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THEME

COOLING-ASSISTED PERFORMANCE IMPROVEMENT OF PHOTOVOLTAIC SYSTEMS

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Dedication

*First and foremost, thanks to Allah for granting me the strength and perseverance to complete
this humble work.*

*I dedicate this thesis to my beloved parents for their endless support, encouragement, and
sacrifices throughout my academic journey.*

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General Introduction

General Introduction

Energy is one of the most essential elements necessary for life at the present time, and the world is witnessing a wide increase in demand for energy due to the growing population, industrial facilities, and others. It should be mentioned that most sources used for energy generation in our era are fossil energy sources such as oil, gas, and coal, as they represent 80% of the energy used in the world. Their negative impact on the environment and climate in general, and especially due to the emissions resulting from their generation like CO₂, has emerged. This has caused an increase in the planet's temperature as a result of the greenhouse effect, affecting humanity in particular. According to statistics from the World Health Organization (WHO), climate change causes 160,000 deaths annually, and this number is likely to rise in the coming years. Based on this, some countries have turned towards clean and renewable energy, as they are largely free of toxic emissions and are sustainable [1].

This global shift towards clean and sustainable energy sources has made solar photovoltaic (PV) technology a leading solution, especially in regions with high solar radiation such as southern Algeria. The Ouargla region, for example, receives solar radiation exceeding 2500 kWh/m²/year, making it an ideal site for large-scale solar installations [2].

One of the most significant factors affecting the performance of a photovoltaic (PV) system is temperature. The efficiency of PV panels decreases by approximately 0.24% - 0.50% for every 1 °C increase above the standard test condition temperature of 25 °C [3]. This leads to considerable energy losses, particularly in desert regions characterized by high ambient temperatures and intense solar radiation during hot periods. In response to this issue, the present study focuses on photovoltaic energy and the different cooling techniques used to improve PV panel performance, with particular emphasis on the heat sink cooling method.

This study aims to explain some of the most famous methods and proposed ideas for cooling photovoltaic panels to increase efficiency, and to test the cooling method

through heat dissipation via V-shaped Galvanized steel fins, showing the challenges they face and observing their results on energy production.

The structural framework of this thesis is systematically organized into four core chapters, culminating in a general conclusion. It initiates with **Chapter 1 (Overview)**, which establishes a comprehensive foundational background on photovoltaic (PV) technology, underscores its strategic significance, highlights the operational bottlenecks induced by elevated cell operating temperatures, and classifies the fundamental thermodynamics of diverse solar cooling mechanisms. Building upon this baseline, **Chapter 2 (Literature Review)** conducts a critical academic appraisal and rigorous evaluation of prior investigations surrounding PV cooling techniques and their determining environmental stressors, thereby mapping out the specific research gaps that this study aims to address. Subsequently, **Chapter 3 (Methodology)** provides an exhaustive disclosure of the empirical framework, delineating the physical specifications of the experimental PV plant, the structural design of the adapted heat sink assemblies, the boundary conditions of the testing regimes, and the calibrated instrumentation utilized for precise data acquisition. The practical findings are then unveiled in **Chapter 4 (Results and Discussion)**, which delivers a detailed graphical and parametric analysis of the collected datasets, contrasting the achieved thermal mitigation and electrical efficiency enhancements against theoretical models and historical benchmarks, while incorporating a dedicated wind-thermal sensitivity evaluation. Finally, the study draws to a close with the **General Conclusion**, which synthesizes the key engineering outcomes and empirical breakthroughs, addresses the physical limitations encountered during the campaign, and outlines strategic recommendations alongside future research vectors within the domain of passive PV cooling systems.

CHAPTER 1

OVERVIEW

I.1: Introduction

In ancient times, the sun was worshipped as a life-giver planet. Later, as education and the industrial age evolved, the knowledge of the sun as energy source was understood. The importance of such a discovery reached its peak in the current era, where the extraction of fossil fuel for energy production has been proven to affect the planet's ambient temperature. Each day the sun provides 10,000 times the energy needed on the planet. Water, bio-energy, or wind powers were all sources used in early human societies and they are in one way or another derived from solar power. Technologies which can harness the powers of the sun continued to improve right up to the early years of the industrial revolution [4].

Renewable energy sources can be defined as energy obtained from the continuous or repetitive currents on energy recurring in the natural environment or as energy flows which are replenished at the same rate as they are used. All the earth's renewable energy sources are generated from solar radiation, which can be converted directly or indirectly to energy using various technologies. This radiation is perceived as white light since it spans over a wide spectrum of wavelengths, from the short-wave infrared to ultraviolet. Such radiation plays a major role in generating electricity either producing high temperature heat to power an engine mechanical energy which in turn drives an electrical generator or by directly converting it to electricity by means of the photovoltaic (PV) effect. It is well known that PV is the simplest technology to design and install, however it is still one of the most expensive renewable technologies. But its advantage will always lie in the fact it is environmentally friendly and a non-pollutant low maintenance energy source [5]. This chapter will briefly describe the principles and history of photovoltaic energy systems and will explore in details the various available technologies while reflecting on the advancement of each technology and its advantages and disadvantages.

I.2: Brief History of Photovoltaic Technology (Timeline of Key Milestones)

The development of photovoltaic (PV) technology has progressed over nearly two centuries, marked by several important scientific and technological milestones.

1839: Discovery of the Photovoltaic Effect: The history of PV technology began in 1839, when French physicist Alexandre-Edmond Becquerel discovered the photovoltaic effect, observing that light could generate an electric current in certain electrochemical systems [6].

1873: Photoconductivity in Selenium: In 1873, Willoughby Smith discovered the photoconductivity of selenium, demonstrating that solid materials can change their electrical properties under illumination, which represented a key step toward solid-state photovoltaic devices [7].

1883: First Selenium Solar Cell: Charles Fritts developed the first selenium-based solar cell in 1883. Although its efficiency was very low, this device was the first solid-state attempt to convert sunlight directly into electricity [8].

1905: Photoelectric Theory Development: Albert Einstein published the theoretical explanation of the photoelectric effect in 1905, providing the scientific foundation for understanding light-to-electricity conversion processes [9].

1940s–1950s: Semiconductor Development: Advances in semiconductor physics during the mid-20th century enabled the development of modern electronic devices and laid the foundation for silicon-based solar cells [10].

1954: First Practical Silicon Solar Cell: In 1954, Bell Laboratories developed the first practical silicon solar cell with an efficiency of approximately 6%, marking the beginning of modern photovoltaic technology [11].

1960s: Space Applications: Photovoltaic systems were widely adopted in space applications during the 1960s, particularly for powering satellites due to their reliability and independence from fuel-based systems [12].

1970s: Energy Crisis and Renewed Interest: The oil crisis of the 1970s increased global interest in renewable energy sources, leading to accelerated research and development in PV technologies [13].

1980s–2000s: Commercialization Phase: During this period, PV systems became increasingly commercialized, with continuous improvements in efficiency, manufacturing processes, and cost reduction [14].

21st Century: Global Expansion of PV Systems: In the modern era, photovoltaic technology has become one of the fastest-growing renewable energy sources worldwide, supported by advances in thin-film technologies, multi-junction cells, and large-scale solar deployment [15].

I.3: Solar Energy Potential

I.3.1: Solar energy resources worldwide

Global solar energy growth is expanding beyond traditional electricity generation into innovative infrastructure integrations that maximize resource efficiency and human utility. These modern applications include floating photovoltaics deployed on water bodies and building-integrated systems that blend solar cells directly into building structures to provide simultaneous thermal insulation and power. Furthermore, highly efficient solutions like agri-photovoltaics combine farming and electricity generation on shared land boosting land-use efficiency by up to 186% while multi-functional solar carports provide shade for vehicles while generating power to support the rise of electric vehicles, proving that solar potential lies in its smart integration into daily environments [16].

I.3.2: Solar energy potential in Algeria

Algeria is exceptionally positioned as a prime global destination for solar energy development due to its strategic location at the northern gateway of Africa and its vast renewable potential, highlighted by an annual sunshine duration ranging from 3,000 to 3,500 hours in the Saharan region. The country's daily Global Horizontal Irradiance averages between 5.1 kWh per square meter in the north and up to 6.6 kWh per square meter in the Great South, making it highly attractive for major solar projects. Consequently, despite historically relying heavily on fossil fuel revenues, the Algerian government has recently intensified its efforts to promote a strategic transition toward clean and renewable energies [17] [18].

Confirming this exceptional promise, the German Aerospace Center (DLR) identifies Algeria as having the highest solar capacity in the entire Mediterranean basin. The scale of this resource is such that the solar energy striking the country's territory surpasses its total current power production by an estimated factor of 5,000. In light of this vast natural wealth, the Algerian government continues to intensify its support for research, development, and investment incentives aimed at ensuring the optimal and sustainable exploitation of this inexhaustible energy source [16].

I.4: Status of PV Systems

I.4.1: PV deployment and applications worldwide

The year 2024 marked a record-breaking period for global solar PV deployment, with new installations reaching between 553 GW and 601 GW, representing a 29% increase from 2023 driven by climate initiatives, falling module costs, and manufacturing expansions. China firmly dominated the global market by accounting for nearly 60% of these new installations (309–357 GW), while the European Union followed with 66 GW—internally led by Germany—and the United States and India added 47 GW and 32 GW respectively. This rapid expansion means that nearly half of the world's total cumulative solar capacity was installed in just the last three years, cementing photovoltaics as a vital cornerstone of global electricity generation across dozens of GW-scale countries [19].

I.4.2: PV status and developments in Algeria

Algeria is strategically positioning photovoltaic energy as the foundation of its clean energy transition, demonstrating notable progress as its cumulative solar PV capacity surged to 460 MW in 2022 compared to just 344 MW from 24 power plants four years prior. Under its National Renewable Energy Development Program, the country sets ambitious targets for 2030, aiming for a production capacity of 12,000 MW for domestic consumption and 10,000 MW for export. The largest share of these goals is dedicated specifically to photovoltaic energy, which is planned to reach 13,575 MW, driving Algeria toward substantial industrial growth and enhanced competitiveness within the regional renewable energy sector.

I.5: Photovoltaic Systems: Fundamentals

We will see the Fundamentals of Photovoltaic System

I.5.1: Basic principle of PV energy conversion

The Earth's atmosphere and cloud cover absorb, reflect, and scatter some of the solar radiation entering the atmosphere. Nonetheless, enormous amounts of direct and diffuse sunshine energy reach the Earth's surface and can be used to produce photovoltaic electricity. Although the atmosphere absorbs and reflects this radiation, a vast amount still reaches the Earth's surface; the amount of sunlight striking the Earth varies by region, season, time of day, climate, and measure of air pollution [20].

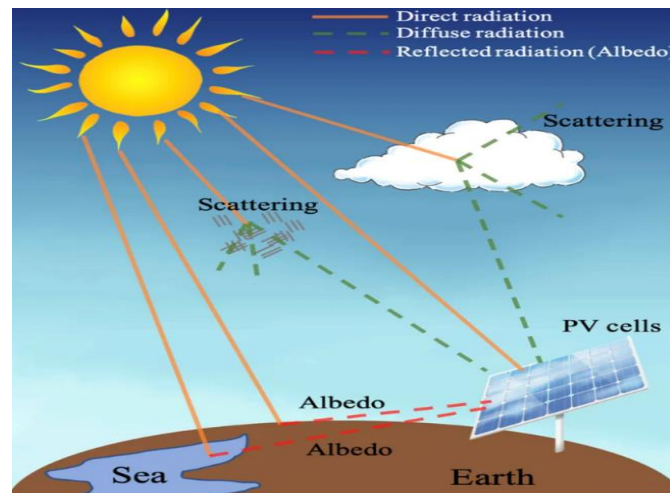


Figure I-1: Types of sunlight reach the photovoltaic cell panel [21].

I.5.2 :The p-n junction

The p-n junction is the fundamental component of a solar cell, formed by joining two specially treated layers of silicon:

- **n-type layer:** Doped with phosphorus atoms, giving it excess free electrons (negative charge carriers) [20].
- **p-type layer:** Doped with boron atoms, creating excess electron holes (positive charge carriers) [20].

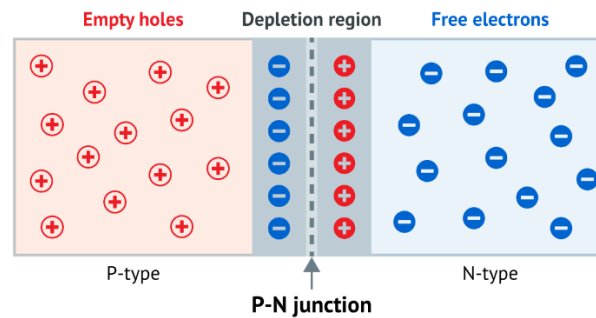


Figure I-2: n-type and p-type Silicon [22].

As shown in **Figure 1-2**, one side has surplus electrons and the other has surplus holes before contact.

When the two layers are joined, electrons diffuse from the n-side to the p-side, while holes diffuse in the opposite direction

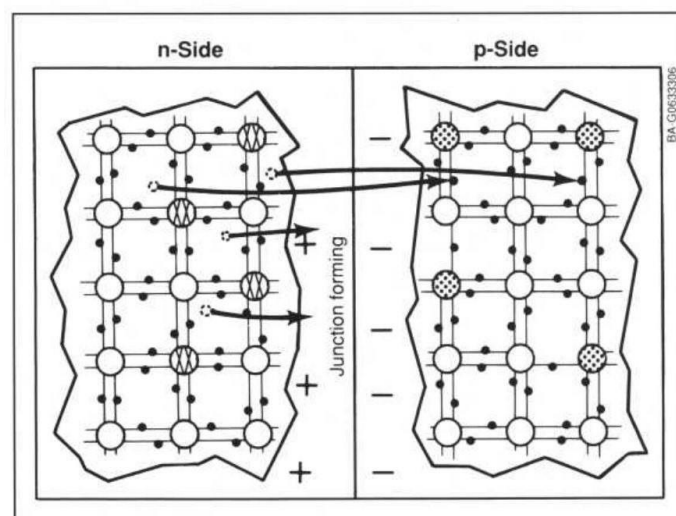


Figure I-3: Forming the p-n Junction [20].

Figure 1-3 illustrates this diffusion process, which results in a buildup of positive charge on the n-side of the interface and negative charge on the p-side, creating a strong internal electric field at the junction region [20].

When sunlight strikes the cell, photons are absorbed, generating electron-hole pairs. The internal electric field immediately separates these charge carriers, driving electrons toward the n-side and holes toward the p-side. This charge separation

creates an electrical voltage. When the cell is connected to an external circuit, direct electric current flows [20].

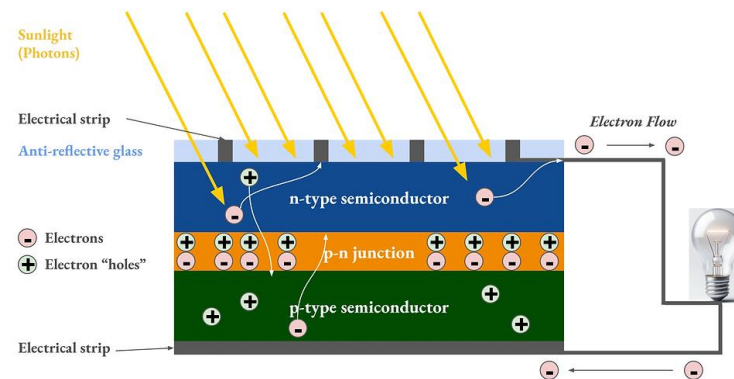


Figure I-4: Schematic diagram of a PV cell [23]

1.5.3: Types of PV technologies

The document describes three main categories of materials and technologies used in solar cells:

1.5.3.1 : Mono-Crystal Silicon

The most widely used commercial type. It features a highly regular atomic structure, enabling relatively high conversion efficiency. It is produced through costly processes like the Czochralski process, which involves pulling a single cylindrical crystal from molten silicon and then sawing it into thin wafers [20]



Figure I-5: Mono-crystalline Silicon PV [24].

I.5.3.2 : Semi-crystalline and Polycrystalline Silicon

Here, the material is composed of multiple large or small crystalline grains. Its production cost (e.g., via Casting) is lower than single-crystal silicon, but its efficiency is somewhat reduced due to the presence of grain boundaries, which promote the recombination of electrons and holes [20].



Figure 1-6: Polycrystalline Silicon PV [25].

I.5.3.3 : Thin-Film Solar Cells

These cells are manufactured by depositing extremely thin (a few microns) semiconductor layers onto a substrate (glass, plastic, metal), reducing material usage and enabling potentially lower-cost manufacturing techniques. Key materials include [20]:

- Amorphous Silicon (a-Si)
- Copper Indium selenide (CIS)
- Cadmium Telluride (CdTe)

I.5.3.4 : Gallium Arsenide (GaAs) Solar Cells

These very high-efficiency cells are used primarily in space applications and concentrator systems. They feature a near-ideal band gap and high radiation resistance [20].

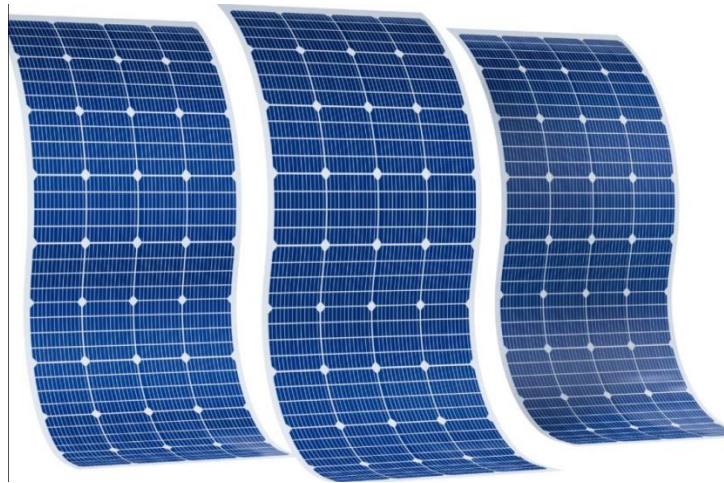


Figure I-7: Thin-Film Solar Cells PV [26].

1.5.4: Electrical performance parameters

The performance of a PV cell or module is evaluated by several key parameters:

1.5.4.1: Efficiency:

IEA PVPS has released its latest Trends in Photovoltaic Applications 2025 report, revealing that the world's cumulative installed PV capacity surpassed 2 260 GW by the end of 2024, marking a 29% year-on-year increase [27].

1.5.4.2 : I–V Characteristics:

Cell performance is represented by its Current-Voltage (I-V) curve. Key performance points derived from this curve include [28]:

- 1. Short-Circuit Current (I_{sc}):** The maximum current produced by the cell when the voltage is zero.
- 2. Open-Circuit Voltage (V_{oc}):** The maximum voltage produced by the cell when the current is zero.

1.5.4.3 : Power Output:

Equal to the product of voltage and current at the operating point ($P = V \times I$). It is influenced by incident light, temperature, and cell characteristics. An individual cell typically produces between 1 and 2 watts. Power can be increased by connecting cells

in series (to increase voltage) and in parallel (to increase current) to form modules and arrays [28].

I.5.4.4 : Maximum Power Point (MPP):

The Maximum Power Point is the operating point on the current–voltage (I–V) curve of a photovoltaic device at which the product of current and voltage reaches its maximum value, corresponding to the maximum electrical power output.

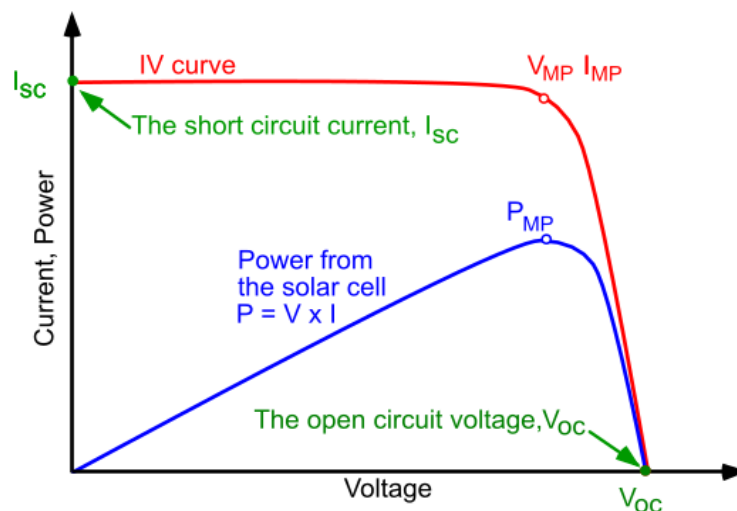


Figure I-8: I–V Characteristics and power output

I.6 : Thermal Effects on PV Performance

I.6.1 : Influence of temperature on electrical efficiency

General Effect: Rising cell temperature slightly increases output current but significantly decreases output voltage, leading to an overall drop in total power output [29].

Technology Comparison (Sensitivity to Heat) [29]:

- Thin-film: Least affected by temperature (loses 0.0984% energy yield per 1°C rise above 25°C).
- Mono-crystalline: Moderately affected (loses 0.109% per 1°C).
- Poly-crystalline: Most affected by heat (loses 0.124% per 1°C).

I.6.2 : Mechanisms of thermal losses in PV modules

The primary mechanism of thermal loss is the conversion of a significant portion of absorbed solar energy into heat rather than electricity. When photons with energy higher than the band gap (E_g) strike the semiconductor, the excess energy is dissipated as heat through lattice vibrations (phonons). This process does not contribute to additional charge carrier generation; instead, it raises the cell temperature, negatively affecting material properties and device performance [29].

Elevated temperature directly affects semiconductor properties, most notably [29]:

I.6.2.1 : Band gap (E_g)

Its value decreases with rising temperature due to increased atomic vibration amplitude and weakened interatomic bonds, reducing the energy required to excite electrons. This decrease leads to an increase in the intrinsic carrier concentration (n_i), which in turn significantly raises the reverse saturation current (I_S).

I.6.2.2 : Absorption coefficient ($\propto$)

It increases with temperature due to a rise in the imaginary part of the complex refractive index (k), enhancing the charge carrier generation rate and thus affecting the output current.

At the cell performance level, thermal losses manifest mainly in:

I.6.2.3 : Decrease in open-circuit voltage (V_{oc})

This is the most temperature-sensitive parameter, as V_{oc} is inversely related to I_S , which increases exponentially with temperature. This decrease is the primary factor in reducing the maximum power (P_{MP}) and overall efficiency.

I.6.2.4 : Variation in series (R_s) and shunt (R_{sh}) resistances

Temperature affects charge carrier mobility and can lead to an increase in series resistance or a decrease in shunt resistance, increasing ohmic losses and reducing the fill factor (FF).

I.6.2.5 : Increase in recombination rates

As temperature rises, the intrinsic carrier concentration increases, boosting recombination rates in the bulk and at junctions, reducing minority carrier lifetime, and degrading charge collection efficiency.

Furthermore, external factors such as solar irradiance and environmental conditions contribute to raising the module temperature above ambient levels. The relationship between cell temperature (T_{cell}), ambient temperature (T_{amb}), and irradiance (G) is described in the dynamic thermal model, where increased irradiance leads to additional heat generation, elevating cell temperature even under natural cooling conditions [29].

1.6.3 : Importance of maintaining optimal operating temperatures

The Problem: In hot climates, PV module temperatures routinely exceed 25°C (STC), triggering heavy losses that can surpass 15–20% of the annual energy yield. High temperatures drop voltage (V_{oc}), cut maximum power, and accelerate semiconductor/protective layer degradation shortening lifespan and raising maintenance costs.

The Benefits of Cooling: Thermal management keeps the Fill Factor (FF), series resistance, and shunt resistance within optimal design ranges. It mitigates thermal hysteresis (e.g., in perovskite cells), ensures stable output, and—in hybrid PV-Thermal (PVT) systems recovers waste heat to boost overall economic value.

Conclusion: Integrating passive or active cooling systems during the preliminary planning phase is a fundamental requirement to secure project viability and lifespan in high-irradiance regions.

1.7 : Cooling Strategies for PV Systems

Cooling systems added to photovoltaic panels are essential in hot climates, as they lower the cell temperature, which improves panel efficiency and increases its productivity, as well as extending its operational life and reducing material degradation. In hybrid systems, they allow for the recovery of waste heat and its conversion into useful energy. We will explain some of the different types of cooling systems in the following part:

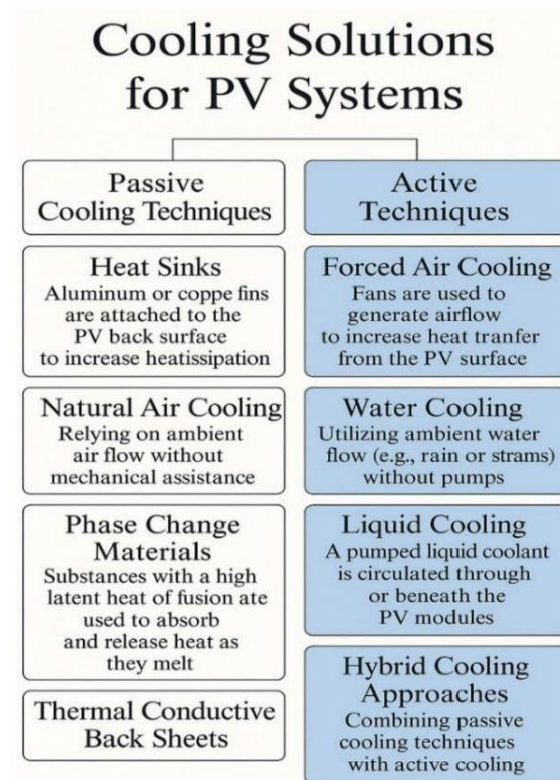


Figure I-9: Diagram showing PV Cooling Methods [30].

I.7.1: Passive cooling techniques (natural convection, heat sinks, thermal conductive materials)

Passive cooling relies on natural conduction and convection to transfer heat from the solar panel without using external energy. Examples include using heat sinks made from metals like aluminum and copper, and phase change materials (PCM) that absorb heat upon melting. This system is reliable and requires minimal maintenance, but its effectiveness is limited in extremely hot climates [31].

These techniques rely on natural heat transfer mechanisms without external energy consumption.

I.7.1.1 : Heat Sinks (Fins)

A heat sink and PV cooling system were put together to ensure controlled cooling of the thermal system of PV panels. Figure 10 illustrates that the system comprises a PV panel and several horizontal heat sinks affixed to its rear. Air enters the system from below, passes through the heat sinks, and exits through a vent at the top. The

way it moves the heat away from the panel reduces its temperature and helps the panel to work more efficiently with less power [31].

Part two of Figure 1-10 shows the technical drawing of setting up the heat sink. The PV panel has a width of 500 mm, with the heat sinks measuring 480 mm in length and separated by 30 mm. There are sixteen holes of 6 mm diameter in every heat sink, giving it a bigger area for the exchange of heat and better airflow. With it, every part of the PV module receives similar cooling, which helps to reduce the effect of temperature on the module in hot places [31].

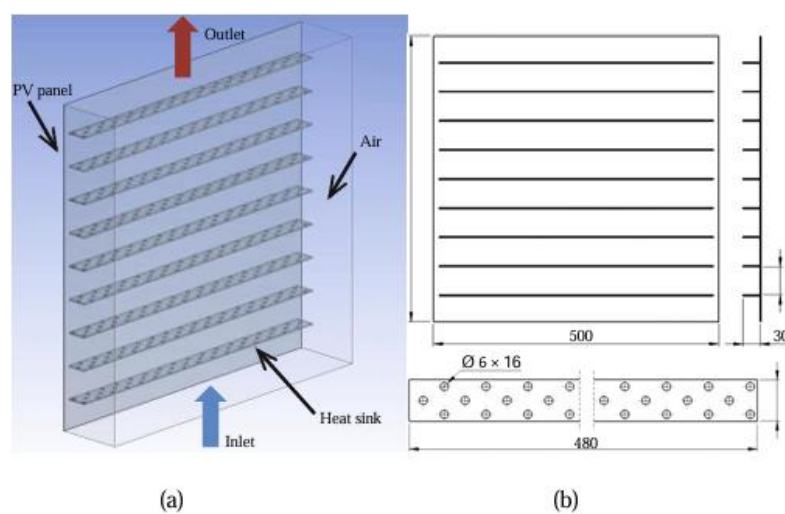


Figure I-10: Proposed geometry and dimensions of a PV panel with aluminum heat sinks [32]

I.7.1.2 : High Thermal Conductive Materials

Passive cooling layers known as Thermal Conductive Back Sheets decorate the back of PV modules using high thermal conductivity materials as (graphite composites or aluminum laminates). They remove heat from cells without consuming extra energy, thus lowering the temperatures by 5-10°C and increasing the efficiency by 3-6%, they extend the system's life span – especially so in hot climates [33] [34] .

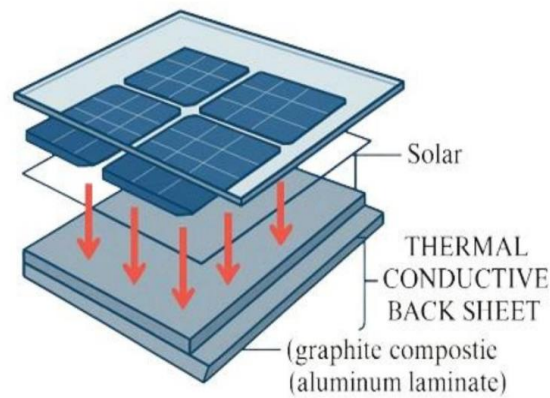


Figure I-11: Photovoltaic Module with a Thermally Conductive Back Sheet [35].

1. Natural air cooling

This is achieved by creating an air gap or channel behind the PV panel, natural air cooling commonly occurs by the passing of ambient air by buoyancy-driven convection through the chimney effect. The channel air warms and rises as the panel warms in the sun, drawing down cooler air, and replenishing the heat removing air at the panel's backside. These natural air flows directly contribute to extension of longevity and electrical efficiency of the PV modules and facilitates maintaining low operating temperatures [33] [34].

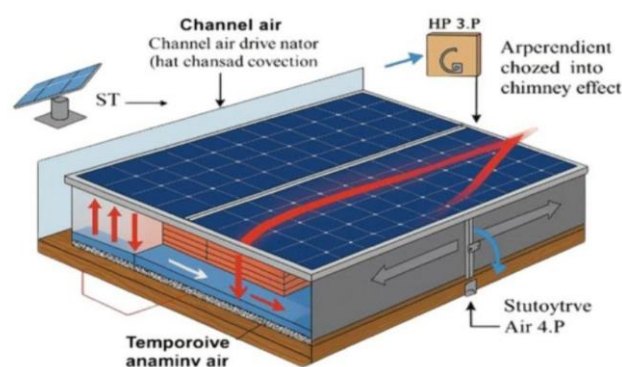


Figure I-0-12: Natural Air Cooling [36].

1.7.2 : Active cooling techniques

Active cooling consumes electrical energy to operate pumps and fans to forcibly cool the solar panel. Examples include a circulating water film system on the panel's surface and hybrid (PV/T) systems that utilize waste heat. These systems significantly

improve electrical efficiency but are more costly and require ongoing maintenance [37].

These techniques consume external energy to power mechanical components that enhance the cooling process.

I.7.2.1 : Active Water Cooling

Front Water Film Cooling: Circulates a thin film of water over the front surface of the panel using a pump. It reduces temperature and minimizes reflective losses, with the potential to utilize the heated water. Found to increase efficiency by about 1%.

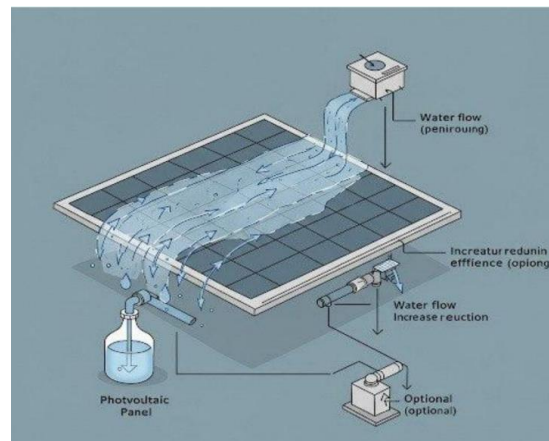


Figure I-13: Water Cooling System for Photovoltaic Panel [38].

I.7.2.2 : Active Air Cooling

The Forced Air Cooling uses electric fan or blowers to push a flow of air across the PV modules surface. This increases the heat convection and removes heat accumulation rapidly. It is particularly useful in enclosed, or rooftop installations which natural air flow is restricted [39].

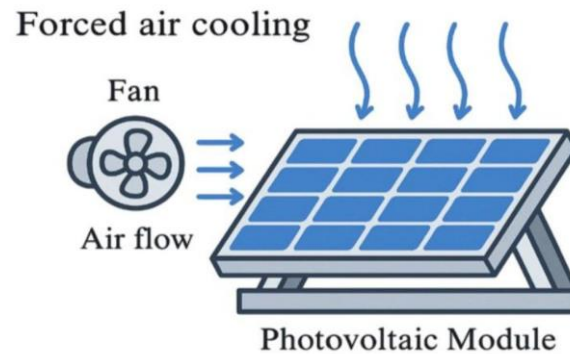


Figure I-14: Forced Air Cooling for PV Panels [40].

I.7.2.3 : Liquid cooling

Liquid Cooling is the process of flowing (a liquid coolant like water or a glycol-based solution in pipes/channels) in or underneath PV modules. The liquid takes in the heat and the latter is conveyed from the panel, as the pressure in the system is maintained at a good level. This approach is very effective but necessitates pumps and sensible system design [39].

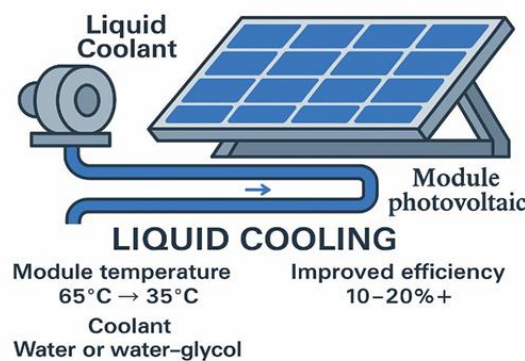


Figure I-15: Forced Air Cooling for PV Panels [39].

I.7.2 : Comparative advantages and limitations

I.7.2.1 : Passive Cooling: Advantages and Limitations

Advantages: Passive systems utilize natural conduction, convection, and radiation without consuming electrical energy (e.g., heat sinks, PCMs). They offer high

reliability, simple design, low cost, and minimal maintenance—ideal for remote desert environments.

Limitations: Performance is highly constrained by ambient conditions (wind speed, temperature, irradiance). In extreme desert climates like Ouargla, cooling capacity can become insufficient. Additionally, Phase Change Materials (PCMs) can suffer from low thermal conductivity and lose effectiveness once fully melted.

I.7.2.2 :Active Cooling: Advantages and Limitations

Advantages: Active systems use external energy to drive mechanical devices (pumps, fans, fluid circulation). They provide superior, controllable cooling under extreme irradiance and high temperatures, stabilize power output, and enable waste heat recovery in hybrid PV-Thermal (PV/T) systems to boost overall efficiency.

Drawbacks: They consume parasitic electrical power, reducing net system yield. The inclusion of moving parts increases mechanical complexity, installation difficulty, and risks of wear, leakage, or failure—leading to higher maintenance costs and lower long-term reliability compared to passive options..

I.7.2.3 : Selection Criteria Between Passive and Active Cooling

Therefore, the selection between passive and active cooling techniques depends mainly on climatic conditions, economic considerations, system complexity, and the required cooling performance. For hot desert regions, passive cooling remains an attractive low-cost solution, while active cooling may be preferred when higher thermal regulation and maximum electrical efficiency are required.

CHAPTER 2

COOLING BACKGROUND RESEARCH

II.1 : Introduction

One of the main objectives of this thesis is to study cooling systems and reduce the impact of temperature on photovoltaic energy systems. Several methods have been adopted to achieve higher efficiency. In this chapter, we will discuss the most commonly used techniques, review previous studies on these systems, present the obtained results, compare the outcomes of each study, and identify the existing research gaps.

This chapter is organized into three main sections as follows:

- **Cooling techniques applied to photovoltaic systems**

This section presents the different cooling methods used for photovoltaic panels, including experimental investigations, numerical and simulation-based studies, and comparative analyses of various cooling strategies.

- **Factors affecting cooling performance**

This section discusses the main environmental and operating parameters influencing the effectiveness of photovoltaic cooling systems, such as solar irradiance, ambient temperature, and wind speed.

- **Research gaps**

This section highlights the limitations of previous studies and identifies existing gaps related to electrical and thermal performance analysis, cooling efficiency, and the influence of local climatic conditions on PV cooling systems.

II.2 : Cooling Techniques Applied to PV Systems

II.2.1 : Experimental studies on PV cooling

Siti Noraisiah Rezali et al [41], in a 2023 study published in Case Studies in Thermal Engineering that the continuous exposure of photovoltaic (PV) modules to solar radiation leads to significant temperature rise, which in turn degrades their electrical performance. To address this issue, they developed an innovative passive cooling system known as the Multi-Transversal Finned Heat Sink (MTFHS). This design incorporates fins of varying heights and multiple orientations, which enhance heat transfer and promote airflow circulation within the central region of the PV

panel. The configuration induces boundary layer disruption within the confined space between the fins, thereby improving convective heat dissipation.

To evaluate the effectiveness of the system, outdoor experimental tests were conducted using modern half-cut PERC PV modules rated at 405 W, representing advanced photovoltaic technology. Two panels were tested under real climatic conditions in Malaysia, with solar irradiance ranging from 200 to 1000 W/m² and ambient temperatures between 26°C and 38°C. The results demonstrated that the MTFHS system reduced the panel temperature by up to 12°C, decreasing the maximum temperature from 69°C to 57°C under peak irradiance of 1000 W/m².

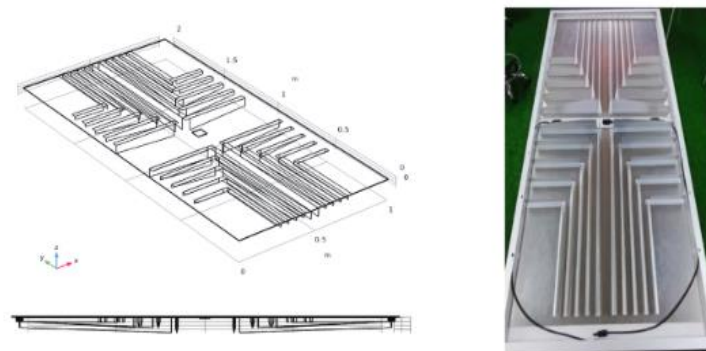


Figure II-1: The experimental setup overview [41].

This significant temperature reduction positively influenced electrical performance. The relative electrical efficiency increased by 1.53% at maximum irradiance, reaching 18.98% compared to the uncooled panel. Additionally, improvements were observed in both short-circuit current and open-circuit voltage, resulting in an increase in maximum power output from 243 W to 290 W. The researchers concluded that the multi-directional fin configuration played a crucial role in enhancing heat dissipation and airflow patterns, making the MTFHS a promising solution for thermal management of PV modules in hot and tropical climates. They also recommended future studies integrating this system with forced convection techniques to further enhance cooling performance and mitigate hotspot formation in central panel regions.

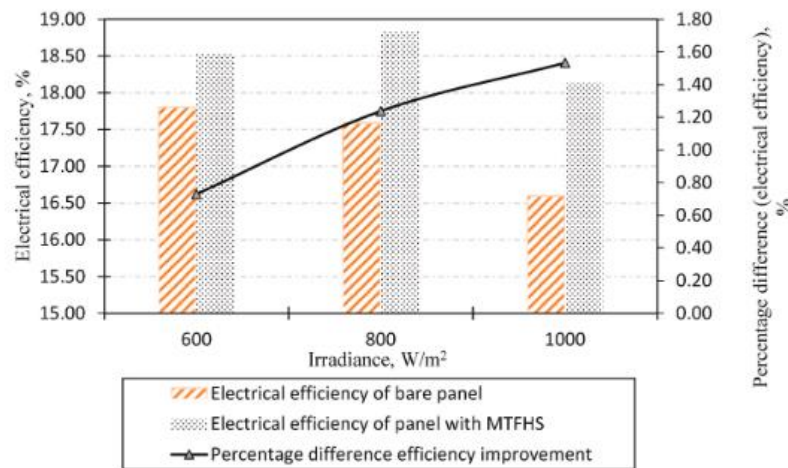


Figure II-2: Electrical efficiency of bare PV and PV modules with MTFHS fins [41].

Mohamed Sharaf et al [42], in a comprehensive review study published in 2022 in the Environmental Science and Pollution Research, the use of phase change materials (PCM) for cooling photovoltaic (PV) panels is considered one of the most promising approaches for thermal management of solar cells. This is attributed to the ability of PCM to absorb excess heat generated by the panel during peak solar hours through latent heat of fusion, thereby reducing the panel temperature and maintaining it close to the optimal operating condition of 25 °C for a certain period.

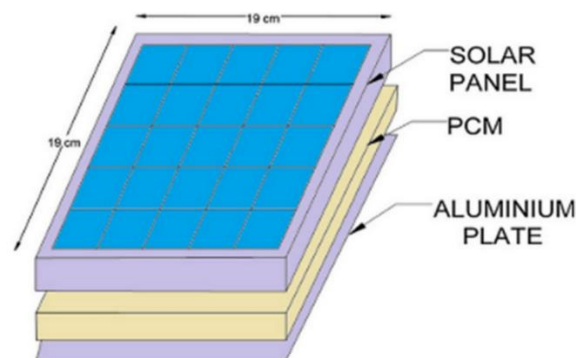


Figure II-3: Three-dimensional sketched of PV/PCM with aluminum sheet [42].

The researchers reported that the best outcomes achieved in this field include a temperature reduction of up to approximately 35 °C, along with an improvement in electrical efficiency of up to 16%. Furthermore, PCM was found to be more effective during summer than in winter due to higher solar irradiance and ambient

temperatures, with power output increases reaching up to 23% when using a suitable material such as RT28 HC.

To address the main limitation of PCM namely its low thermal conductivity, which restricts effective heat transfer the researchers investigated several enhancement techniques. These include the incorporation of fins, nanoparticles, and porous metallic materials.

The addition of fins is considered a relatively basic method, as it improves heat transfer only in regions adjacent to the fins. This approach achieved temperature reductions ranging from 5 °C to 20 °C, with a maximum recorded reduction of 26.6 °C, and an increase in electrical efficiency from 10.1% to 12.1% when using 11 fins with a PCM whose melting point is close to 25 °C.

In contrast, the incorporation of nanoparticles represents a more advanced technique, yielding better performance than fins. For instance, the addition of Al₂O₃ nanoparticles to PCM resulted in a temperature reduction of 10.6 °C and an electrical efficiency improvement of 12.1%. Similarly, the use of SiC nanoparticles in a PV/T system increased electrical efficiency from 7.1% to 13.7%, along with a temperature reduction of 17 °C. However, the researchers noted that the high cost of nanoparticles limits their large-scale economic feasibility.

The most effective and cost-efficient approach, according to the study, is the integration of porous metallic materials such as copper foam, aluminum foam, or metal fibers—into PCM. These materials provide a high surface area-to-volume ratio, enhanced thermal conductivity, low weight, and strong structural integrity, resulting in heat transfer rates up to ten times higher than that of pure PCM.

Experimental results showed that the use of copper foam with PCM improved electrical efficiency by 4.3% and achieved a thermal efficiency of up to 83%. Additionally, incorporating an aluminum matrix into PCM increased conversion efficiency by 8%, compared to 3.5% when using PCM alone. Aluminum fins reduced PCM melting time by up to 25% and lowered panel temperature by 24 °C, while metal fibers achieved temperature reductions of up to 21 °C.

The researchers concluded that this method is superior among the studied cooling techniques, as the addition of porous materials significantly enhances thermal

conductivity without substantially reducing the heat storage capacity of PCM. This leads to improved power output stability and prolonged thermal regulation during peak solar periods.

II.2.2 : Simulation-based studies

Sebastian Valeriu Hudişteanu et al [43], The Methodology (2021 Study): Researchers developed a detailed Computational Fluid Dynamics (CFD) model using an enthalpy-porosity framework to investigate passive cooling for a PV panel inclined at 45°. Unlike previous simplified studies, this model incorporated realistic airflow and wind directions around the entire structure.

Calibration & Validation: The baseline uncooled panel was calibrated under NOCT conditions (800 W/m² irradiance, 1 m/s rear wind, 20°C ambient air), closely matching manufacturer specifications and literature experimental data.

Tested Configurations: Analyzed six heat sink configurations under varying environmental loads: horizontal (transversal) and vertical (longitudinal) fins, testing both non-perforated and perforated designs with different hole diameters.

Key Findings & Power Gains: Peak cooling performance occurred under high irradiance and low wind speeds. The optimal configuration was the horizontal perforated fin heat sink with 30 mm holes. Under harsh operating conditions, this optimized design successfully boosted relative electrical power output by up to 6.49% compared to the uncooled baseline.

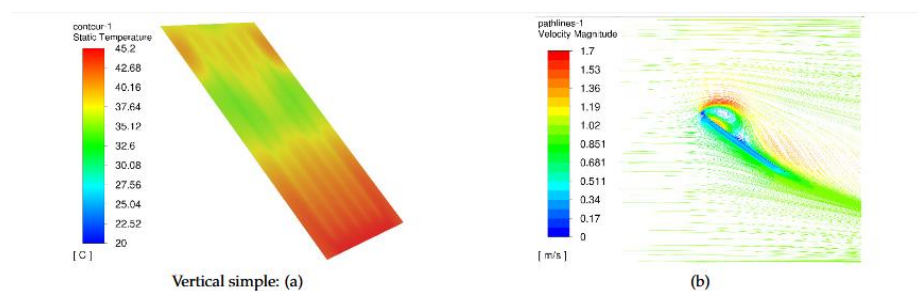


Figure II-4: Simulation of heat transfer using thermal fins in the vertical position [43]

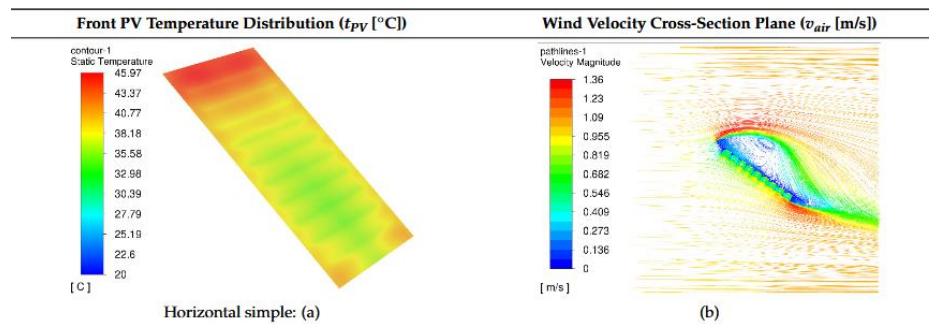


Figure II-5: Simulation of heat transfer using thermal fins in the horizontal position

[43]

Qualitative analysis further revealed that the fins enhance airflow turbulence and improve heat transfer, especially in the rear region of the panel. The researchers concluded that perforated horizontal fins with a diameter of 30 mm represent an optimal design for passive cooling in hot climates. They also noted that the cooling effect is more pronounced under low wind and high irradiance conditions, while it diminishes at higher wind speeds or lower ambient temperatures. The study recommends implementing such designs in residential, urban, and large-scale PV installations to improve overall efficiency and extend panel lifespan.

Yahya Sheikh et al [44], The Innovation (2024 Study): To overcome the low thermal conductivity of organic PCMs and the high cost/weight of metallic PCMs, researchers designed a hybrid, multi-layered passive cooling system combining an organic PCM (RT44 - high latent heat) and a metallic PCM (CERROLOW-117 alloy - high thermal conductivity).

Methodology: Simulated via ANSYS FLUENT (enthalpy–porosity model; validated with a $\leq 7\%$ max deviation) under extreme conditions (40°C ambient, 1000 W/m² irradiance).

Optimal Setup & Thermal Performance: The ideal configuration is a 15:85 thickness ratio (MPCM:OPCM) with a 40 mm total thickness at a 90° vertical inclination (ideal for BIPV/bifacial vertical panels). It slashed PV temperatures by up to 59.6°C compared to an uncooled panel.

Electrical Gains: The hybrid setup yielded a $> 5\%$ higher relative efficiency than OPCM alone. Compared to the uncooled panel, it achieved an average relative efficiency boost of 35.8% during peak hours, maxing out at 42.4%.

Efficiency & Future Work: Thermal energy transfer efficiency reached 96.5%. Future recommendations include integrating this with low-concentration PV (CPV) and adding internal fins or metal foams.

Table II-1: A summary of previous studies about using passive cooling systems for PV solar panel

Study type	Cooling technique	PCM tested-its melting point (°C)	. Radiation intensity/ heat flux (kW/m ²)	Finding(s)	
				Temperature reduction ΔT (°C)	Enhancement in efficiency
Numerical	PCM	CaCl ₂ -6H ₂ O-29.8	1.00	17.5	4.5–5.8 %
Numerical	PCM	PCM RT-25HC-26.6	1.00	8–9	–
Experimental, outdoor	evaporative cooling	–	0.9	40	19.1 %
Numerical	PCM	PCM RT-21	0.3	27	6 %
Experimental, outdoor	PCM filled in finned container	Palm wax-52	0.9	6.1	5.3 %
Experimental & Numerical	PCM filled in a container	Paraffin-40	0.6	10.5	5.9 %
Experimental & Numerical	PCM/expanded graphite	Paraffin-33	0.9	4.7	7.28 %
Experimental, indoor	PCM filled in a container	PCM RT-42	1.2	–	6.8 %
Experimental, outdoor	Air cooling/ aluminum fins	–	1.2	–	5 %
Numerical	Flat heat pipes with PCM	PCM-SP31	3.7	13	8 %
Experimental, outdoor	PCM-aluminum foam	PCM RT-42	0.8	12	14 %
Numerical	MPCM-OPCM multi-layered PCMs	MPCM (CERROLOW-117® alloy) and OPCM (RT-44)	1.00	59.6	35.8 %

II.3 : Factors Affecting Cooling Performance

II.3.1 : Environmental factors

II.3.1.1 : Solar Irradiance

Solar irradiance is the most influential factor affecting the performance of photovoltaic (PV) panels, as it varies significantly both spatially and temporally. The intensity of irradiance impacts key performance parameters of solar cells, including open-circuit voltage, short-circuit current, cell temperature, and efficiency. The current exhibits a linear relationship with irradiance, whereas voltage varies logarithmically [45].

Cell efficiency increases with irradiance up to approximately 600 W/m², after which it slightly declines until reaching 1000 W/m². In addition, the spectral distribution of irradiance characterized by the average photon energy affects different PV technologies differently. Technologies such as amorphous silicon, crystalline

silicon, gallium arsenide, and cadmium telluride are particularly sensitive to spectral variations [45].

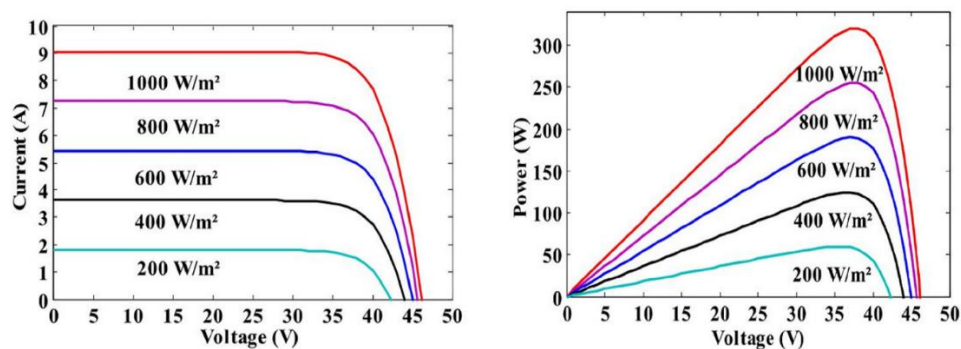


Figure II-6: Solar cell I-V and P-V curves at different irradiance intensities at a constant temperature of 25 °C [45]

- (left) shows that irradiance has a stronger effect on short-circuit current than on open-circuit voltage.
- (right) shows that power output increases near-linearly with irradiance.

II.3.1.2 : Ambient Air Temperature

Ambient temperature has an inverse effect on PV performance. While the short-circuit current increases slightly with temperature, the open-circuit voltage decreases significantly, leading to a reduction in output power and overall efficiency. The temperature coefficient of power for commercial PV modules typically ranges between -0.4% and -0.5% per °C [45].

This coefficient varies depending on the cell technology. For example, cadmium telluride cells exhibit a temperature coefficient between -0.24% and -0.26% per Kelvin, whereas polycrystalline silicon cells range from -0.434% to -0.47% per Kelvin [45].

Elevated temperatures also accelerate the degradation of PV cells and associated components through mechanisms such as adhesive bond failure, corrosion, discoloration, swelling, delamination, glass cracking, and interconnection failure [45].

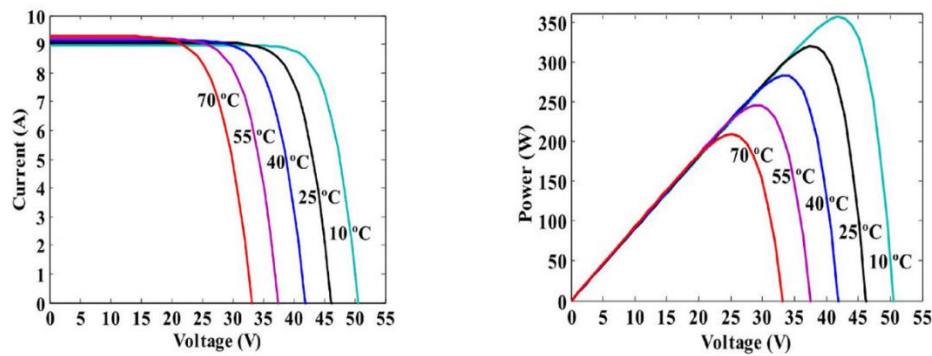


Figure II-7: Solar cell I-V and P-V curves at different temperatures at a constant irradiance intensity of 1000 W/m^2 [45]

- (left) shows that temperature has a stronger effect on open-circuit voltage than the increase in short-circuit current.
- (right) shows that power output decreases near-linearly with temperature

II.4: Research Gaps

II.4.1 : Limitations in previous studies

II.4.1.1 : Studies on Cooling Using Phase Change Materials (PCM)

Most previous studies relied mainly on organic PCMs, which suffer from low thermal conductivity and limited cooling efficiency during peak heat periods. Metallic PCMs improve conductivity but are heavier and more expensive. In addition, many studies did not sufficiently examine multilayer PCM thickness ratios, tilt angle effects, or high ambient temperatures above 40°C under real operating conditions.

II.4.1.2 : Studies on Cooling Using Fins and Heat Sinks

Most research has focused on simple rectangular fin designs, with limited exploration of advanced geometries such as tapered multidirectional fins. Field studies on modern high-power PV panels ($>400 \text{ W}$) remain scarce, and many experiments rely on laboratory models that do not fully represent real conditions. Wind direction effects have also been insufficiently investigated.

II.4.1.3 : Numerical Simulation Studies (CFD)

Many CFD studies use simplified assumptions, such as constant material properties and neglecting thermal radiation, which reduce realism. Coarse computational meshes and limited validation under real operating conditions also reduce the accuracy and general applicability of their results.

II.4.2 : Specific gaps in local climatic conditions

II.4.2.1 : Effect of High Temperature

The Environment of Ouargla: Characterized by a harsh desert climate with high solar irradiance but extreme summer temperatures frequently exceeding 41°C–42°C. Low humidity and lack of rainfall create a persistent thermal load.

The Thermal Problem: While solar resource is abundant, PV panels absorb excess radiation as heat rather than electricity. This elevated cell temperature alters semiconductor properties, causing a sharp drop in output voltage (Voc) and electrical efficiency.

Long-Term Impact: Continuous thermal stress accelerates material degradation and drastically shortens the operational lifespan of the modules.

Conclusion: High temperature is the dominant limiting factor for solar energy in desert regions. Implementing thermal management/cooling is critical to prevent efficiency loss and secure long-term system reliability.

II.4.2.2 : harsh desert climate

In Ouargla's harsh desert climate, dust significantly worsens PV performance by both blocking solar radiation and trapping heat, which increases panel temperature and reduces efficiency. However, most studies have examined dust and temperature separately, with limited evaluation of cleaning methods under Ouargla's frequent dust storms and water scarcity.



Figure II-8: (A) cleaned panel, (B) dusty panel [46]

Despite these challenges, Ouargla benefits from very high solar irradiance, offering strong potential for extensive photovoltaic solar energy exploitation.

CHAPTER 3

METHODOLOGY

III.1: Introduction

In this chapter, we will discuss the methodology adopted to study the effect of passive cooling on the performance of photovoltaic (PV) modules. The objective of this study is to test and evaluate the cooling system using heat sinks mounted on the back of the photovoltaic panel and to examine its effectiveness in improving the performance of these modules under high-temperature conditions in the desert region of Ouargla, Algeria.

Throughout this chapter, we will present the design of the experimental setup, which includes both the reference photovoltaic panel and the modified photovoltaic panel equipped with heat sinks. We will also explain the steps of conducting the experiment, the modifications made to the system, the instruments used, and a description of the area where the experiment was carried out.

III.2: Experimental zone characterization

A thorough understanding of the study area is essential to facilitate the application of theoretical frameworks to field conditions. This requires a comprehensive spatial analysis, including the identification of its geographical location, assessment of its significance, and characterization of its geomorphological features. Additionally, it is crucial to examine the climatic parameters of the region under investigation [47].

III.2.1: Location and Boundaries

The study area is located in the Ouargla region, in southeastern Algeria, within the Saharan domain. It represents one of the most important desert zones in the country, characterized by an arid environment and exposure to extreme climatic conditions, which makes it highly suitable for solar energy studies. Administratively, Ouargla is bounded by Djelfa, El Oued, and Biskra to the north, Ghardaïa to the west, and Tamanrasset and Illizi to the south, while extending toward the Tunisian border in the east [46]. Figure III-1 illustrates the geographical location of Ouargla within Algeria.

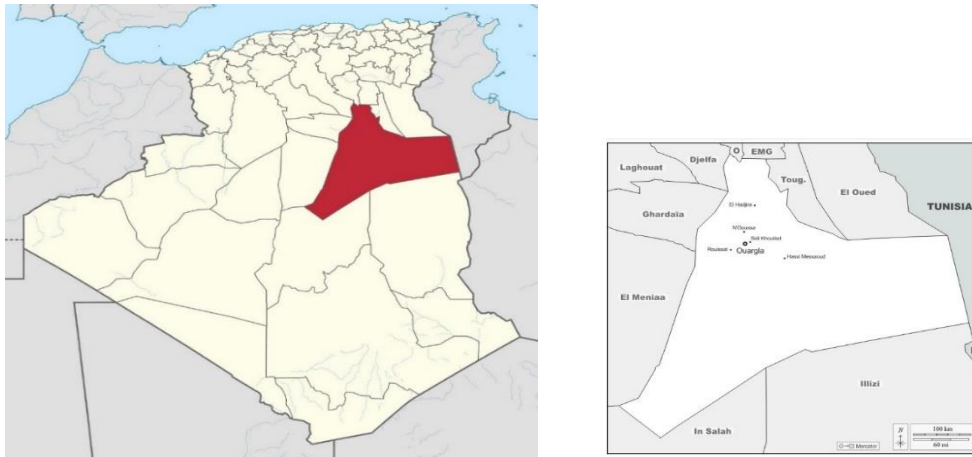


Figure III-1: Location of Ouargla on the map (Before the last administrative division) [47].

The Ouargla Basin forms part of the Great Saharan Depression. It extends over approximately 30 km in length and between 12 and 18 km in width, with elevations ranging from 103 m to 150 m above sea level. The basin is framed by two elevated plateaus, reaching about 230 m to the west and 160 m to the east, and is connected to the dune fields of the Great Eastern Erg, which further emphasizes its desert geomorphology [47].

From an astronomical perspective, Ouargla is located at 31°56' North latitude and 24°05' East longitude, with an average altitude of 143.6 m above sea level and covering a large administrative area of approximately 163,233 km² [47]. This geographical positioning strongly influences the solar potential of the region by affecting solar radiation intensity, incidence angle, and sunshine duration throughout the year [47].

III.2.2: Bioclimatic Framework

The Wilaya of Ouargla is characterized by an arid desert climate (hot desert climate), distinguished by low precipitation rates, high thermal regimes, and intense evapotranspiration. These conditions are typical of Saharan regions and have a direct impact on the performance of photovoltaic systems.

III.2.3: Ambient Temperature Profile

The temperature profile of Ouargla shows a strong seasonal variation, typical of continental desert climates. Maximum temperatures can reach up to 47.6°C in August, while minimum values drop to around 1.5°C in January. This represents a significant annual thermal amplitude exceeding 46°C, highlighting the extreme nature of the local climate.

These high temperatures, particularly during summer, have a direct impact on photovoltaic module efficiency due to increased thermal losses.

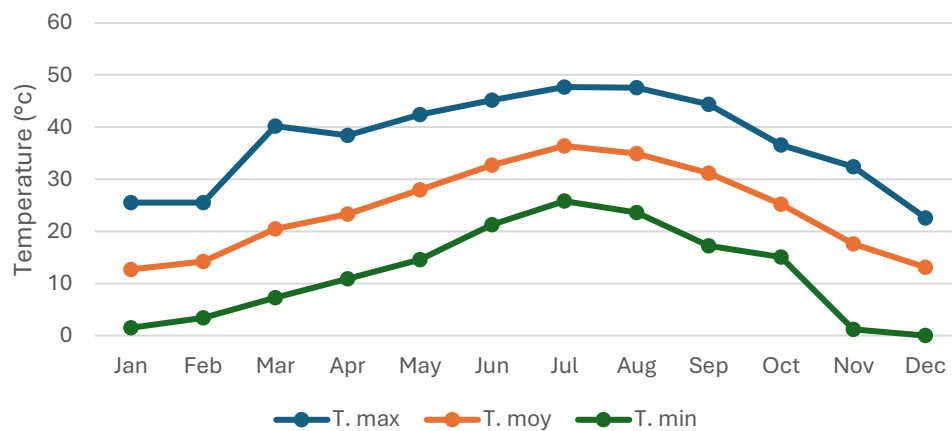


Figure III-2: Monthly temperature variation during 2025 [48]

III.2.4 : Humidity and Wind characteristics

The relative humidity in Ouargla remains generally low, ranging between 14% and 45%, confirming the dry desert nature of the region. Wind speed varies approximately between 7.4 km/h and 18 km/h, indicating moderate air movement throughout the year.

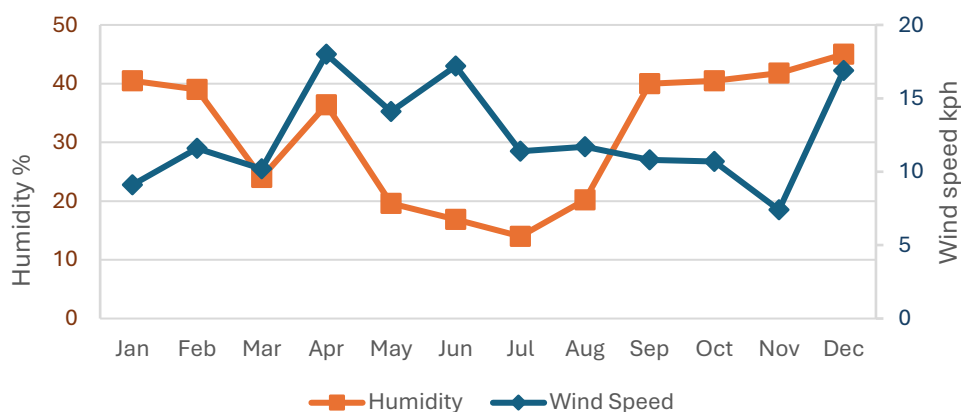


Figure III-3: Variation of humidity and wind speed during 2025 [48].

The data does not show a direct correlation between humidity and wind speed. For instance, low humidity values may coincide with relatively high wind speeds, while higher humidity levels may correspond to weaker winds. This indicates that additional

meteorological factors such as temperature gradients and wind direction influence local atmospheric conditions.

III.3: PV System Description

III.3.1: PV modules type and specifications

In this study, two SY-M80W polycrystalline solar panels were employed (see Figure III.4) each with a rated power output of 80 watts. Polycrystalline cells were chosen for their cost-effectiveness and moderate efficiency, offering a balance between performance and affordability.

Table III.1 presents the electrical specifications of the polycrystalline PV module used in this study, measured under standard test conditions (STC).



Figure III-4: Polycrystalline Panels

Table III-1 : Electrical and structural characteristics of the SY-M80W solar panel.

Property	Value
Model	SY-M80W
Panel Type	Polycrystalline Solar Panel
Maximum Power (P _{max})	80W
Voltage at P _{max} (V _{mp})	17.4V
Current at P _{max} (I _{mp})	4.61A
Open-circuit Voltage (V _{oc})	22.0V

Short-circuit Current (Isc)	4.85A
Max System Voltage	600V
Tolerance	±5%
Standard Test Conditions	1000W/m ² , AM 1.5 Global, 25°C cell temperature
Panel Size	900mm x 670mm (Length x Width)

III.4: Cooling System Design

III.4.1: Passive Cooling Component Specifications

To mitigate the efficiency drops caused by the extreme thermal conditions of the Ouargla region, galvanized steel finned heat sinks were integrated as passive thermal management components. These cooling devices are mounted directly to the rear side of the photovoltaic (PV) modules to accelerate heat dissipation, thereby lowering the operating cell temperature and enhancing electrical conversion efficiency. The geometric configuration of the heat sink employed in this investigation is illustrated in Figure III-5.



Figure III-5: Physical layout of the employed heat sink

The basic physical, thermal, and mechanical properties of the selected galvanized steel material are detailed in Table III-2.

Table III-2 : Basic Physical Properties of Galvanized.

Property	Value / Range	Unit
Density	7,800 - 8,000	kg/m ³

Melting Point	1,370 - 1,450	°C
Thermal Conductivity	45 – 55	W/(m·K)
Thermal Expansion Coefficient	11 - 13 × 10 ⁻⁶	1/K
Tensile Strength	250 – 550	MPa
Yield Strength	200 – 400	MPa
Hardness (Brinell)	120 – 160	HB
Material Thickness	1.2	mm
Length	(835-700)(615-250)	mm
Width	250	mm
Height	250	mm
Corrosion Resistance	High	-
Weldability	Possible with zinc removal	-

III.4.2: Material Selection Justification

The Galvanized steel is used as a heat sink for the following reasons:

- Galvanized steel has a thermal conductivity ranging between 45 and 55 W/(m·K), allowing it to efficiently transfer heat from hot surfaces to the external environment.
- The zinc layer protects the material from rust and corrosion, especially when exposed to humidity or harsh weather conditions, thereby increasing the lifespan of the heat sink.
- Galvanized steel is less expensive than aluminum or copper, making it an economical choice for thermal cooling applications.
- Galvanized steel is characterized by a tensile strength ranging from 250 to 550 megapascals, allowing it to withstand mechanical stresses without bending or cracking.
- It can be easily shaped into different forms (angles, plates, fins), making it easier to design custom heat sinks for specific applications.
- Zinc acts as a sacrificial anode, protecting the base metal from oxidation and corrosion at high temperatures.
- It can be easily combined with other materials such as aluminum and copper to improve thermal performance in composite systems.

III.4.3: Heat Sink Fin Geometric Dimensions

The geometric parameters of the fin array were precisely selected to maximize the heat dissipation area while maintaining an optimal boundary layer for natural air convection. The heat sink encompasses a total rear surface area of approximately $62.5\text{cm} \times 83.5\text{cm}$. The specific dimensional breakdown of the fin design includes:

- **Fin Height (2.5 cm):** Maximizes the effective convective surface area exposed to the air without creating a structural obstacle to fluid flow.
- **Fin Thickness (1.2 mm):** Guarantees a stable thermal conduction path while minimizing the dead weight and material volume added to the PV module assembly.

III.5: Experimental Setup

The experimental test configuration was established to monitor and compare the electrical and thermal behavior of the modified cooling system against a baseline standard. The setup involves two separate testing channels operating simultaneously: a baseline Reference PV Module (uncooled) and a Modified PV Module equipped with interchangeable fin arrangements.

The core operational workflow was conducted according to the following framework:

- **Fin Orientation Phases:** The experiments were carried out in two distinct geometric phases. First, the heat sinks were fixed in a vertical configuration to promote chimney-effect buoyant airflow. Second, the fins were reorganized into a horizontal configuration to evaluate the impact of orientation on cross-flow cooling.
- **Comparative Control:** The uncooled reference panel was operated under identical environmental conditions alongside the modified panel during all testing loops to establish a precise control baseline.
- **Temporal Framework:** Each configuration (vertical vs. horizontal) was continuously monitored over three non-consecutive days under mixed cloudy and clear sky condition.
- **Data Logging Intervals:** Manual data logging routines were maintained from 08:00 AM to 04:00 PM at fixed 30 minute increments.

- **Impedance Matching ($P_{\max}$ tracking):** Throughout the testing cycles, the variable load resistance within the module electrical circuits was manually swept to accurately identify the maximum power point ($P_{\max}$) under varying solar irradiance levels.
- **Acquisition Parameters:** The system manually recorded all raw electrical output variables (voltage, current, power) and matching environmental inputs (incident solar flux, ambient temperature).

III.6: Instrumentation and Data Collection

III.6.1: Thermal Measurement Instrumentation

Surface and ambient temperatures were monitored using an OMEGA RDXL4SD four-channel logging thermometer (Figure III-6). This instrument was selected based on the following capabilities:

- **Multi-Channel Acquisition:** Equipped with four independent thermocouple ports, allowing the simultaneous acquisition of three surface temperature points (T_1, T_2, T_3) alongside the local ambient air temperature.
- **Thermocouple Compatibility:** Fully compatible with fine-wire K-type thermocouples, which minimize localized thermal mass errors on the PV backsheet.
- **Integrated Display:** Features a real-time digital display showing all active channels concurrently for instantaneous auditing.



Figure III-6: OMEGA RDXL4SD four-channel digital thermometer.

III.6.2: Electrical Output Measurement

A DT-9205 digital multimeter (Figure III-7) was used to measure the electrical parameters generated by the modules. This unit is capable of measuring direct current voltage (DC voltage up to 1000 V), DC current, and line resistance. It includes a high-contrast digital readout and a manual rotary range selector.



Figure III-7: DT-9205 digital multimeter.

III.6.3: Electrical Loading System

To regulate the current draw and map the module I-V curves, ECO 1/2 tube-type power resistors were utilized as static loads (Figure III-8). Each power resistor features a nominal resistance of 10 Ω , a maximum current threshold of 5.7 A, and a maximum breakdown voltage rating of 250 V. Their semi-cylindrical physical geometry aids in high convective heat dissipation, preventing temperature-induced resistance drift during manual load sweeps.



Figure III-8: ECO 1/2 tube-type power resistors.

III.6.4: Solar Radiation Measurement

Incident solar irradiance was quantified using a digital pyranometer/solar power sensor (Figure III-9). The instrument provides real-time solar flux density measurements directly in W/m^2 ensuring that both the reference and cooled modules received uniform solar exposure during comparative testing.



Figure III-9: Solar power sensor for solar irradiance measurement.

III.6.5: Wind Velocity and Ambient Temperature Monitoring

An AM-4203 digital turbine anemometer (Figure III-10) was utilized to measure regional wind speed. The instrument incorporates a low-friction rotating vane assembly sensitive to subtle air movements and features:

- Real-time, average, and maximum wind speed tracking (units in m/s).
- Integrated ambient temperature sensing ($^{\circ}\text{C}$).
- A data-hold functions for accurate manual logging.



Figure III-10 : AM-4203 digital turbine anemometer.

III.7: Experimental Developments and Procedures

III.7.1: Fabrication and Installation of the Heat Sinks

To improve the thermal management of the photovoltaic panel, two passive cooling configurations using galvanized steel heat sink angles were experimentally investigated: a vertical-fin arrangement and a horizontal-fin arrangement. Six galvanized steel bars, each measuring 615 mm for H and 835 mm for V in length 1.5 mm in thickness, and with a cross-section of 25 mm * 25 mm, were used for the fabrication of both cooling systems.

- **Vertical-Fin Assembly:** For the vertical orientation phase, the raw bars were sectioned into 19 individual fins. The peripheral fins were cut to a length of 83.5 cm, while the interior central fins were short-cut to 70 cm to clear the module's factory junction box. This layout established unobstructed vertical air corridors that leverage natural buoyancy-induced thermal updrafts.



Figure III-11: Installation phase of the vertical galvanized steel fin array.

- **Horizontal-Fin Assembly:** For the horizontal configuration phase, the structural stock was partitioned into 30 uniform long pieces measuring 61.5 cm along with 6 short supporting pieces of 25 cm. The long segments were placed horizontally across the module width, while the shorter segments were structurally fitted around the junction box perimeter to maintain thermal contact continuity.



Figure III-12: Structural layout of the horizontal heat sink configuration.

Before installation, the rear surface of the photovoltaic panel was carefully cleaned to ensure optimal thermal contact. The metallic fins were then fixed using a quick-setting industrial adhesive. To enhance mechanical stability and reinforce the structure, small plastic pipe segments were strategically positioned along the corners and edges of the panel.

These cooling configurations were designed to increase the heat exchange area between the photovoltaic panel and the surrounding air, thereby enhancing heat dissipation through natural convection. Consequently, the operating temperature of the PV module can be reduced, which may improve the electrical efficiency and overall thermal performance of the system.

III.7.2: Operational Test Procedure

The systemic execution of the outdoor experimentation was completed as follows:

- Both photovoltaic panels were secured onto fixed-tilt structures oriented toward the equator under unshaded outdoor conditions.
- The testing routine was split into two sequential blocks: the vertical fin arrangement was tracked continuously for three testing days, followed by the complete installation and three-day testing block of the horizontal fin system.
- K-type thermocouples were attached at three distinct height positions—top, middle, and bottom—along the geometric centerlines of both panel backsheets (Figure III-15). This spatial distribution map captures the development of vertical thermal gradients across the modules.



Figure III-13 : Completed vertical fin configuration field installation and Completed horizontal fin configuration field installation.

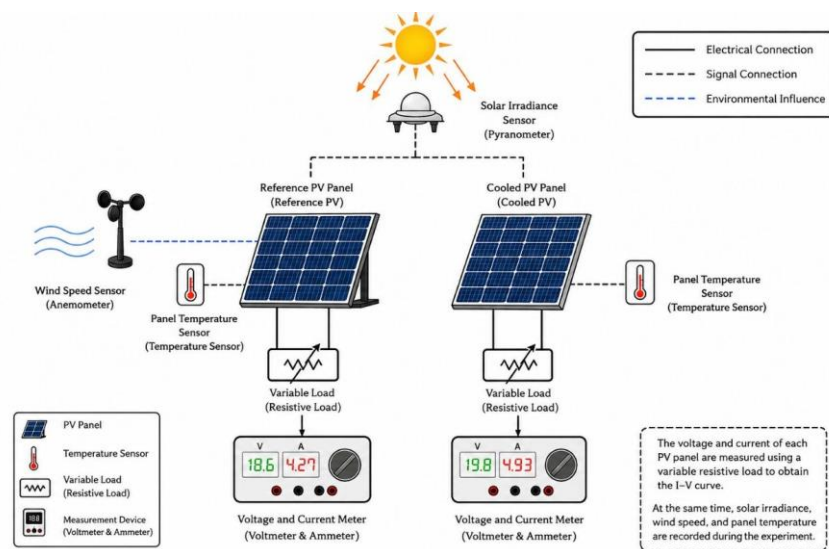


Figure III-14 : Experimental Setup for PV Panel Performance Measurement.

Thermocouples were attached at three different positions (top, middle, and bottom) on the back surface of each panel to monitor the temperature distribution, as shown in Figure III.14. The temperature values and electrical measurements, namely voltage and current, were recorded manually using appropriate measuring instruments.

At the same time, the ambient environmental conditions were monitored using a pyranometer to measure solar irradiance intensity, and an anemometer to measure ambient temperature and wind speed. The wind speed was also measured beneath the panel. The experiments were carried out under real outdoor operating conditions in order to evaluate the effectiveness of the two passive cooling systems and analyze the impact of fin orientation on heat dissipation and improving the efficiency of the photovoltaic panels.

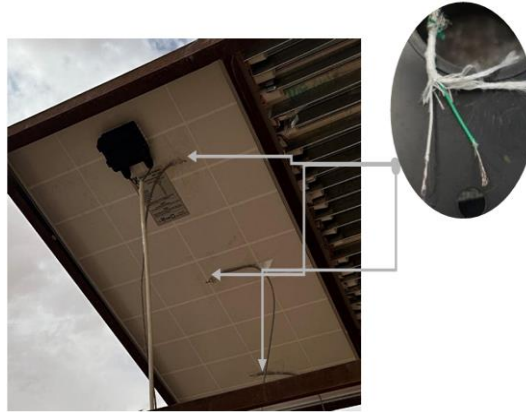


Figure III-15 : Distribution and attachment method of the thermocouple sensors.

III.7.3 : Objectives of the Experiment

The present study aims to:

- Compare the thermal behavior of the reference photovoltaic panel with the panels equipped with passive cooling systems;
- Evaluate and compare the performance of the two cooling configurations, namely the vertical-fin arrangement and the horizontal-fin arrangement;
- Analyze the temperature distribution and the vertical thermal gradient from the top to the bottom of each PV module;
- Investigate the influence of fin orientation on natural convection and heat dissipation under real outdoor operating conditions;
- Assess the effectiveness of passive cooling in reducing the operating temperature of photovoltaic panels and improving their electrical performance and overall efficiency.

CHAPTER 4

RESULTS AND DISCUSSION

IV.1: Introduction

This chapter presents and discusses the experimental results obtained from the photovoltaic (PV) systems under real operating conditions. The analysis focuses on evaluating the influence of climatic parameters, including solar irradiance, ambient temperature, and wind speed, on the electrical and thermal behavior of the PV modules.

Particular attention is given to the assessment of the proposed passive cooling technique based on galvanized steel heat sinks mounted on the rear surface of the photovoltaic panel. The performance of the cooled PV modules is compared with that of an uncooled reference module in order to determine the effectiveness of the cooling system in reducing module temperature and improving electrical output.

The chapter is organized into several sections. First, the influence of climatic conditions on PV performance is analyzed. Then, the thermal and electrical performances of the photovoltaic modules equipped with vertical and horizontal fin configurations are presented and discussed. Finally, a comparative analysis between the different cooling configurations is carried out to identify the most effective arrangement for photovoltaic applications under the desert climatic conditions of Ouargla.

IV.2: First experiment: Vertical fin assembly

IV.2.1: Meteorological and Ambient Conditions

In this section, the meteorological parameters recorded during the experimental days (06/05/2026, 09/05/2026, and 10/05/2026) in the region of Ouargla are presented and analyzed. These parameters include solar irradiance (G), ambient temperature (T_{amb}), and wind speed (W_s), which directly influence the thermal and electrical performance of the photovoltaic modules.

To ensure a comprehensive evaluation of the proposed passive cooling system under different desert weather conditions, the experiments were carried out during both sunny and partially cloudy days. The selected period included two predominantly sunny days (06/05/2026 and 10/05/2026) and one partially cloudy day (09/05/2026). Slight cloud passages were also observed during the sunny days, causing temporary fluctuations in the recorded meteorological data.

IV.2.2 : Solar Irradiance and Ambient Temperature Analysis

Figure IV-1 illustrates the evolution of solar irradiance and ambient temperature between 08:00 and 16:00 for the selected testing days.

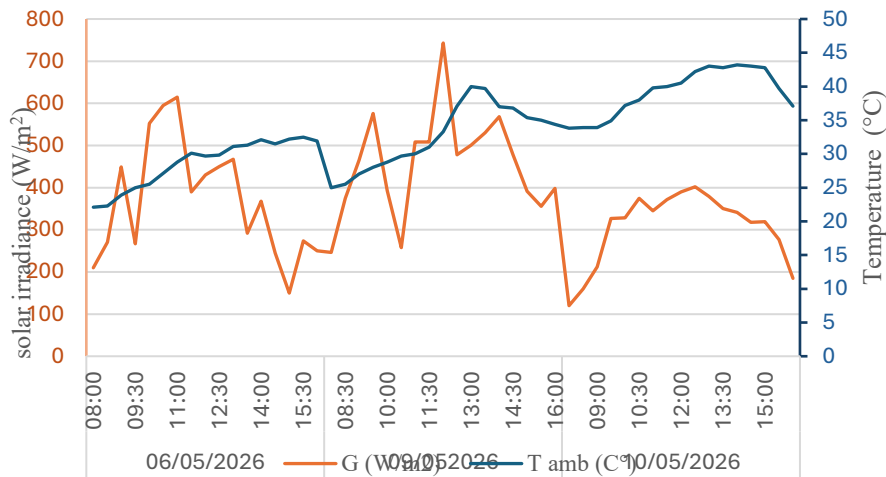


Figure IV-1: The variation of solar irradiance (G) and ambient temperature (T_{amb}) from 08:00 to 16:00 for the selected testing days in Ouargla

- 06/05/2026 (Sunny / Passing Clouds): Stable, progressive solar irradiance peaking at 615 W/m^2 (11:00); ambient temperature rose steadily from 25°C to 33°C .
- 09/05/2026 (Partially Cloudy): Highly fluctuating irradiance due to clouds, peaking at 745 W/m^2 (12:00); temperature spiked to nearly 40°C (13:00–13:30).
- 10/05/2026 (Sunny / Stable): Smooth, continuous radiation peaking at 400 W/m^2 (12:30); desert air masses drove temperatures to a peak of 43°C (13:30–14:30), ideal for testing thermal degradation.

The combination of intense solar radiation and extreme ambient temperatures (especially on May 9th and 10th) creates severe thermal stress for PV modules. This environment directly demonstrates the necessity and adaptability of the proposed galvanized steel heat sink for thermal protection..

IV.2.3: Wind Speed Analysis

Figure IV-2 illustrates the variation of wind speed profiles over the three experimental days, from 08:00 to 16:00, under different meteorological conditions in the Ouargla region.

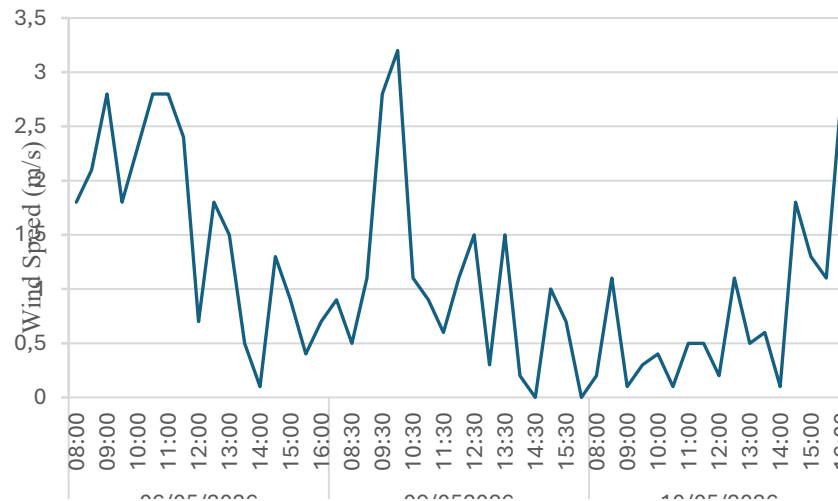


Figure IV-2: The wind speed profile (Ws) across the three testing days

Wind speed plays a crucial role in the passive cooling mechanism by enhancing convective heat transfer from the fins to the environment.

- 06/05/2026: Moderate wind (1.5 to 2.8 m/s), providing steady natural convection over the PV modules.
- 09/05/2026: High fluctuations; reached the period's peak of 3.2 m/s (10:00) but dropped to near-zero (0.1–0.2 m/s) during peak temperature hours (13:30–14:30), minimizing cooling.
- 10/05/2026: Calm morning (< 0.5 m/s between 09:00–12:00), later picking up in the afternoon to peak at 2.8 m/s (16:00).

IV.2.4 : Thermal Performance and Temperature Difference Analysis

In this section, a comprehensive thermal evaluation of the photovoltaic modules is conducted. The effectiveness of the proposed galvanized steel fins is verified by comparing the temperature profiles of the cooled PV module (T_c) and the uncooled witness PV module (T_w) across the three testing days in Ouargla.

IV.2.4.1 : Temperature Distribution Analysis

Figure IV-3 presents the temperature evolution recorded by the six sensors distributed over both photovoltaic modules. The results clearly show that the temperatures measured on the uncooled witness panel remained consistently higher than those recorded on the cooled panel during the main sunshine period for all experimental days.

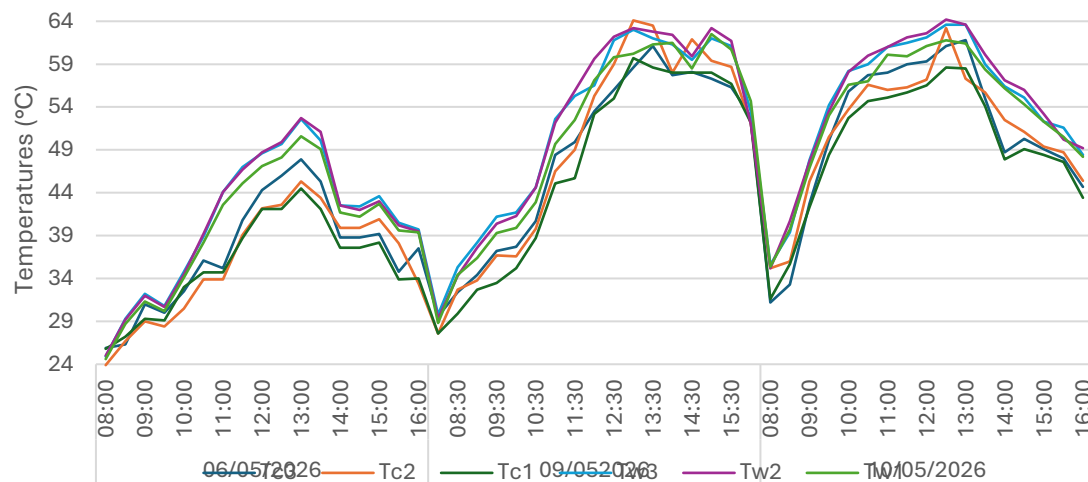


Figure IV-3: Temperature profiles of the cooled panel sensors (Tc1, Tc2, Tc3) and witness panel sensors (Tw1, Tw2, Tw3)

Thermal Stress Reduction: On sunny days (May 6 and 10), the uncooled witness panel exceeded 60°C, while the galvanized steel fins successfully blocked heat buildup, keeping the cooled panel significantly cooler.

Uniform Cooling: Consistent sensor data proved that the cooling effect was evenly distributed across the entire PV module surface.

Hot-Spot Prevention: Excellent thermal coupling between the PV backsheet and the cooling system eliminated localized thermal resistance, successfully preventing damaging "hot-spots."

IV.2.4.2 : Comparison of Average Module Temperatures

Figure IV-4 illustrates the variation of the average temperatures of both photovoltaic modules during the testing campaign. The cooled module maintained lower average temperatures than the reference module throughout the experimental period.

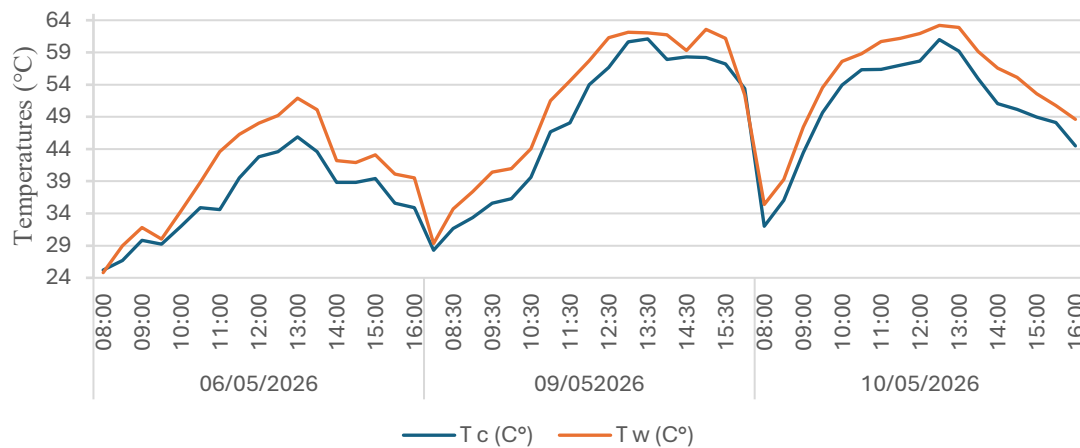


Figure IV-4: the average temperatures of the cooled module (T_c) and the witness module (T_w)

Throughout the entire testing campaign, the average temperature curve of the cooled panel (T_c), represented by the blue line) remains lower than the uncooled panel curve (T_w), represented by the orange line).

- 06/05/2026 (Sunny): Witness module peaked at 51.5°C (13:00); cooled module stayed lower at 46.5°C (a 5°C reduction).
- 09/05/2026 (Partially Cloudy): Witness module reached 63°C (13:00) despite cloud dips; cooled module was kept at 60.5°C.
- 10/05/2026 (Sunny / Hot Desert Air): Highest thermal load; witness module peaked at a critical 63.5°C (12:30), while the heat sink depressed the cooled module to 61°C.

The Physics (Newton's Law of Cooling): The temperature reduction directly follows $Q_{conv} = h \cdot S \cdot \Delta T$. By using fins to multiply the surface area (S), thermal resistance is reduced, allowing heat to dissipate faster and establishing a lower operating temperature.

IV.2.4.3 : Evolution of the Temperature Difference

Figure IV-5 presents the evolution of the temperature difference between the witness and cooled photovoltaic modules during the experimental days.

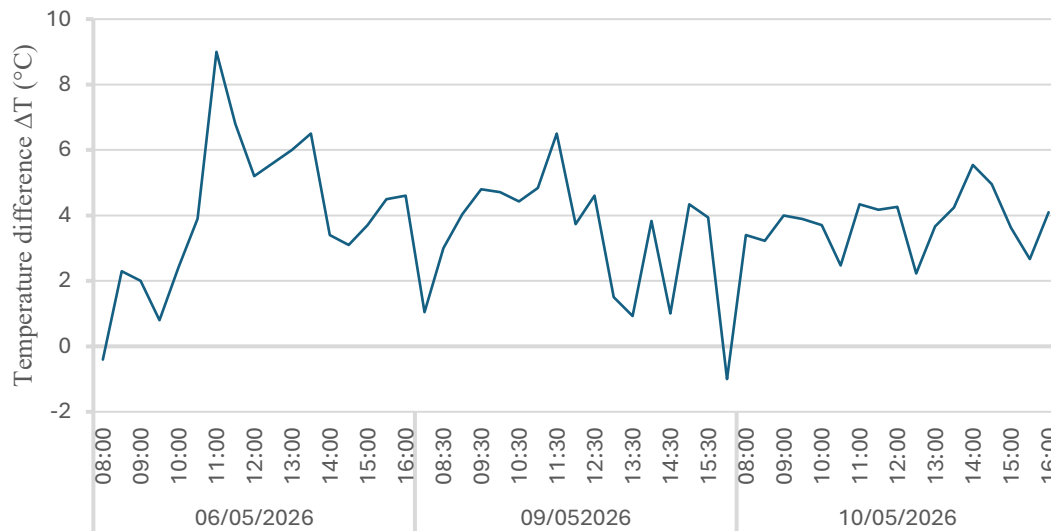


Figure IV-5: the temperature difference (ΔT)

06/05/2026 (Max Cooling): ΔT hit an outstanding peak of 9.2°C (11:00). This maximum relief strongly correlates with high wind speeds (2.8 m/s), proving the fins maximize natural wind-assisted convection.

- 09/05/2026 (Thermal Inversion): ΔT peaked at 6.5°C (11:30) but dropped to -1°C during sudden cloud shading (16:00).
- 10/05/2026 (Stable Performance): ΔT hovered consistently between 3°C and 5.8°C during peak hours (10:00–15:00).

The Physics (Thermal Inertia): The negative ΔT inversion is driven by thermal mass. The uncooled panel has low thermal mass and cools instantly when shaded. Conversely, the galvanized steel fins have a higher specific heat capacity ($C_p \approx 490 \text{ J/kg}\cdot\text{K}$), acting as a temporary heat reservoir that discharges heat more slowly.

Conclusion: The galvanized steel fins provide reliable passive cooling, lowering operating temperatures by up to 9.2°C and significantly mitigating PV cell degradation in arid climates.

IV.2.5 : Electrical Performance and Efficiency Analysis

The thermal mitigation achieved by the galvanized steel fins directly reflects on the electrical output of the photovoltaic system. In this section, the impact of cooling on the output power (P) and electrical efficiency (η) is evaluated and physically interpreted.

IV.2.5.1: Power Output Analysis (P_{out})

Figure IV-6 presents the variation of the electrical power generated by both photovoltaic modules during the three experimental days. The results show that the cooled photovoltaic module consistently produced higher electrical power compared to the uncooled reference module.

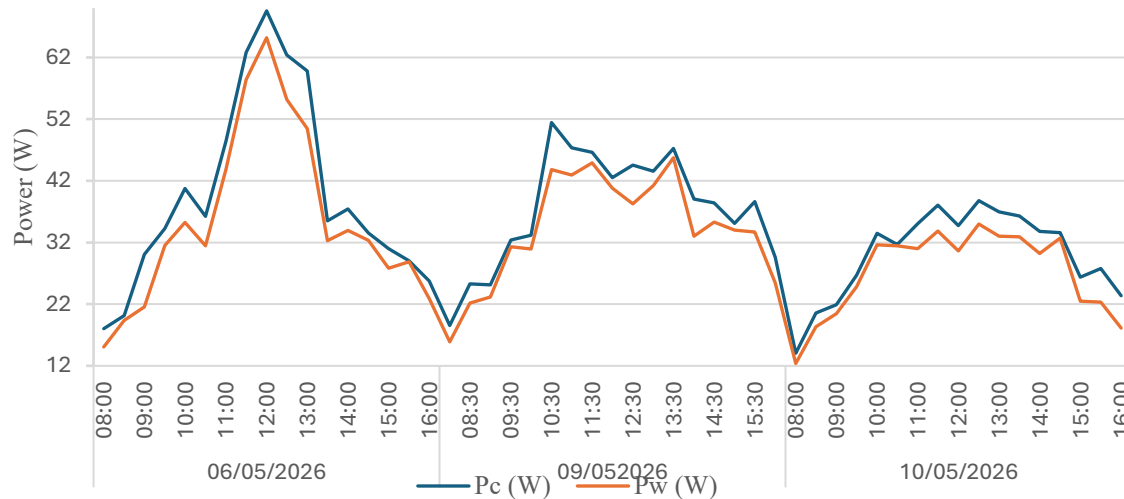


Figure IV-6: The comparison of the generated electrical power between the cooled PV module (P_c) and the uncooled witness module (P_w) across the testing days

- 06/05/2026: Maximum power gap occurred between 11:30 and 12:00; the cooled panel produced 69 W compared to 64 W from the uncooled panel, yielding a 5 W net power gain.
- 09/05/2026: Despite massive power drops from cloud shading, the cooled panel maintained a strong advantage during peak irradiance (10:30), outputting 51.5 W versus the uncooled panel's 44 W (a 7.5 W gain).
- 10/05/2026: Stable solar conditions led to a steady power advantage of 3 W to 4 W for the cooled panel during the hottest afternoon hours (12:00–14:30).

Semiconductor Physics ($P=V \times I$): Higher operating temperatures shrink the semiconductor bandgap. This slightly increases short-circuit current (I_{sc}) but causes a severe, exponential drop in open-circuit voltage (V_{oc}). Because voltage drops dominate the electrical behavior, cooling the module by up to 9.2°C minimizes this voltage loss and protects power output.

IV.2.5.2 : Electrical Efficiency Analysis (η)

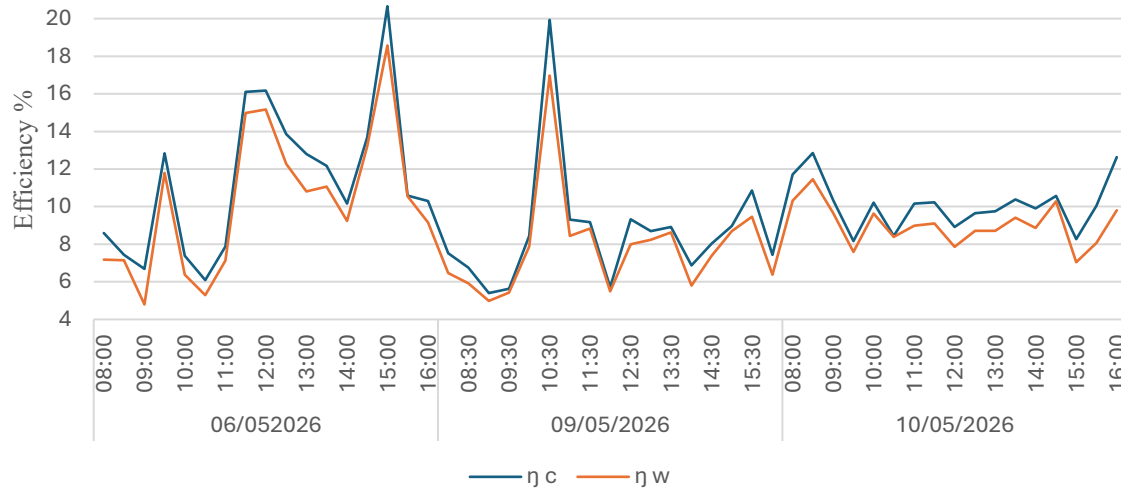


Figure IV-7: The dynamic changes in the electrical efficiency for both the cooled (η_c) and witness (η_w) panels

The electrical efficiency curve of the cooled PV module (blue line) remains strictly positioned above the uncooled module curve (orange line) during all operative hours.

Weather & Wind: Testing in Ouargla (May 6–10, 2026) featured high solar irradiance (up to 745 W/m^2), extreme desert temperatures (up to 43°C), and fluctuating winds (0.1 to 3.2 m/s).

Thermal Relief (ΔT): The galvanized steel fins ($C_p \approx 490 \text{ J/kg}\cdot\text{K}$) expanded the cooling surface ($Q_{\text{conv}} = h \cdot S \cdot \Delta T$), lowering panel temperatures by up to 9.2°C and preventing damaging hot-spots. Sudden shading caused a brief -1°C thermal inversion due to the fins' thermal inertia.

Electrical Gain: Cooling minimized the temperature-dependent bandgap shrinkage and exponential voltage (V_{oc}) drop ($P = V \times I$). This yielded a peak power gain of 5 W and an efficiency advantage of up to 3% , keeping mid-day efficiency above 10% under extreme heat.

IV.3: Second experiment: Horizontal fin assembly

IV.3.1: Meteorological Conditions

In this section too, the meteorological parameters recorded during the experimental days (12/05/2026, 16/05/2026, and 18/05/2026) in the region of Ouargla are presented and analyzed. These parameters include solar irradiance (G), ambient temperature (T_{amb}), and

wind speed (W_s), which directly influence the thermal and electrical performance of the photovoltaic modules.

To evaluate the cooling system under different real-world climatic behaviors of the Algerian desert, the testing period included two predominantly sunny days (12/05/2026 and 18/05/2026) and one partially cloudy day (16/05/2026). It is worth noting that light passing clouds were observed across all testing days, introducing minor transient fluctuations even during the sunny periods.

IV.3.2 : Solar Irradiance and Ambient Temperature Analysis

In this section, the environmental factors governing the microclimate during the second experimental campaign (12/05/2026, 16/05/2026, and 18/05/2026) in the arid region of Ouargla are presented and analyzed. These ambient parameters consist of solar irradiance (G), ambient temperature (T_{amb}), and wind speed (W_s). Figure IV-8 illustrates the temporal evolution of solar irradiance and ambient temperature during the experimental period.

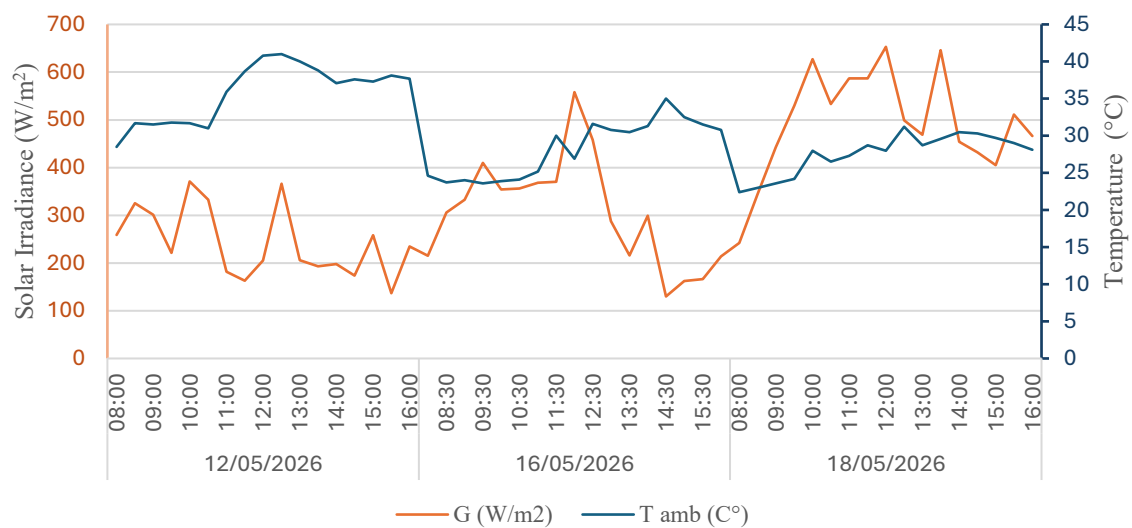


Figure IV-8: solar irradiance (G) and ambient temperature (T_{amb})

- 12/05/2026: Ambient temperature climbed from 29°C (08:00) to a peak of 41.5°C (12:00–12:30). Irradiance was highly unstable and saw-toothed, dropping from a 360 W/m² peak down to its sharpest low of 120 W/m² (15:30).
- 16/05/2026: Irradiance peaked at 550 W/m² (12:00) before abruptly collapsing to 110 W/m² (14:30), forcing the ambient temperature down from 32°C to 28°C.

- 18/05/2026: Registered the highest solar irradiance with twin peaks of 630 W/m² (12:00) and 620 W/m² (13:30), while temperatures remained stable between 28°C and 31.5°C.

The jagged, saw-toothed irradiance profiles indicate a high density of fast-moving, intermittent cloud patches over Ouargla. Thermodynamically, this irregular weather prevents the PV modules from reaching a thermal steady-state, forcing cells to alternate rapidly between intense radiative heat absorption and sudden transient cooling. This traps thermal energy from non-converted infrared photons, causing critical thermal stress.

IV.3.3 : Wind Speed Analysis

Figure IV-9 presents the temporal variation of wind speed during the operational period.

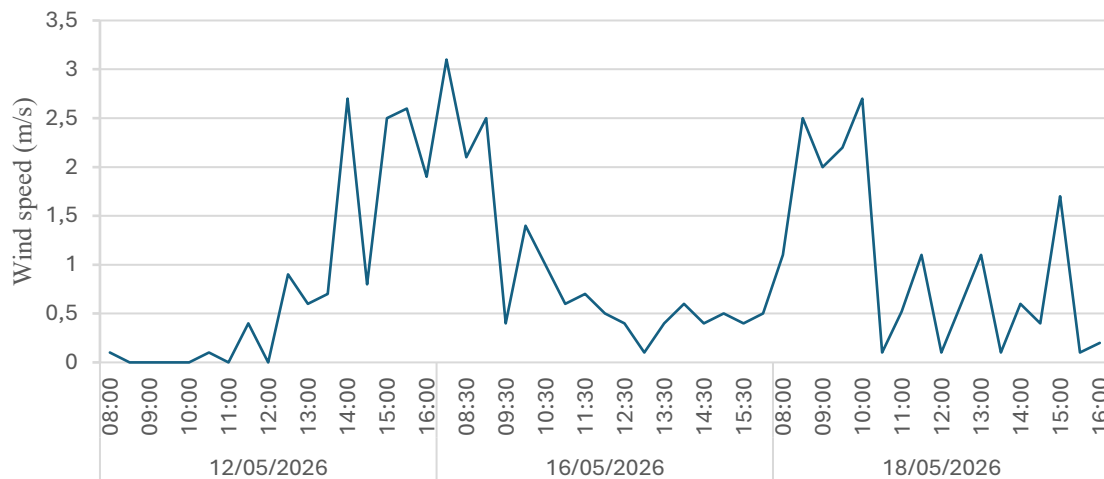


Figure IV-9: The real-time evaluation of wind speed (Ws) throughout the operative hours

- **12/05/2026:** Calm morning (< 0.5 m/s), followed by a turbulent afternoon with sharp peaks of **2.7 m/s** (14:00) and **2.6 m/s** (15:30).
- **16/05/2026:** Maximum peak of **3.1 m/s** early at 08:00, followed by a continuous decline to a weak average < 0.6 m/s from 11:00 onwards, hitting a minimum of **0.1 m/s** (13:00).
- **18/05/2026:** Cyclic profile starting with morning gusts of **2.7 m/s** (10:00), dropping to a near-zero calm of **0.1 m/s** (11:00 and 12:00), before rising again in the afternoon.

Fluid Dynamics Impact: Wind speed directly governs the external convective heat transfer coefficient (). When wind drops to near-zero (afternoons of May 16 and 18), cooling

relies solely on **natural convection**, where stagnant air boundaries trap severe heat in the solar cells. Conversely, gusts exceeding **2.5 m/s** force a transition into **mixed/forced convection**, disrupting the thermal boundary layer on the rear structure to accelerate heat extraction.

IV.3.4 : Thermal Performance and Temperature Distribution

IV.3.4.1: Temperature Distribution Across Sensors

Figure IV-10 presents the temperature evolution recorded by six sensors: three embedded in the cooled module (Tc1, Tc2, Tc3) and three in the reference uncooled module (Tw1, Tw2, Tw3).

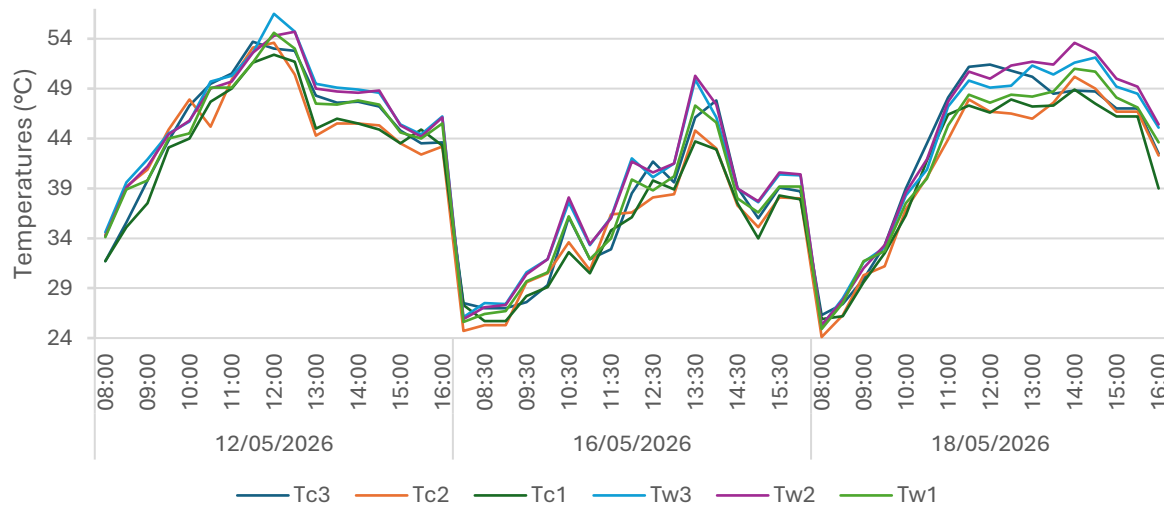


Figure IV-10: the six embedded temperature sensors (Tc1, Tc2, Tc3) for the cooled module, and (Tw1, Tw2, Tw3) for the uncooled witness module)

- Witness Module (Tw1,Tw2,Tw3): Consistently grouped at higher levels, peaking near 55°C (12:00 on 12/05/2026) and 53°C (14:00 on 18/05/2026).
- Cooled Module (Tc1,Tc2,Tc3): Closely mirrored the witness curves but remained clustered at noticeably lower temperatures.
- Thermal Plunges: Weather fluctuations on 16/05/2026 caused sharp, simultaneous vertical drops across all sensors down to 27°C.

The precise, parallel tracking between sensor groups validates data reliability. The tight clustering of the cooled sensors proves fully uniform conductive coupling between the PV

backsheet and the galvanized steel heat sink. This uniform connection eliminates localized thermal resistance, ensuring even cooling across the entire panel surface and preventing cell-damaging "hot-spots."

IV.3.4.2 : Comparison of Average Module Temperatures

Figure IV-11 compares the average temperature evolution of the cooled module (T_c) and the reference module (T_w).

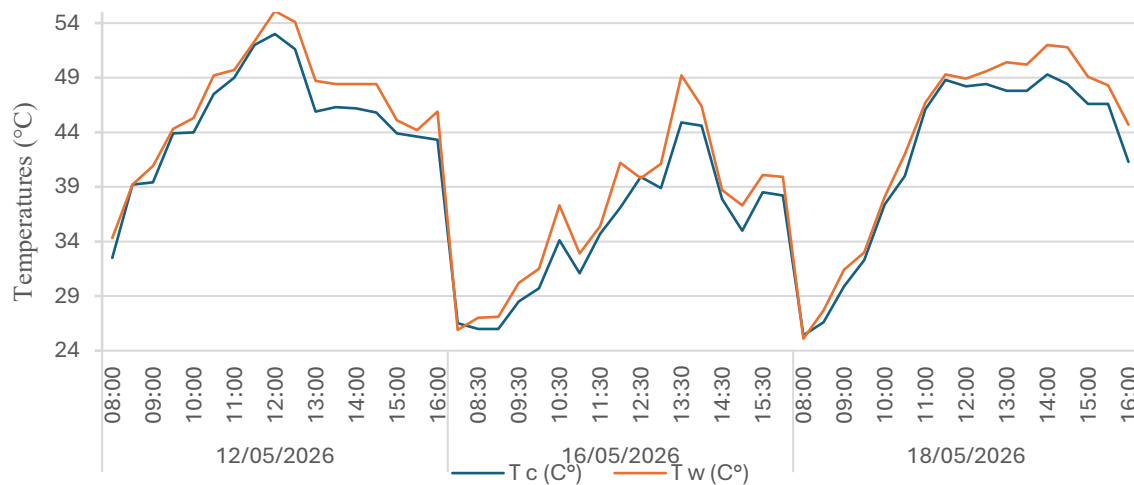


Figure IV-11: The synchronized tracking of the average operating temperatures for the cooled module (T_c) and the uncooled witness module (T_w)

- 12/05/2026: Witness panel (T_w) peaked at 54.2°C (12:00); cooled panel (T_c) stayed at 51.6°C (a 2.6°C reduction).
- 16/05/2026: Thermal relief was sustained through weather drops; cooled module ran at 48°C compared to over 51°C for the witness module (13:30).
- 18/05/2026: Under sustained thermal load, witness panel peaked at 53.5°C (14:00); cooled panel peak was suppressed to 50.1°C (a 3.4°C reduction).

Governed by Newton's Law of Cooling, convective heat rejection (Q_{conv}) is directly proportional to the exposed surface area (S). While the witness panel relies only on its flat rear surface, the galvanized steel fins multiply the effective geometric surface area. This minimizes overall thermal resistance to the ambient air, accelerates heat dissipation, and permanently forces a lower steady-state operating temperature ($T_c < T_w$).

IV.3.4.3 : Evolution of the Temperature Difference (ΔT)

Figure IV-12 presents the temporal evolution of the temperature difference between the reference and cooled modules.

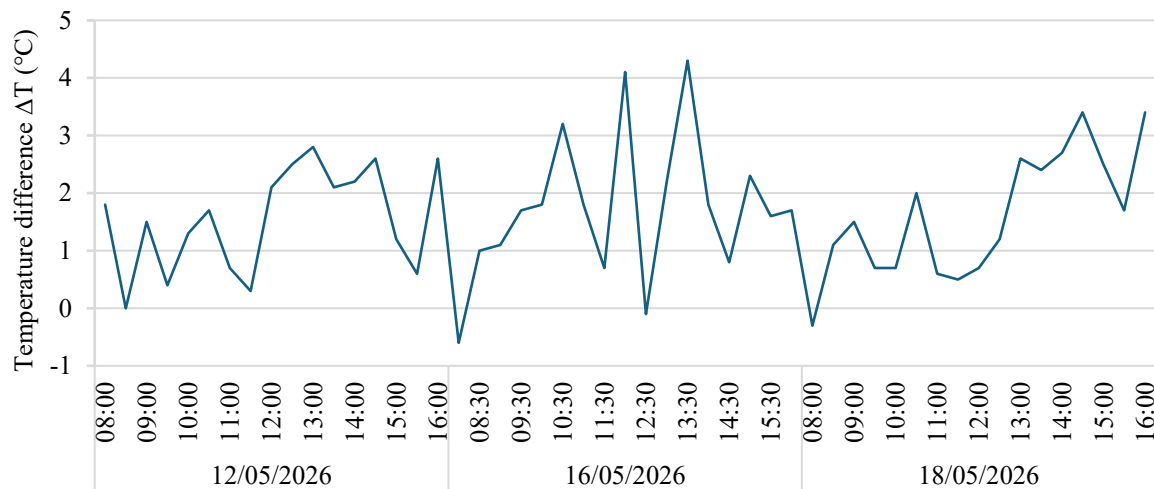


Figure IV-12: The net real-time cooling impact, quantified as the temperature difference (ΔT)

The system maintained a positive thermal relief ($\Delta T > 0$ °C) for the majority of the operational hours across the three days, generally oscillating between (1 °C) and (3.5 °C).

- 12/05/2026: Steady ΔT performance, reaching a notable afternoon peak of 2.7°C (13:00).
- 16/05/2026 (Most Dynamic): ΔT achieved a maximum positive peak of 4.4°C (13:30) but also suffered sharp, instantaneous negative drops to -0.6°C (08:00) and -0.4°C (12:30).
- 18/05/2026: Sustained a strong afternoon cooling peak of 3.5°C at both 14:30 and 16:00.

Negative ΔT drops (thermal inversion: $T_c > T_w$) are governed by thermal mass differences. Galvanized steel fins have a high specific heat capacity ($C_p \approx 490$ J/kg·K). When sudden clouds block the sun, the low-mass uncooled panel cools down instantly. Meanwhile, the high-mass cooling assembly acts as a temporary thermal reservoir, retaining and discharging stored heat more slowly, which briefly keeps the cooled panel warmer until thermal equilibrium is reached.

IV.3.5 : Electrical Performance and Efficiency Analysis

IV.3.5.1 : Power Output Analysis (P_{out})

Figure IV-13 compares the electrical power output of the cooled (P_c) and reference (P_w) PV modules.

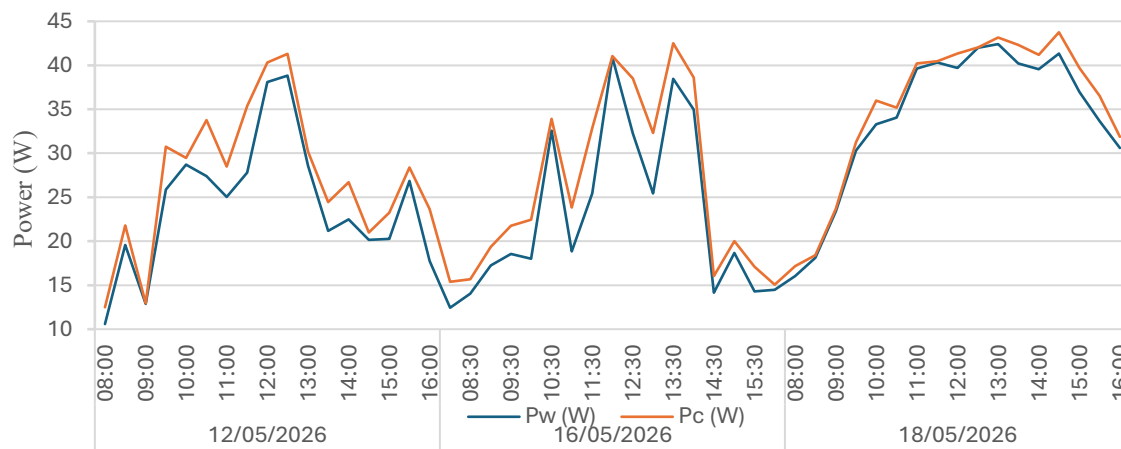


Figure IV-13: The real-time electrical power outputs for both the cooled PV panel (P_c) and the uncooled witness PV panel (P_w) across the testing period

- The output power of the cooled panel (P_c , orange line) maintains a continuous gap above the uncooled witness panel (P_w , blue line) throughout the peak solar hours of all test days.
- 12/05/2026: Cooled panel (P_c) peaked at 41.8 W (12:30) vs. 40.1 W for the witness panel (P_w). A notable gap occurred at 11:00 (P_c was 33 W while P_w dropped to 27.5 W).
- 16/05/2026: Intense cloud-induced fluctuations occurred; at 13:30, peaked at 42.5 W, maintaining a clear advantage over P_w at 39.5 W.
- 18/05/2026: Under steady radiation, achieved its absolute highest peak of 43.8 W (14:30), outperforming P_w at 41.8 W.

Photovoltaic Physics : Rising cell temperatures contract the semiconductor energy bandgap, exponentially increasing the thermal recombination rate of charge carriers. This severely drops the open-circuit voltage, which dominates the power loss. The galvanized steel fins continuously conduct heat away, mitigating this degradation and maintaining a superior power profile.

IV.3.5.2 : Electrical Efficiency Analysis (η)

Figure IV-14 presents the instantaneous conversion efficiency for both systems.

- 12/05/2026: Cooled panel efficiency (η_{Pc}) reached a major peak of 21.5% (11:30) vs. 18.5% for the witness panel (η_{Pw}), yielding a 3% absolute efficiency gain.
- 16/05/2026: Both curves showed sharp jagged spikes from solar drops; at 13:30, the cooled panel held 19.8% efficiency over the uncooled module's 18.2%.
- 18/05/2026: High ambient thermal loads dropped overall baselines, but the cooled panel maintained a steady advantage, tracking at 10.2% (14:30) compared to 9.5% for the witness panel.
- Conclusion: The passively cooled panel's efficiency curve remained consistently positioned above the uncooled witness panel across all primary testing hours.

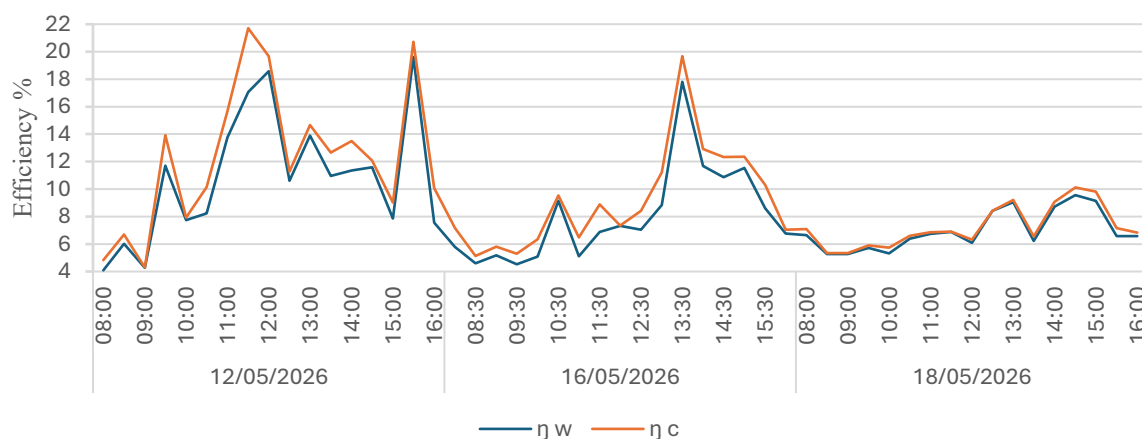


Figure IV-14: The instantaneous electrical conversion efficiencies for the cooled configuration (η_c) and the uncooled reference system (η_w)

The Problem: Photovoltaic efficiency is tied to a negative temperature coefficient ($\beta = -0.4\%/^{\circ}\text{C}$). Extreme desert heat causes heavy thermal stress, escalating the kinetic scattering of free electrons within the silicon lattice. This increases internal electrical resistance and degrades the Fill Factor (FF).

The horizontal galvanized steel heat sink acts as an expanded passive thermal stabilizer. By boosting heat rejection, it curtails kinetic losses, sustains electron mobility, and preserves a higher net photon-to-electricity conversion efficiency.

IV.4 : Combined Influence of Wind Speed on Thermal Mitigation (ΔT)

Figures IV-15 and IV-16 illustrate the relationship between wind speed and temperature difference for both fin configurations.

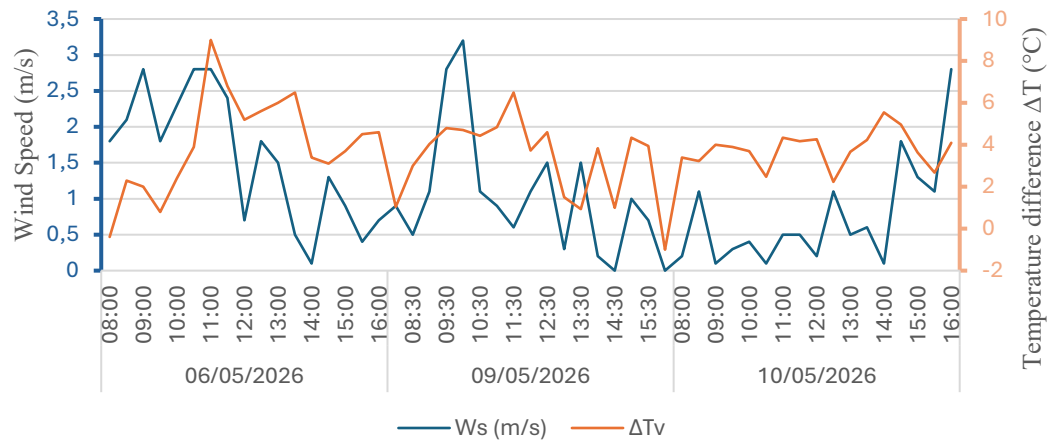


Figure IV-15: wind speed (W_s), and the net temperature difference (ΔT) for the vertical fin configuration.

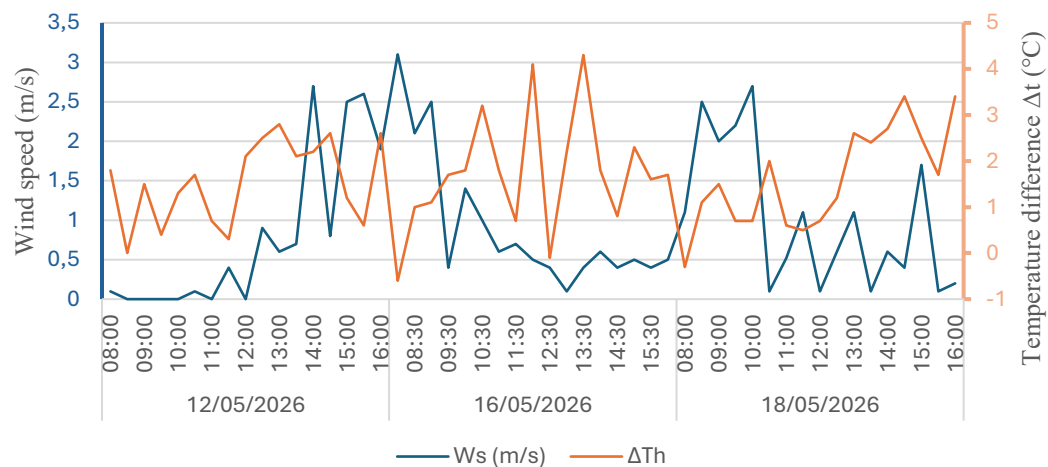


Figure IV-16: wind speed (W_s), and the net temperature difference (ΔT) for the horizontal fin configuration.

Vertical Channels (The Winner): Aligned perfectly with natural buoyancy and wind vectors, enhancing the "Chimney Effect". Wind uniformly scrubs the fin walls, dropping boundary layer resistance to hit a maximum thermal relief of $\Delta T=9.2^{\circ}\text{C}$ at 2.8 m/s .

Horizontal Channels (The Flow Blocker): Fins cut across air currents, acting as aerodynamic obstacles. This forces flow separation, creating stagnant warm wake zones and localized recirculation vortices that trap heat and raise thermal resistance.

Transient Calm Periods: When wind drops to 0.1 m/s, the high thermal inertia of the horizontal configuration traps heat longer than the lightweight reference panel, crashing the cooling curve into a negative thermal inversion ($\Delta T = -0.5^\circ\text{C}$).

IV.5 : Comparative Evaluation of the Cooling Configurations

To evaluate the engineering design that offers optimal performance under the desert environment of Ouargla, a direct comparison is conducted between the first configuration (Vertical Fins, representing Test 1) and the second configuration (Horizontal Fins, representing Test 2). This evaluation focuses precisely on the net temperature difference (ΔT) and the corresponding electrical efficiency optimization.

IV.5.1 : Overall Temperature Difference Comparison (ΔT)

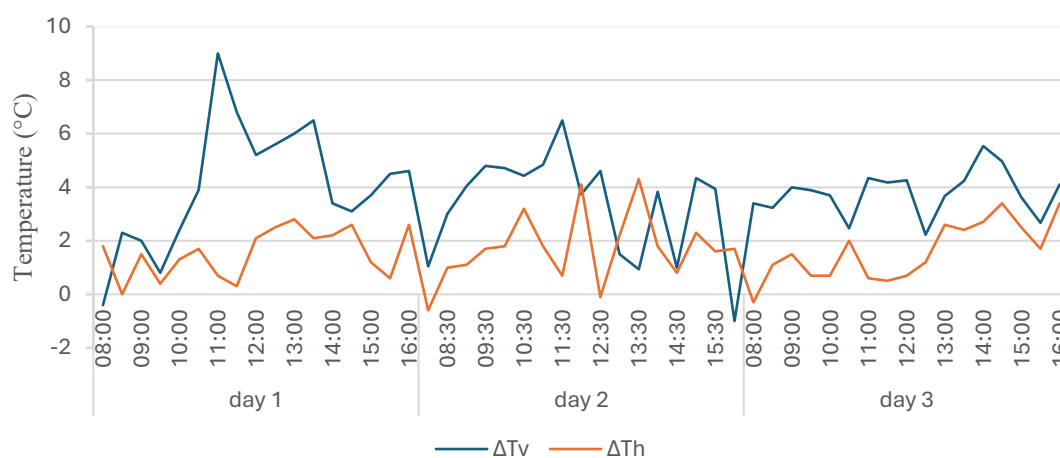


Figure IV-17: The simultaneous real-time comparison of the temperature differences achieved by both setups (ΔT)

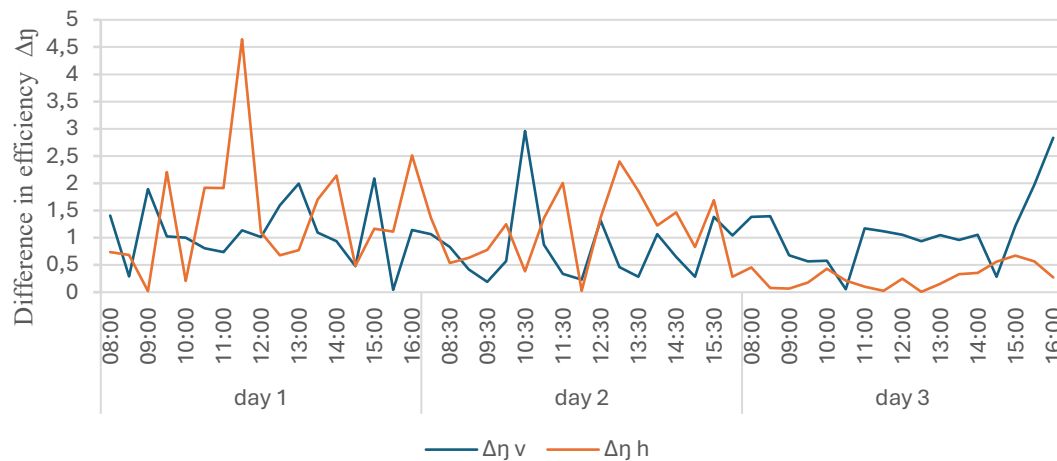


Figure IV-18: the Difference in efficiency ($\Delta\eta$) of the V Fin Configuration and H Fin Configuration

A simultaneous, cross-sectional evaluation of the empirical curves representing the net temperature difference (ΔT) and the instantaneous electrical conversion efficiency (η) reveals a clear and sustained superiority of the Vertical Fin Configuration over the Horizontal Fin Configuration throughout the operational hours.

As demonstrated in the combined thermal relief graph, the vertical setup maintains a consistently higher temperature gradient (ΔT_v), peaking at an absolute maximum of (9.2 °C) during the solar noon hours. In stark contrast, the horizontal curve (ΔT_h) remains heavily compressed in the lower bounds of the graph, failing to exceed (4.4 °C) and fluctuating mostly between (1 °C) and (3.5 °C).

This thermal divergence directly governs the electrical responsiveness shown in the conversion efficiency graph. The vertical configuration delivers a prominent upward stabilization in conversion efficiency (η_{cv}), yielding a net enhancement of (2.2%) to (3%). Conversely, the horizontal configuration's efficiency curve (η_{ch}) remains limited, lagging behind the vertical installation by a net average margin of (1%) to (1.5%) under identical solar irradiance levels.

IV.5.1 : Aerodynamic and Thermodynamic Interpretation (The Chimney Effect)

The fundamental divergence in thermal and electrical performance between the two configurations is scientifically explained by the principles of Fluid Dynamics and the geometric interaction between the extended surfaces and localized air flow regimes:

IV.5.2 : Activation of the Chimney Effect (Stack Effect)

Alignment: The parallel channels formed by the vertical galvanized steel fins align perfectly with the natural buoyancy vector of heated fluid. As the PV backsheet heats the adjacent air, the air density drops sharply, causing it to rise rapidly toward the upper exit. This upward escape creates a continuous low-pressure zone at the bottom, constantly drawing in cooler ambient air. This self-sustaining loop acts as a thermal chimney, ensuring a high convective heat transfer coefficient (h) and an uninterrupted flush of heat without consuming external parasitic energy.

IV.5.3 : Aerodynamic Obstruction and Air Entrapment

In contrast, the horizontal fins act as perpendicular physical barriers (cross-blocks) that abruptly cut off the natural upward buoyancy path of the heated air. This structural layout forces the air to detach from the cooling surfaces, creating localized recirculation vortices and stagnant warm air pockets trapped between the fin gaps. These stagnant wake zones act as localized thermal insulation barriers rather than heat dissipators, thereby increasing the overall thermal resistance underneath the panel and heavily capping the cooling efficiency.

IV.5.4 : Synergy with Wind-Driven Forced Convection

Under the prevailing wind profiles of the Ouargla desert, the vertical channels present minimum aerodynamic drag. When external wind sweeps underneath the panel, it flows smoothly through the open vertical paths, effectively scrubbing the fin walls and accelerating heat extraction. In the horizontal configuration, however, incoming wind collides destructively with the perpendicular fins, generating chaotic turbulence that is highly inefficient in removing heat from the module backsheet.

IV.5.5 : Section Verdict

These experimental findings conclusively prove that optimizing a passive thermal management system is not merely dependent on expanding the conductive surface area (the presence of fins), but is strictly governed by the geometric orientation of the installation. Proper vertical alignment ensures optimal fluid flow synchronization, suppressing

semiconductor bandgap degradation and preserving the open-circuit voltage (V_{oc}) to yield the recorded performance upgrades under harsh desert climates.

IV.6: Conclusion

The comparative analysis between vertical and horizontal fin configurations clearly demonstrates the superior thermofluid performance of the vertical arrangement. The vertical fin system achieved a maximum temperature reduction of up to 9.2 °C, which is approximately twice the cooling effectiveness observed in the horizontal configuration. This enhanced performance is primarily attributed to the more favorable airflow dynamics, where buoyancy-driven convection and wind-assisted chimney effects are fully exploited.

This substantial thermal improvement directly translated into enhanced electrical performance. By effectively limiting the operating temperature of the photovoltaic modules, the vertical configuration reduced thermal-induced voltage degradation, leading to an increase in power output of approximately 5 W and an improvement in electrical efficiency of up to 3% under peak operating conditions. These gains confirm the strong coupling between thermal regulation and photovoltaic conversion efficiency.

From a practical perspective, the vertical fin configuration represents a highly efficient, passive, and low-cost cooling strategy that requires no external energy input. Its ability to enhance heat dissipation while maintaining system simplicity makes it particularly suitable for deployment in harsh desert climates such as Ouargla, where high irradiance and extreme temperatures significantly limit PV performance. Consequently, the vertical fin design can be considered a robust and scalable solution for improving photovoltaic energy yield and mitigating long-term thermal degradation.

General Conclusion

General Conclusion

This study addressed the issue of excessive operating temperatures affecting photovoltaic (PV) panels under the harsh desert climate conditions of Ouargla, Algeria, where elevated ambient temperatures represent one of the major factors limiting PV system efficiency and long-term performance. The main objective of this work was to evaluate the effectiveness of passive cooling techniques based on heat sinks, while conducting a comparative investigation between horizontal and vertical heat sink configurations in order to identify the most efficient design for enhancing the thermal and electrical performance of photovoltaic modules.

The literature review revealed that the combination of high solar irradiance and extreme ambient temperatures in desert environments leads to a significant reduction in electrical conversion efficiency and accelerates the degradation rate of PV modules. Previous studies have also demonstrated that passive cooling technologies, particularly heat sinks, constitute one of the most practical and reliable thermal management solutions due to their simplicity, low operational cost, and independence from external energy consumption compared to active cooling systems.

The experimental results obtained in this study confirmed that integrating heat sinks on the rear surface of photovoltaic panels effectively reduced the operating temperature of the modules, which directly improved the electrical power output and the overall system efficiency. Furthermore, the comparative analysis between the two heat sink configurations demonstrated that vertical heat sinks provided superior thermal performance compared to horizontal heat sinks. The vertical arrangement exhibited a greater capability for heat dissipation and enhanced natural ventilation around the PV module, especially during peak thermal conditions. This improvement can be attributed to the ability of the vertical fins to promote natural convective heat transfer and facilitate airflow circulation between the fins, thereby minimizing heat accumulation on the backside of the photovoltaic module.

In addition, the study highlighted the influence of climatic parameters, particularly airflow velocity beneath the photovoltaic panel and solar irradiance intensity, on the effectiveness of the cooling systems. The cooling performance increased with enhanced airflow circulation underneath the module, which provided an additional advantage to the vertical heat sink configuration under the local climatic conditions of Ouargla. This behavior is mainly

associated with the improved air passage and strengthened natural convection mechanism generated by the vertical fin arrangement.

Overall, the findings of this research demonstrate that vertical heat sinks represent an efficient and practical passive thermal management solution for improving the thermal and electrical performance of photovoltaic systems operating in hot and arid regions. Moreover, such cooling strategies contribute to mitigating thermal degradation and extending the operational lifetime of solar modules. The study also emphasizes the importance of integrating passive thermal management approaches into future solar energy development strategies in Algeria, particularly in desert regions characterized by severe climatic conditions.

Future investigations may focus on the development of hybrid cooling systems combining multiple thermal management techniques, the evaluation of advanced materials with higher thermal conductivity for heat sink fabrication, and large-scale experimental assessments under various environmental and operating conditions. Such research directions could contribute to the advancement of more efficient, sustainable, and climate-resilient photovoltaic technologies.

Bibliography

- [1] M. HamidurRahman, "MODELLING THE IMPACT OF TEMPERATURE COEFFICIENTS ON PV SYSTEM PERFORMANCE IN HOT AND HUMID CLIMATES," *International Journal of Scientific Interdisciplinary Research*, 24 December 2022.
- [2] D. Du, "Thermal management systems for Photovoltaics (PV) installations: A critical review," *Centre for Sustainable Energy Technologies, University of Nottingham, Ningbo, China*, 14 September 2013.
- [3] "solar tech," Best Solar Panels for Hot Climates: 2025 Expert Guide, 19 12 2025. [Online]. Available: <https://solartechonline.com/blog/best-solar-panels-hot-climates-guide/>.
- [4] A. Green, "Photovoltaics: technology overview," *Centre for photovoltaic Engineering, University of New South Wales, Sydney, NSW 2052, Australia*, 24 may 2000.
- [5] A. Green, "Photovoltaics: technology overview," *Centre for photovoltaic Engineering, University of New South Wales, Sydney, NSW 2052, Australia*, November 2000.
- [6] E. Becquerel, "Mémoire sur les effets électriques produits sous l'influence des rayons solaires," *Comptes Rendus de l'Académie des Sciences*, 1839.
- [7] W. Smith, ""Effect of Light on Selenium during the passage of an Electric Current," *Nature*, 1873.
- [8] E. Fritts, "On a New Form of Selenium Cell, and of Electromotive Action by Light.," *American Journal of Science*, 1885.
- [9] A. Einstein, ""Über einen die Erzeugung und Verwandlung des Lichtes betreffenden heuristischen Gesichtspunkt," *Annalen der Physik*,, 1905.
- [10] W. Shockley, "Electrons and holes in semiconductors: with applications to transistor electronics". *Van Nostrand Company*..
- [11] F. Chapin, "A New Silicon p-n Junction Photocell for Converting Solar Radiation into Electrical Power," *Journal of Applied Physics*, 1954.
- [12] J. Perlin, "From Space to Earth: The Story of Solar Electricity," *Harvard University Press*, 1999.
- [13] D. Yergin, "the Prize: The Epic Quest for Oil, Money, and Power," *Simon & Schuster* أو أي تقرير رسمي من وكالة الطاقة الدولية حول أزمة), 1991.
- [14] A. Green, ""Photovoltaics: technology overview," *Energy Policy*, 2001.

- [15] I. E. A. (IEA), "Trends in Photovoltaic Applications 2023 IEA-PVPS Report," 2023.
- [16] Y. Halimi, "Spatially-optimized photovoltaic site selection in Algeria: Assessing solar potential using high-resolution data, GIS, and multicriteria analysis," *Energy Conversion and Management*, 1 jan 2025.
- [17] T. Zakaria Bouzid*†, "Overview of Solar Potential, State of the Art and," *INTERNATIONAL JOURNAL of RENEWABLE ENERGY RESEARCH*, vol. 18, p. may, 2015.
- [18] E. Agency, FUTURE OF SOLAR PHOTOVOLTAIC, 2019.
- [19] Gaëtan Masson, "Trends in PV Applications," *international energy agency*, 2025.
- [20] B. Gary Cook, Photovoltaic FUNDAMENTALS.
- [21] ResearchGate. "Different Solar Radiation Components in the Atmosphere." Accessed June 22, 2026. https://www.researchgate.net/figure/Different-solar-radiation-components-in-the-atmosphere-9_fig1_382673638.
- [22] Energy Encyclopedia. "P-N Junction Glossary." Accessed June 22, 2026. <https://www.energyencyclopedia.com/en/glossary/p-n-junction>.
- [23] EcoFlow. "How Do Photovoltaic Cells Work?" EcoFlow Blog. Accessed June 22, 2026. <https://www.ecoflow.com/us/blog/how-do-photovoltaic-cells-work>.
- [24] Sollatek. "Monocrystalline Solar Modules Product Details." Accessed June 22, 2026. <https://www.sollatek.com/products/monocrystalline/>.
- [25] SolarSquare. "Polycrystalline Solar Panels: Types, Efficiency, and Cost." SolarSquare Blog. Accessed June 22, 2026. <https://www.solarsquare.in/blog/poly-crystalline-solar-panels-types/>.
- [26] Sistine Solar. "Thin-Film Solar Panels: Everything You Need to Know." Accessed June 22, 2026. <https://sistinesolar.com/thin-film-solar-panels/>.
- [27] G. Masson, "technology collabration programme," international energy agency photovoltaic systems programme, https://iea-pvps.org/trends_reports/trends-2025/.
- [28] -S. Jehad Adeeb1, "Temperature Effect on Performance of Different Solar Cell," *Journal of Ecological Engineering*, vol. 09, p. april, 2019.
- [29] A. Corrêa, "The temperature influence in the photovoltaic panels," *tecnico lisboa*, march 2021.
- [30] M. Mbumba, "Degradation mechanism and addressing techniques of thermal instability in halide perovskite solar cells," *Solar Energy*, 2021.

- [31] n. AmitSahaya, "Renewable and Sustainable Energy Reviews".*elsevier*.
- [32] a. Arifin, "Numerical and experimental investigation of air cooling for photovoltaic panels using aluminum heat sinks.," *International Journal of Photoenergy*,, 2020.
- [33] Harmailil, " A review on recent photovoltaic module cooling techniques: Types and assessment methods," *Results in Engineering*, p. 22, 2024.
- [34] Y. Rajput, "Comparison of heat sink and water type PV/T collector for polycrystalline photovoltaic panel cooling," *Renewable Energy*, p. 116, 2018.
- [35] N. Ouezzani., "Thermal management of solar PV module to Enhance Power Output Performance," 2025.
- [36] Y. Rajput, " Comparison of heat sink and water type PV/T collector for polycrystalline photovoltaic panel cooling," *Renewable Energy*, 2018.
- [37] S. Kalaiselvan[1], "Solar PV Active and Passive cooling technologies – a Review," *School of Electrical and Electronics Engineering, SASTRA University - Thanjavur.*, p. 167, 2018.
- [38] a. Elminshawy, "Performance of PV panel coupled with geothermal air cooling system subjected to hot climatic," *Applied Thermal Engineering*,, 2019.
- [39] a. Cuce, "Effects of passive cooling on performance of silicon photovoltaic cells.," *International Journal of Low-Carbon Technologies*, pp. 299-308, 2011.
- [40] a. Cuce, "Effects of passive cooling on performance of silicon photovoltaic cells," *International Journal of Low-Carbon Technologies*,, 2011.
- [41] a. ibrahim, "Performance enhancement of photovoltaic modules with passive cooling multidirectional tapered fin heat sinks (MTFHS)," *elsevier*, 2023.
- [42] a. Huzayyin1, "Review of cooling techniques used to enhance the efficiency of photovoltaic power systems," *Environmental Science and Pollution Research*, 2022.
- [43] Sebastian Valeriu Hudis et al, "Enhancement of PV Panel Power Production by Passive Cooling Using Heat Sinks with Perforated Fins," *applied sciences*, 2021.
- [44] O. Hamdan, "Enhancing PV solar panel efficiency through integration with a passive Multi-layered PCMs cooling system: A numerical study," *sciencedirect*, 2024.
- [45] Olusola Bamisile et al, "The environmental factors affecting solar photovoltaic output," *elsevier*, february 2025.
- [46] a. Zineb Chaich, "Experimental analysis of dust’s impact on solar photovoltaic system efficiency in arid environments: a case study in Southern Algeria," *Environmental Science*

and Pollution Research, august 2024.

[50] Alam El Arab. "Map of the Arab World - Map 5." Accessed June 22, 2026.

https://www.alamelarab.com/a-map/map_5.html.

[48] Tutiempo Network. "Climat Ouargla Janvier 2024 (Station: 605800)." Accessed June 22, 2026. <https://fr.tutiempo.net/climat/01-2024/ws-605800.html>.

[49] R. Ghosh, "Global Deployment of Solar Photovoltaics: Its Opportunities and Challenges," *Presented at ISGT*, 2016.

[47] ش. د. .. ب. ا. الخير, "التحميل الجوي و الجغرافي لدرجة الحرارة في الجنوب الشرقي," 2017

[51] Bonkaney, Abdou Latif, Saïdou Madougou, and Rabani Adamou. "Temperature Effect on PV Characteristics (Rekioua) [10]." Figure 3 in "Ambient Temperature and Relative Humidity Impacts on a Photovoltaic Module under Niamey Climatic Conditions." ResearchGate. Accessed June 22, 2026. https://www.researchgate.net/figure/Temperature-effect-on-PV-characteristics-Rekioua-10_fig1_328743854.

ABSTRACT

This study focuses on improving the thermal management of photovoltaic (PV) panels in the hot desert climate of Ouargla, Algeria, where high temperatures significantly reduce electrical efficiency and shorten panel lifespan. A low-cost passive cooling system based on galvanized steel heat sinks mounted on the rear side of the PV panel was investigated using two configurations: vertical and horizontal.

Experimental tests were conducted using two identical polycrystalline PV panels. One panel was equipped with heat sinks, while the other served as an uncooled reference panel. Data were collected over six days in May under different weather conditions.

The results showed that the vertical configuration provided the best thermal performance, reducing panel temperature by 6 – 9.2°C due to the enhanced chimney effect and improved natural airflow. In contrast, the horizontal configuration achieved a temperature reduction of only 1– 4.4°C. Wind speed also contributed to cooling enhancement, particularly when it exceeded 2.5 m/s.

The thermal improvement led to better electrical performance. The vertical configuration increased electrical efficiency by more than 2.2%, whereas the horizontal configuration achieved less than 1.5%. These findings demonstrate that galvanized steel heat sinks offer an effective, economical, and energy-free cooling solution for improving PV performance in desert environments.

Keywords: PV Cooling, Passive Thermal Management, Galvanized Fins, Chimney Effect, Forced Convection, Arid Climate, Ouargla.

ملخص

تركز هذه الدراسة على تحسين الإدارة الحرارية للألواح الكهروضوئية في المناخ الصحراوي الحار لمدينة ورقلة، حيث يؤدي ارتفاع درجة الحرارة إلى انخفاض الكفاءة الكهربائية وتقليص العمر التشغيلي للألواح. تم تقييم نظام تبريد سلبي منخفض التكلفة يعتمد على مشتتات حرارية من الحديد المجلفن مثبتة على الجهة الخلفية للوح بوضعيتين هندسيتين: عمودية وأفقية.

أُجريت التجارب باستخدام لوحين كهروضوئيين متماثلين من نوع Polycrystalline ، أحدهما مزود بالمشتتات الحرارية والآخر استُخدم كمرجع دون تبريد. جُمعت البيانات خلال ستة أيام من شهر ماي تحت ظروف مناخية متنوعة.

أظهرت النتائج أن التثبيت العمودي كان الأكثر فعالية، حيث خُفّض درجة حرارة اللوح بين 6 و 9.2 درجات مئوية بفضل تعزيز تأثير المدخنة وتحسين حركة الهواء الطبيعية. أما التثبيت الأفقي فحقق انخفاضاً حرارياً تراوح بين 1 و 4.4 درجات مئوية فقط. كما ساهمت سرعة الرياح، خاصة عند تجاوز 2.5 م/ث، في تعزيز عملية التبريد.

انعكس هذا التحسن الحراري على الأداء الكهربائي، إذ ارتفعت الكفاءة بأكثر من 2.2% في الوضعية العمودية مقارنة بأقل من 1.5% في الوضعية الأفقية. وتؤكد النتائج أن المشتتات الحرارية المصنوعة من الحديد المجلفن تمثل حلاً فعالاً واقتصادياً لتحسين أداء الألواح الكهروضوئية في المناطق الصحراوية.

الكلمات المفتاحية: تبريد الألواح الكهروضوئية، تبريد سلبي، زعانف مجلفنة، تأثير المدخنة، حمل قسري، مناخ جاف، ورقلة.

RESUME

Cette étude porte sur l'amélioration de la gestion thermique des panneaux photovoltaïques dans le climat désertique chaud de Ouargla, où les températures élevées réduisent considérablement le rendement électrique et la durée de vie des panneaux. Un système de refroidissement passif à faible coût, basé sur des dissipateurs thermiques en acier galvanisé fixés à l'arrière du panneau, a été évalué selon deux configurations : verticale et horizontale.

Les essais expérimentaux ont été réalisés à l'aide de deux panneaux photovoltaïques polycristallins identiques. L'un était équipé de dissipateurs thermiques, tandis que l'autre servait de panneau de référence sans refroidissement. Les mesures ont été effectuées durant six journées du mois de mai sous différentes conditions météorologiques.

Les résultats ont montré que la configuration verticale était la plus performante, avec une réduction de température comprise entre 6 et 9,2 °C grâce à l'effet de cheminée et à une meilleure circulation naturelle de l'air. La configuration horizontale n'a permis qu'une réduction comprise entre 1 et 4,4 °C. La vitesse du vent a également favorisé le refroidissement, notamment au-delà de 2,5 m/s.

Cette amélioration thermique s'est traduite par une augmentation du rendement électrique supérieure à 2,2 % pour la configuration verticale, contre moins de 1,5 % pour la configuration horizontale. Les résultats confirment que les dissipateurs thermiques en acier galvanisé constituent une solution simple, économique et efficace pour améliorer les performances des panneaux photovoltaïques en milieu désertique.

Mots-clés : Refroidissement PV, Gestion Thermique Passive, Ailettes Galvanisées, Effet de Cheminée, Convection Forcée, Climat Aride, Ouargla.