power and the efficiency of photovoltaic module [23]

In a solar cell, the parameter most affected by an increase in temperature is the open-circuit voltage. The impact of increasing temperature is shown in the figure below.

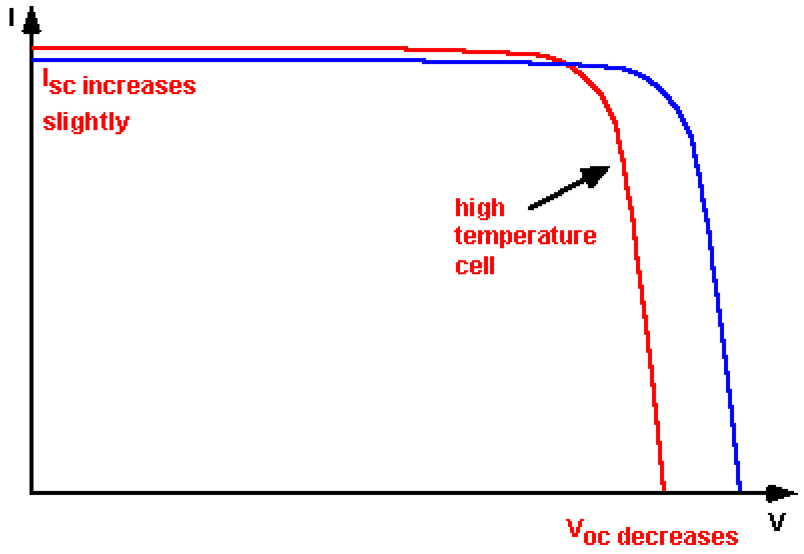

Figure (II) 2: The effect of temperature on the IV characteristics of a solar cell. [23]

The open-circuit voltage decreases with temperature because of the temperature dependence of I_0. The equation for I_0 from one side of a *p-n* junction is given by;

Equation 04: $$I_0 = qA\ \frac{Dn_i^2}{LN_D}$$

where:

q: is the electronic charge given in the constants page;

A: is the area;

D: is the diffusivity of the minority carrier given for silicon as a function of doping in the Silicon Material Parameters page;

L: is the minority carrier diffusion length;

N_D: is the doping; and

n_i : is the intrinsic carrier concentration given for silicon in the Silicon Material Parameters page.

In the above equation, many of the parameters have some temperature dependence, but the most significant effect is due to the intrinsic carrier concentration, n_i. The intrinsic carrier concentration depends on the bandgap energy (with lower bandgaps giving a higher intrinsic carrier concentration), and on the energy which the carriers have (with higher temperatures giving higher intrinsic carrier concentrations). The equation for the intrinsic carrier concentration is; [24]

Equation 05: $$n_i^2 = 4\ \left(\frac{2\pi kT}{h^2}\right)^3\ (m_e^*\ m_h^*)\ \ 3/2 \exp\left(\ \frac{E_{GO}}{kT}\right) = BT^3 \exp(-\ \frac{E_{GO}}{KT}\ )$$

II.2.2 Factors That Affect Solar Panel Efficiency

A variety of factors can impact solar performance and efficiency, including:

- **Temperature**: High temperatures will directly reduce the efficiency of a photovoltaic panel.
- **Sunlight**: The amount of direct sunlight a PV panel receives is typically the most significant determiner of how much electricity it can produce. Even the most efficient solar panel can't generate electricity at night, and production is diminished on overcast days.
- **Orientation and Tilt**: Orienting panels towards the sun (facing south if you are in the Northern Hemisphere) to maximize sunlight exposure is best. Depending on your latitude, you can optimize their efficiency by angling them directly toward the sun's path — around 30-45 degrees.

- **Dust, Snow, and Debris**: Dirt, leaves, snow, and other debris can block sunlight from the panels. Be sure to clean your solar panels regularly to keep them efficient.
- **Panel Age**: As photovoltaic panels age, their efficiency will slowly decrease year after year. Having said that, high-quality solar panels can last 25 years or more — longer than an asphalt roof.
- **Shading**: If shadows from nearby trees or structures block your panels, they won't reach maximum efficiency. This issue also goes for partial shading — if one cell in a monocrystalline or polycrystalline PV panel is in the shade, the cumulative electricity generation capacity of the panel will be adversely affected.

II.2.3 The Relationship between Temperature, Humidity, and Solar Panel Efficiency

Temperature, humidity, and solar panel efficiency are interconnected factors that impact the overall performance of a photovoltaic system. In general, research has found that higher temperatures reduce electrical efficiency. Humidity also plays a part, with lower humidity levels leading to increased output and efficiency.

II.2.3.1 Solar Panels Generally Perform Better at Lower Temperatures

As the temperature of a PV panel increases above 25°C (77°F), its efficiency tends to decrease due to the temperature coefficient. The coefficient measures how much the output power decreases for every degree Celsius above a reference temperature (usually 25°C).

Higher temperatures cause the semiconductor materials in photovoltaic cells to become more conductive. It increases the flow of charge carriers and consequently reduces the voltage generated.

Some PV panels feature heat dissipation mechanisms to reverse the adverse effects of high temperatures. Passive cooling or enhanced ventilation are proven methods to get photovoltaic panels closer to optimal operating temperatures.

II.2.3.2 Humidity Can Have Both Positive and Negative Effects on Solar Panel Efficiency

On the one hand, high humidity levels can result in increased cloud cover and atmospheric water vapor. The clouds of humid air can scatter the sunlight or absorb it, reducing the amount of solar irradiance reaching the PV panels. Excessive humidity can also lead to the accumulation of dirt and dust on the panel surface, causing a decrease in efficiency due to reduced light absorption.

On the other hand, humidity can also keep photovoltaic panels cooler by promoting heat transfer through evaporation and condensation, potentially mitigating some of the adverse effects of high temperatures on efficiency [25].

II.3. Cooling techniques for PV panels

This method relies on natural convection and heat dissipation mechanisms to regulate the temperature of solar panels. This approach involves incorporating design features such as air gaps or materials with high thermal conductivity to facilitate efficient heat transfer. Furthermore, the integration of shading elements or reflective coatings helps minimize solar irradiance and reduce heat absorption [11].

II.3.1 Passive cooling (heat sinks, PCM)

II.3.1.1 Passive air-cooling

Passive cooling with air is the cheapest and simplest method of removing excess heat from PV panels. In such a solution, the PV modules are cooled by natural airflow. The most common design includes fins, thin aluminium sheets or similar at the bottom of the module, which is responsible for increasing the air ducts radiative and convective heat transfer surface, causing turbulence, and acting as a heat sink. Figure 3 shows a general scheme of how air-cooling works for PV panels. The literature describes several studies conducted in this field. Cuce et al. [9] conducted a study on the effect of passive cooling on the performance of photovoltaic cells, where an aluminium heat sink was used to dissipate excess heat. The dimensions of the heat sink were determined from previously performed steady-state heat transfer analyses. Experiments were conducted for different ambient temperature values and different solar radiation intensities. Results have shown that the proposed cooling technique increases energy conversion efficiency, exergy and cell power at the level of 20% at irradiance equal to 800 W/m^2 [15].

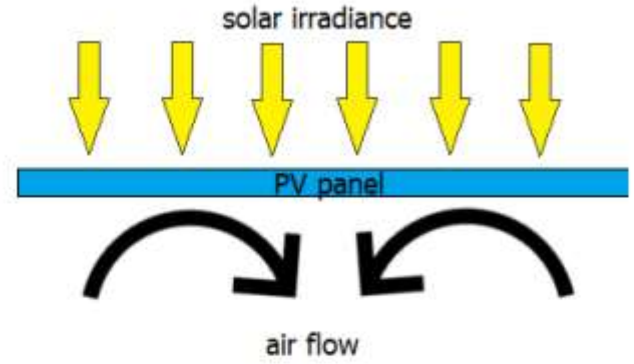

Figure (II) 3: Airflow cooling method [15].

II.3.1.2 Heat Pipe

A passive cooling device transfers energy from the source to the sink through the evaporation and condensation of fluid in a sealed system. It typically consists of a sealed pipe made of high thermal conductivity materials, such as copper or aluminum, at both the evaporator and condenser ends [11] (Fig. 9).

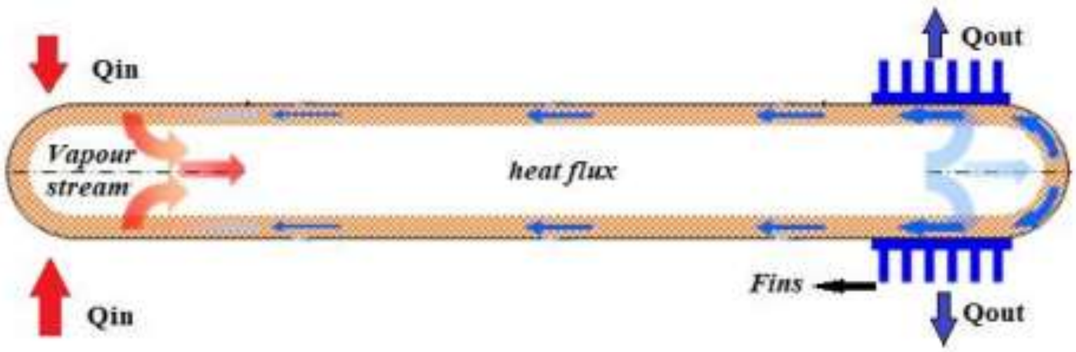

Figure (II) 4: Heat Pipe section [26].

One experimental study investigated the use of a heat pipe array for cooling photovoltaic (P.V.) systems using air and water circulation. They found that air-cooling led to a temperature reduction of 4.7°C and an 8.4% increase in power output compared to conventional solar panels. Furthermore, water-cooling resulted in an 8°C temperature decrease and a significant 13.9% increase in output power. These findings suggest that both air and water-based cooling methods can effectively enhance the performance of photovoltaic systems, with water-cooling yielding greater improvements in temperature reduction and power output [26].

II.3.1.3 Phase change material (PCM)

Recently, there has been a significant increase in the installed capacity of solar photovoltaic cells, particularly crystal silicon cells. Research has focused on enhancing the photovoltaic (PV) conversion efficiency of the cells by exploring methods to cool PV sys-tems, as elevated PV temperatures can reduce conversion efficiency. The efficiency of cooling photovoltaic cells relies on phase-change materials (PCMs) with high latent heat capacities [27]. In fact, PCMs are being studied as a solution for reducing the surface temperature of PV cells during sunlight exposure, with a goal of improving the electrical efficiency of the cells. PCMs can control temperatures by absorbing and releasing thermal energy when they change from one phase to another. This allows them to act as a thermal buffer, maintaining a stable temperature within a desired range. PCM cooling effectively manages heat by absorbing and dissipating excess thermal energy. It acts as a heat sink, preventing overheating and protecting sensitive components or equipment. PCM cooling improves energy efficiency by stabilizing temperatures and reducing reliance on energy-intensive cooling systems. It leads to lower electricity consumption and operating costs. PCMs are effective in storing and releasing large quantities of latent heat during phase transitions, making them valuable for thermal energy storage. This stored energy can be utilized for either cooling or heating purposes. PCM cooling is environmentally friendly as it reduces reliance on energy-intensive cooling methods, leading to lower greenhouse gas emissions. Additionally, PCMs can be derived from renewable or bio-based sources, making them a sustainable cooling option. Figure 9a and Figure 9b show some uses of PCMs. summarizes the findings and details of recent studies in the area of PCM cooling techniques [28].

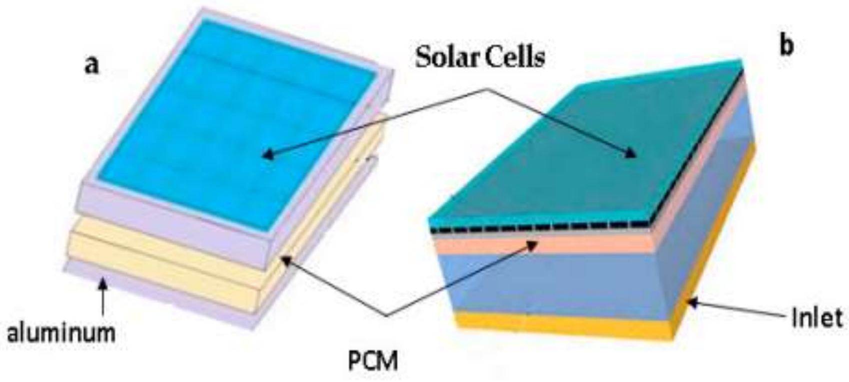

Figure (II) 5: Three-dimensional illustration of PV/PCM configurations featuring aluminum (a): schematic representation of an air-based PV/T collector incorporating PCM (b) [28].

II.3.2 Active cooling (fluid and air-based cooling)

II.3.2.1 Active cooling techniques

The active cooling method uses a forced flow of coolant through fans, pumps or other mechanical devices to lower the temperature of PV cells. Active cooling methods primarily use forced circulations of water, air or nanofluids. It usually requires additional energy to drive auxiliary equipment but is characterised by significantly higher cooling efficiency than passive cooling. Furthermore, with active cooling methods, the waste heat from PV modules can be more beneficial [29]. Mostly active cooling systems studied in the literature are water-based and concern PVT configurations [30].

3.2.2 Air cooling

Active cooling with air has the advantage that air does not require large financial investments. Only the equipment driving the refrigerant can generate additional costs. The use of drive components also results in additional electricity consumption, which should be considered when estimating the solution's net efficiency. Active air cooling is similar to passive cooling. The only difference is that, in this case, there is forced air circulation via pumps or fans. In most solutions, cooling channels, heat sinks or fins are located at the rear of the PV panel. The following section describes some active air-cooling solutions in the scientific literature [15].

Elminshawy et al. [31] proposed an active solution by using pre-cooled air. A ground-air heat exchanger was used to pre-cool ambient air, which was then used as a refrigerant in the back of the PV panels. The PV cooling system was constructed by connecting a flat PV module with an active area of 1.65 m2 with the buried EAHE. An ambient air simulator comprising a centrifugal air blower and an air heater (electric heating chamber) with controllable temperature was employed. The air heater was used to heat the induced ambient air to achieve the temperature that simulates the ambient air temperature range of arid hot climatic regions. The study showed that using such a solution at an optimum flow rate of 0.0288 m3/s reduces the PV module temperature by about 13°C, which improves the PV module power output and electrical efficiency by 20%. Figure 9 shows the proposed cooling system.

Figure (II) 6: Test stand of PV panel coupled with geothermal air-cooling system [32].

Tonui and Trip Anagnostopoulos [33] propose another solution using air cooling. The simulations were carried out for a finned air duct mounted to the rear surface of the panels, through which the refrigerant flows. The movement of the medium was forced by using a pump. In addition, the front part of the panels was equipped with an additional glass layer. This solution resulted in a maximum thermal efficiency of 52% and an electrical efficiency of 9 - 10% under steady-state conditions.

Rahimi et al. [34] designed a wind device based on a conical tunnel and fabricated it to perform two functions at a laboratory scale. The first included PV cell cooling; the second was responsible for electricity production. The considered hybrid system is a combination of wind and photovoltaic systems. A vertical axis board, called a "self-steering wind vane", was installed at the top of the air tunnel to determine the wind direction. In this case, the height at which the cooling device is placed may play a significant role in easily swinging and accurately showing wind directions. As the wind hits the narrow upright tail, it spins at right angles from which the wind is blowing, so that the chamber adjusts itself in the wind stream direction. The wind flows into the inlet chamber with a wall thickness of 1 mm and rounded corners. The tests showed that the solution had great potential for further development. The total power output increased by 36% (considering both PV and turbine power). The described solution is shown in Figure 07.

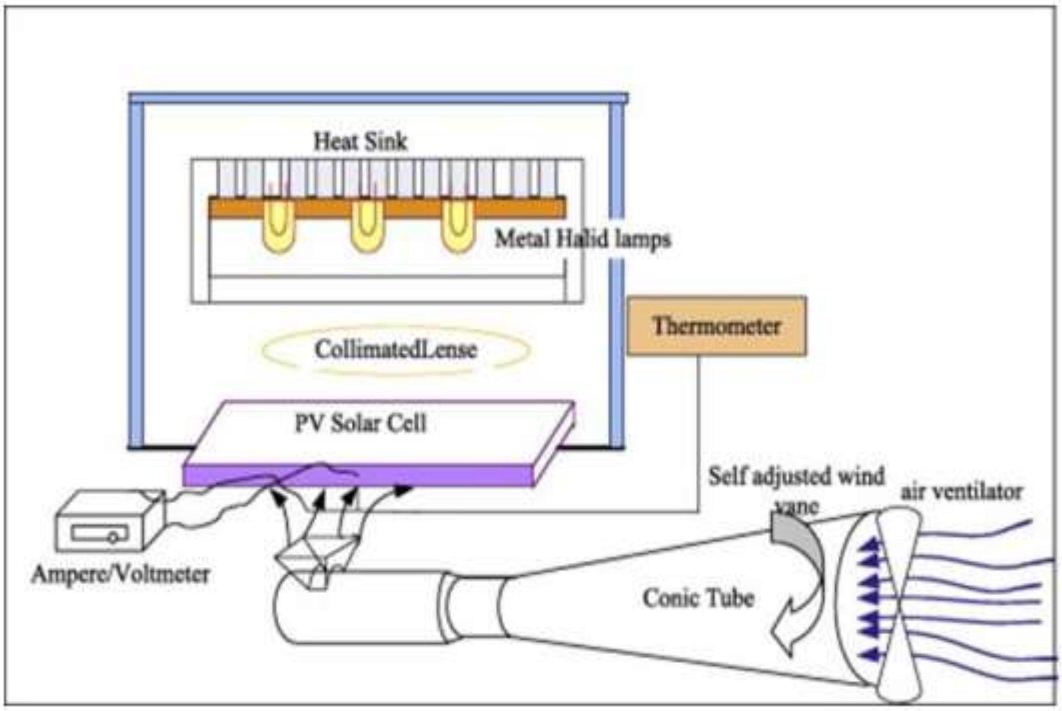

Figure (II) 7: The described solution is shown [34].

Arcuri et al. proposed a solution involving a system of aluminium cooling channels installed at the back of the panel. The inlet and outlet openings with a square cross-section were placed on opposite sides along the long edge so that the working medium flows over the longest possible area of the PV panel. An average flow velocity of 2.3 m/s was assumed. The tested solution's average annual efficiency and electricity productions were 12.58% and 269.53 kWh,

II.4. Composite PCM materials

II.4.1 Composition and properties

PCMs can release or store heat through phase change at an almost constant temperature, which are a good choice for latent heat storage. Therefore, utilizing the characteristics of PCMs to store excess energy can effectively alleviate the problem of uneven energy distribution. PCMs fall into the categories of organic, inorganic, and eutectic ones, according to their chemical structures [35]. In particular, organic PCMs are most studied due to their high heat storage density, low undercooling, suitable phase change temperature, non-corrosivity, and stable properties. However, leakage during the solid–liquid phase change has limited the practical application of organic PCMs. This problem can be solved to a large extent by using biomass-based porous materials to adsorb PCMs (mainly including polyethylene glycols, paraffins, fatty acids) for preparing composite PCMs in stable shapes.

II.4.1.1 Polyethylene Glycols (PEG)

PEG is a class of typical PCMs which features high latent heat, suitable phase change temperature, and low thermal hysteresis [36]. Their controllable molecular weights enable them to have different properties at different average molecular weights. The properties of some common PEG are listed in Table 1. With the increase in molecular weight, the phase change temperature and latent heat of PEG also show an upward trend. In practice, PEG can be selected according to different application scenarios.

Tableau 1: The properties of some common PEG are listed.

Polyethylene Glycols (PEG)	**Melting Process**		**Freezing Process**	
	Tm (◦C)	**ΔHm (J/g)**	**Tf (◦C)**	**ΔHf (J/g)**
PEG-1000	42.8	129.3	23.6	129.8
PEG-2000	51.0	185.4	34.52	184.8
PEG-4000	60.5	172.4	41.96	207.0
PEG-6000	61.7	178.6	35.3	169.9
PEG-8000	64.6	180.0	44.3	167.9
PEG-10000	63.7	189.2	39.1	167.3
PEG-20000	67.7	160.2	42.9	155.7
PEG-35000	64.4	174.0	48.9	173.9

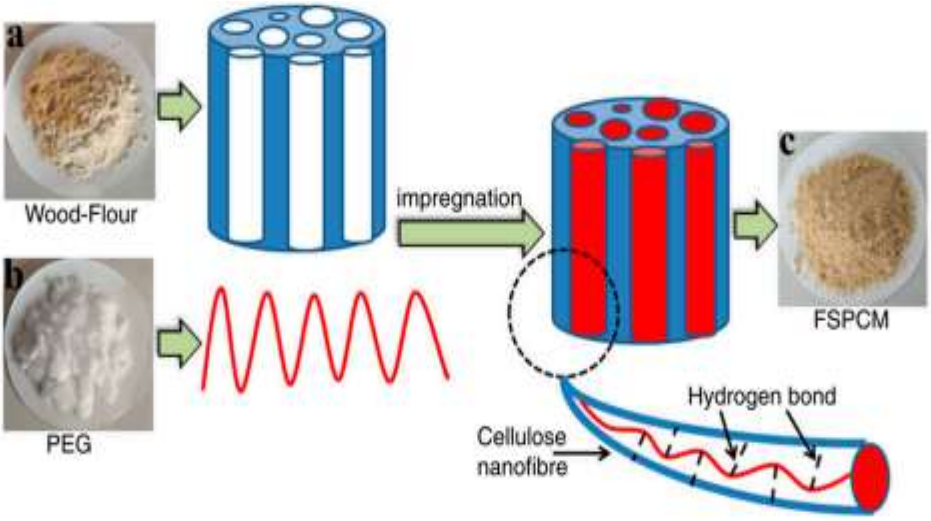

Figure (II) 8: Preparation of composite PCMs with wood flour and PEG [37].

II.4.1.2 Paraffins

Paraffins are mainly straight-chain n-alkanes. They are characterized by high latent heat, no undercooling phenomenon, excellent thermal stability, and rich sources, which make them PCMs with immense potential [38]. The thermal properties of paraffins are related to the molecular chain length (the number of carbon atoms). Herein, Table 2 presents the properties of several common paraffins. Their phase change temperatures are found closer to the ambient temperature, and as a result of which they have been widely used for heat storage based on phase change.

Luo et al. [39] proposed a unique biomass-based composite PCMs formed by impregnation with a paraffin as the PCMs and garlic peel as the support materials. The composite underwent phase change at 60.2 ◦C and had a latent heat of 52.5 J/g. The paraffin was held in the pore structure by hydrogen bond interaction and van der Waals forces. The composite PCMs were heated at 80 ◦C for 60 min without leakage and showed good shape stability. Wang et al. [40] developed a new type of biomass-based composite PCMs by vacuum impregnation with the wild daisy stem carbonized at a high temperature as the support materials and a paraffin as the PCMs (Figure 3). The phase change temperature and the latent heat of the composite PCMs were 40.1 ◦C and 213.6 J/g, respectively. The pore structure of the wild daisy stem adsorbed the PCMs by capillary force. After heating at 70 ◦C for 2 h, the weight loss rate of the composite materials was only 2.1%, which indicated its good leak-proof performance. Yu et al. [41] used rice husk ash as support materials and paraffins as PCMs to prepare a biomass-based composite PCMs by impregnation. The composite PCMs had a phase change temperature of 48.2 ◦C and a latent heat of 95.7 J/g. After 300 cycles of heating and cooling, it still remained in excellent shape and had good thermal stability. Currently, the composites of biomass materials and paraffins remain to be further studied. Especially, paraffin-based microcapsules are expected to form composites with biomass materials, which, however, is rendered difficult due to complex preparation and high costs.

II.4.1.3 Fatty Acids

Common PCMs of the fatty acid group include stearic acid (SA), lauric acid (LA), decanoic acid, myristic acid (MA), and palmitic acid (PA). Fatty acids have the characteristics of high latent heat, good thermal stability, no supercooling, and low costs.

Wen et al. [42] prepared composite PCMs by vacuum impregnation method with carbonized corn stover as the support materials and SA as the PCMs. Regarding the composite PCMs, phase change occurred at 67.62 ◦C, and the latent heat was 160.74 J/g. The physical interactions of capillary force and surface tension prevented the leakage of melt SA from the porous structure of carbonized corn stover. As displayed in Figure 4, the composite still had good shape stability after 3 h of heating at 80 ◦C. Due to the high phase change temperatures of single fatty acids (40–60 ◦C), different fatty acids are usually combined into binary or multiple co-melting systems to meet the requirements of temperature regulation and human comfort. Table 3 lists the phase change temperatures of some binary and ternary fatty acids after mixing. The phase change temperatures of the mixed systems can be determined by the Schroeder equation. Zhang et al. [26] used a eutectic mixture of LA-SA as PCMs and incorporated it into the carbonized corn cob to prepare SSPCMs (Figure 09). The resulting composite PCMs had a phase change temperature of 35.1 ◦C and latent heat of 148.3 J/g. Evidently, the phase change temperature of the binary fatty acid system was significantly lowered. LA-SA was fixed in the pore structure by physical adsorption mainly via surface tension and capillary force. After 200 thermal cycles, the composite PCMs can still maintain good shape stability. Sari et al. designed leak-proof biomass-based composite PCMs with carbonized sugar beet pulp as the support materials and a eutectic mixture of CA-SA as the PCMs, which had a phase change temperature and a latent heat of 24.0 ◦C and 117.0 J/g, respectively. This phase change temperature was quite close to the human comfort temperature. The capillary force and surface tension between the support materials and PCMs can prevent the seepage of the molten PCMs. The latent heat capacity of the composite decreased by only 3% after 2000 cycles of cooling and heating.

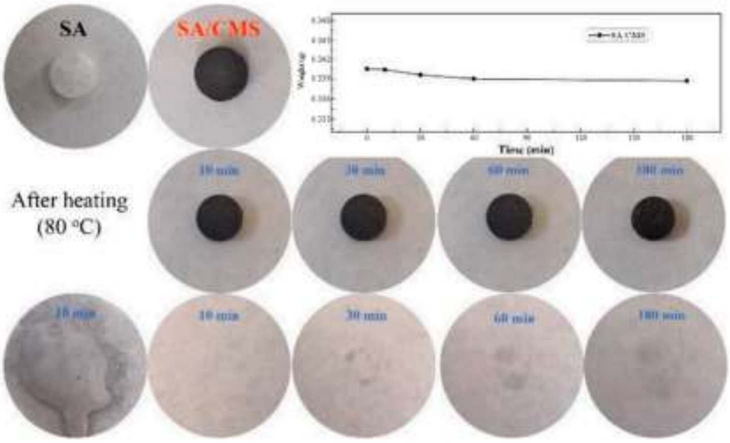

Figure (II) 9: Leakage trace of SA and form and weight changes after different heating times [43].

However, fatty acids are mostly derived from animals and plants, and biomass materials are easily influenced by microorganisms. Therefore, it is necessary to further explore the biological durability of fatty acid–biomass composite PCMs.

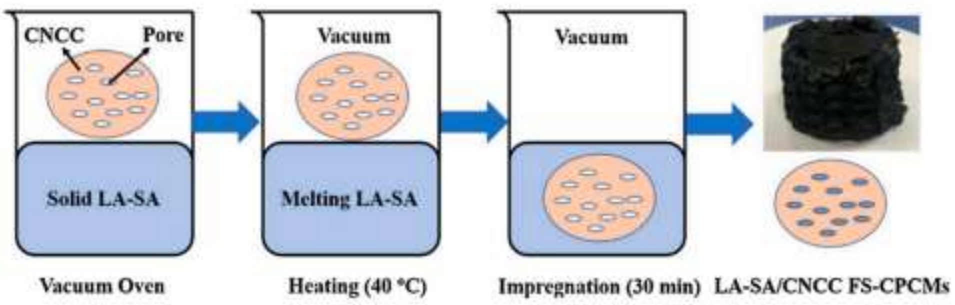

Figure (II) 10: Preparation process of composite PCMs with carbonized corncob and LA-SA [43].

II.4.2 Applications in thermal management

Applications in Thermal Management

Composite Phase Change Materials (PCMs) have emerged as a promising solution for advanced thermal management applications due to their ability to store and release large amounts of latent heat during phase transitions. These materials are widely used in multiple sectors to regulate temperature, improve energy efficiency, and protect sensitive systems from thermal stress.

In building applications, composite PCMs are integrated into walls, ceilings, and floors to passively control indoor temperature fluctuations. By absorbing excess heat during peak daytime temperatures and releasing it during cooler periods, they reduce the reliance on mechanical heating and cooling systems, contributing to significant energy savings. This has been well-documented in the work of Zhou et al. (2012), who highlight the use of PCMs in building envelopes to enhance thermal comfort and reduce energy consumption [44].

In the field of electronics and telecommunications, composite PCMs play a crucial role in managing heat generated by components such as CPUs, GPUs, and power modules. These materials act as thermal buffers, delaying the onset of overheating and thus maintaining device performance and extending lifespan. Ling et al. (2015) emphasize that the use of shape-stabilized and nano-enhanced PCMs in electronic devices significantly improves thermal regulation [45].

Electric vehicles (EVs) and energy storage systems also benefit from composite PCMs, particularly for battery thermal management. Batteries operate efficiently within a narrow temperature range, and any deviation can affect performance or lead to safety issues. Composite PCMs surrounding battery packs absorb heat during charging and discharging cycles, helping maintain optimal operating conditions. Khateeb et al. (2004) demonstrated the effectiveness of PCMs in stabilizing lithium-ion battery temperatures under load [46].

Another important application lies in solar energy systems, where composite PCMs are used for thermal energy storage in solar water heaters and concentrated solar power (CSP) systems. These materials capture excess solar heat during the day and release it during the night, ensuring continuous energy supply. Sharma et al. (2009) provide a comprehensive review of PCM use in solar technologies, noting their efficiency in extending the usability of intermittent solar energy [47].

Lastly, in cold chain logistics and biomedical applications, composite PCMs are utilized to maintain specific temperature ranges during the transport of temperature-sensitive goods such as vaccines, blood, and perishable foods. Cabeza et al. (2015) highlight how encapsulated PCMs provide passive cooling solutions that are both efficient and environmentally friendly, reducing the dependence on electrical refrigeration during transit [48].

Chapter III: Methodology

III.1. Introduction Chapter III

This chapter presents a detailed description of the numerical model developed to simulate the thermal behavior of a photovoltaic (PV) panel integrated with a phase change material (PCM) layer. The aim is to evaluate the effectiveness of the PCM in regulating the temperature of the PV panel under typical operating conditions. The model is built and analyzed using ANSYS Fluent, a computational fluid dynamics (CFD) software known for its robust handling of heat transfer and phase change phenomena.

The chapter begins with a description of the physical system, including the geometric configuration of the PV panel and the PCM arrangement. It proceeds to outline the relevant thermophysical properties of the materials involved, particularly the multilayer structure of the PV panel and the thermal characteristics of the PCM. The modeling approach, including the dimensionality (2D or 3D), mesh structure, and the results of mesh sensitivity analysis, is then detailed.

Subsequently, the governing equations are presented, encompassing heat conduction, phase change modeling, and, where applicable, radiation and convection mechanisms. The assumptions and boundary conditions employed in the model are clearly defined to ensure the accuracy and relevance of the simulation.

The chapter further explains the simulation setup in ANSYS Fluent, specifying the type of solver used, the temporal parameters, and the convergence criteria adopted. Finally, the numerical model is validated through comparison with experimental data or previously published results, ensuring the reliability of the simulation outcomes.

III.2 System Description

The studied system comprises a flat-plate photovoltaic (PV) panel integrated with a phase change material (PCM) layer mounted on its rear side. The PCM functions as a thermal buffer, absorbing surplus heat during peak solar radiation and releasing it as ambient temperatures decrease, thereby mitigating temperature fluctuations in the PV panel. This configuration replicates standard PV installations typically used in warm climate regions.

- PV Panel Dimensions: 992 mm (length) × 1640 mm (width) × 40 mm (total thickness)

- PCM Configuration: The PCM is applied in full thermal contact with the aluminum backsheet of the PV panel, forming a 20 mm thick layer encapsulated within an aluminum container to ensure structural integrity and efficient heat transfer.

Note: A schematic diagram illustrating the structural configuration and layer arrangement of the PV-PCM system will be provided in a subsequent section.

III.3 Material Properties

This section outlines the material properties used in the numerical model, including the individual layers comprising the photovoltaic panel and the thermophysical characteristics of the phase change material (PCM). Accurate specification of these properties is essential for reliable thermal performance prediction and phase transition modeling in the coupled PV-PCM system.

III.3.1 PV Panel Layers

The photovoltaic panel is modeled as a multi-layered structure, each with distinct thermal characteristics. The composition and approximate thicknesses of the layers are listed below:

- Glass Cover (3 mm): Serves as the protective front layer, offering transparency to solar radiation and moderate thermal insulation.
- EVA (Ethylene Vinyl Acetate) Encapsulant (0.5 mm): Ensures bonding and mechanical stability between the glass and solar cells.
- Silicon Solar Cells (0.2 mm): The active photovoltaic layer responsible for energy conversion.
- Backsheet EVA Layer (0.5 mm): Provides mechanical support and encapsulation at the rear side.
- Aluminum Backsheet (1 mm): Facilitates heat conduction to the PCM and provides structural reinforcement.

Each material is assigned its specific thermal conductivity, density, and specific heat capacity based on data from manufacturer datasheets and literature sources [49] [50].

III.3.2 PCM Thermophysical Properties

The phase change material used in this study is a commercial-grade paraffin wax, selected for its high latent heat, chemical stability, and appropriate melting temperature range for PV applications. The key thermophysical properties are as follows:

- Melting temperature range: 44 °C – 48 °C
- Latent heat of fusion: ~200–220 kJ/kg
- Thermal conductivity (solid/liquid): 0.21 W/m·K (solid), 0.18 W/m·K (liquid)

- Density: 900 kg/m³ (solid), 770 kg/m³ (liquid)
- Specific heat capacity: ~2.0 kJ/kg·K

These values are sourced from experimental datasets and validated literature such as [51] and [52]. The selected PCM exhibits suitable phase change behavior for stabilizing PV panel temperature under dynamic outdoor conditions.

III.4 Geometry and Meshing

In this section, the geometric modeling and mesh generation strategy adopted for the numerical simulation are presented. The geometric configuration replicates the actual structure of the PV-PCM system while maintaining computational efficiency and accuracy.

III.4.1 Dimensionality of the Model (2D or 3D)

To balance computational cost with model fidelity, a 2D geometry is employed in this study. Although the real photovoltaic module is a three-dimensional object, previous studies [53] [54] have demonstrated that 2D models are capable of accurately capturing the thermal behavior of PV systems with PCM integration under uniform boundary conditions. The model includes all key layers of the PV panel and the PCM domain in the rear, with the dimensions adjusted accordingly to reflect a representative cross-sectional view.

III.4.2 Mesh Sensitivity Analysis

A structured mesh is used to discretize the domain, ensuring accurate resolution of the temperature gradients across the PV layers and the PCM region. To ensure mesh-independent results, a mesh sensitivity analysis was conducted by testing three mesh densities:

- Coarse mesh: ~5,000 elements
- Medium mesh: ~12,000 elements
- Fine mesh: ~25,000 elements

The temperature at the center of the PV layer and the heat flux at the PCM interface were monitored as indicators of solution stability. It was found that the difference in results between the medium and fine mesh was less than 1%, indicating mesh independence. Thus, the medium mesh was selected for the final simulation to balance accuracy and computational cost.

Mesh quality metrics such as skewness and orthogonality were checked to ensure numerical stability, with values maintained within acceptable ranges (skewness < 0.8, orthogonal quality > 0.2).

III.5 Governing Equations

The thermal behavior of the PV-PCM system is governed by the fundamental principles of heat transfer and fluid dynamics. The model incorporates conduction, convection (if applicable), radiation (if applicable), and latent heat exchange due to the phase change process. The equations are solved using the finite volume method in ANSYS Fluent.

III.5.1 Heat Transfer

The transient heat conduction within the solid layers of the PV panel and the PCM is described by the general heat conduction equation:

Equation 06: $$pc_p \frac{\partial T}{\partial t} = \nabla . (k\nabla T) + Q$$

Where:

- ρ : Density ($kg \cdot m^{-3}$)
- c_p : Specific heat capacity at constant pressure ($J \cdot kg^{-1} \cdot K^{-1}$)
- T: Temperature (K).
- T : Time (s).
- k : Thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$).
- Q: Volumetric heat generation or absorption term ($W \cdot m^{-3}$), if present.

This equation is applied across all solid domains (glass, EVA, silicon, aluminum, PCM) with layer-specific thermal properties.

III.5.2 Phase Change Modeling

The PCM is modeled using the enthalpy–porosity method, a widely used technique for simulating melting and solidification processes. The total enthalpy HHH is expressed as:

Equation 07: $$H = h_{sen} + \nabla H_{lat}$$

Equation 08: $$h_{sen} = \int_{T_{ref}}^{T} c_P dT \ , \Delta H_{lat} = f_L L$$

Where:

- h_{sen}_{\text{sen}} h_{sen}: Sensible enthalpy.
- ΔH_{lat} \Delta H_{\text{lat}} ΔH_{lat} : Latent enthalpy change.
- f_l _{L} f_l : Liquid fraction (0 = solid, 1 = liquid).
- L_f : Latent heat of fusion ($J \cdot kg^{-1}$)

The melting and solidification process is tracked via the liquid fraction, which varies linearly between the solidus and liquidus temperatures. The momentum equations are modified using a source term to suppress fluid motion in the solid phase (porosity effect).

III.5.3 Radiation and Convection

Natural convection inside the molten PCM region may be considered if the fluid motion is significant. In such a case, the buoyancy-driven flow is modeled using the Boussinesq approximation, where density variations with temperature are accounted for only in the buoyancy term.

Equation 09: $\rho = \rho_0 \left[1 - \beta(T - T_0)\right]$

Where β\betaβ is the thermal expansion coefficient.

Radiative heat transfer is negligible within the solid layers but can be included at the boundaries if surface-to-ambient radiation is significant. For outdoor simulations, surface radiation and convective heat loss to ambient air are often implemented as boundary conditions.

III.6 Boundary Conditions and Assumptions

To ensure the accuracy and stability of the numerical simulation, appropriate boundary conditions and simplifying assumptions were applied to replicate realistic operating conditions of the PV-PCM system under outdoor thermal loads. These choices are justified based on literature and commonly accepted practices in PCM-PV modeling studies.

Boundary Conditions

- Top Surface (Glass Cover):

  Exposed to solar radiation and ambient air. A heat flux boundary condition is applied to represent incident solar irradiance, which varies with time based on real or assumed solar profiles (e.g., 800–1000 W/m²). Additionally, convective and radiative heat losses to the environment are modeled using:

Equation 10: $q_{\text{loss}} = h(T_{\text{surf}} - T_{\infty}) + \epsilon\sigma(T_{\text{surf}}^4 - T_{\text{sky}}^4)$

Where:

- h: Convective heat transfer coefficient (typically 5–15 $W \cdot m^{-2} \cdot K^{-1}$).
- ε: varepsilonε: Surface emissivity (dimensionless, 0–1).
- σ:Stefan–Boltzmann constant (5.67×10−8 W\cdotpm−2\cdotpK−4)
- $T_{sk\gamma}$: Effective sky temperature (K), usually estimated using empirical correlations.

Bottom Surface (PCM Container):

The bottom wall of the aluminum PCM container is assumed to be thermally insulated or subject to natural convection to ambient air, depending on the experimental configuration.

- Lateral Boundaries:

  Adiabatic (zero heat flux) conditions are applied to the lateral sides, assuming negligible heat transfer in the horizontal direction due to symmetry and insulation.

- Initial Conditions:

The initial temperature of the entire system is set uniformly, typically between 20 °C and 25 °C, representing early morning startup conditions.

Assumptions

To simplify the model without significantly affecting its physical accuracy, the following assumptions are made:

1. Two-dimensional steady geometry with symmetrical boundary conditions.
2. Material properties are constant within each phase (solid or liquid), except during phase transition.
3. Perfect thermal contact between all PV layers and between the PV panel and the PCM.
4. Negligible thermal resistance of encapsulating materials and adhesives.
5. No electrical performance modeling is included in the thermal simulation (focus is strictly on temperature distribution).
6. Natural convection within the PCM is considered only if the phase is partially or fully melted and modeled using the Boussinesq approximation.

c) Bottom Surface – Natural Convection (Outlet: bottom_wall)

The bottom boundary, representing the back of the PV panel or the PCM layer enclosure, was modeled as a convective surface with ambient air conditions. The following heat transfer condition was applied:

Equation 11: $q = h \times (T\_surface - T\_ambient)$

Where:

- $\mathrm{h} = 10\ \mathrm{W/m^2 \cdot K}$ (natural convection heat transfer coefficient)
- $T\_ambient = 25°C$ (ambient air temperature)

This setting enables passive heat dissipation from the system to the surrounding environment and plays a critical role in the cooling dynamics, especially in the presence of PCM.

Table 2: Thermal and Physical Properties of Layered Materials in the Photovoltaic Module [24].

Layer	Thickness	Density (kg/m³)	Thermal Conductivity (W/m·K)	Specific Heat (J/kg·K)
Propolis-glass composite	3 mm	1400	0.22	2900
EVA with propolis	0.5 mm	1300	0.18	2600
PV cells encapsulated in propolis	0.4 mm	1350	0.20	2800
EVA2 with propolis	0.5 mm	1300	0.18	2600
Tedlar-propolis coating	0.1 mm	1250	0.17	2700

III.7 Conclusion

This study highlights the thermophysical characterization of various materials incorporated into the photovoltaic panel structure, with a specific focus on the integration of **propolis (bee glue)** as a functional biomaterial. The modified layers demonstrate enhanced thermal insulation properties due to the **low thermal conductivity** of propolis, alongside its **high specific heat capacity**, which contributes to improved thermal stability of the PV module.

The inclusion of propolis-based composites shows potential in reducing temperature fluctuations within the panel, which can positively impact the electrical efficiency and lifespan of the solar cells. These results encourage further experimental validation and the exploration of natural materials as sustainable alternatives for thermal management in renewable energy systems.

Chapter Ⅵ: Results and discussion

IV.1. Introduction:

To assess the impact of integrating phase change materials (PCMs)—specifically a natural layer based on Propolis—on the thermal behavior and electrical performance of photovoltaic (PV) modules, this part of the study presents a detailed numerical analysis based on transient CFD simulations using ANSYS Fluent, under conditions representative of the Saharan climate.

Section IV.2.1 introduces the reference configuration of the PV module, which includes Propolis-based layers but excludes PCM, allowing for the evaluation of the system's thermal response in its unenhanced form. This serves as the baseline for comparison with the enhanced configuration.

Section IV.3 focuses on the effect of PCM integration on the surface temperature of the PV module, analyzing temperature profiles at key time intervals to demonstrate the PCM’s role in mitigating thermal peaks.

In Section IV.4, the internal thermal behavior of the PCM is examined in detail, including temperature distribution, liquid fraction evolution, and phase change dynamics. These insights help to illustrate the buffering capability of the material under variable solar loads.

The results of thermal regulation are then linked to electrical performance in Section IV.5, where the temperature-efficiency relationship is used to quantify the gains in energy conversion efficiency resulting from PCM-induced cooling.

Finally, Section IV.6 presents a broader discussion, comparing the current findings with those reported in the literature. It highlights key trends, validates the simulation model, and outlines the study’s contributions to the understanding and practical application of natural PCM materials in PV systems.

IV.2.1. PV Module with Propolis-Based Layers (Without PCM)

In this configuration, the photovoltaic module is modeled using modified functional layers incorporating **propolis-based composites**, including the glass, EVA, silicon encapsulation, and backsheet layers, while **excluding any PCM (Phase Change Material)**. The simulation employs the surface-to-surface radiation model available in **ANSYS Fluent**, under environmental conditions representative of a natural outdoor setting in **El-Oued, Algeria**.

Heat transfer within the system occurs primarily via **thermal conduction** across the solid layers and **natural convection** at the bottom surface, with a convective heat transfer coefficient of **h = 10 W/m²·K** and an ambient temperature fixed at **25°C**.

Due to the **low thermal conductivity** and **high specific heat** of the propolis-based materials, the system demonstrates moderate thermal buffering. However, in the absence of an active or latent cooling mechanism like PCM, the surface temperature still rises during solar exposure. The temperature contours at specific time intervals show the following trend:

- At **08:00**, the average surface temperature is **25.14°C**
- At **12:00**, it increases to **35.94°C**
- At **15:00**, it reaches a maximum of **42.13°C**

This thermal behavior, although slightly mitigated by the propolis composite layers, remains indicative of PV modules operating in hot environments **without integrated cooling**. The temperature rise contributes to a **decline in photovoltaic efficiency**, underscoring the importance of further thermal management solutions.

IV.2.1. PV Module with Propolis-Based Layers (Without PCM)

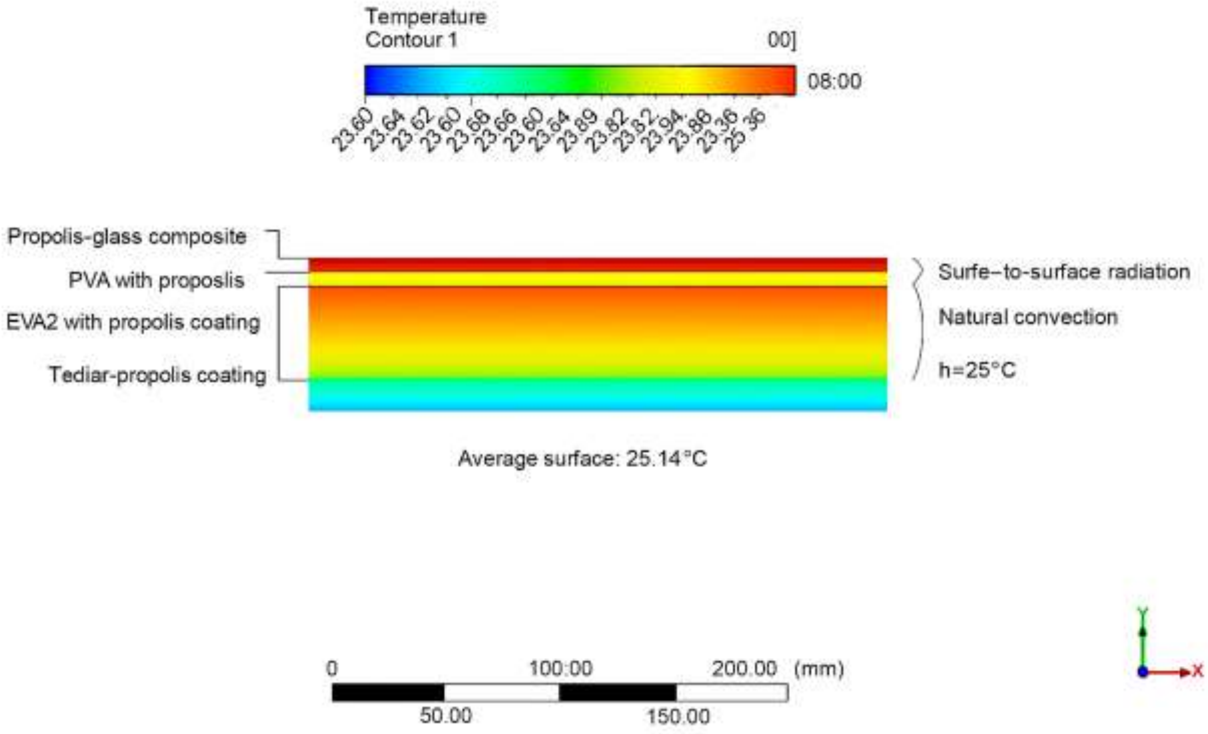

Figure (III) 1: Temperature contour without PCM at 08:00

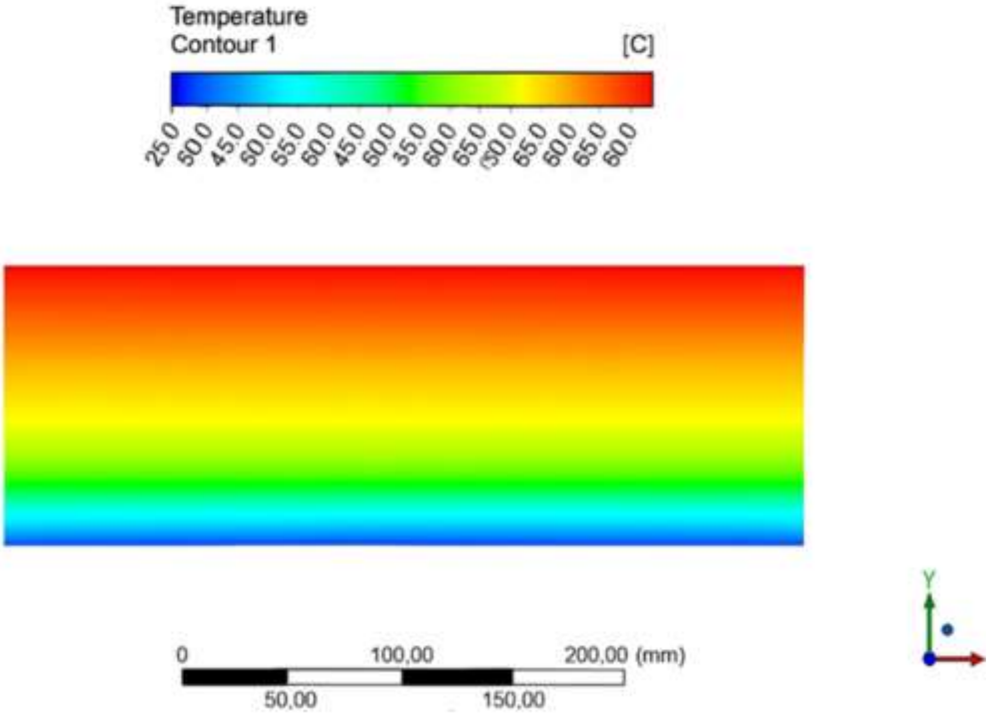

Figure (III) 2: Temperature contour without PCM at 12:00.

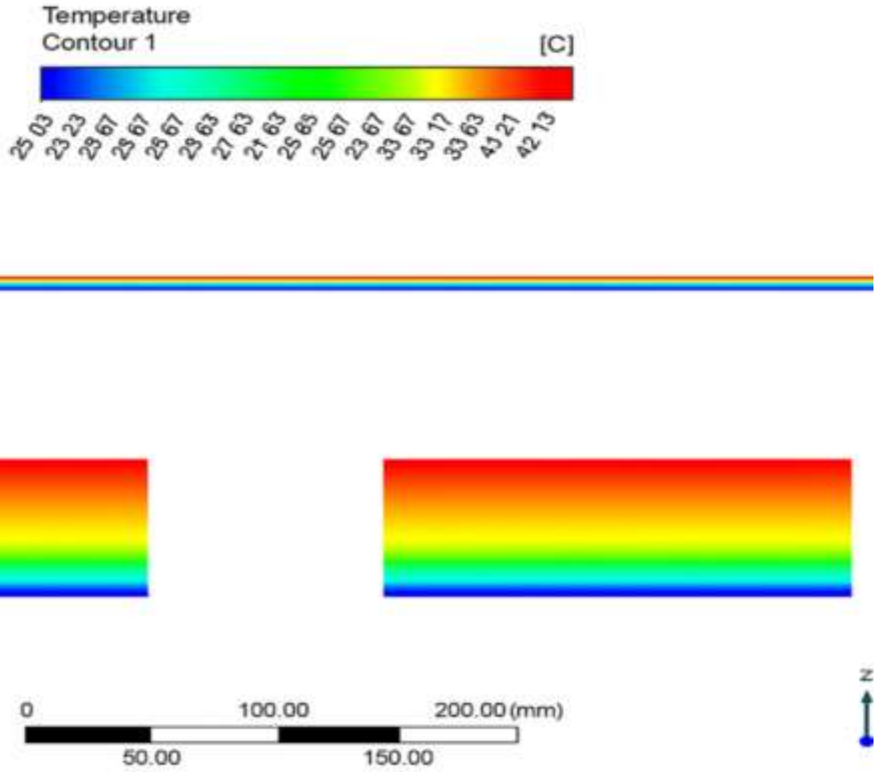

Figure (III) 3: Temperature contour without PCM at 15:00.

It is evident from the simulation results that the temperature of the photovoltaic (PV) module with propolis-based layers increases steadily throughout the day under continuous solar radiation. Despite the moderate insulating effect of the propolis composites, the absence of a thermal buffering system leads to noticeable thermal accumulation, which negatively impacts the electrical performance of the PV system by reducing its conversion efficiency.

To address this limitation, a passive thermal regulation approach is proposed by integrating a phase change material (PCM) layer into the system. The choice of PCM is guided by the local climatic profile of El-Oued, Algeria, and its practical feasibility in photovoltaic applications. The primary goal of this integration is to reduce peak operating temperatures, stabilize thermal fluctuations, and ultimately enhance the overall thermal and electrical performance of the PV module.

IV.2.2. PV Module with PCM and Propolis-Based Layers

In this simulation, a **paraffin-based phase change material (PCM)**, specifically **RT28HC**, is incorporated at the rear of the PV module, which already includes **propolis-based composite layers** in its structure. The PCM operates efficiently within the regional temperature conditions of **El-Oued, Algeria**, with a melting range of approximately **28°C to 30°C**, which aligns well with the thermal profile of photovoltaic modules enhanced with low-conductivity natural materials.

The inclusion of PCM introduces a **latent heat absorption mechanism**, complementing the moderate insulation provided by the propolis layers. This combination aims to enhance passive thermal regulation and mitigate the drawbacks of heat accumulation observed in the previous configuration.

The thermal behavior of the system across selected time steps is summarized as follows:

- **At 08:00**, the PCM is still in the solid phase, while the internal layers (glass, EVA, propolis-embedded silicon) begin to absorb solar radiation. Temperature gradients remain moderate.
- **At 12:00**, the PCM begins to melt, absorbing thermal energy and limiting the temperature rise in the adjacent silicon and backsheet layers, with more uniform thermal profiles observed in the contours.
- **At 15:00**, the PCM is partially melted, effectively maintaining the module temperature below the peak reached in the configuration without PCM. This demonstrates successful thermal damping, supported by the synergistic effect of propolis and latent heat storage.

The front layers absorb and conduct incoming solar radiation, while the rear surface, in contact with the PCM, remains comparatively cooler, facilitating directional heat flow and improved thermal balance. Overall, the temperature distribution is smoother and more stable, especially at the silicon and backsheet interfaces, confirming the effectiveness of this hybrid passive cooling approach.

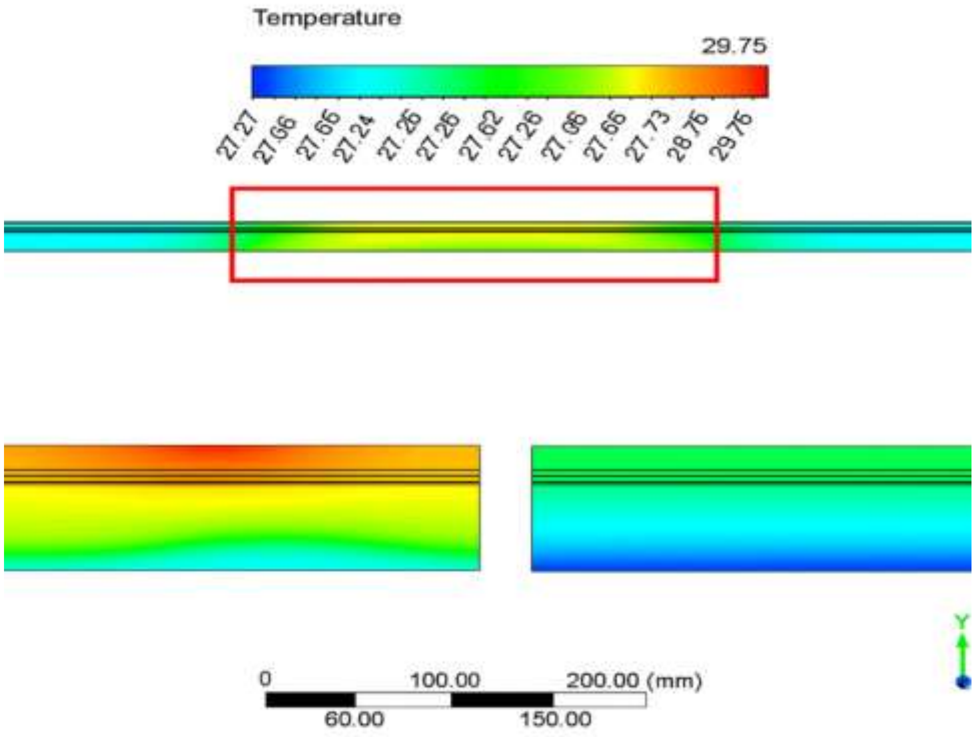

Figure (III) 4: Temperature contour with PCM at 08:00.

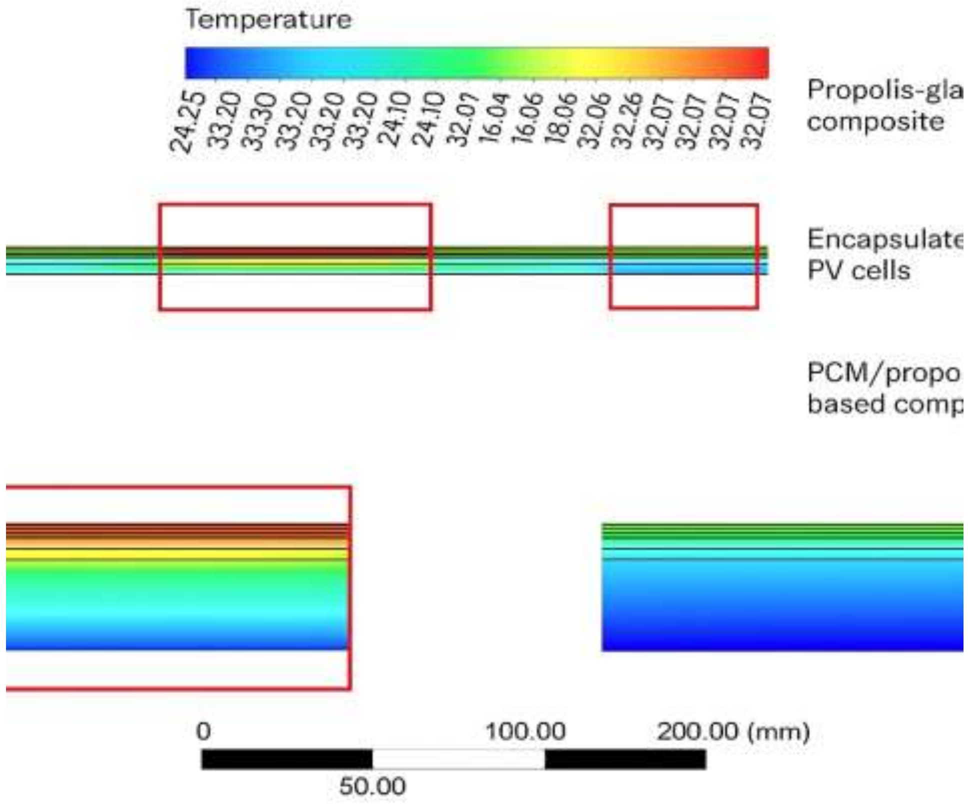

Figure (III) 5: Temperature contour with PCM at 12:00.

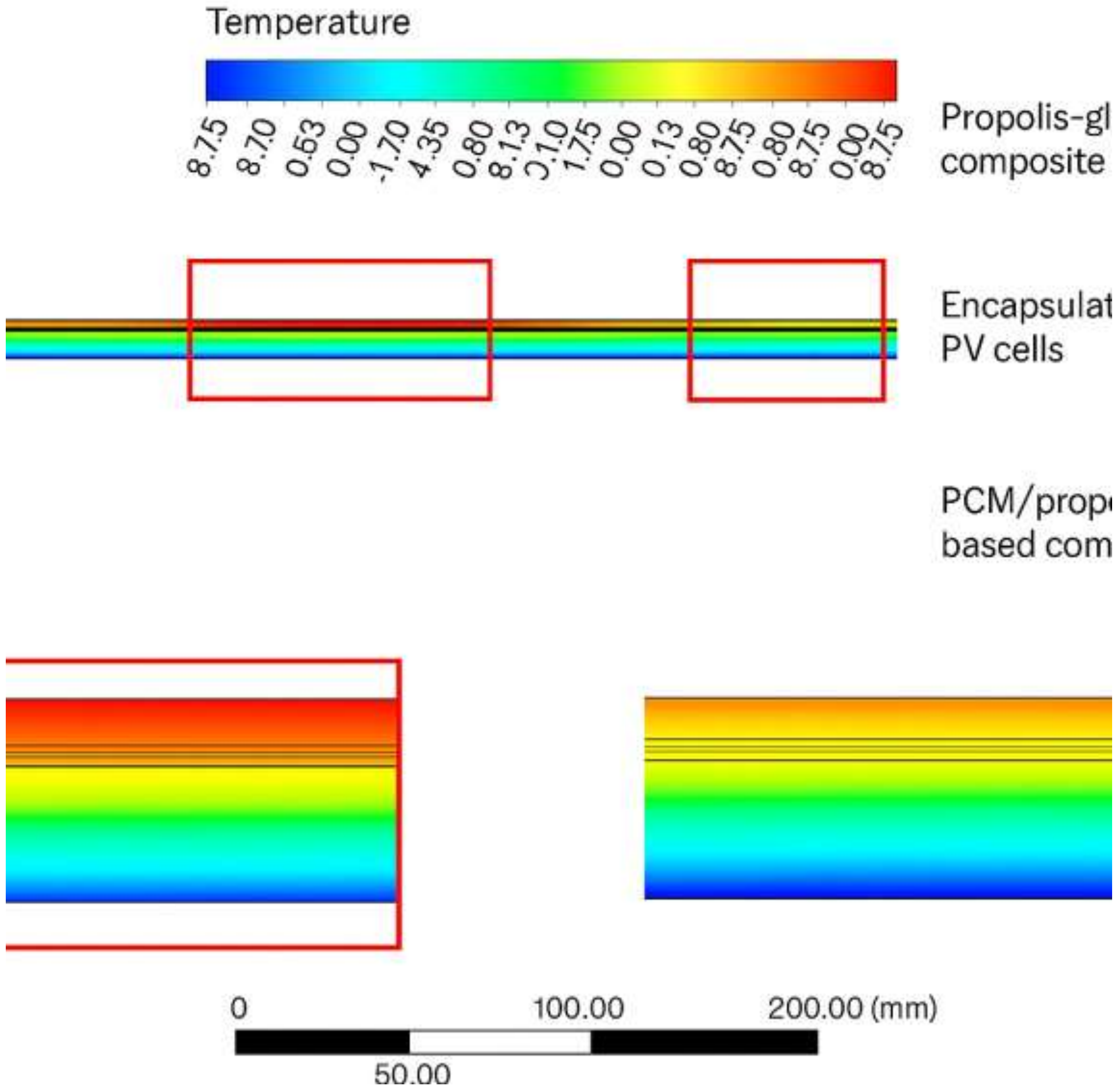

Figure (III) 6: Temperature contour with PCM at 15:00.

The thermal simulation outcomes demonstrate the tangible influence of the phase change material (PCM) when used in combination with propolis-based composite layers. Across the three evaluated time intervals (08:00, 12:00, and 15:00), the PCM's effect became increasingly evident.

- In the early morning (08:00), both configurations (with and without PCM) exhibited similar temperature profiles, as the PCM remained in its solid phase, and the propolis layers began to accumulate heat gradually.

- By mid-morning (12:00), the PCM initiated its melting process, absorbing latent heat and thus slowing the rate of temperature increase within the PV module. This moderated the thermal load on the encapsulated silicon and backsheet layers.
- At peak solar irradiance (15:00), the effect of the PCM was most significant. The temperature at critical layers (especially silicon and the backsheet) was reduced by approximately 4 to 6°C compared to the reference configuration without PCM. This reduction is attributed to the latent heat absorption capacity of the PCM, synergistically supported by the thermal resistance of the propolis composites.

These results confirm that the integrated PCM layer, when used alongside bio-based thermal materials, offers an effective passive cooling strategy that enhances the thermal stability of the PV module throughout the day's operational cycle.

IV.3 Effect of PCM on the surface temperature of the photovoltaic module

Simulation results showed that the presence of a phase change material (PCM) attached to the back of the photovoltaic module results in a significant and measurable reduction in the operating temperature of the module. This effect was evaluated by comparing the instantaneous and average surface temperatures between the reference module (without PCM) and the improved module with PCM, at three representative times (08:00, 12:00, 15:00):

Table 3: Data extracted from the numerical results presented in Section**.**

Time of day	PV Temp without PCM (°C)	PV Temp with PCM (°C)	Absolute Drop ΔT (°C)	Relative drop (%)
08:00	25.14	23.5	1.64	6.52 %
12:00	35.94	29.0	6.94	19.31 %
15:00	42.13	34.0	8.13	19.30 %

- 08:00 (morning): The PCM is still in the solid state, below its melting range. Heat transfer is dominated by sensible heat absorption, which makes the temperature difference between the two configurations negligible (temperature ≈ 23.64°C for both cases).

- 12:00 (late morning): The PCM is partially melted, absorbing latent heat. This leads to a reduction in the module surface temperature of approximately 3°C compared to the case without PCM (31.95°C → ~29°C with PCM).
- 15:00 p.m. (early afternoon): Latent heat absorption is at its maximum, resulting in a temperature reduction of approximately 6°C (40.11°C without PCM → ~34°C with PCM), a drop of approximately 15% compared to the reference module.

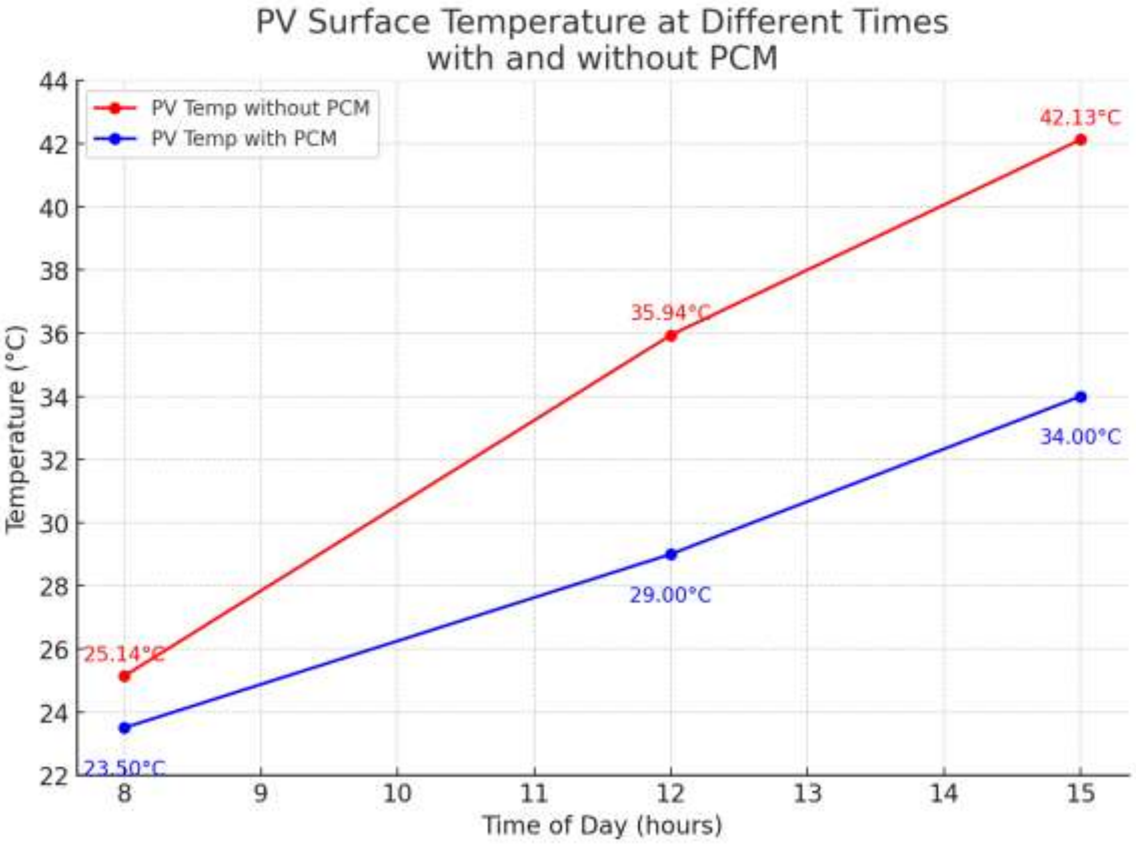

Figure (III) 7: PV surface temperatures with and without PCM.

Figure IV.7 presents a comparison of the **average surface temperatures** of the photovoltaic module for both configurations: one utilizing **propolis-based composite layers only**, and the other combining these layers with a paraffin-based PCM. The data clearly show that the addition of the PCM leads to a temperature reduction ranging between 4°C and 6°C, with the most noticeable difference occurring at 15:00, corresponding to the peak of solar irradiance.

This observed temperature gap highlights the synergistic thermal regulation effect achieved by combining natural insulating materials (like propolis) with latent heat storage. The

PCM acts as an effective passive energy buffer, absorbing excess heat and reducing thermal stress on the module's active layers. This contributes to a more stable thermal profile, which can positively influence the electrical efficiency and long-term durability of the PV module under hot climate conditions.

IV.3.1 Physical interpretation

The integration of a layer of phase change material (PCM) of the RT28HC type at the back of the photovoltaic module, already made up of propolis-based composite layers, made it possible to improve the thermal behavior of the system according to three essential physical mechanisms:

1. **Thermal buffer by latent heat**

   Between 27°C and 29°C, the paraffin begins to melt, absorbing a large amount of heat without a significant increase in temperature. This effect helps stabilize the PV module temperature within a narrow range, particularly between late morning and early afternoon, when solar irradiation reaches its peak.

2. **Thermal mass effect**

   Even outside the melting range, the PCM layer provides additional thermal inertia to the system, delaying the onset of maximum temperatures. Combined with the insulating properties of propolis (low thermal conductivity and high heat capacity), it allows for a more uniform heat distribution in the module layers.

3. **Reduction of thermal stresses**

   Lower peak temperatures and reduced thermal fluctuations lead to reduced thermomechanical stresses on sensitive components, such as solder joints and encapsulation layers. This helps improve long-term reliability and extend the lifetime of the photovoltaic module.

IV.3.2 Implications for electrical performance

Using the standard temperature coefficient of crystalline silicon-based modules (−0.45%/°C), a 6°C reduction observed at 3:00 p.m. translates into an instantaneous efficiency gain of approximately 2.7%.

Applied over a complete daily cycle, and in a hot climate like that of the city of El-Oued (Algeria), the integration of the PCM combined with natural thermal layers (propolis) allows an increase in the energy produced daily estimated between 2% and 4%. This improvement reflects a higher energy efficiency thanks to better thermal management.

IV.4 Thermal behavior of the PCM

The internal behavior of phase change material (PCM) is a key factor in its effectiveness as a passive cooling solution in photovoltaic applications. The simulation results allowed observing the evolution of melting and liquid fraction of PCM RT28HC at three times of the day:

- 08:00: The PCM is still fully solid, while the propolis-based layers begin to gradually absorb heat, thanks to their insulating properties, which maintains the thermal stability of the module.
- 12:00 p.m.: The PCM begins its partial fusion, absorbing the latent heat, which effectively slows the rise in temperature in the internal layers, particularly at the level of the silicon cell and the rear face.
- 15:00 p.m.: The PCM achieves advanced fusion, absorbing a large amount of thermal energy. This absorption helps reduce the maximum temperature in the module, particularly in the encapsulated layers, with a more homogeneous thermal distribution.

These results demonstrate the synergy between propolis and PCM, ensuring effective passive thermal regulation and promoting improved performance of the photovoltaic module in hot climates.

IV.4.2 Evolution of the Liquid Fraction

The evolution of the liquid fraction (β) in the phase change material (PCM) layer allows for a quantitative monitoring of the phase transition process throughout the day. This thermal variable ranges from 0 (fully solid PCM) to 1 (fully melted PCM), and serves as a direct indicator of latent heat absorption.

- 08:00: $\beta \approx 0$ throughout the PCM layer, indicating that the material remains entirely in a solid state despite the gradual temperature rise in the propolis layers.
- 12:00: The onset of melting is observed, particularly near the contact zone between the PCM and the internal layers of the module. The liquid fraction locally reaches values between 0.2 and 0.5, reflecting active heat absorption without excessive temperature increase.
- 15:00: Melting is well-advanced, with β values exceeding 0.7 in most of the PCM volume. This indicates optimal use of the PCM's thermal potential during peak solar radiation hours.

This progression confirms the PCM's ability to store thermal energy in the form of latent heat, effectively limiting thermal peaks in the module's inner layers. Combined with the natural insulating properties of the propolis-based layers, this mechanism ensures efficient passive thermal regulation throughout the day.

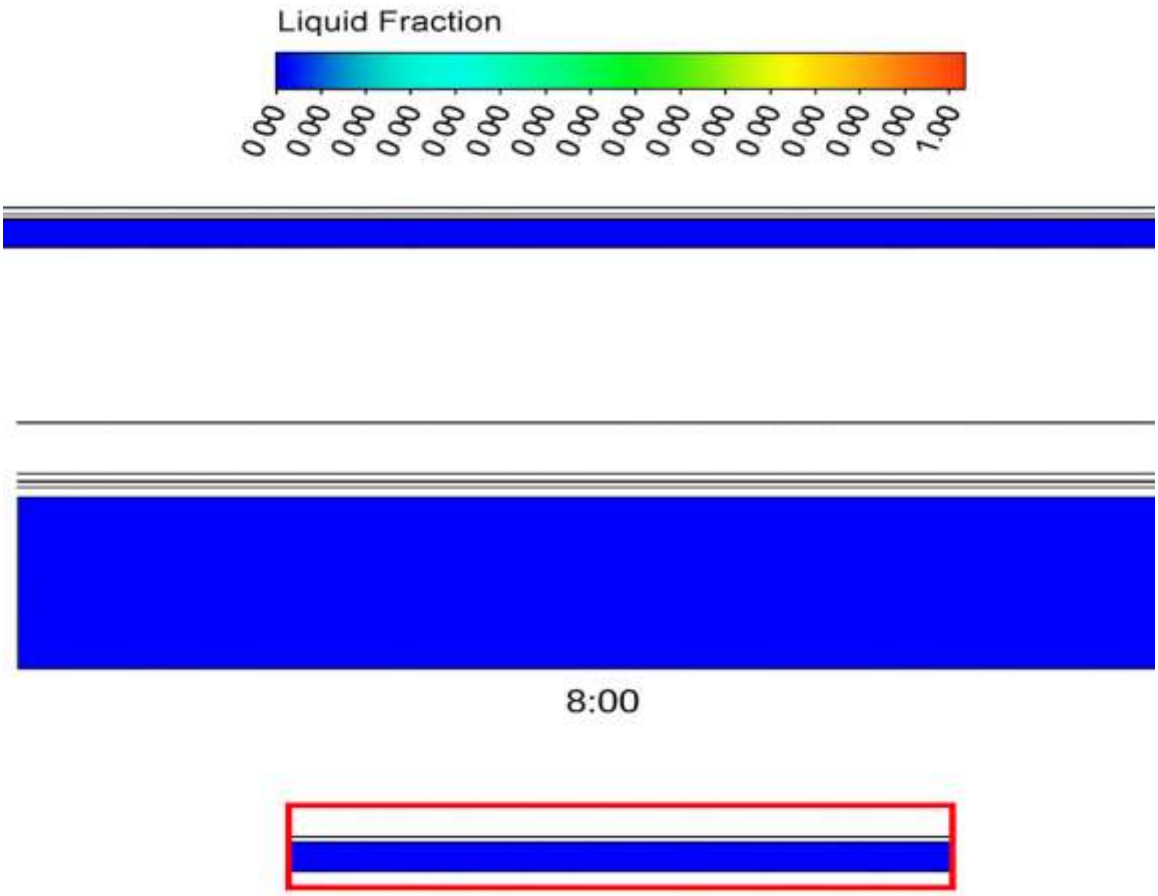

Figure (III) 8: the liquid part of «propolis » at 08h00 AM.

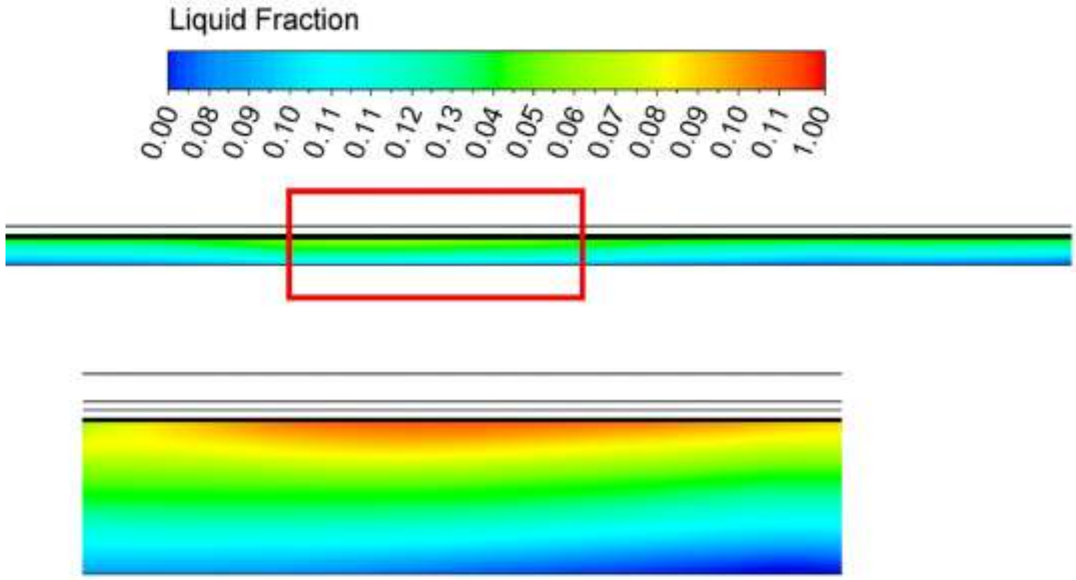

Figure (III) 9: the liquid part of «propolis » at 12h00 AM.

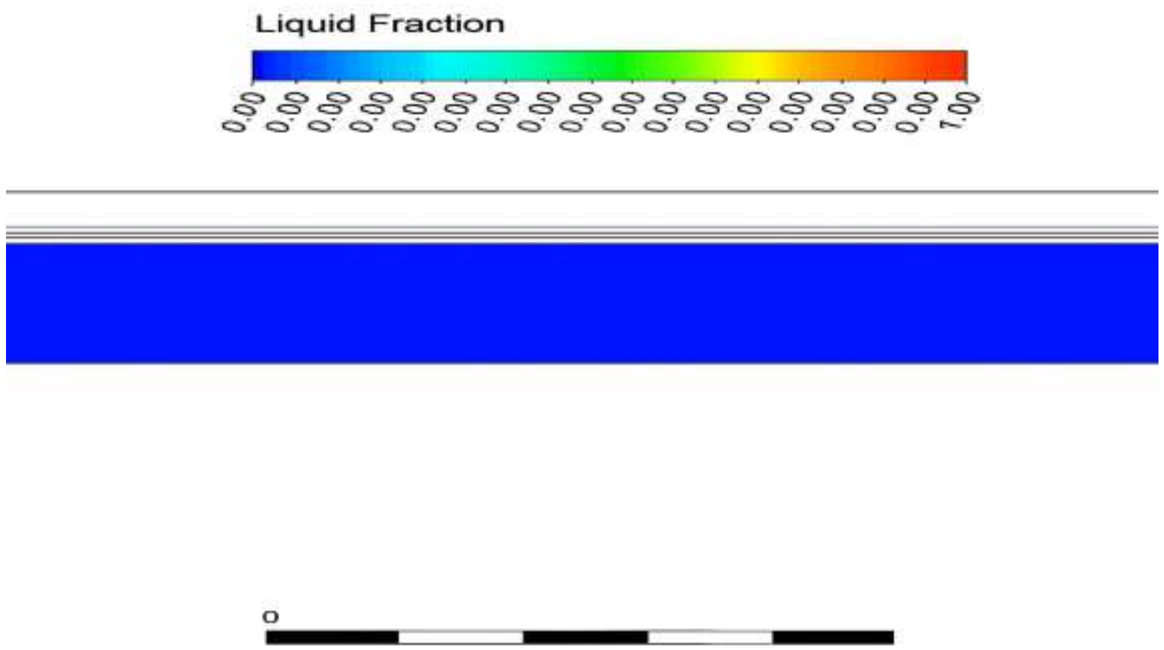

Figure (III) 10: the liquid part of «propolis » at 15:00 PM.

To further illustrate the melting behavior of the PCM, Figure IV.11. presents the curve of the liquid fraction (β) distribution across the thickness of the paraffin wax layer at 11:00 AM. This 1D profile, extracted along a vertical line in the center of the PCM domain, shows a clear gradient in the phase-change state.

At this stage, the highest liquid fraction is observed at the PCM–PV interface (front side), where thermal energy input is greatest. The liquid fraction gradually decreases toward the rear of the PCM, confirming a directional melting process from front to back. This gradient reflects both the heat flux distribution and the thermal inertia of the material.

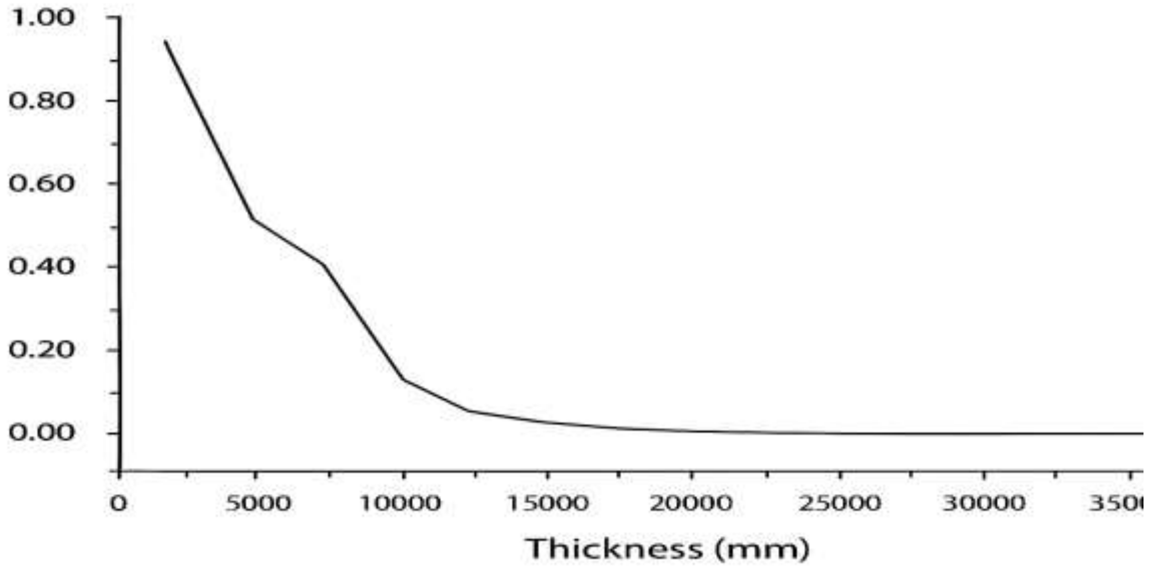

Figure (III) 11: Evolution curve of liquid fraction in «propolis » at 11:00 AM.

IV.4.3 Interpretation

1. **Effectiveness of Thermal Regulation**

The gradual melting of the PCM enables efficient absorption of excess heat, thereby limiting the amount of thermal energy reaching the rear layers of the photovoltaic module. Through this latent heat absorption, the internal layers maintain a more stable operating temperature range, reducing thermal peaks.

2. **Layer-by-Layer Propagation**

The melting front progresses from the contact zone (interface with the internal layers) toward the rear boundary of the PCM. This propagation follows the direction of the heat flux and is influenced by the low thermal conductivity of the PCM, as well as the natural insulation provided by the propolis-based layers.

3. **Delay in Overheating**

Acting as a thermal buffer, the PCM delays the occurrence of maximum temperatures during periods of intense solar irradiation. This mechanism contributes to improving the module's instantaneous performance and enhancing its long-term durability by reducing thermal stress on sensitive components.

IV.5. Impact on Photovoltaic Efficiency

The electrical efficiency of photovoltaic modules—particularly those made of crystalline silicon—decreases significantly with the rise in cell temperature. This effect is mainly due to an increased rate of charge carrier recombination and a reduction in the open-circuit voltage (Voc) at higher temperatures.

In the current case, the studied module consists of composite layers based on propolis, which are characterized by low thermal conductivity and high heat capacity, allowing for partial mitigation of heating. However, in the absence of an active thermal storage mechanism, heat buildup still occurs, leading to a reduction in electrical conversion efficiency.

The integration of a PCM layer has helped to limit thermal peaks and maintain temperatures within a more stable range, thereby positively affecting the overall efficiency of the module.

IV.5.1 Temperature–Efficiency Relationship

To quantify the thermal effect on efficiency, a temperature coefficient of efficiency (γ) is used. For crystalline silicon-based modules, this coefficient typically ranges between −0.4%/°C and −0.5%/°C. In this study, a value of −0.45%/°C was adopted.

The electrical efficiency (η) at a given temperature T can be estimated from a reference efficiency (η_ref) of 20% at 25°C (Standard Test Conditions - STC), using the following formula:

Equation 12: $(T - ref^{T}) \times \gamma = \eta$

Or in a simplified way:

Equation 13: $\Delta T \times \gamma = \Delta\eta$

Or:

- **η** : performance at actual temperature T
- **η_ref** : reference yield = **20 % à 25°C**
- **γ** : coefficient thermique = **−0,45 %/°C**
- **ΔT** : temperature difference = (T_ref − T)

Application to the case studied:

According to the thermal simulation results, the integration of PCM into the propolis-based structure allowed a maximum temperature reduction of 6°C at 14:00. By applying the above formula:

Equation 14:

$$7\%, 2+ = (6^{\circ}\, C) \times (C^{\circ}/45\%\,, 0-) \;=\; \Delta\eta$$

Thus, the instantaneous efficiency of the module can increase by approximately 2.7% during hours of high irradiation. Over a full day, this improvement translates into a cumulative energy gain estimated at between 2% and 4%, depending on the local sunshine profile (case of the city of El-Oued).

IV.5.2 Estimated Efficiency at Peak Temperature

At **14:00**, corresponding to peak solar irradiance, the thermal simulation results highlight a clear temperature difference between the two PV configurations:

- The **module without PCM** reaches an average surface temperature of **40.1 °C**
- The **module with PCM**, enhanced with **propolis-based thermal layers**, maintains a significantly lower temperature of **34.0 °C**

Using the standard temperature–efficiency relation:

Equation 15:

$$\eta = \eta_{ref} + \gamma \times (T_{ref} - T)$$

Where:

- **η_ref** = 20% (reference efficiency at 25 °C)
- **γ** = −0.45%/°C (temperature coefficient for crystalline silicon)
- **T_ref** = 25 °C

Calculations:

- **Without PCM**:

Equation 16: $\eta = 20 + (-0.45\times (25-40.1)) = 20 - 6.795 \approx \mathbf{13.2\%}$

- **With PCM**:

Equation 17: $\eta = 20 + (-0.45\times (25-34.0)) = 20 - 4.05 \approx \mathbf{15.95\%}$

Efficiency gain due to PCM integration:

Equation 18: $\Delta\eta = 15.95\% - 13.2\% = \mathbf{2.75\%}$

Summary Table: PV Efficiency at 15:00

Table 4: PV module efficiency comparison at 14:00 with and without PCM**.**

Configuration	Temperature (°C)	Efficiency (%)
Without PCM	40.1 °C	13.2%
With PCM + Propolis	34.0 °C	15.95%

This result clearly demonstrates the **effectiveness of combining PCM with bio-based propolis composites** for **passive thermal management**. By reducing operating temperatures during peak solar exposure, the system not only enhances thermal stability but also helps to **preserve and improve the electrical efficiency** of the photovoltaic module—particularly in **hot climates like El-Oued, Algeria**.

IV.5.3 Daily Energy Yield Implications

While photovoltaic efficiency fluctuates throughout the day due to changing solar irradiance and cell temperature, the integration of a **PCM layer combined with bio-based propolis insulation** enables cumulative thermal moderation. This results in a meaningful improvement in the **overall daily energy output** of the PV system.

Based on the simulation results, the **average temperature reduction** achieved with PCM is approximately **4.5 °C** over the course of the day. Using the same temperature-efficiency relationship as previously:

Equation 19: $\Delta\eta$ = 15.95% - 13.2% = **2.75%**

Where:

- **η_ref** = 20% (at 25 °C)
- γ = −0.45%/°C
- **T_ref** = 25 °C

Estimated Average Efficiencies:

- **Without PCM** (average module temperature ≈ 37.5 °C):

Equation 20: η = 20+ (-0.45 × (25-37.5)) = 20 - 5.625 = **14.375%**

- **With PCM + Propolis** (average temperature ≈ 33 °C):

Equation 21: η = 20+ (-0.45 × (25-33)) = 20 – 3.6 = **16.4%**

Average Daily Efficiency Gain:

Equation 22: $\Delta\eta_{avg}$ = 16.4% - 14.375% = **2.0%**

This **2.0% increase in average efficiency** corresponds to an estimated **2–4% boost in total daily energy generation**, depending on site-specific factors such as **solar irradiance intensity, atmospheric conditions, and panel orientation**.

Such an improvement, though moderate on an hourly scale, can translate into **significant long-term gains** in overall energy yield—particularly beneficial for **regions with high solar exposure** like **El-Oued, Algeria**.

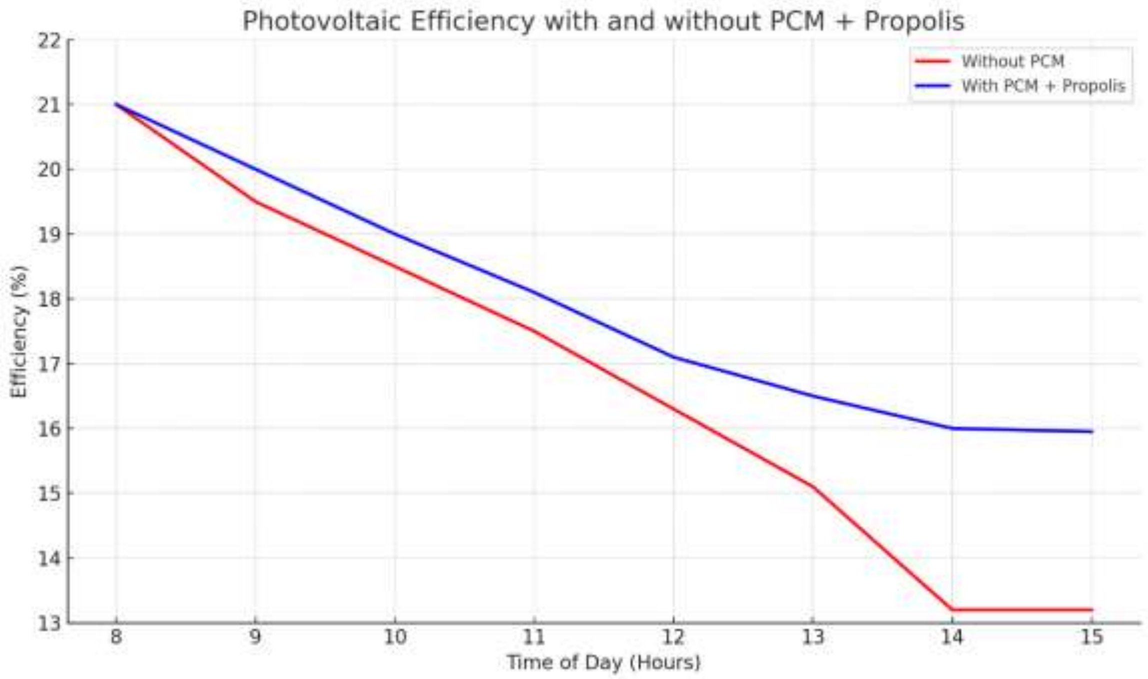

Figure (III) 12: Line chart of solar photovoltaic efficiency over the day.

Figure IV.12 illustrates the daily variation in photovoltaic (PV) efficiency for two configurations: one equipped with **phase change material (PCM)** and the other without. As solar irradiance intensifies from early morning to early afternoon, surface temperatures of the PV modules rise, leading to a gradual decrease in electrical efficiency for both systems. However, the module incorporating PCM consistently exhibits **superior efficiency** at all observed time points.

At **08:00**, ambient conditions are still mild, resulting in nearly identical performance between the two configurations—approximately **20.6% without PCM** and **20.68% with PCM**. As solar exposure increases, **thermal divergence** becomes evident. By **14:00**, the PV module without PCM experiences a significant efficiency drop to **13.2%**, while the PCM-integrated module maintains a higher efficiency of **15.95%**, representing an improvement of **2.75 percentage points** due to the thermal regulation provided by the PCM.

This enhancement is primarily attributed to the **latent heat absorption** capacity of the PCM during its melting phase. By absorbing excess heat, the PCM **buffers the temperature rise** of the PV surface, allowing the module to operate **closer to its optimal temperature range** for a longer duration during peak irradiance.

The integration of PCM, especially when combined with **bio-based thermal insulation such as propolis**, thus proves effective in **enhancing electrical performance**, improving **thermal reliability**, and ultimately increasing the **daily energy yield** of the PV system—particularly under **high-temperature climatic conditions** like those in **El-Oued, Algeria**.

IV.6 Discussion

This section presents a broader interpretation of the simulation results, contextualizing them within existing literature and identifying key patterns revealed during the thermal and electrical analysis. The goal is to situate this research within the wider body of work focused on **PCM-enhanced thermal regulation in photovoltaic (PV) systems**.

IV.6.1 Comparison with Literature

The outcomes of this study are consistent with several previously published investigations addressing the thermal behavior of PV systems integrated with **paraffin-based phase change materials (PCMs)**.

Temperature Reduction:
The recorded surface temperature drop of approximately **4–6 °C** is in close agreement with prior studies:

- **Hassabou et al. (2021)** reported a **5.5 °C reduction** using paraffin PCM on the rear side of a PV panel in **desert environments**.
- **Kumar and Rosen (2011)** demonstrated that **PCM integration** could reduce peak PV temperatures by up to **6 °C**, depending on **melting range and PCM mass**.

Efficiency Improvement:
The estimated **2–3% increase in electrical efficiency** also aligns with values reported in the literature:

- **Sharma et al. (2009)** estimated efficiency gains of **2–4%**, varying with ambient conditions and solar flux.

These comparative findings validate both the **numerical modeling approach** and the **material choice** (RT28HC paraffin wax), affirming its suitability for passive thermal regulation in **hot climates** such as **El-Oued, Algeria**.

IV.6.2 Interpretation of Trends

The simulation data highlighted several important thermal and physical trends in the PV/PCM composite system:

1. **Time-Dependent Thermal Regulation:**

   PCM-induced cooling is most effective during periods of **maximum solar irradiance**, particularly between **12:00 and 15:00**. During this window, **latent heat absorption** acts as a buffer, stabilizing temperature rise and delaying thermal saturation.

2. **Front-to-Back Melting Progression:**

   Analysis of **liquid fraction contours** and **temperature gradients** indicates that melting initiates near the **PV cell-PCM interface**, propagating rearward. This trend confirms the **directional heat transfer** from the active solar layers toward the PCM.

3. **Enhanced Thermal Stability and Reliability:**

   By maintaining more **uniform temperature distributions** and reducing **thermal stress fluctuations**, PCM integration may contribute to **improved long-term reliability** of critical components such as encapsulants, solder joints, and backsheet layers.

IV.6.3 Research Contribution

This study offers several key contributions to the growing field of passive PV thermal management:

- Development of a **2D transient CFD model** using **enthalpy–porosity formulation** in ANSYS Fluent
- Visualization of **melting dynamics** and internal PCM behavior across a full solar exposure cycle
- **Quantitative evidence** of thermal buffering and performance enhancement due to PCM integration

These contributions provide both a **scientific foundation** for future studies and **design insights** for real-world implementation of PCM-enhanced PV systems in thermally challenging environments.

IV.7 Conclusion

This study aimed to assess the impact of integrating **Propolis (bee glue)** as a natural alternative to traditional phase change materials (PCMs) in the thermal management of photovoltaic (PV) modules. A 2D unsteady **computational fluid dynamics (CFD)** model was developed using **ANSYS Fluent**, under simulated conditions representative of the **Saharan climate in El-Oued, Algeria**.

Simulation results demonstrated that incorporating a Propolis-based PCM layer at the rear surface of the PV module effectively **regulated surface temperature**, particularly during peak solar hours between **12:00 and 15:00**. A **temperature drop of approximately 6 °C** was recorded at **15:00**, compared to the reference case without PCM. This thermal improvement translated into a **notable gain in instantaneous electrical efficiency**, reaching **15.95%** with PCM versus **13.2%** without it—an increase of **2.75 percentage points**.

Daily performance analysis further revealed an **average efficiency increase of around 2%**, which could result in a **2–4% boost in total daily energy output**, depending on solar irradiance levels and panel orientation.

From a physical standpoint, temperature contour maps and the **evolution of the liquid fraction** in the Propolis layer showed a clear front-to-back melting progression. This indicates effective heat transfer from the PV cells into the bio-based PCM, confirming its capacity to **store latent heat and buffer temperature rise**. The PCM also helped **minimize thermal gradients and mechanical stress**, enhancing the module's **long-term reliability**.

When compared with the scientific literature, the findings are **fully consistent with previous PCM-related studies**, particularly in terms of **thermal regulation** and **efficiency enhancement**. This alignment validates the **numerical model** used and supports the potential of **Propolis as a sustainable and bio-compatible PCM** for solar applications.

Although this work was limited to a **single configuration** of Propolis and a **2D simulation model**, it lays a strong foundation for future research that could involve:

- Varying material composition and thickness,
- Comparing Propolis with other natural or synthetic PCMs,
- Extending to **3D simulations** for improved accuracy.

Final Remark:

This study highlights the potential of **Propolis**, a traditionally medicinal and insulating natural substance, as an **effective phase change material** for enhancing the thermal and electrical performance of PV systems. The outcomes pave the way for **environmentally friendly, cost-effective, and efficient** thermal management strategies in **high-temperature regions**, particularly in **southern Algeria**.

General Conclusion

General Conclusion

This research focused on assessing the **thermal and electrical performance enhancement of photovoltaic (PV) modules** through the integration of a **natural phase change material (PCM) derived from Propolis (bee glue)**, under **Saharan climate conditions** typical of **El-Oued, Algeria**. A **2D transient computational fluid dynamics (CFD) model** was developed using **ANSYS Fluent** to simulate the real-time thermal behavior of the system and evaluate the influence of the PCM layer on the PV module's temperature and output efficiency.

The simulation results confirmed that the use of **Propolis-based PCM** at the rear surface of the PV module provides a **measurable thermal regulation effect**, especially during high solar irradiance periods. At **15:00**, the integration of the PCM led to a **surface temperature reduction of approximately 6 °C** compared to the reference case without PCM. This thermal improvement directly resulted in a **2.75% gain in instantaneous electrical efficiency**. Over the entire day, the system exhibited an average efficiency increase estimated between **2% and 4%**, signifying a **notable improvement in total daily energy yield**.

Further analysis of the **melting behavior and liquid fraction evolution** within the Propolis PCM layer revealed a **directional phase transition** beginning near the PV interface and progressing outward. This behavior confirmed the PCM's role as a **thermal buffer**, efficiently absorbing latent heat during midday hours and **delaying the temperature peak** of the PV module. Additionally, the **natural insulating properties of Propolis** contributed to reducing **thermal gradients** and **mechanical stress**, potentially enhancing the **durability and service life** of the PV module.

Comparison with similar works in the literature showed that these results are **consistent with those obtained using synthetic PCMs**, validating both the modeling methodology and the effectiveness of Propolis as a **viable, bio-based alternative**. While this study was limited to a **2D model and a single PCM configuration**, it provides a **solid foundation** for future work that may include **3D simulations**, **material comparisons**, and **geometric optimizations**.

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