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Theme

**Thermal management of solar PV module to
Enhance Power Output Performance**

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Dedication

To those who have been a guiding light and unwavering support throughout my journey...

To my dear father and loving mother, thank you for every moment of encouragement and every sincere prayer.

*To my brothers, sisters, and all members of my **NOUNE** family who never failed to cheer me on with their kind words and genuine smiles.*

To my dear friends, companions through both joyful and challenging times.

*To my esteemed professors, especially Ms. **Sabrin Korichi** and Mr. **Dida Mustapha**, who stood by my side and were a true source of support and guidance. Their dedication, encouragement, and tireless efforts have left a profound impact on me, and this achievement would not have been possible without their invaluable help.*

To everyone who has left a positive mark on my life,

I dedicate the fruit of my efforts to you, with deep gratitude and appreciation, hoping to always be worthy of your trust.

Noune Haissane



Dedication

To those who have greatly influenced my journey...

*To my dear father and beloved mother,
who have instilled in me values and principles, and have always been my greatest source
of support and encouragement.*

*To my cherished family, OUEZZANI
whose love and reassurance have surrounded me at every stage of my life.*

*To everyone who supported me with a kind word or a sincere prayer,
I dedicate the fruit of my efforts to you as a token of love and gratitude.*

Ouezzani Mohammed Selmane

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General introduction

General introduction

The global shift towards sustainable and clean energy sources has made solar photovoltaic (PV) technology a leading solution, particularly in regions with high solar irradiance such as southern Algeria. The Ouargla region, for instance, receives solar radiation exceeding 2,500 kWh/m²/year, making it an ideal candidate for large-scale solar installations [2].

Despite this potential, PV modules installed in desert environments face serious performance limitations due to high ambient temperatures. Elevated temperatures reduce panel efficiency and accelerate material degradation [3]. In fact, PV efficiency may drop by about 0.5% for every 1 °C above the standard test condition of 25 °C [4], which can lead to up to 25% efficiency loss in desert climates.

Therefore, improving thermal management is essential for enhancing the performance and lifespan of PV modules in hot environments. This study investigates passive cooling techniques—specifically, aluminum heat sinks—aimed at reducing the operating temperature of PV modules and increasing their output efficiency under harsh climatic conditions.

The structure of the thesis is organized as follows:

- **Chapter I** provides the theoretical background on solar photovoltaic energy, including the basic principles of PV conversion, types of solar cells, system components, and factors affecting PV performance such as temperature, radiation, and environmental conditions. Various passive and active cooling strategies are also discussed in detail.
- **Chapter II** offers a comprehensive literature review of recent research in PV thermal management. It focuses on passive, active, and hybrid cooling methods, reviewing experimental results from global studies and analyzing their effectiveness and feasibility in arid regions.
- **Chapter III** describes the experimental methodology. It includes the technical characteristics of the PV panels used, the design and installation of the heat sink, the data acquisition system, and the environmental conditions of the test site in Ouargla.
- **Chapter IV** presents the experimental results and analysis. This chapter compares the performance of cooled and uncooled PV panels over three test days, discussing temperature variation, power output, and overall efficiency gains.

This study aims to provide practical insights and quantitative evidence for improving the thermal regulation of PV modules in desert environments—contributing to more sustainable and efficient renewable energy systems in Algeria and similar regions.

Chapter I: Generalities of Background

I.1 Introduction to Solar Photovoltaic Energy

The energy infrastructure across the world transforms toward sustainability because environmental challenges and natural resource exhaustion alongside air pollution issues persist nationally and globally. The renewable energy sources include wind power, hydroelectricity, biomass, and geothermal, but solar energy emerges as the most abundant accessible renewable source with advanced technological capabilities. Strong adoption of photovoltaic systems has become possible because of performance enhancements and decreasing prices in solar power applications. The hot climate environment of Ouargla, Algeria, causes severe degradation of PV performance that leads to reduced system efficiency together with material deterioration. The thesis operates to resolve performance-limiting challenges by implementing thermal management methods, including passive, active, and hybrid approaches for solar PV devices under hot climates.

I.2 Basic Principles of Solar Energy Conversion

Sunlight transforms through solar energy conversion to obtain two main energy outputs, which include electricity and heat. The two predominant methods are:

- Sunlight transforms through solar energy conversion to obtain two main energy outputs, which include electricity and heat. The two predominant methods are:
- The photovoltaic (PV) conversion method transforms sunlight into electricity through semiconductor materials when using photovoltaic effects. The semiconductor material generates electric current through electron excitation following photon impact.
- Through the solar thermal conversion process, sunlight becomes heat that works both for heating systems and thermodynamic cycles to produce electricity.
- Engines used to convert solar energy operate with efficiency levels that are determined by sunlight strength and incident angle, material behavior, and environmental heat level. Modern advances in materials technology and engineering practice have resulted in improved solar energy systems that are less costly and more energy-efficient.
- Performance optimization of solar systems together with system design optimization becomes essential in areas with high solar potential and changing climatic conditions due to the understanding of these fundamental principles [5].

I.3 Types of Photovoltaic Cells and Their Characteristics

PV cells transform solar energy to electric power using semiconductor materials to function. PV cells receive their categorization through material makeup and technological construction methods

that control both their operational capabilities and pricing structures and possible implementation areas.

I.3.1 Monocrystalline Silicon (Mono-Si)

The formation of monocrystalline PV cells requires silicon material to grow a single continuous crystal structure. These cells demonstrate a high-performance level that extends between 18% to 22% efficiency while maintaining robust functionality under low-light conditions [6].

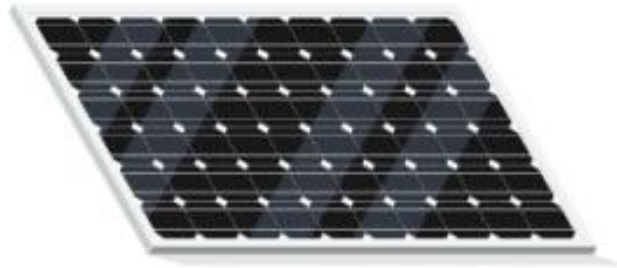


Figure I.1 monocrystalline silicon [7]

I.3.2 Polycrystalline Silicon (Poly-Si)

The silicon crystals of polycrystalline cells join together into several pieces. The production methods for poly-Si cells simplify manufacturing which leads to affordability even though their efficiency rate stands at 15–17%. A distinct characteristic of poly-Si cells is their blue fractured appearance that allows easy visual recognition [8].



Figure I.2 Polycrystalline Silicon [7]

I.3.3 Thin-Film Solar Cells

The production of photovoltaic material through thin-film techniques occurs by placing one or more layers onto glass or plastic or metal substrates. Photovoltaic materials of three major types consist of Cadmium Telluride (CdTe), Copper Indium Gallium Selenide (CIGS) and Amorphous Silicon (a-Si). The cells possess both flexibility and lightness which enables their use in building-integrated photovoltaics (BIPV) systems and portable solar energy devices. These cells provide efficiency rates between 10–13% yet their operational life spans are reduced in comparison to crystalline silicon cells [9].



Figure I.3 Thin-Film Solar Cells [7].

I.4 Key Components of a Photovoltaic (PV) System

The main systems which make up a Photovoltaic (PV) system include key components. The photovoltaic system turns solar energy into electricity by bringing together different essential components that ensure high performance and safety outcomes. The following list demonstrates essential components that a complete PV system usually contains:

I.4.1 Photovoltaic Modules (Solar Panels)

The main power-generating device serves as the basic solar energy converter which uses photovoltaic effect to transform sunlight into direct current electricity. The desired voltage and current output require solar cells from the photovoltaic modules to link in series and parallel configurations. The system output depends directly on module efficiency together with orientation positioning and the tilt angle design [3].

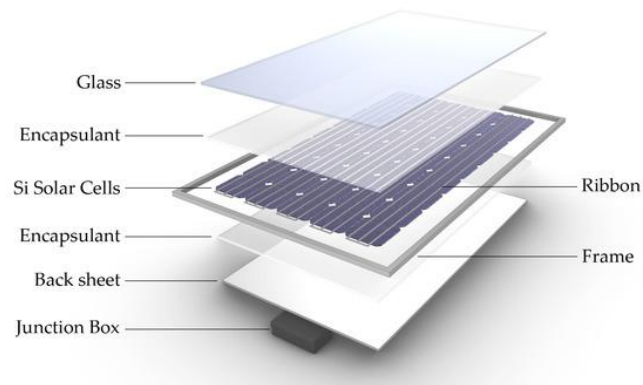


Figure I.4 Photovoltaic Modules Solar Panels [10].

I.4.2 Inverter

The inverter turns the DC electricity created by solar panels into alternate current (AC) power that matches what the power grid and home devices use. The three main types of inverters in solar installations include string inverters, microinverters, and combinations of off-grid and grid-tied systems. These devices supply monitoring features in addition to safety features with functions for grid synchronization[11].



Figure I.5 Inverter [12].

I.4.3 Mounting Structures

They keep the PV modules placed accordingly at different slopes and directions. Sun exposure during the day can be maximized by having sun trackers (single- or dual-axis) or by using fixed systems. When materials can handle the environment, they usually perform well for a longer period [13].



Figure I.6 Mounting Structures [14].

I.4.4 Battery Storage (Optional)

Excess electricity generated during light periods goes into batteries which provide power during times of low sunlight and darkness. The main battery varieties consist of lead-acid batteries and lithium-ion batteries and flow batteries. The dimensional scale of batteries alongside their operational management considerably influences both reliabilities along with system financial aspects.[15]

I.4.5 Charge Controller

A charge controller for battery-based systems protects batteries from both overcharging and deep discharging through precise voltage and current regulation from the solar panels. The device deepens battery power duration and increases safety measures.[16]



Figure I.7 Charge Controller [17].

I.5 Performance Factors Affecting Photovoltaic Energy Systems

The efficiency and performance of photovoltaic systems depend from many conditions, from the outside and from inside the system itself. Main environmental factors are solar irradiance, temperature, shading and soiling. System-related factors also involve quality of PV modules, efficiency of inverter, as well as configuration of system. For example, shading from adjacent

structures can highly decrease the power production; while dust and dirt on the panels (soiling) can decrease the sunlight that reaches the photovoltaic cells, thereby reducing its efficiency. Also the orientation and inclination of the solar panel also affects with getting maximum sunlight and thus solves the performance [18].

I.5.1 Solar Radiation and Its Efficiency

Solar radiation is the base of solar photovoltaic devices the power that can be generated by photovoltaic system is depending on the solar radiation. The efficiency of a PV system depends strongly on the quantity of solar irradiance that it receives. Areas with high solar irradiance levels, for example deserts produce more energy from a PV system compared to areas with low irradiance.

Similarly, the angle of incidence, the angle that sunlight hits the panel, factors in to how much energy is absorbed. Best position and tilt of the panels allow the most sunlight exposure during the day so that we have higher efficiency [19].

I.5.2 Temperature

Temperature is one of the key parameters determining operation of photovoltaic systems. The efficiency of PV cells works well when they are not hot as their efficiency is likely to fall as their temperature increases. This primarily due to decrease in open-circuit voltage (V_{OC}) with escalating temperatures which have more effect than slight increment in short-circuit current (I_{SC}) as a result, leading an overall slice in power generation.

Temperature coefficient is a quantity that describes a change in the efficiency as a function of our temperature. However, for crystalline silicon solar cells, for every degree of increase in temperature above 25°C, the efficiency is in the order of 0.5%. This underscores the need of thermal management in PV system particularly for hot climates.

Cooling techniques such as regional refractive cooling can help counteract the negative outcomes of high temperatures. These methods ensure proper operating temperatures for PV modules – to sustain their efficiency and extend their lifespan [20].

I.6 Effect of High Temperature on Photovoltaic Modules

High temperatures affect the performance and longevity of photovoltaic (PV) modules badly. High temperatures make power plants work less efficiently, age faster, and lose power. Knowledge of these effects is important for the PV system performance optimization, particularly in regions with a high level of ambient temperature.

I.6.1 Temperature Dependence of PV Efficiency

The efficiency of PV modules is a function inversely proportional to the operating temperature. As the temperature rises, open-circuit voltage (V_{OC}) of solar cells below, the short-circuit current (I_{SC}). Although the V_{OC} got reduced, downside, since increase in I_{SC} as well as, totally energy output conductivity drops. This correlation is expressed by the temperature index, which depends on the type of PV technology adopted. For example, crystalline silicon modules have a temperature coefficient around -0.5% per °C. So that as temperature rises above the standard test temperatures (25°C) the modules produce power drops off by a back about 0.5% for every degree Celsius increase in temperature [21].

I.6.2 Thermal Degradation Mechanisms in Solar Cells

Extended exposure to high temperatures can also accelerate several degradation processes within solar cells. Thermal stress can cause initiating micro-cracks in the semiconductor material. These physical changes damage the rigid structure and electrical functions of the PV modules. Also, high temperatures can enhance the chemical chemical reactions that chemical reactions worse the photovoltaic material and contains reduced the mounting material efficiency and misses[22].

I.6.3 Power Output Reduction Due to Elevated Temperatures

Temperature plays a significant role on the performance of photovoltaic systems. PV Cell efficiency efficiency is usually reduced as PV Cell temperature increases. This can be primarily attributed to the drop in open-circuit voltage (V_{OC}) as the temperature increases outshines the slight rise in short-circuit current (I_{SC}) and hence sees an overall fall in the output power.

Temperature coefficient is the quantity that characterizes the change of the efficiency depending on temperature. For crystalline silicon solar cells, the efficiency drops typically by around 0.5% for every degree Celsius above 25°C. This emphasizes the importance in PV systems especially in warm regions of thermal handling.

Cooling methods like passive radiative cooling can help counter the unintended consequences of temperatures above 32°C. These techniques keep appropriate working temperatures of PV modules leading to allow for optimal efficiency and improved lasting affecting the modules [20].

I.7 Cooling solutions for PV systems

Most of operating photovoltaic (PV) systems are deployed in these hot, dry regions where very adverse negative environmental effects, such as high temperatures and intensive UV radiation can

contribute not only to decreases in module performance but also in system efficiencies. In an attempt to overcome this problem, many researchers have come up and engineered a number of cooling techniques to optimize temperature during operation and efficiency in the system. Generally, these are classified into two major categories of cooling methods; passive cooling methods and active cooling methods, as it can be observed in the given table[23]

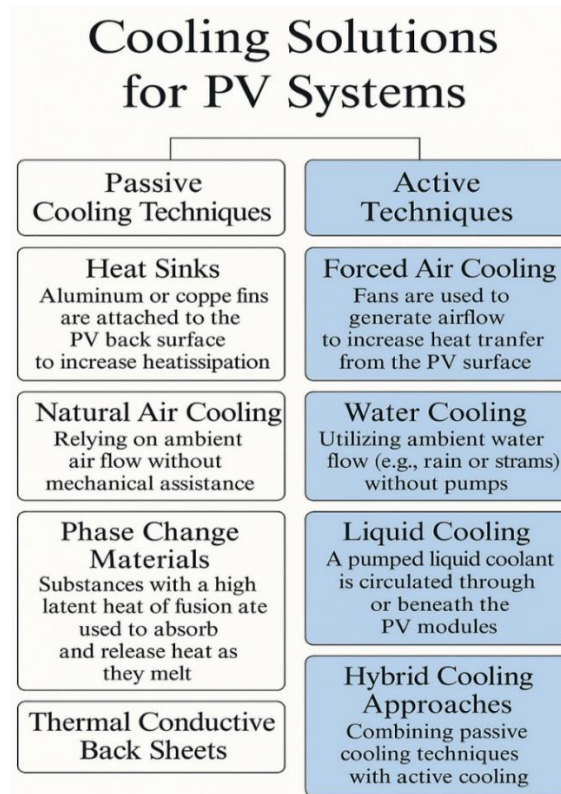


Figure I.8 Thermal management of solar PV modules [23].

Passive cooling is generally less costly and relies on natural heat dissipation processes. They range from natural air to cooling using natural water, heat sink, fins, heat pipes, and heat sink using phase change materials (PCMs). PCMs on the other hand are very effective since during phase transformation, they act as heat sinks absorbing excess heat in the process helping to keep module temperatures as close as possible to optimal temperatures during peak sunlight hours.

Active cooling methods involve input of external energy to promote heat removal, though. These are forced air cooling through fans or blowers, water circulation (systems), water immersion (cooling), and thermoelectric cooling, etc. Although active cooling is generally more efficient in lowering the temperatures of PV modules and delivering more uniform temperature distribution, input of power into active cooling means that less net, electrical output is achieved from the PV system[23].

I.7.1 Passive cooling technique

Passive cooling approaches are widespread for photovoltaic (PV) modules since they are easy to employ, cheap, and do not require energy. These methods do not require any external source of power or mechanical implementation in order to cool PV units by means of natural processes such as convection, conduction, phase change or radiation. In order to keep the operating temperatures lower and improve the electrical efficiency and lifespan of the PV modules, the simple concept is to reject the excess energy generated during conversion of solar energy [24].

I.7.1.1 Heat sinks

A heat sink and PV cooling system were put together to ensure controlled cooling of the thermal system of PV panels. Figure X 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.

Part two of Figure X 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[1].

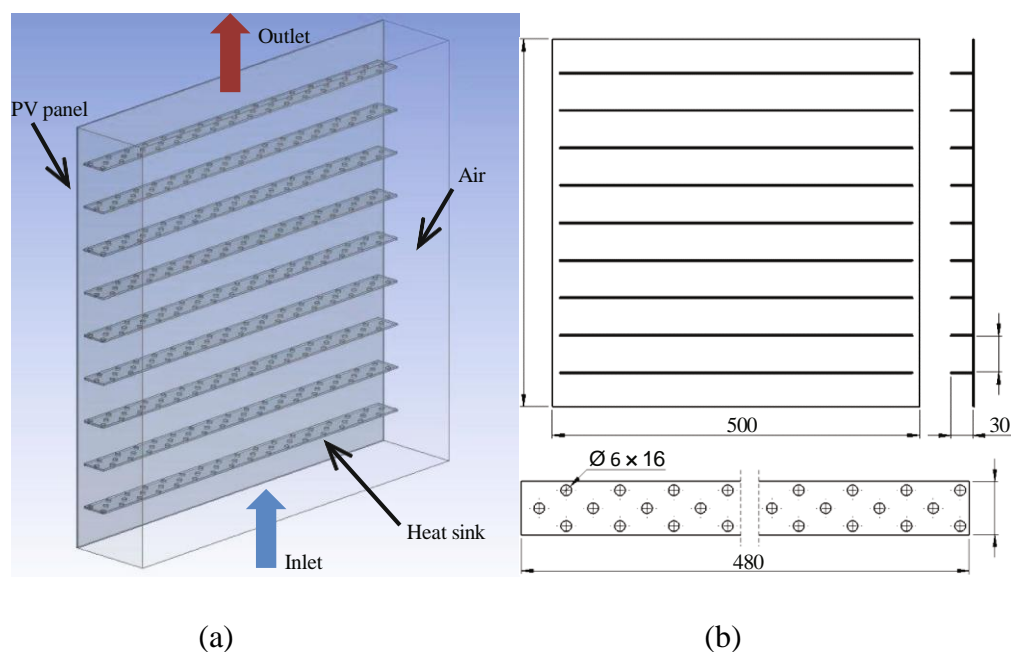


Figure I.9 The (a) proposed geometry and (b) dimensions of a PV panel with aluminum heat sinks[1].

I.7.1.2 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.

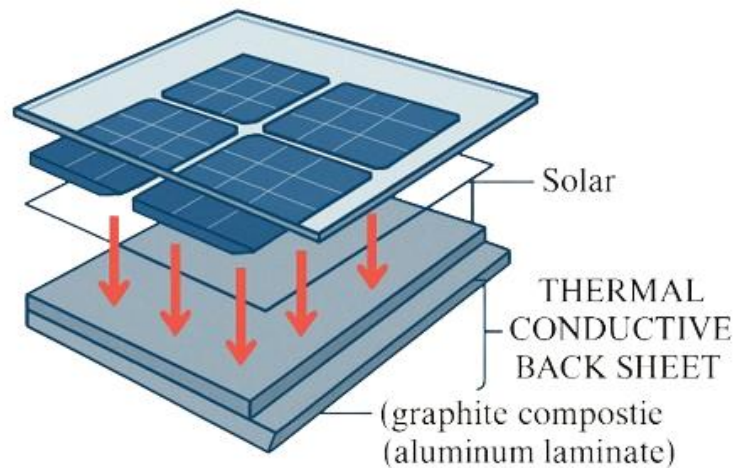


Figure I.10 Photovoltaic Module with a Thermally Conductive Back Sheet

I.7.1.3 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 [25, 26].

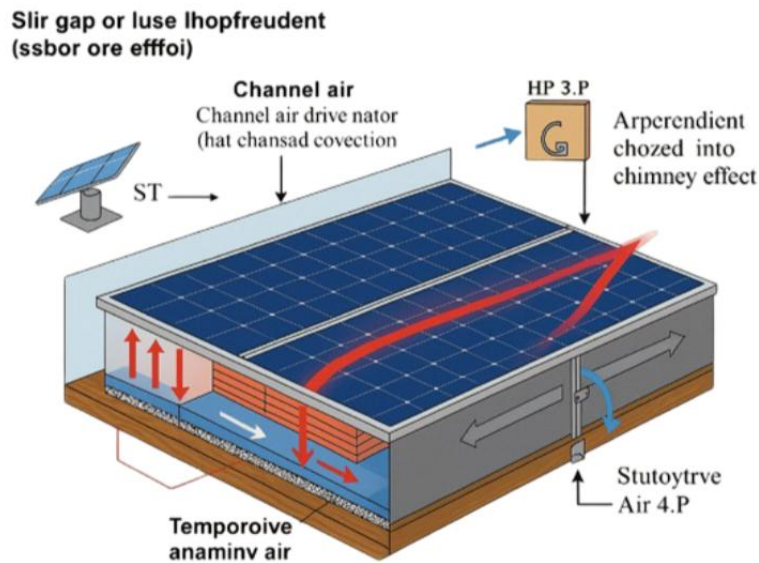


Figure I.11 Natural Air Cooling [26]

I.7.2 Active Cooling Techniques

Active cooling is more complex but it is also more efficient; it is especially relevant in places with high intensity solar radiation or for the high efficiency PV systems. These systems need to receive an external energy supply, in the form of electric, to operate fans, pumps or other cooling methods. Although they entail increased costs of maintenance, they provide substantial modifications in thermal control and energy efficiency.

I.7.2.1 Forced 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[27].

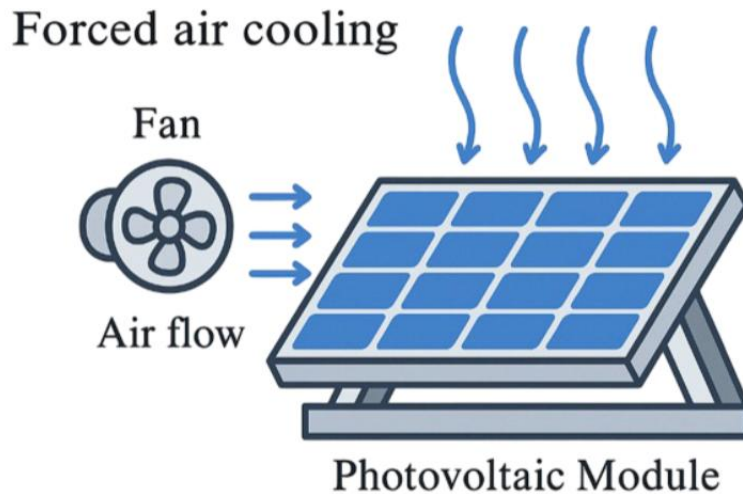


Figure:I.12 Forced Air Cooling for PV Panels [27].

I.7.2.2 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 [27].

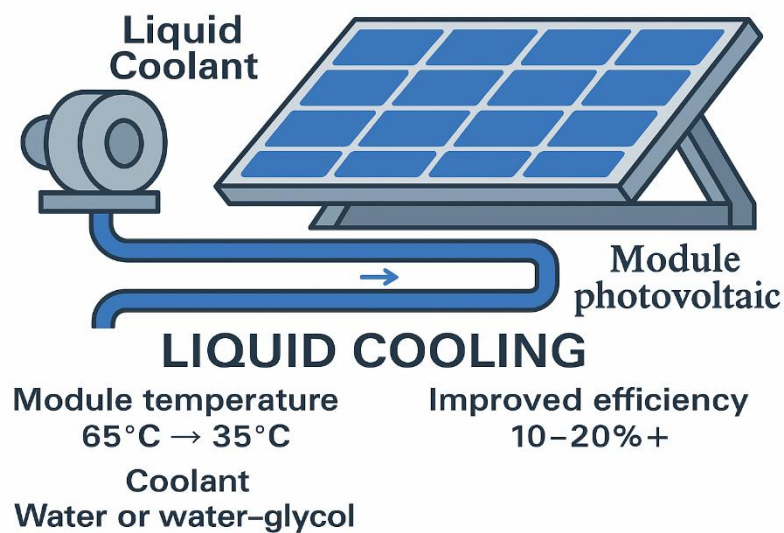


Figure I.13 Liquid Cooling for PV Modules[27].

I.7.2.3 Water cooling

Water cooling is a liquid method of transferring water across or below the surface of photovoltaic (PV) panels to cool them down. This approach can not only improve panel efficiency, but can also be used to harvest thermal energy for other purposes such as heating water. It is energy-dependent as hinges on pumps working for the water to flow. Solutions such as spraying concentrated water occur especially at lower panels, thereby making temperatures reduce further. A range of parameters include flow-rate, spray methodology, and nozzle type influencing system performance. Water cooling can reduce PV module temperature by up to 25 °C, increase power generation by 16.3%, and improve efficiency by 14.1% to 17%) [28].

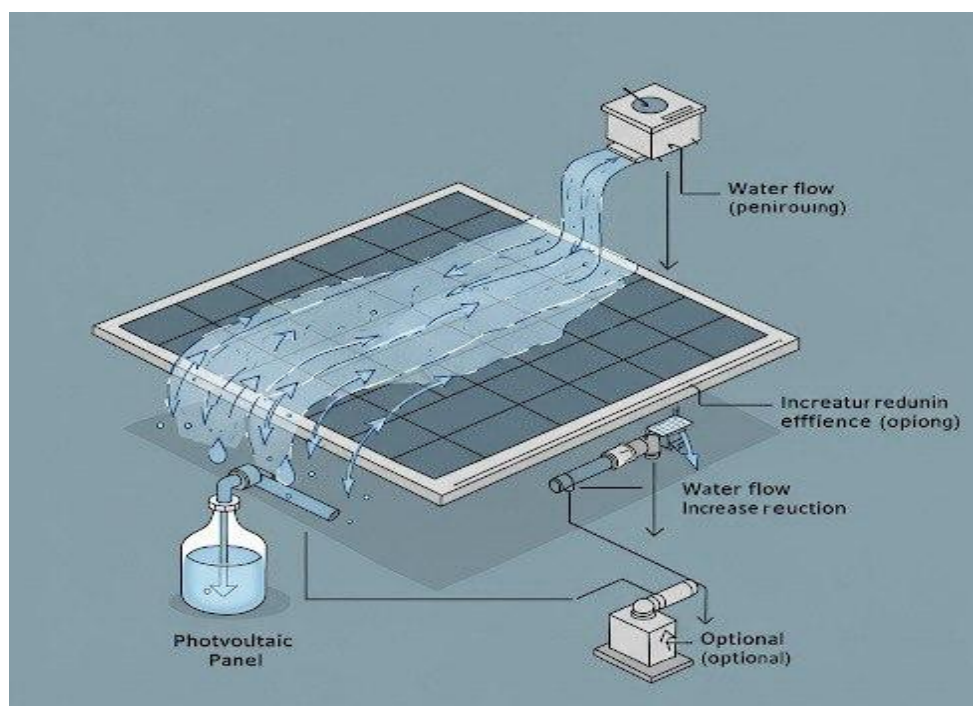


Figure I.14 Water Cooling System for Photovoltaic Panel[28].

I.7.2.4 Phase-change materials (PCMs)

PCMs present considerable opportunities for solar thermal applications while solar storage technology heavily relies on these materials for operation. The main characteristic of most PCMs is their high energy density contrasted against their heat transmission problems. The process needs heat transfer enhancement methods to reduce impacts from the low thermal conductivity when applied in thermal storage. Nanoparticles integrated with basic PCM serve as an effective thermal performance improvement method. The PCM latent heat capacity will decrease when a large portion of nanoparticles interact with the PCM substance .[29] PCMs fall into two groups which include organic and inorganic chemical substances. Hydrocarbon or fatty acid organic PCMs

which include paraffin wax alongside polyethylene glycol represent the most commonly used types in this category. PCR Inorganic substances consist of sodium sulphate and calcium chloride hexa-hydrate along with various other hydrated salts. PCM brings value to multiple situations because of its diverse range of latent heat capacities and melting and solidification temperatures and additional properties[30].

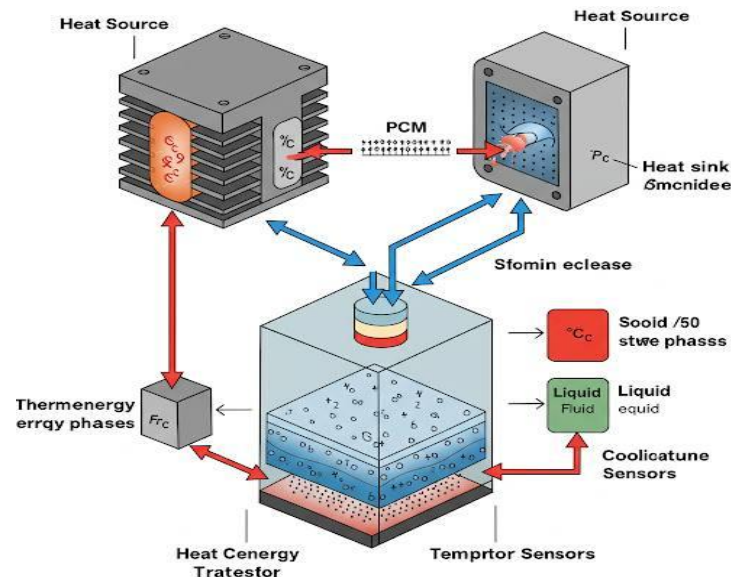


Figure I.15 PCM heat transfer with nanoparticles[30].

I.8 Progress and future tendencies in PV Technologies of cooling unit

Some recent PV panel studies are focusing on new cooling systems that can reduce temperatures and extend the furniture.

Usually, coolers use convection and liquid to remove heat from the CPU. In the recent past, PCM, together with forced-air cooling, thermoelectric, and PV/T technologies. They focus on improving the method of heat transfer on the panels and ensure that the temperatures stay under control when exposed to intense sunlight.

The best way to do this is to place PCM behind the solar panels and have fans direct air or water flow to help cool the entire PV panel while it radiates heat in the sun. Closely studying the use of PV and storage has confirmed that they together reduce high temperatures, make electricity generation more efficient, and can extend the use of solar panels.

Researchers are now aiming to develop systems that do not use much money or an excessive amount of resources and keep cooling better than today's systems. Special substances known as

hydrogels have been formulated by scientists to decrease the temperature of the panels and improve the way the energy from the sun is received.

Increasing the cooling abilities of PV panels leads to more reliance on solar energy, pushes for change in the clean energy sector, and cuts both costs and pollution, helping to reduce climate change[31].

I.8.1 Emerging materials for improved dissipation of heat.

Choosing certain innovative materials can help improve heat removal from PV systems.

Graphene and Graphene Derivatives: Due to its high in-plane thermal conductivity (3000–5000 W/m·K), graphene can remove a lot of heat. Graphene can be found in thermal interface materials, phase change materials, filters, and nanofluids. They have improved efficiency levels (by up to 12%) and helped reduce temperatures in PV panels by almost 36%.

Hydrated salts and paraffin waxes, which are phase change materials (PCM), help keep the PV panels stable by absorbing heat when they change forms. When graphene or other additives are included in PCMs, they conduct heat better (an increase of up to 157%) and give better temperature distribution, which leads to stronger and safer power connections.

Using innovative materials, hydrogels have managed to cool solar cells by up to 23°C and are much lighter and take up less space than other cooling methods. Consequently, it helps make generators more energy-efficient and saves on materials for production[32].

I.8.2 Integration of Cooling Systems with Bifacial and Concentrated PV

Solar photovoltaic (PV) systems, particularly bifacial and concentrated PV (CPV) units, face efficiency losses and material degradation due to high operating temperatures. Integrating effective cooling systems is essential to enhance their performance and durability.

For bifacial PV panels, which capture sunlight on both sides and boost energy yield by 5–30%, thermal management is crucial as they tend to run hotter due to increased irradiance. Cooling strategies include:

- Passive cooling using reflective or cool roof coatings to reduce heat buildup,
- Active cooling through airflow and forced convection,
- Hybrid cooling combining phase change materials (PCM) with airflow to stabilize temperatures.

These methods can reduce panel temperatures by 1–5°C, improving efficiency by 2–5%, increasing power output, and extending lifespan by reducing thermal stress.

For concentrated PV systems, which focus intense sunlight onto small cells causing significant heat, advanced cooling is vital. Techniques include:

- Liquid cooling with microchannel heat sinks and nanofluids,
- Pulsating flow cooling to enhance heat transfer via increased turbulence,
- PCM for thermal energy storage,
- Infrared optical filters to block heat-inducing radiation.

These cooling solutions maintain cell temperatures within safe limits, preserving over 90% of peak efficiency, improving reliability, and reducing maintenance. Pulsating flow cooling, in particular, can boost heat transfer rates by 15–30% compared to conventional methods.

Overall, integrating these cooling systems significantly improves the thermal management of bifacial and CPV technologies, leading to better performance and longer operational life[33, 34].

I.9 Current Situation of Photovoltaic Technology in the World

Photovoltaic (PV) technology has become a leading driver in the global shift to renewable energy and has significantly improved in recent years. The fast-development and technological progress in pv, a details survey noted that a lot more vital position in the sustainable power generation.

The global PV Market Has Witnessed a Steady Rise Supported by Decreasing Costs, Increasing Efficiency and Favorable Policies. Innovations in technology, such as perovskite-silicon tandem cells, have achieved efficiencies of over 28%, making solar so much more viable for many things. In addition, the falling prices of PV modules have also made the solar energy more affordable and competitive with other traditional energy sources.

For the future, the International Renewable Energy Agency (IRENA) forecasts that solar PV will be critical in the switch to a globally clean energy system. By 2030, renewables are predicted to comprise nearly half of all electricity generated, mostly through PV systems. Yet, problems persist in grid integration, energy storage and in maintaining the supply chain stability for raw materials and components[35].

I.10 Photovoltaic Technology in Algeria

Worldwide statistics place Algeria among regions which receive substantial yearly amounts of solar radiation. Near all areas of Algerian territory experience extended daily insolation of over

2000 hours throughout the year that reaches up to 3900 hours specifically in highland and Saharan regions. A horizontal surface measuring 1 square meter gathers approximately 5 kilowatt hours per day across the nation's principal regions from solar energy.

The Northern portion receives approximately 1700 kWh/m²/year of solar energy yet the Southern part obtains 2263 kWh/m²/year[36, 37].

I.10.1 Solar Resources in Algeria

Algeria features among some of the highest solar energy rich regions worldwide, especially in the south of the country. The country's numerous desert regions are the recipients of huge solar irradiance values; hence they are privileged for solar energy. As per analysis of assessment of solar potential on basis of high-resolution data and GIS, Algeria has witnessed around 460 MW of cumulative solar power capacity till 2022 hence Algeria has seen rapid investment in solar energy infrastructure[38].

I.10.2 State of Photovoltaic Technology in Algeria

As of September 2024, Algeria had 436,8 MW of photovoltaic (PV) power, 388,95 MW (82.4%) of which were connected to the grid and 47,85 MW (10,1%) of which ran off-grid. Solar power is the leading source of renewable electricity in the country. Recent massive tenders are expected to take the national PV capacity above 4 GW in the coming years[39].

In addition, domestic solar module assembly capacity is also expanding. Algeria had an assembly capacity of 500 MW for solar cells by the end of November 2024 and is expected to reach 600 MW to 700 MW by year-end 2025[40].

I.10.3 Future Development and Policy

Algeria has made ambitious plans to integrate into the renewable energy mix. To achieve the goal of adding 15 GW of renewable energy by 2035, 15 GW for the fixed domestic power consumption and 10 GW capacity for trade under specified circumstances. It is expected that about 30-40% of electricity generated for household consumption would be coming from solar energy by 2035.

In order to fasten the use of solar energy, Algeria has started implementing the Solar 1000 MW Project (2023-2027) in which photovoltaic (PV) farms must be set up in different places, particularly where the sun shines brightest like Ghardaia. The programme is expected to bring in foreign and domestic investments, generate new employment opportunities and increase the percentage of solar energy feeding into national grid[41].

I.11 Conclusion

Excessive heat appears as a crucial problem in solar photovoltaic technology since it decreases performance efficiency while simultaneously hastening material degradation. The chapter delivered an extensive introduction to PV technology along with its composition and operational characteristics and many heat dissipation solutions. The combination of passive, active and hybrid cooling methods enables efficient temperature loss reduction needed for achieving optimal energy production.

Chapter II: Literature Review

II.1 Introduction

Thermal management of photovoltaic (PV) systems has emerged as a critical research focus, especially in high-irradiance regions such as Ouargla, Algeria, where excessive heat poses a serious challenge. Elevated temperatures negatively impact both the efficiency and the operational lifespan of PV modules, highlighting the need for effective cooling solutions.

Recent studies have been dedicated to investigating a range of cooling strategies passive, active, and hybrid in order to mitigate these thermal effects and enhance the overall performance of PV systems. This chapter presents a comprehensive review of thermal management strategies for photovoltaic (PV) systems, synthesizing a broad range of experimental and theoretical studies. It explores the underlying principles, implementation methods, and performance outcomes of various cooling techniques, with a focus on recent advancements in passive, active, and hybrid systems. The chapter also identifies existing research gaps and highlights the need for further investigation to optimize PV performance in hot climates. This review establishes the foundation for the subsequent analysis aimed at enhancing PV efficiency and ensuring stable, sustainable electricity generation under high-temperature conditions.

II.2 Environmental Factors Affecting PV Performance

Several environmental factors influence the electrical characteristics and overall efficiency of photovoltaic (PV) modules. Key factors include solar irradiation, shading, dust deposition, and temperature, each impacting the electrical output and durability of PV systems.

II.2.1 Solar Irradiation

Solar irradiation is the amount of solar energy received per unit area and consists of direct, diffuse, and reflected radiation. PV panels convert this solar energy into electrical power via the photovoltaic effect. PV modules reach peak power output and maximum efficiency under Standard Test Conditions (STC), which are defined as 1000 W/m² irradiance, 25 °C ambient temperature, and 1.5 m/s wind speed. However, real-world conditions vary, causing fluctuations in irradiance due to environmental and climatic changes throughout the day, which directly affect PV performance and efficiency.

The electrical output, particularly the short-circuit current (I_{sc}) and open-circuit voltage (V_{oc}), responds differently to irradiance changes. Lower irradiance reduces power output, while higher irradiance increases current and power generated. The conversion efficiency generally declines when solar irradiation falls below 1000 W/m², with the extent depending on the PV cell technology used.

Thus, solar irradiance intensity has a direct and significant correlation with the electrical current and power produced by PV modules[42, 43].

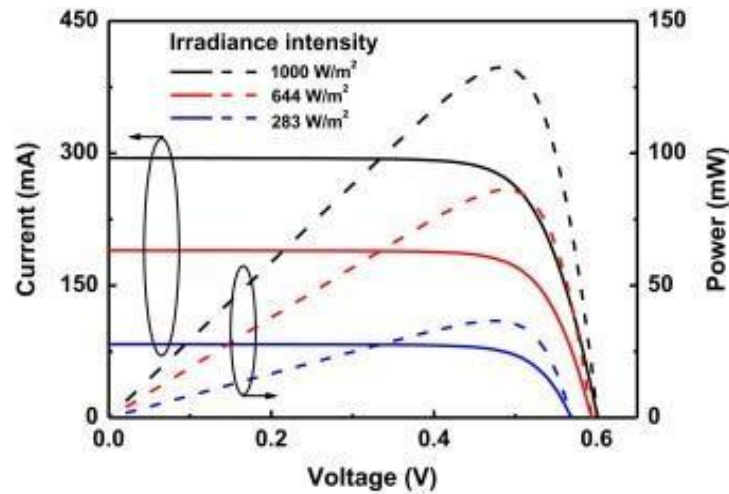


Figure II.1(I–V) and (P–V) characteristics of PV cell at 25°C under various irradiance intensities[44].

II.2.2 Shading Effects

Shading, whether partial or complete, can severely reduce PV power generation. Causes include static obstacles (buildings, trees), dynamic elements (moving clouds), or temporary obstructions (birds). Since PV output is proportional to solar irradiance, shading reduces performance. In series-connected PV arrays, the overall current is limited by the cell with the lowest current, so even a single shaded cell can drastically reduce the entire module's output.

Partial shading can also cause hot spots due to the reverse bias of shaded cells, which dissipate power as heat, potentially damaging the module. To mitigate this, bypass diodes are incorporated to divert current around shaded cells, preventing damage and reducing energy losses. This feature is especially important in series-connected arrays, where shaded modules limit total current. Bypass diodes help maintain system performance by allowing current to bypass shaded modules[45].

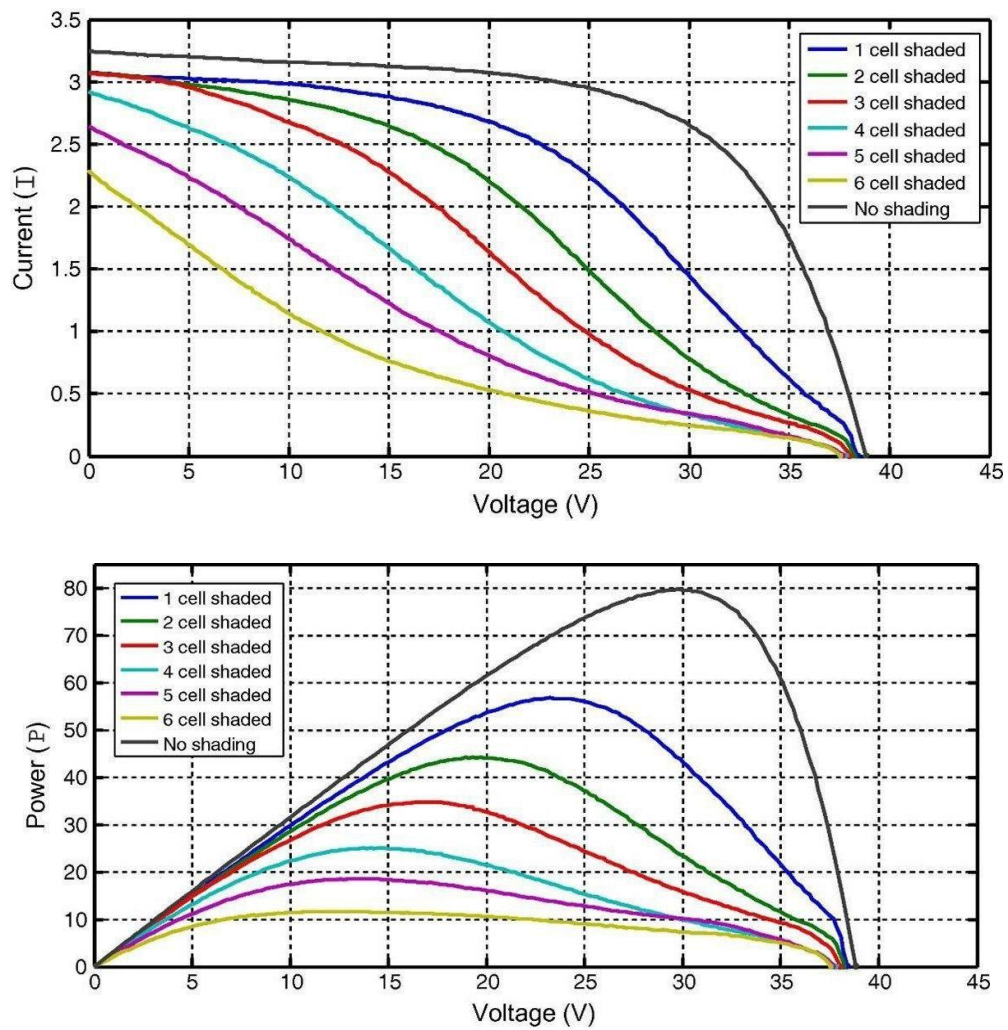


Figure II.2 I-V and P-V curves of tested PV module under partial shading [46].

II.2.3 Dust deposition

Dust accumulation on PV surfaces, particularly in arid and desert environments, reduces the transmissivity of the glass cover, limiting solar irradiation reaching the cells. This leads to a decrease in power output and overall system efficiency. Dust deposition is a significant environmental factor that must be managed to maintain optimal PV performance[47, 48].

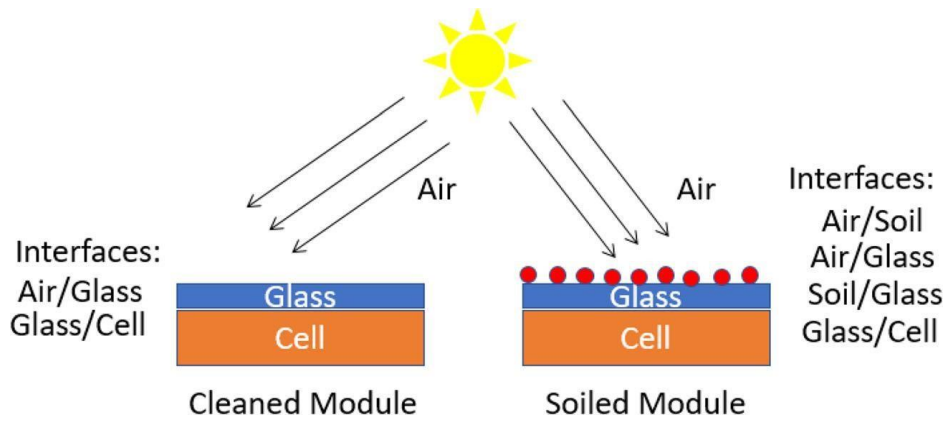


Figure II.3 Effect of dust deposition[47].

II.2.4 Temperature Effect

PV modules convert only about 5–25% of incident solar energy into electrical power; the remainder primarily converts into heat, raising module temperature. Increased temperature negatively impacts PV electrical performance:

- As temperature rises above STC (25 °C), conversion efficiency decreases due to semiconductor properties. For crystalline silicon modules, efficiency drops approximately 0.4–0.5% per 1 °C increase.
- Voltage output decreases with rising temperature, while current slightly increases, but the net effect is a reduction in maximum power output.
- In hot climates, module temperatures can reach 75 °C or higher, causing efficiency reductions up to 25%[49].

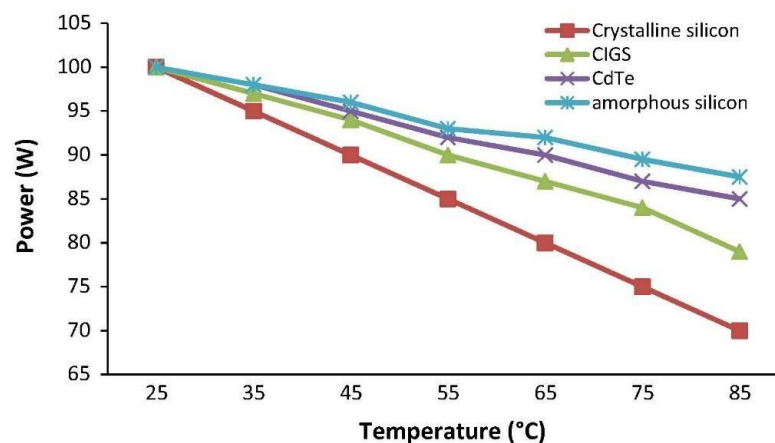


Figure II.4 Temperature effect on various PV cell technologies[49].

II.2.4.1 Failure types

Sustained high temperatures cause irreversible damage to PV modules, reducing lifespan and performance. Common failure modes include:

- Delamination and loss of backsheet adhesion
- Cell cracking and solder bond deterioration
- Busbar corrosion and interconnect ribbon disconnection

Thermal stress combined with UV exposure accelerates ageing and optical degradation, such as encapsulant discolouration and glass breakage. Long-term field studies report annual

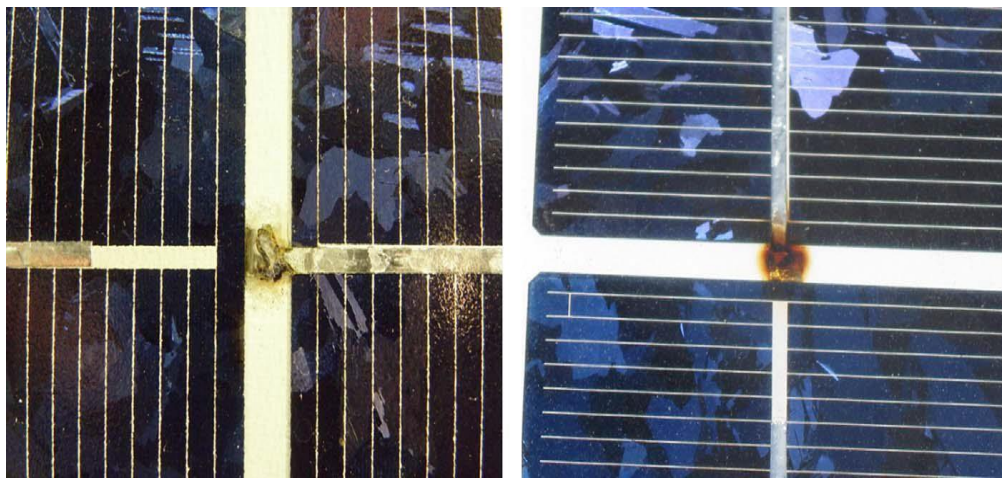


Figure II.5 Degraded soldering and/or broken interconnecting ribbons[50].

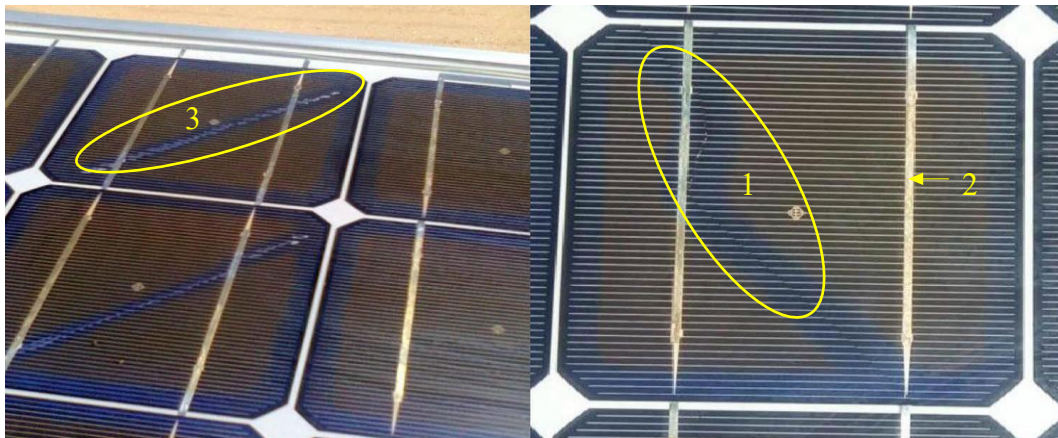


Figure II.6 (1) cracking of solar cells, (2) busbar corrosion and (3) delamination at the diagonal of PV cells[51].

II.3 Cooling techniques

Operating photovoltaic (PV) systems are often located in arid and desert regions, where high temperatures and intense UV radiation are prevalent. These environmental factors significantly degrade PV module efficiency and reduce system reliability. To mitigate these effects, numerous cooling techniques have been developed to lower the operating temperature of PV modules and improve their electrical efficiency. Cooling methods for PV modules are generally categorized into two types: active and passive techniques.

Passive cooling systems, which do not require external power sources, rely on natural processes to dissipate heat. These systems include the use of Phase Change Materials (PCMs), heat pipes, natural air ventilation, heat fins, and natural water evaporation. On the other hand, active cooling systems require external power sources and include mechanisms such as pumps and fans. These systems often involve forced air ventilation, water spraying on both the front and back surfaces of the PV panels, and forced water circulation to reduce module temperatures [52, 53].

II.3.1 Passive cooling techniques

The most cost-effective cooling method that enhances PV module efficiency without the use of mechanical components is passive cooling. These systems operate without external energy sources, relying instead on natural heat dissipation through conduction, convection, and radiation. This paper explores various passive cooling solutions employed for the thermal management of PV modules, including evaporative cooling, heat pipe cooling, water cooling, phase change material (PCM) cooling, and natural air cooling.

II.3.1.1 Water cooling

Water is the second most commonly used coolant for removing excess heat from PV panels, and it has been shown to produce effective cooling results. This cooling method consistently enhances the electrical efficiency of PV modules, regardless of the cooling system size or water temperature. Water-based cooling works by utilizing various techniques, including free convection, water spray, heat pipes, and immersion methods. These methods help to lower the temperature of PV panels by spraying or circulating water across their surfaces. **Figure II.7** illustrates a schematic of a water-cooling system. The heat absorbed from the PV panels can be utilized in several ways, with one of the simplest applications being the use of the heated water for domestic hot water preparation.

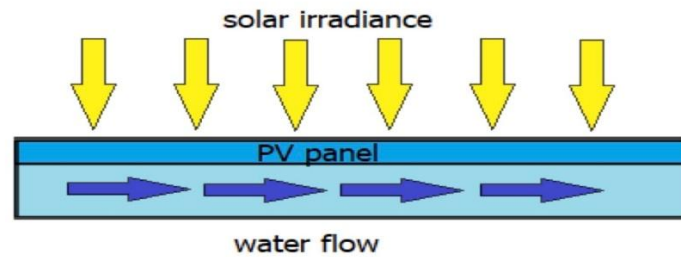


Figure II.7 water – flow cooling method [54].

A water-spraying cooling method for PV panels was proposed by Yang et al. In this system, water is sprayed onto the back of the PV panel, where it then flows back into a tank for recycling. To enhance the cooling capacity, a U-shaped borehole heat exchanger (UBHE) is installed in an existing well, utilizing shallow geothermal energy to facilitate heat exchange. After the water is sprayed onto the panel and absorbs heat, it is returned to the system and cooled using the shallow geothermal energy via the UBHE, maintaining the system's cooling capacity. Experimental results indicate that this approach leads to an increase in efficiency of 14.3%. The schematic of the described solution is shown in **Figure II.8**[54].

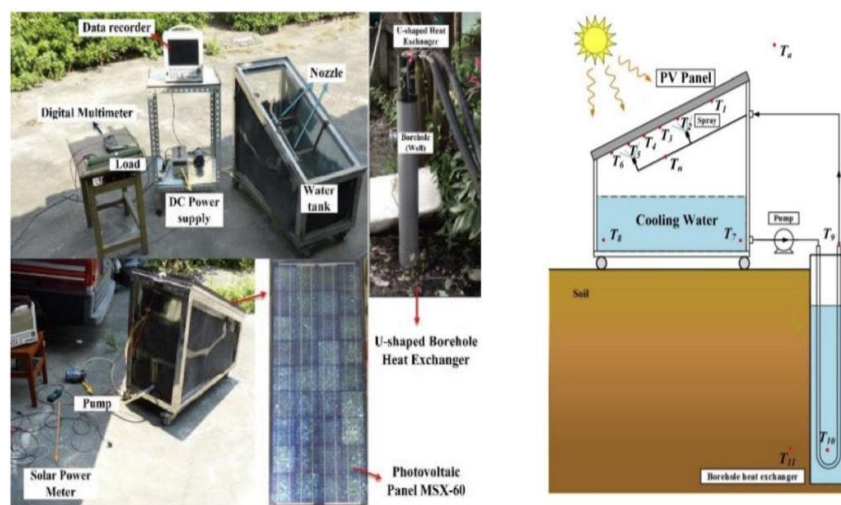


Figure II.8 Photographic and schematic view of the experimental stand[54].

Wu and Xiong proposed a passive cooling method that uses rainwater delivered through a gas expansion mechanism[54]. The amount of solar energy reaching the cooling system determines the volume of water that flows through it. This radiation causes an increase in the gas volume within the expansion device. As a result of this mechanism, the electrical efficiency of the PV panels increased by 8.3%.

Disadvantages of this study

Scientists have explored water-based cooling methods as a means to lower PV panel operating temperatures while improving efficiency. However, these approaches face several operational challenges:

- **Continuous Water Supply:** Techniques such as water spraying and water flow require a consistent water supply, which may not be feasible in arid regions or areas facing water scarcity.
- **Installation Complexity:** The use of water-cooling methods adds significant complexity to PV system installations, particularly due to components like gas expansion devices and U-shaped borehole heat exchangers (UBHE). The intricate system structure demands more maintenance and may lead to equipment malfunctions.
- **Environmental Impact:** The environmental consequences of water-based cooling systems need to be carefully considered, especially in regions with limited water resources. Professionals must assess how water runoff could potentially affect the local ecosystem.
- **Cost Considerations:** The high setup and maintenance costs of integrated water-cooling systems may make them financially unviable for certain installations, reducing their overall feasibility [55]

II.3.1.2 Heat pipe

Anderson et al. [56] demonstrated an effective method for evacuating heat from a concentrating photovoltaic (CPV) cell using a copper/water heat pipe integrated with aluminum components. A CFD analysis was also conducted to determine the optimal fin size and spacing. Experiments were carried out in an experimental test setting with a heat flux of 40 W/cm². The results showed that the heat rejected by the heat pipe led to a 40°C increase in the overall temperature from the cells to the surrounding air.

Gang and associates [57] experimentally investigated a heat pipe photovoltaic/thermal system (HP-PV/T) and developed a dynamic model to predict its performance. The experiments, conducted in May using four collectors with a total PV cell area of 2.91 m², showed that the mean water temperature in the storage tank increased from 28.1°C to 44.2°C. The average heat output per unit surface area was 276.9 W/m², while the average electrical power generated per unit PV area was 62.3 W/m². The thermal and electrical efficiencies were calculated to be 41.9% and 9.4%, respectively.

Moradgholi et al. [58] incorporated a heat pipe into a PV/T system to lower the solar panel's temperature and enhance electricity production. Tests were conducted in both spring and summer. The results showed that the thermal efficiency of the PV/T system increased by 16.35% in spring, and its electrical power increased by 5.67% on average. During summer, the system achieved a thermal efficiency of 45.14%, producing 7.7% more electricity. The panel's temperature dropped by 15°C, resulting in an increase in electricity generation by 1.1 W in spring and 1.26 W in summer.

Du et al. [59] introduced an innovative hybrid photovoltaic/thermal management system to mitigate the efficiency losses caused by rising solar panel temperatures. The thermal management system utilized a heat pipe plate consisting of micro-grooved channels and compressed metal foams coated with nanotechnology, as illustrated in **Figure II.9**.

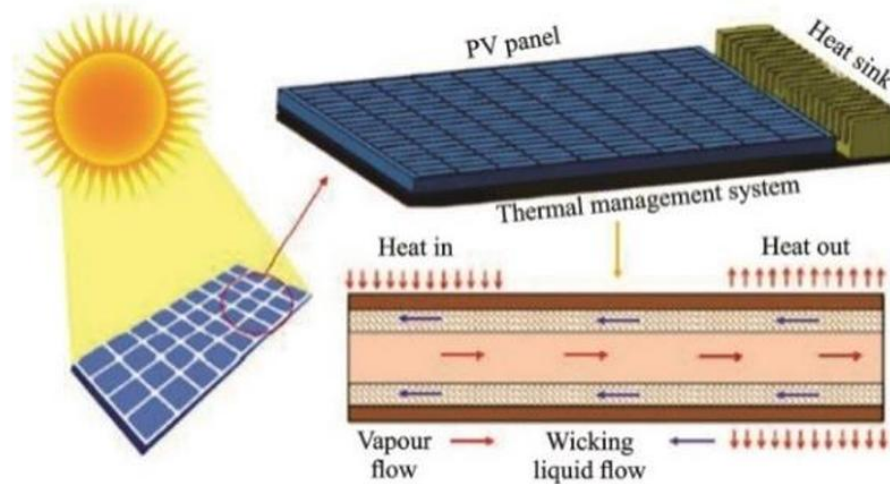


Figure II.9 Representation of the hybrid PV/T system using heat pipe[59].

The studies were conducted under ambient temperatures of 25°C, wind speeds ranging from 0 to 1 m/s, and radiation intensities between 300 and 1000 W/m². As shown in **Figure II.10** the maximum evaporative heat flux is approximately 450 W/m², which helps maintain the solar cell temperature below 40°C, resulting in a temperature reduction of more than 22°C. An experimental investigation by Koundniya et al. [60] focused on the role of a finned heat pipe in cooling a solar PV panel. A copper-water heat pipe was used to remove heat from the panel, and aluminum fins were attached to the heat pipe to enhance heat removal through natural convection.

Experimental results showed that the panel's maximum temperature rose to 73.2°C in the absence of the finned heat pipe, whereas it decreased to 58.2°C when the finned heat pipe was utilized, indicating a total temperature reduction of 13.8°C.

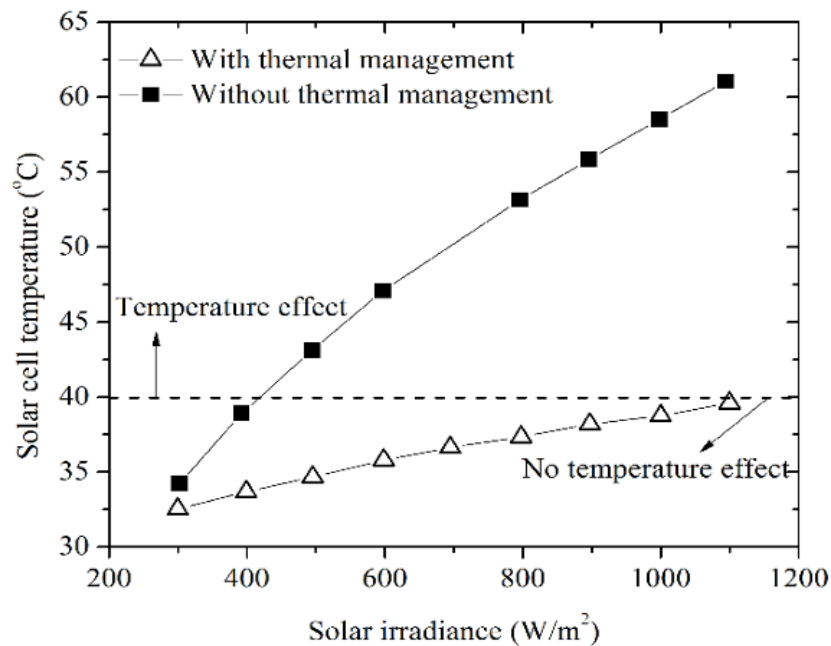


Figure II.10 Effect of heat pipe cooling on solar cell temperature[59].

Disadvantages of this study

This research highlights heat pipe technology as an effective cooling strategy to enhance the efficiency of photovoltaic (PV) panels through thermal management. However, several challenges and limitations have been identified when integrating this technology into PV systems:

Design complexity and cost: Heat pipe systems require precise design specifications, including the optimal selection of fin dimensions, spacing, and material properties. While these enhancements can improve efficiency, they may also increase manufacturing and installation costs due to the system's technical complexity.

Environmental sensitivity: The performance of heat pipe cooling systems is significantly influenced by fluctuating environmental conditions such as solar radiation and ambient temperature. Ensuring stable performance across various climates necessitates further research and adaptable system designs.

Integration challenges: Incorporating heat pipe systems into existing PV modules requires careful consideration of thermal interface quality and structural compatibility. Improper integration may result in installation difficulties and compromise overall system reliability.

Maintenance requirements: Heat pipes may require periodic maintenance due to potential issues such as working fluid leakage or degradation in thermal performance over time. For widespread adoption, these systems must demonstrate long-term reliability and minimal maintenance needs [61].

II.3.2 Active cooling method

Active cooling refers to methods that enhance heat transfer by utilizing external devices. For controlling the temperature of PV panels, active cooling techniques rely on forced air or water flow. When water is used as the working fluid, a pump is employed; if air is the working fluid, a fan is used. These external devices increase the rate of fluid flow, which in turn raises the convection heat transfer coefficient, resulting in higher heat transfer rates. While active cooling systems are generally more cost-effective than passive cooling methods, they do consume more electricity. However, they offer superior thermal and electrical efficiency.

II.3.2.1 Forced water cooling

Active cooling of photovoltaic panels with liquids is more efficient method than air cooling allowing satisfactory results to be achieved. In research, water cooling is often combined with microchannels. The active water-based cooling technique uses forced water circulation through channels or tubes in the back of the PV panel.

Odeh et al. [62] conducted an experimental investigation to evaluate the impact of water cooling on the power output of PV panels used for irrigation purposes. They designed and constructed an outdoor test facility that included a multi-crystalline PV module, a submersible pump, a water surge tank, and a water trickling tube **Figure II.11** The water trickling tube, with a 2.5 cm diameter and 32 holes, was mounted at the upper edge of the module to ensure continuous water flow. During the experiment, a constant flow rate of 4 l/min was maintained over the surface of the PV module.

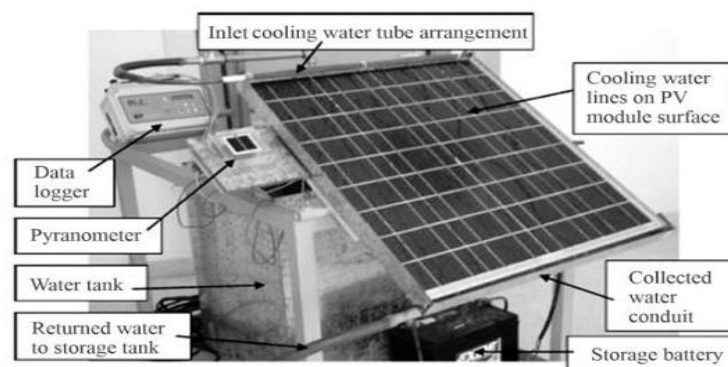


Figure II.11 PV water cooling test rig[62].

Rahimi et al. investigated water cooling using two types of microchannels: single-headed and multi-headed. Water at varying flow rates was passed through the channels. The analysis revealed that multi-headed microchannels produced a higher amount of heat, resulting in a greater decrease in average temperature and an increase in power compared to the single-headed microchannels. The results indicated a 28% increase in power and a 6.8% decrease in temperature for the multi-head microchannels [63].

Barrau et al.[64] explored a solution for a device that combines the effects of a fracture jet and the uneven distribution of microchannels. In the jet impingement zone, heat is absorbed by the fluid only from the bottom of the heat sink. The observed increase in temperature is attributed to boundary layer separation. The heat exchange area, through which the liquid absorbs heat, expands along the flow direction, combining the microchannel surface with the heat sink's bottom surface area. Within these microchannels, the heat flux at the bottom of the heat sink decreases gradually due to the reduction in this surface area and the increase in coolant temperature, leading to a decrease in heat transfer across each microchannel section. The net power of the proposed solution was evaluated, showing a minimum thermal resistance coefficient of $2.18 \cdot 10^{-5}$ (Km²)/W, compared to the previous literature limit of 10^{-4} (Km²)/W. Achieving this lower value resulted in a higher output power yield than with microchannels alone. The design of the device allows for the adjustment of local heat dissipation distribution by modifying the internal geometry during the design phase. **Figure II.12** presents the cooling system model described above.

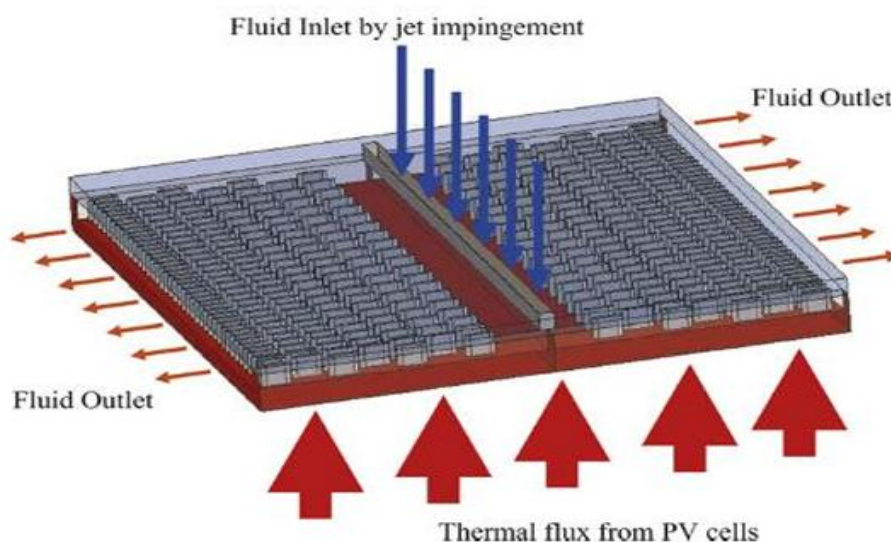


Figure II.12 Model of microchannels for cooling PV[64].

Baloch et al. [65]. presented the use of a converging heat exchanger to reduce the surface temperature of photovoltaic panels. The study compared two scenarios: one with cooling and one without. The results showed that the uncooled cells reached temperatures as high as 71.2°C during summer, while the temperature was successfully reduced to 48.3°C with the cooling system in place. This cooling solution led to a slight increase in power output, from 35.5% to 36.1%. The solution is illustrated in **Figure II.13**.



Figure II.13 Cooling system with convergent heat exchanger[66].

Irwan et al.[67] studied the water cooling of photovoltaic panels by comparing the performance of panels cooled with water flow on the front surface. The experiment, conducted under laboratory conditions, involved spraying water onto the front face of the panels using a water pump. The results showed that the cooling system reduced the panel temperature by 5 to 23°C, leading to an increase in electrical power output from 9% to 22%.

Disadvantages of this study

- The deployment of water-based cooling systems for photovoltaic panels can result in significant water usage. For instance, a single PV panel requires 15.6 liters of water per day for cooling, and the water temperatures exceed 45°C. In regions with limited water resources, the long-term sustainability of such systems becomes questionable, especially in arid areas.
- The complexity of PV installations increases with the integration of microchannel cooling devices. These systems require precise engineering to ensure consistent water flow and

efficient heat dissipation. However, they also require regular maintenance due to the potential clogging of microscopic channels when water contaminants enter the system, which can affect performance.

- Durability and material compatibility present challenges when selecting appropriate materials for microchannels. The materials must be compatible with both the PV panel and the cooling fluid. Ensuring long-term PV panel functionality and maintaining structural integrity over time remain significant concerns.
- Thermal resistance is a key challenge when implementing microchannel cooling systems. While these systems are designed to improve heat dissipation, research shows that even well-designed systems may struggle to achieve sufficient reductions in thermal resistance, limiting their cooling effectiveness and the overall performance of the PV panels.
- The development, setup, and maintenance of microchannel forced water-cooling systems require significant investment. The financial benefits from increased energy output need to outweigh these costs for the technology to be considered economically feasible [68].

II.3.2.1 Nanofluid cooling

Nanofluids have superior heat transfer properties due to their higher thermal conductivity compared to conventional liquids. These properties make them effective for cooling photovoltaic (PV) panels, as they efficiently remove substantial amounts of waste heat, leading to lower surface temperatures. Additionally, nanofluids can act as spectral filters for PV cells, selectively absorbing incident infrared radiation, as demonstrated by Ali [69].

Typically, nanofluids are circulated through microchannels placed at the back of the PV panel. Sardarabadi et al. [70]. proposed using water/(SiO₂) nanofluids with varying weight concentrations between 1% and 3% for cooling PV panels. The experimental setup included a storage tank, heat exchanger, circulating pump, and refrigerant distribution system. Their study showed that the highest reduction in operating temperature, by 19°C, occurred with a 3% water/(SiO₂) solution, which resulted in a 9% increase in electrical efficiency, from 9.2% to 11%.

In a different approach, Rostami et al.[71] introduced a novel cooling method using atomized CuO nanofluid combined with high-frequency ultrasonic waves. CuO nanoparticles were selected due to their high electrical conductivity and unique properties. The nanofluids were applied via an ultrasonic atomizer, which emitted cold vapor through conveyor chambers to the back of the PV panels. The ultrasonic power setting controlled the vapor flow rate. This solution resulted in a cooling capacity increase ranging from 2.75% to 57.25% and a maximum power increase ranging from 3.4% to 51.2%, depending on the vapor flow rate and ultrasonic power.

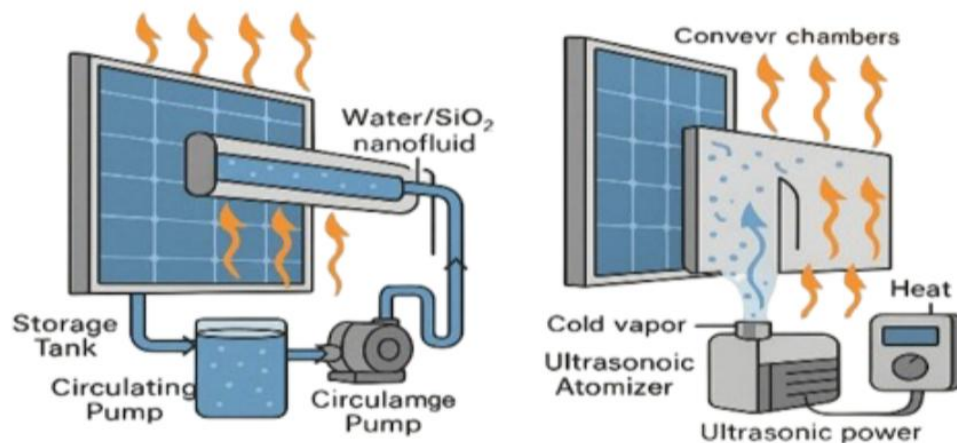


Figure II.14 Nanofluid Cooling[72].

Disadvantages of this study

The usage of nanofluid cooling in PV panels shows promise because it improves both electrical output efficiency and thermal heat disposal capabilities. Despite these benefits there are several problems and disadvantages that remain in such technology.

- Research indicates that nanofluids do not inevitably demonstrate improved thermal conductivity than base fluids despite their predicted value. According to a 30-laboratory study no useful rise in thermal conductivity emerged from several tested nanofluids under different experimental conditions and individual composition types.
- A stable suspension of nanoparticles is necessary to achieve efficient heat transfer. Inactive nanoparticles combined with sedimentation and particle agglomeration processes will cause the cooling system to operate less effectively as time goes by. The cooling process becomes less efficient due to nanoparticle migration caused by thermophoresis and Brownian motion-based movements.

- The manufacturing and maintenance expenses of nanofluids surpass those of normal cooling fluids because their production costs remain high. Financing big PV installations which employ nanofluid cooling demands significant cost reductions since otherwise these solutions cannot pay off.
- The effects of nanofluid use on PV panel components over long periods remain unknown because it is uncertain whether nanofluids will deteriorate or cause panel components to corrode. Research on nanofluid longevity and endurance needs to be extended fully to establish practical nanofluid-based cooling systems.
- Nanoparticle-based production technology presents two sets of concerns that impact both environmental health and human exposure to nanoparticles. Safety procedures and responsible production practices need implementation to minimize these dangers[73].

II.4 Conclusion

This section provides a review of multiple environmental factors and their influence on the performance of photovoltaic (PV) cells. Climatic conditions, such as irradiance intensity, dust deposition, and ambient temperature, significantly affect PV system conversion efficiency.

Specifically, in desert and arid regions, the combination of high ambient temperatures and dust accumulation is the primary cause of performance degradation.

The efficiency of PV cells decreases as temperature rises, and the accumulation of dust further exacerbates this effect. High temperatures in PV cells lead to substantial efficiency losses, potentially causing permanent damage to the cells and shortening their operational lifespan. Dust deposition is particularly harmful, with the extent of performance loss depending on various factors, including location, environmental conditions, and the angle of the panels. Increased dust accumulation results in a more significant reduction in efficiency.

This chapter reviews several techniques aimed at mitigating the effects of dust and high temperatures on PV systems. Among the methods examined, water-based cooling and cleaning techniques have proven to be the most effective in improving PV panel performance. However, the scarcity of water in many regions remains a significant challenge to implementing these solutions on a large scale.

Chapter III: Experimental Methodology

III.1 Introduction

This chapter outlines the methodology used to investigate the impact of passive cooling on the performance of photovoltaic (PV) modules. The study aims to assess how integrating aluminum heat sinks on the back of PV panels can enhance their electrical efficiency under high ambient temperatures, typical of desert regions such as Ouargla.

To achieve this, an experimental setup was designed, including both a reference PV module and a cooled module equipped with heat sinks. The chapter details the experimental procedure, describes the test area, instruments used for data collection, and the parameters measured. This methodological framework ensures the reliability, accuracy, and reproducibility of the results obtained

III.2 Test area description

The experimental study was conducted in Ouargla, a city located in southeastern Algeria, characterized by its position in the heart of the Sahara Desert at approximately 164 meters above sea level. Ouargla's geographic coordinates are 31°57' N latitude and 5°21' E longitude, covering an area of about 211,980 km². As shown in **Figure III.1**, the city lies within a hot desert climate zone, known for being one of the hottest regions in both Algeria and the world.

Summers in Ouargla are marked by extreme heat, with temperatures frequently surpassing 45°C. Notably, in July 2018, temperatures reached a record high of 51.3°C, a rare phenomenon globally [74]. Nighttime temperatures can remain elevated, often staying above 30°C, while relative humidity rarely exceeds 20%. The area experiences very dry conditions, with annual rainfall averaging less than 100 mm, mostly occurring during winter months.

Ouargla benefits from abundant sunshine, resulting in some of the highest solar radiation levels worldwide. The average wind speed is around 3.70 m/s year-round, with frequent sandstorms occurring between February and May. These storms reduce visibility and can deteriorate air quality [75].

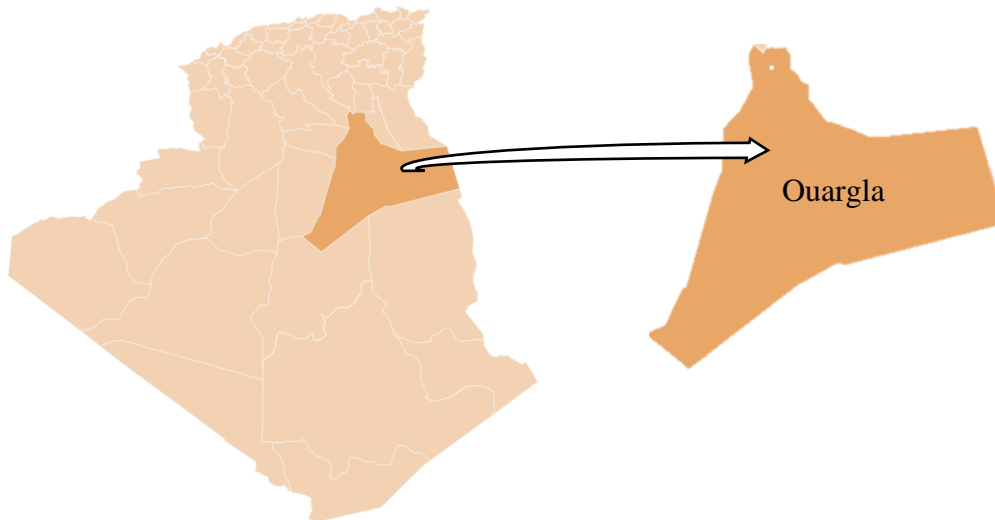


Figure III.1location of Ouargla on the map.

III.3 Experimental Setup

This study focuses on evaluating the thermal management of photovoltaic (PV) panels under harsh environmental conditions. The experimental setup involved monocrystalline PV modules equipped with different types of heat sinks mounted on their rear surfaces. These heat sinks were specifically designed to improve heat dissipation, thereby reducing the operating temperature of the panels and enhancing their overall performance.

In the following sections, we provide a detailed description of the components used in the experimental setup, including the PV modules, heat sinks, measurement instruments, and data acquisition system, along with the methodology employed for performance evaluation.

III.3.1 Solar Panel Specifications

In this study, two SY-M80W polycrystalline solar panels were employed see **Figure III.2** 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.2 Two Solar Panels

Table III.1 PV Module Electricity Performance Parameter

Property	Value
Model	SY-M80W
Panel Type	Polycrystalline Solar Panel
Maximum Power (P_{max})	80W
Voltage at Pmax (V_{mp})	17.4V
Current at Pmax (I_{mp})	4.61A
Open-circuit Voltage (V_{oc})	22.0V
Short-circuit Current (I_{sc})	4.85A
Max System Voltage	600V
Tolerance	$\pm 5\%$
Standard Test Conditions	1000W/m ² , AM 1.5 Global, 25°C cell temperature
Panel Size	1640mm x 990mm (Length x Width)

III.3.2 Description of the Heat Sink

Heat sinks were used in this experiment as thermal cooling components to lower the photovoltaic (PV) panels' working temperature and increase their efficiency. The heat sink employed in this investigation is depicted in **Figure III.3**.

Table III.2 provides a summary of the main physical characteristics of the heat sink employed in this project.

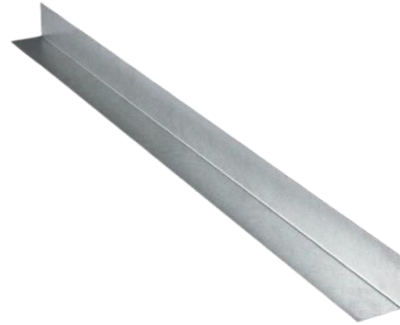


Figure III.3 The shape of the heat sinks used

Table III.2 Basic Physical Properties of Galvanized[76].

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	/K
Tensile Strength	250 – 550	MPa
Yield Strength	200 – 400	MPa
Hardness (Brinell)	120 – 160	HB
Material Thickness	0.5 - 1.2	Mm
Length	2 – 3	Meters
Width	20 – 40	Mm
Height	20 – 40	Mm
Corrosion Resistance	High	-
Weldability	Possible with zinc removal	-

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 Data Processing System**III.4.1 Temperature Acquisition System**

The temperature acquisition system is designed to monitor in real time the thermal behavior of two identical photovoltaic (PV) panels, one of which is equipped with a passive heat sink. This system is based on an Arduino Mega 2560 board, equipped with MAX6675 converter modules that allow digital acquisition of signals from Type K thermocouples (see Figure 3.4).

The setup includes:

- An Arduino Mega 2560 microcontroller board;
- MAX6675 modules that convert analog signals (in mV) into digital values;
- A breadboard for wiring connections;
- Multistrand connectors for organized wiring;
- A set of 6 Type K thermocouples.

The program, developed using the Arduino IDE, enables sequential temperature acquisition via the SPI protocol, displays the readings on a serial monitor, and exports the data for further analysis in Excel. The Arduino Mega 2560 offers high performance with 54 digital I/O pins, 16 analog inputs, and multiple communication interfaces (UART, SPI, I2C), making it well-suited for managing multiple sensors simultaneously. The technical specifications of ARDUINO MEGA 2650 are shown in **Table III.3**.

Table III.3 The Technical Specifications of Arduino Mega 2650

Specification	Description
Microcontroller	ATmega2560
Operating Voltage	5 V
Input Voltage (recommended)	7 to 12 V
Input Voltage (limits)	6 to 20 V
Digital I/O Pins	54 (15 PWM outputs)
Analog Input Pins	16 (10-bit resolution)
Max Current per I/O Pin	40 mA
Flash Memory	256 KB (8 KB used by bootloader)
SRAM	8 KB
EEPROM	4 KB
Clock Speed	16 MHz
Hardware Serial Ports (UART)	4
SPI Interface	Yes (pins 50 (MISO), 51 (MOSI), 52 (SCK), 53 (SS))
I2C Interface (TWI)	Yes (pins 20 (SDA), 21 (SCL))
Reset Pin	Yes
USB Port	USB Type-B for power and communication
Dimensions	101.52 mm x 53.3 mm
Weight	Approximately 37 g

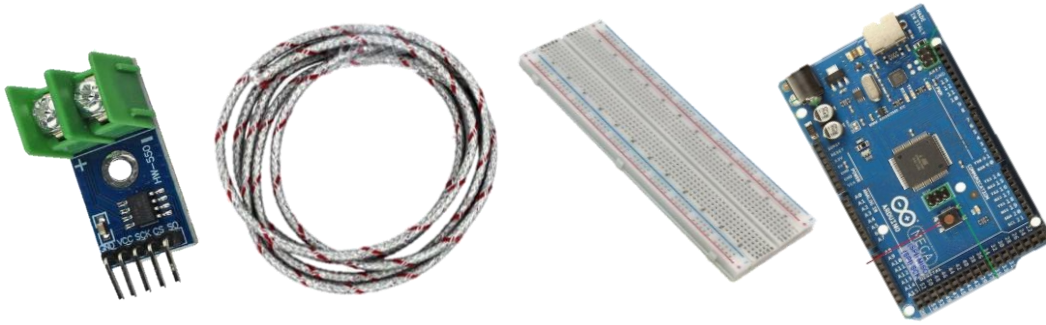


Figure III.4 Arduino Mega 2650 Board, Max6675 Temperature Sensor With K-Type Thermocouple and Breadboard

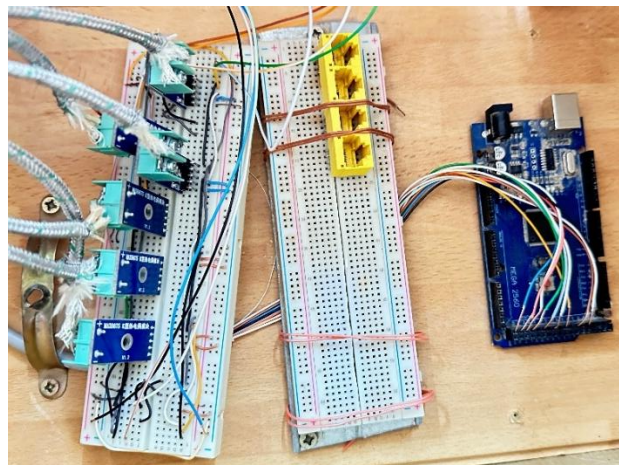


Figure III.5 Devices Link

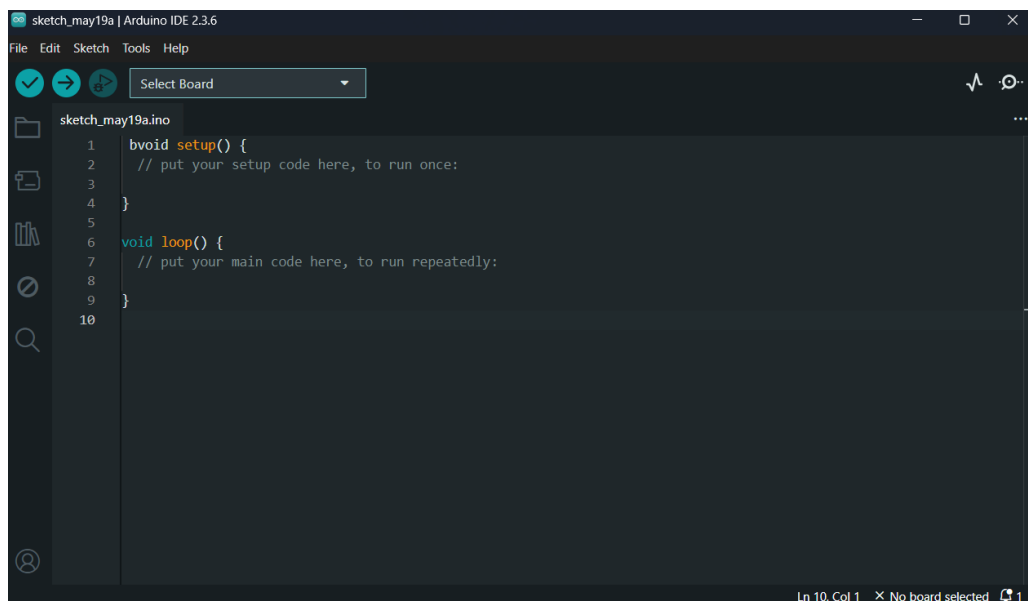


Figure III.6 Arduino Ide Interface

III.4.2 Measuring Instruments

III.4.2.1 Digital Multimeter

A DM750M digital multimeter see **Figure III.7** is used to measure the electrical quantities generated by the PV modules. It can measure:

- DC voltage (up to 60 V);
- DC current;
- Resistance;
- Frequency.

It features a digital display, a rotary switch for function selection, and a transistor testing mode.



Figure III.7 Digital Multimeter Dm750m

III.4.2.2 Load Resistors

Power resistors of the ECO 1/2 tube type are used as loads to regulate the output current. Each resistor has a resistance of 10 ohms, with a maximum current capacity of 5.7 A and a maximum voltage of 250 V **Figure III.8**. Their semi-cylindrical shape aids in better heat dissipation.



Figure III.8 Resistors

III.4.2.3 Pyranometer

A solar power sensor **Figure III.9** is used to measure the solar irradiance incident on the panel surfaces. The device consists of a sensor connected to a digital display and provides readings in W/m^2 . It ensures both panels receive equivalent solar exposure during testing.



Figure III.9 Solar Power

III.4.2.4 Anemometer

The Mini UT363 anemometer **Figure III.10** is used to measure wind speed and ambient temperature. It is equipped with a rotating turbine sensitive to air movement and has the following features:

- Instantaneous, average, and maximum wind speed display (in m/s);
- Temperature measurement (in $^{\circ}C$);
- “Hold” function for data freezing.



Figure III.10 Anemometer

III.5 Experimental Developments

III.5.1 Installation of the Heat Sink

To enhance the thermal management of the photovoltaic panel, a passive cooling system was implemented using galvanized heat sinks angles. Six heat sinks, each measuring 3 meters in length, 0.5 mm in thickness, and 20 mm × 20 mm in cross-section, were selected for the installation.

These bars were cut into:

- 25 pieces of 61.5 cm each, positioned vertically from the bottom of the panel up to the junction box,
- 6 pieces of 25 cm each, placed horizontally along the sides of the junction box.

After cleaning the rear surface of the PV panel to ensure optimal thermal contact, the metal pieces were securely affixed using a quick-setting industrial adhesive. For added mechanical stability and structural reinforcement, small plastic pipe segments were strategically positioned at the corners and edges of the panel see **Figure III.11**. This configuration aims to facilitate better heat dissipation from the panel's surface, thereby reducing operating temperature and potentially enhancing electrical efficiency.

Figure III.12 illustrates the back view of the PV panel equipped with the heat sink assembly, while **Figure III.13** shows the reference panel used for comparison.



Figure III.11 Corner Installation



Figure III.12 A Board Containing a Heat Sink



Figure III.13 Reference Panel

III.5.2 Experimental Procedure

Two identical PV panels were installed on tilted supports under direct sunlight. The experimental panel was equipped with the passive cooling system, while the other served as the reference.

Thermocouples were positioned at three levels (top, center, bottom) on each panel see **Figure III.14**. Temperature readings were collected via the Arduino system, and electrical parameters (voltage, current) were recorded using the multimeter. At the same time, ambient conditions were monitored using the pyranometer (irradiance) and anemometer (wind speed and temperature).

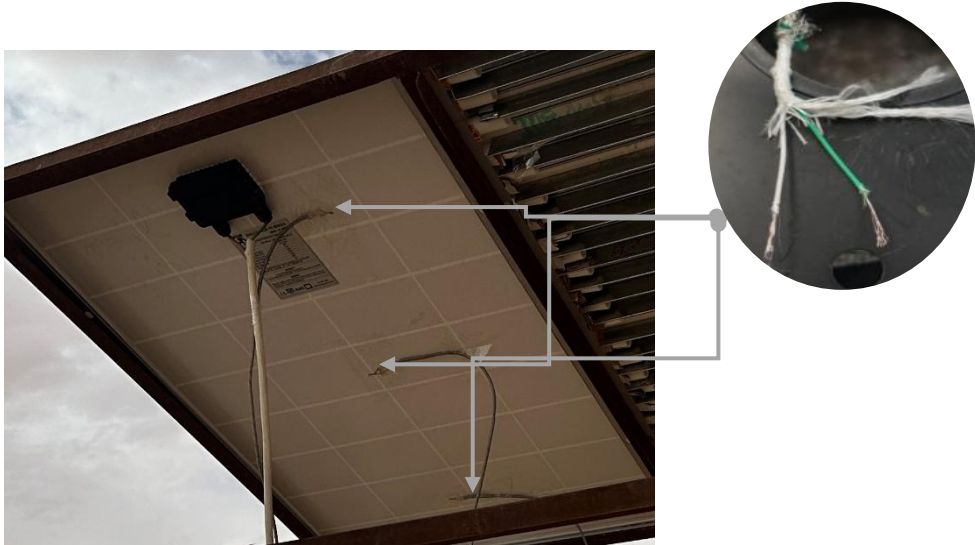


Figure III.14 This way the sensors are mounted on the board

III.5.3 Objectives of the Experiment

The study aims to:

- Compare the thermal profiles between the reference panel and the panel with the heat sink;
- Analyze the vertical temperature gradient from top to bottom of each module;
- Assess the effectiveness of passive cooling in real-world conditions, with the goal of improving electrical performance.

The complete experimental setup is illustrated in **Figure III.15**.

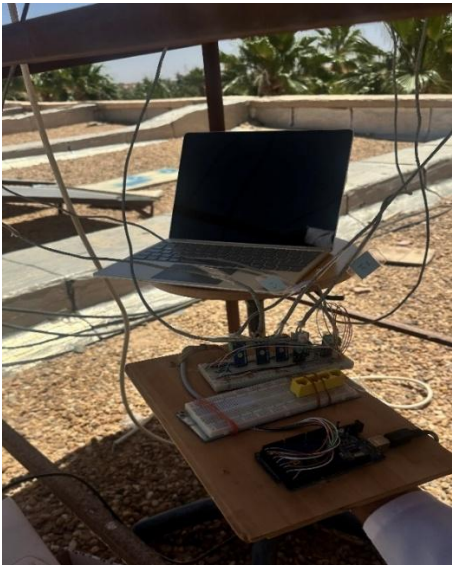


Figure III.15 The experimental setup

Chapter IV: Results and Discussion

IV.1 Introduction:

In this chapter the results of experimental measurements has been presented and discussed, climatic conditions such as solar irradiation, ambient temperature and wind speed are key parameters during the experiments to evaluate the power production of PV panels. The performance measurements of the two PV panels (cooled and witness) were compared and analyzed in this chapter to illustrate the effect of adding of fins on the rear face of a PV module.

IV.2 Climatic condition measurements

The measurements were carried out under the real outdoor conditions of Ouargla city on three different days (Two “02” sunny days and one “01” cloudy day), the three days measurements will allow to best analysis and understanding of the effect of heat sink on the performance of the PV module.

IV.2.1 Results for 28/04/2025 (Sunny Day)

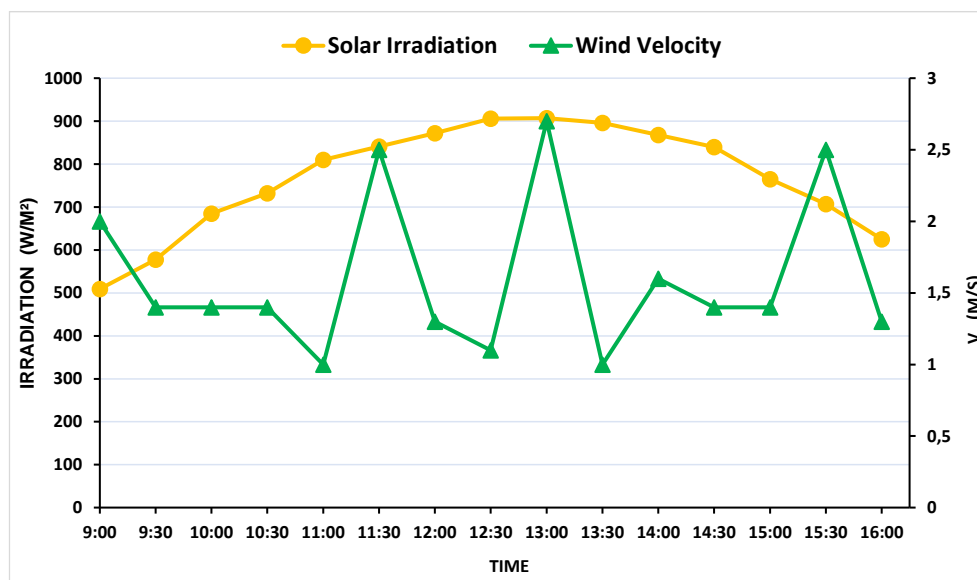


Figure IV.1 Solar radiation intensity and air speed (28/04/2025)

The curves of solar radiation intensity and air speed shown on **Figure IV.1** illustrate clear trends. Solar radiation intensity showed a steady increase during the morning, reaching its peak around midday, before gradually declining towards the evening. This typical diurnal pattern reflects a sunny day with strong solar irradiance. Concurrently, air speed exhibited fluctuations throughout the day, generally increasing during the afternoon hours reaching to its highest value with a speed of 2.7 m/s at 13:00 pm.

IV.2.2 Results for 29/04/2025 (Sunny Day)

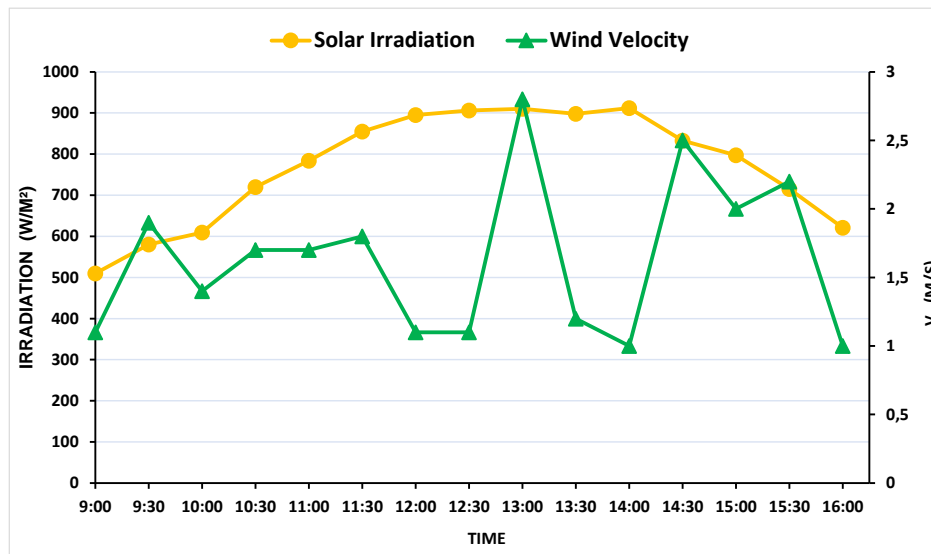


Figure IV.2 Solar radiation intensity and air speed (29/04/2025)

Figure IV.2 shows the measurements of April 29, similar patterns were observed. Solar radiation intensity displayed a pronounced midday peak, indicative of a clear, sunny day with substantial solar energy available for photovoltaic conversion. The airspeed data showed moderate variability with notable peaks in the afternoon with a highest value of speed 2.8 m/s at 13:00 pm. These increased wind speeds effectively augmented the natural convection process, aiding further in heat dissipation. This combination of strong sunlight and faster air speeds highlights the best conditions for testing how well heat sinks work to handle higher heat levels.

IV.2.3 Results for 01/05/2025 (Partly Cloudy Day)

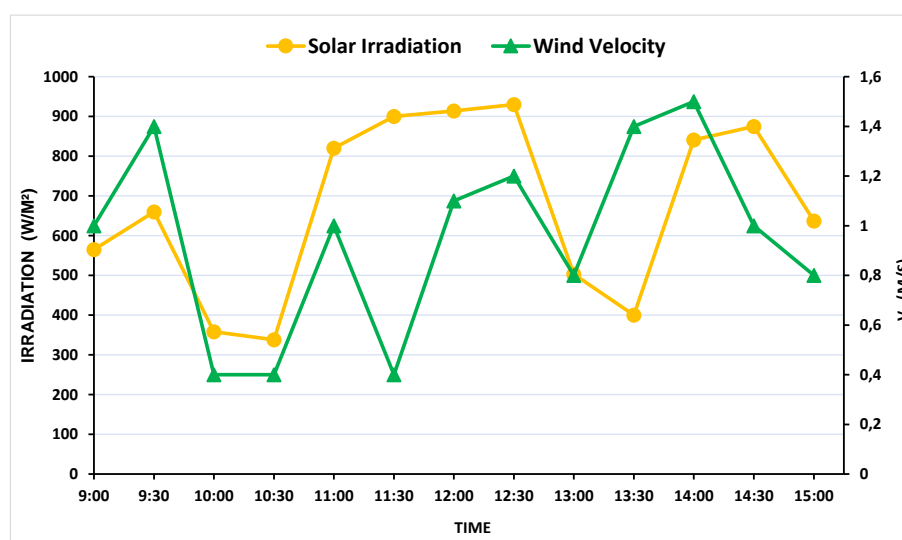


Figure IV.3 Solar radiation intensity and air speed (01/05/2025)

The data presented on **Figure IV.3** depict significantly different characteristics due to partly cloudy conditions. Solar radiation intensity was markedly lower with frequent fluctuations caused by intermittent cloud cover. The recorded air speed was relatively stable with less pronounced fluctuations compared to sunny days.

IV.3 Operating temperatures measurements:

To evaluate the impact of adding fins (heat sinks) to the back surface of the PV module, three type K thermocouples were installed on each module to measure the operating temperature of the PV cells at different locations. The positions of the thermocouples on the surface of the PV modules are illustrated in **Figure IV.4**.

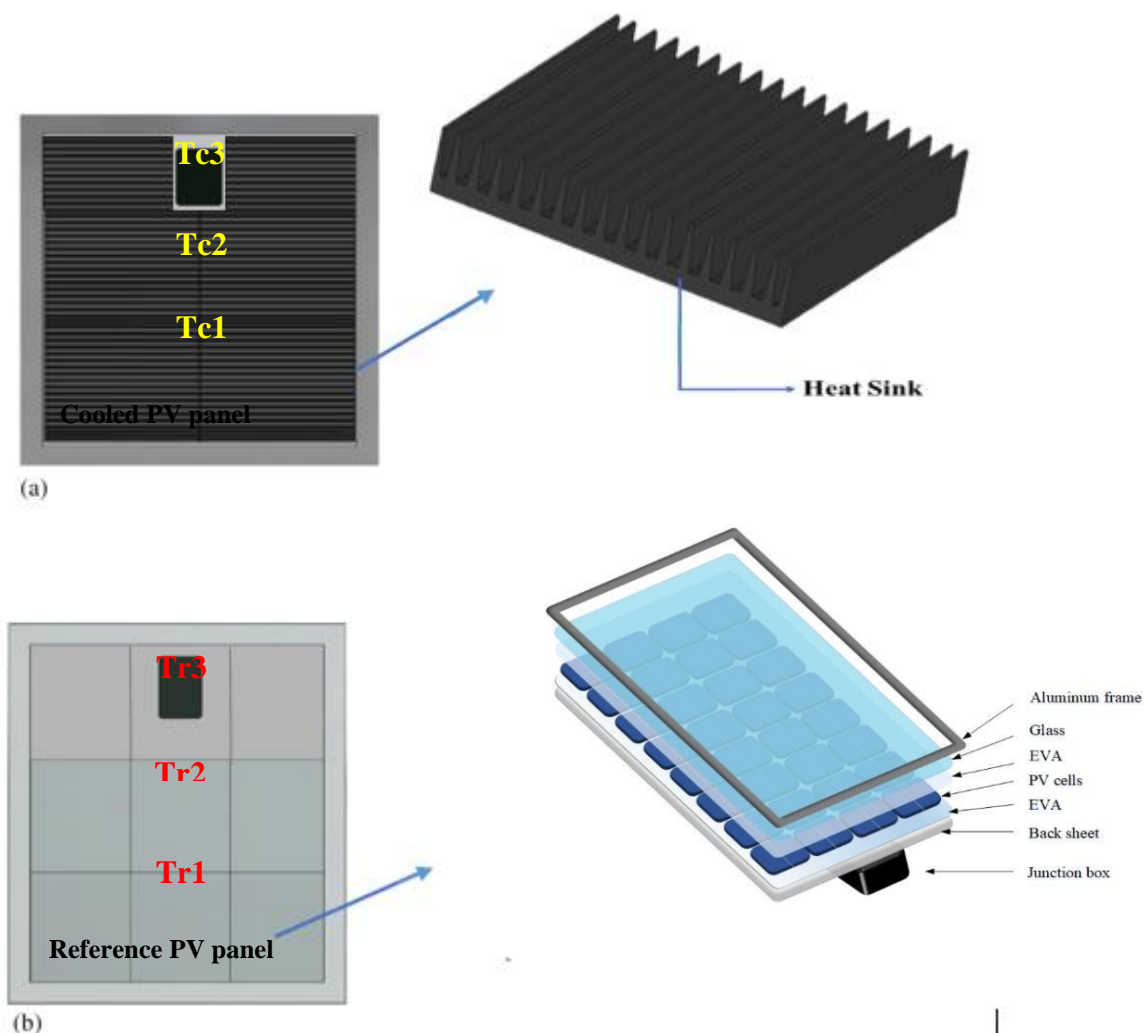


Figure IV.4 Positions of thermocouples on the PV modules.

IV.3.1 Analysis of Experimental Results

The effectiveness of cooling solar photovoltaic (PV) modules using heat sinks on the back surface of the module was assessed through a comparative study involving two identical PV modules. One module was equipped with heat sinks, while the other was used as a reference without cooling. Temperature variations were recorded for three different weather conditions: two sunny days and one partly cloudy day, aiming to evaluate the efficacy of heat sinks in reducing the operating temperature and improving PV module performance.

IV.3.1.1 Results for 28/04/2025 (Sunny Day)

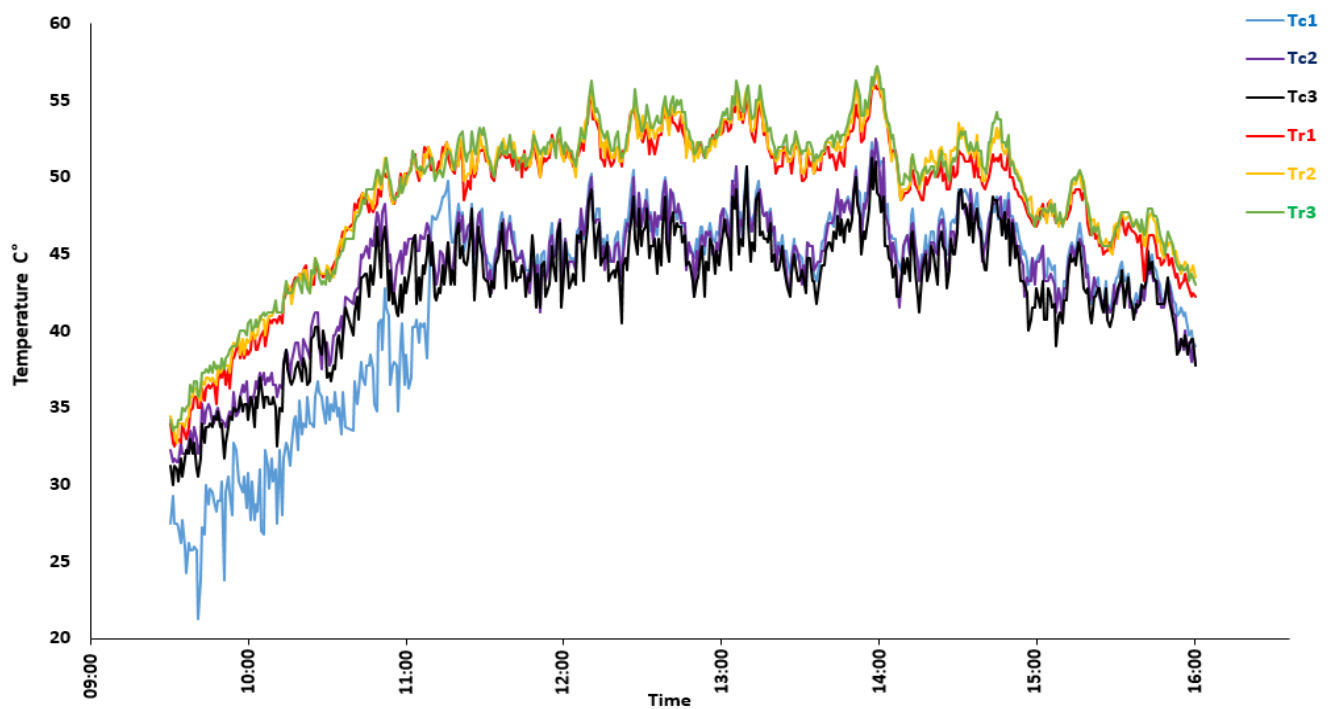


Figure IV.5 Temperatures of Cooled and Witness PV modules (28/04/2025)

The temperature curves recorded on April 28th shown on **Figure IV.5** clearly illustrate significant differences between the two modules. The PV module equipped with heat sinks (Tr1, Tr2 and Tr3) consistently maintained lower temperatures compared to the reference module temperatures (Tc1, Tc2 and Tc3), particularly during peak sunlight hours and ambient temperature around midday. The reduced temperatures observed in the cooled module are attributed to the heat sinks' ability to effectively dissipate heat by increasing the surface area available for thermal exchange with the surrounding air. Between 11:00 AM and 14:00 PM (peak irradiation period), the temperature difference between the modules reached its maximum values, confirming the high efficiency of the heat sinks under intense solar irradiation. This cooling effect significantly decreases internal cell resistance, thus enhancing overall photovoltaic efficiency and electrical output.

IV.3.1.2 Results for 29/04/2025 (Sunny Day)

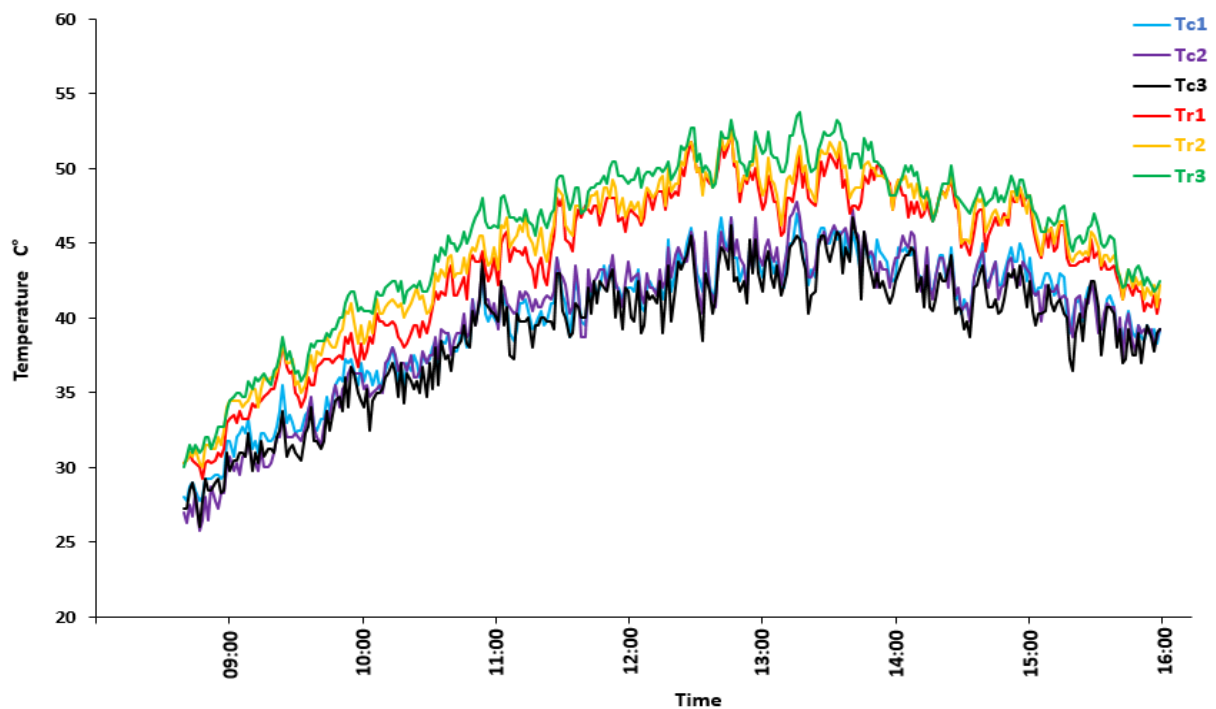


Figure IV.6 Temperatures of Cooled and Witness PV modules (29/04/2025)

On the following sunny day, April 29th, the results corroborated those previously observed, showing an even clearer and more consistent temperature difference favoring the cooled PV module. Throughout the measurement period, temperatures remained notably lower in the module equipped with heat sinks compared to the reference module, especially evident during midday. These results underline the sustained effectiveness of heat sinks in consistently reducing module temperatures. Therefore, the proposed heat sink technique is practically effective for thermal management, particularly under sunny and hot climatic conditions.

IV.3.1.3 Results for 01/05/2025 (Partly Cloudy Day)

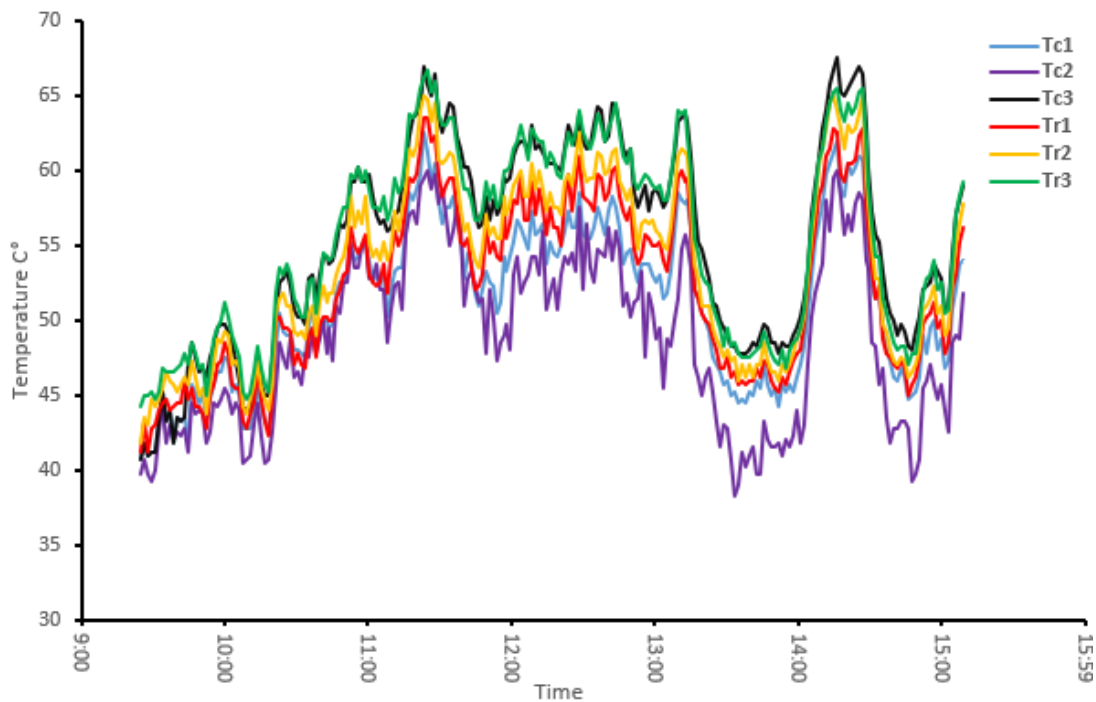


Figure IV.7 Temperatures of Cooled and Witness PV modules (01/05/2025)

Figure IV.7. presents the measurements recorded on May 1, which is characterized by partly cloudy conditions, the results showed a smaller temperature differential between the two modules compared to previous sunny days. Despite reduced direct solar radiation, the module equipped with heat sinks still registered consistently lower temperatures than the reference module, although the temperature difference was less pronounced. The diminished differential in temperature can be explained by the lower solar radiation intensity, resulting in less heat accumulation in both modules. Nevertheless, the cooled module maintained relatively better performance, indicating the continued effectiveness of heat sinks even under suboptimal sunlight conditions. Underscores that heat sink technology remains beneficial across varied weather conditions, although its effectiveness is closely linked to the intensity of available solar radiation.

IV.3.2 Temperature average difference:

The temperature difference, found by taking the average temperature of the cooled module and subtracting it from the average temperature of the witness module, the curve illustrated on Figure 4.8. clearly shows how effective the cooling method with heat sinks is. On April 28, significant temperature differences between 4°C and 9°C were observed, especially during peak solar radiation periods from 11:30 am to 13:30 pm. The positive temperature difference values reflect a notably lower average temperature for the module equipped with heat sinks compared to the witness module.

The finding indicates effective heat dissipation and confirms the high efficiency of the heat sink method under intense sunlight conditions.

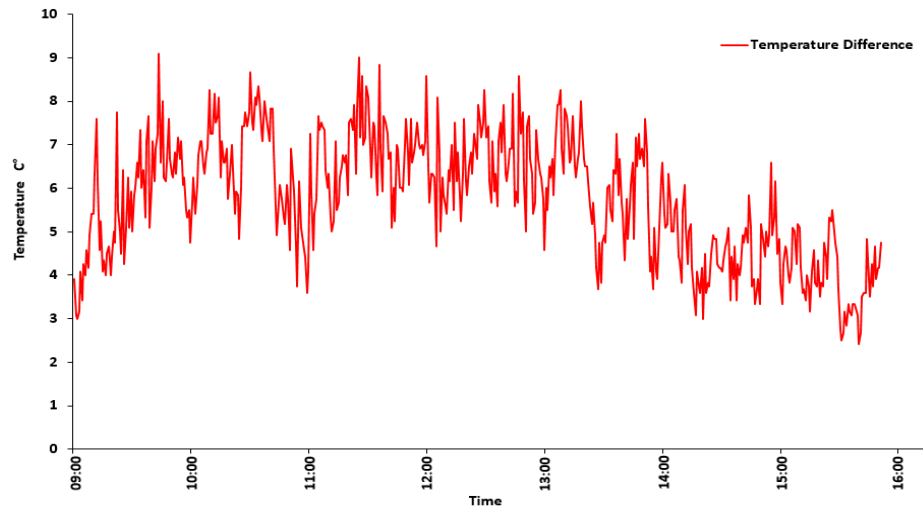


Figure IV.8 Temperatures difference (28/04/2025)

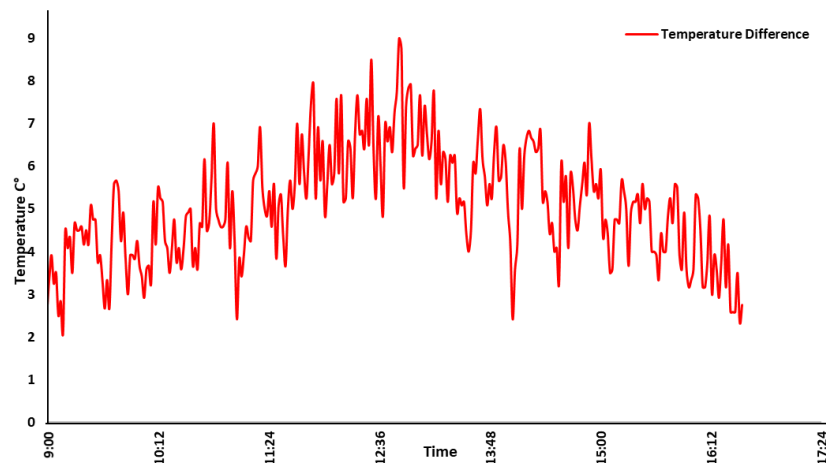


Figure IV.9 Temperatures difference (29/04/2025)

As shown in **Figure IV.9**, on April 29, the trend of positive temperature differences continued, further validating the effectiveness of the heat sink cooling technique. Throughout the day, consistent positive values were noted, emphasizing a steady thermal advantage provided by the heat sinks. This sustained temperature reduction clearly illustrates the heat sinks' capability to continuously manage heat under strong solar exposure. Consequently, these results further reinforce the practical significance of applying heat sinks for efficient thermal management of PV modules.

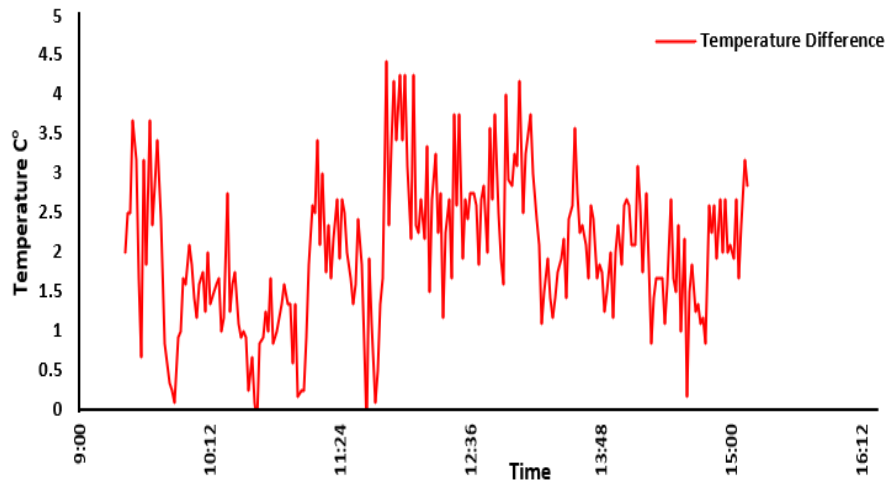


Figure IV.10 Temperatures difference (01/05/2025)

Results recorded on May 1 are presented in **Figure IV.10**; the temperature differences were smaller compared to the sunny days but remained positive (from 0°C to 4°C at maximum). This smaller difference is due to reduced solar radiation levels resulting from partly cloudy conditions, which led to less heat accumulation overall. Nevertheless, the module with heat sinks consistently maintained lower temperatures than the witness module, affirming that the heat sinks remained beneficial even in conditions of lower sunlight intensity. This evidence demonstrates the versatility and reliability of the cooling technique under varying climatic conditions.

IV.4 Analysis of Maximum Output Power:

The electrical characteristics and the output power of each PV module were measured and calculated each 30 minutes to evaluate the effect of adding heat sink on the performance of PV module.

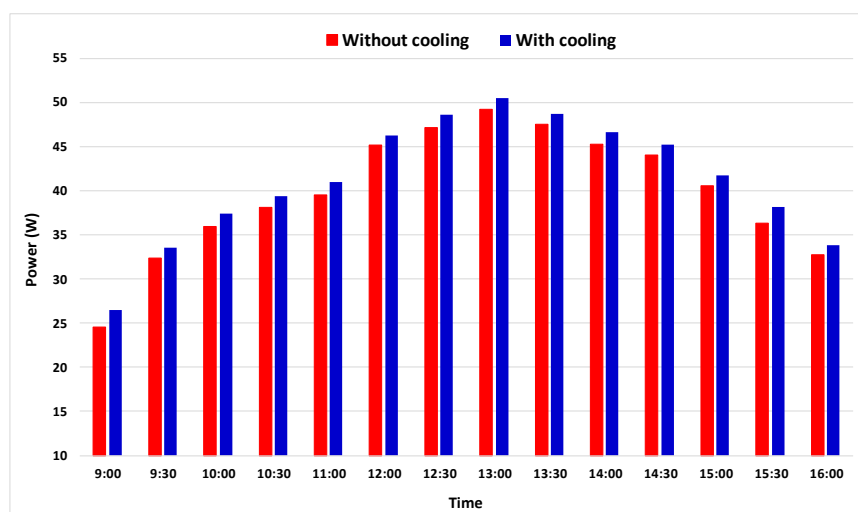


Figure IV.11 Maximum Power of cooled and witness PV panels (sunny day: 28/04/2025)

Analyzing the bar charts representing the maximum power measured every 30 minutes on April 28 reveals a distinct advantage for the PV module equipped with heat sinks compared to the witness module. The cooled module consistently exhibited higher maximum power values. This performance enhancement can be directly attributed to the effective temperature reduction facilitated by the BA13 heat sinks. By reducing the cell temperature, internal electrical resistance decreases, leading to higher electrical efficiency and improved power output. These results clearly highlight the effectiveness of heat sinks in enhancing the electrical performance of PV modules under high solar irradiance conditions.

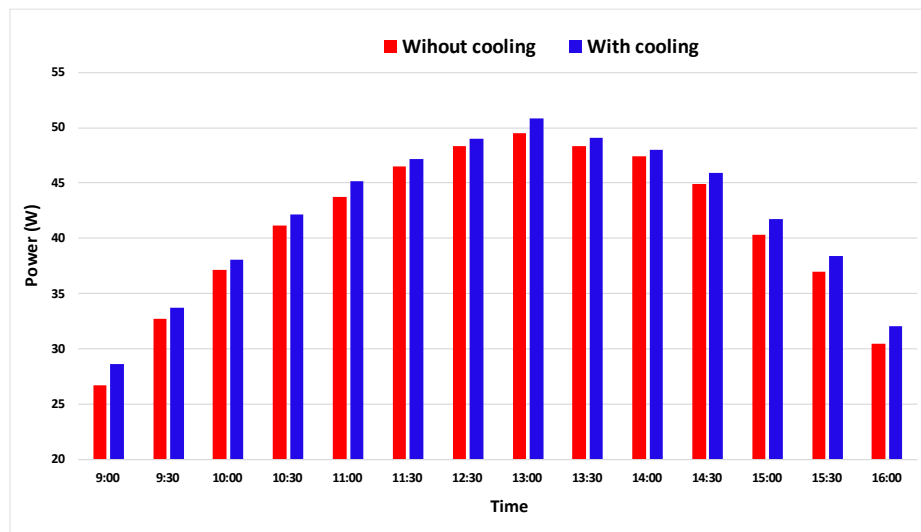


Figure IV.12 Maximum Power of cooled and witness PV panels (sunny day: 29/04/2025)

On April 29, the results further affirmed the previous day's findings. The bar charts indicate that the maximum power output of the cooled module consistently surpassed that of the witness module throughout the measurement period. This consistent and improved power performance emphasizes the stability and effectiveness of employing heat sinks for thermal management. Maintaining lower temperatures significantly contributes to sustaining high photovoltaic efficiency, which is particularly beneficial in sunny, high-temperature environments.

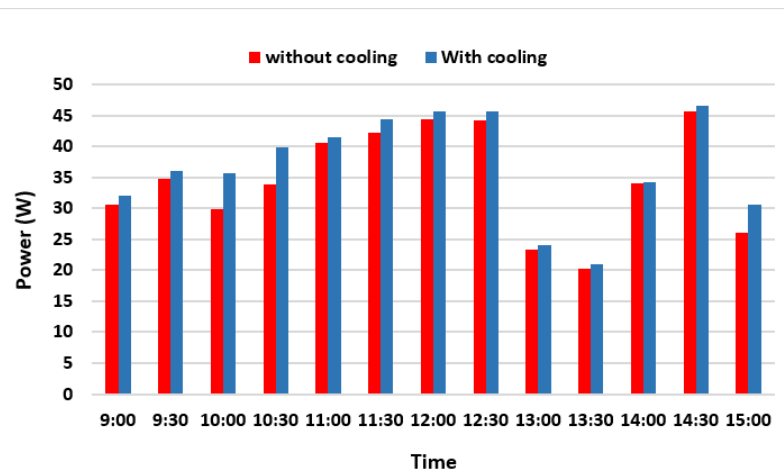


Figure IV.13 Maximum Power of cooled and witness PV panels (cloudy day: 01/05/2025)

On May 1, characterized by partly cloudy conditions, a closer range of maximum power outputs between the two modules was observed, though the cooling module continued to show superior performance most of the time. This smaller differential is primarily due to reduced solar irradiance and less heat accumulation compared to sunnier days. Nevertheless, the continued superior performance of the cooled module underlines the reliability and versatility of heat sinks, demonstrating their effectiveness even under less-than-ideal weather conditions.

IV.5 Effect of wind speed:

Since the operating principle of the heat sink relies on heat transfer by convection, wind speed plays a critical role in its performance. To assess this effect, the variation in wind velocity was monitored and evaluated throughout the experiment. The recorded wind speed data and its influence on heat sink performance are presented in the following **figures IV.14**.

The graph illustrates the variation of temperature difference and wind velocity over time, highlighting the influence of wind speed on the performance of the heat sink. As the operating principle of the heat sink is based on convective heat transfer, an increase in wind velocity enhances the cooling efficiency by promoting greater heat dissipation from the PV module. This effect is evident in the data, where higher wind velocities at around 11:00, 13:00, and 15:00 correspond to increased temperature differences, with the highest values observed at 13:00. Conversely, during periods of reduced wind speed, such as at 12:00 and 14:00, the temperature difference drops, indicating diminished heat sink performance. These fluctuations confirm that the effectiveness of the heat sink is highly sensitive to changes in wind conditions, and that natural airflow plays a crucial role in improving passive cooling in photovoltaic systems.

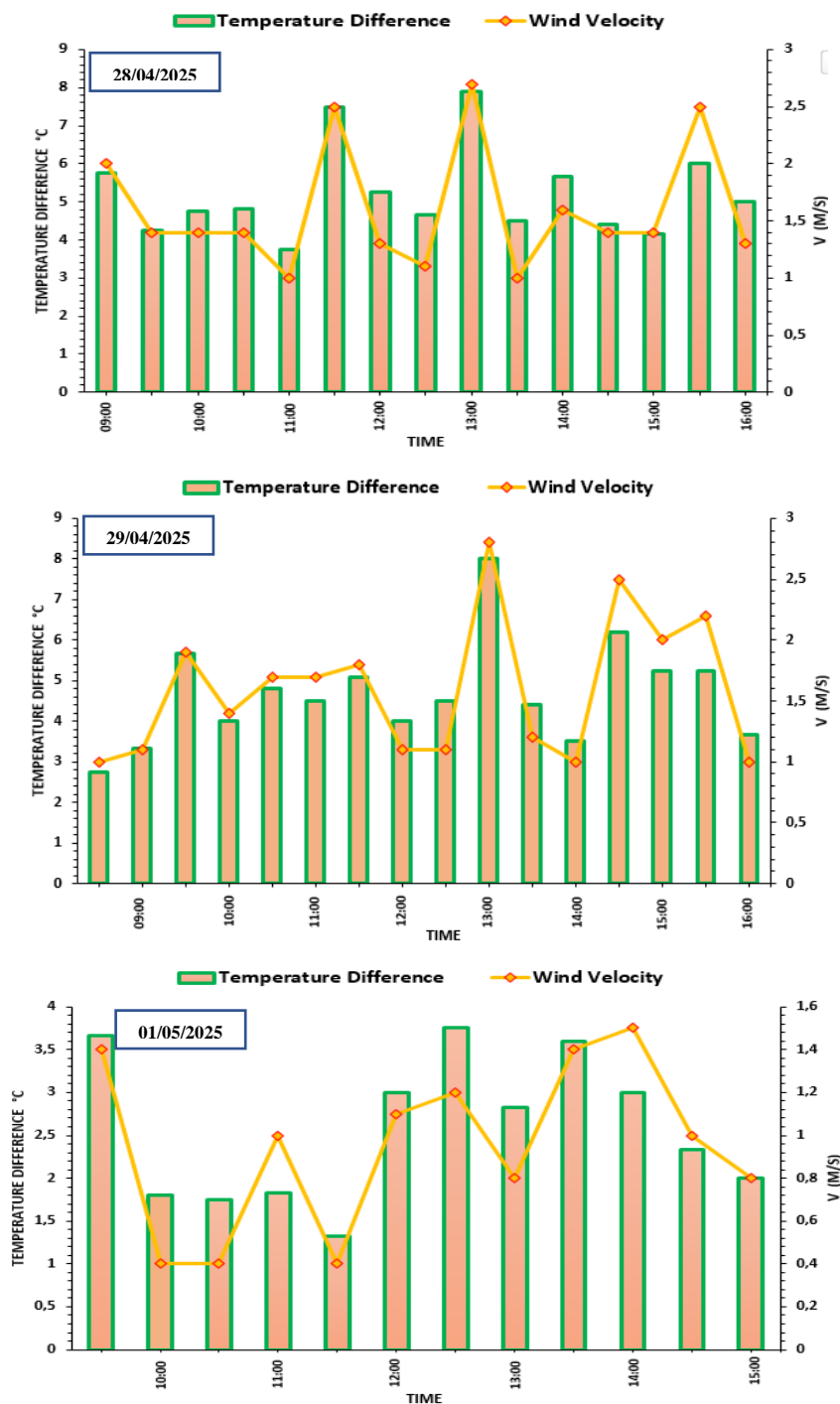


Figure IV.14 Wind Speed and Temperature difference variation

The article comprehensively explores the effects of fins on the back surface of photovoltaic (PV) modules when used in real outdoor environments in Ouargla. The study included three different days with varying weather conditions: two clear days and one cloudy day, enabling a detailed study of the effect of heat sinks.

IV.6 Analysis of Effectiveness Solar Panels:

The efficiency of each PV module was measured and calculated every 30 minutes to evaluate the effect of adding a heat sink on the PV module performance.

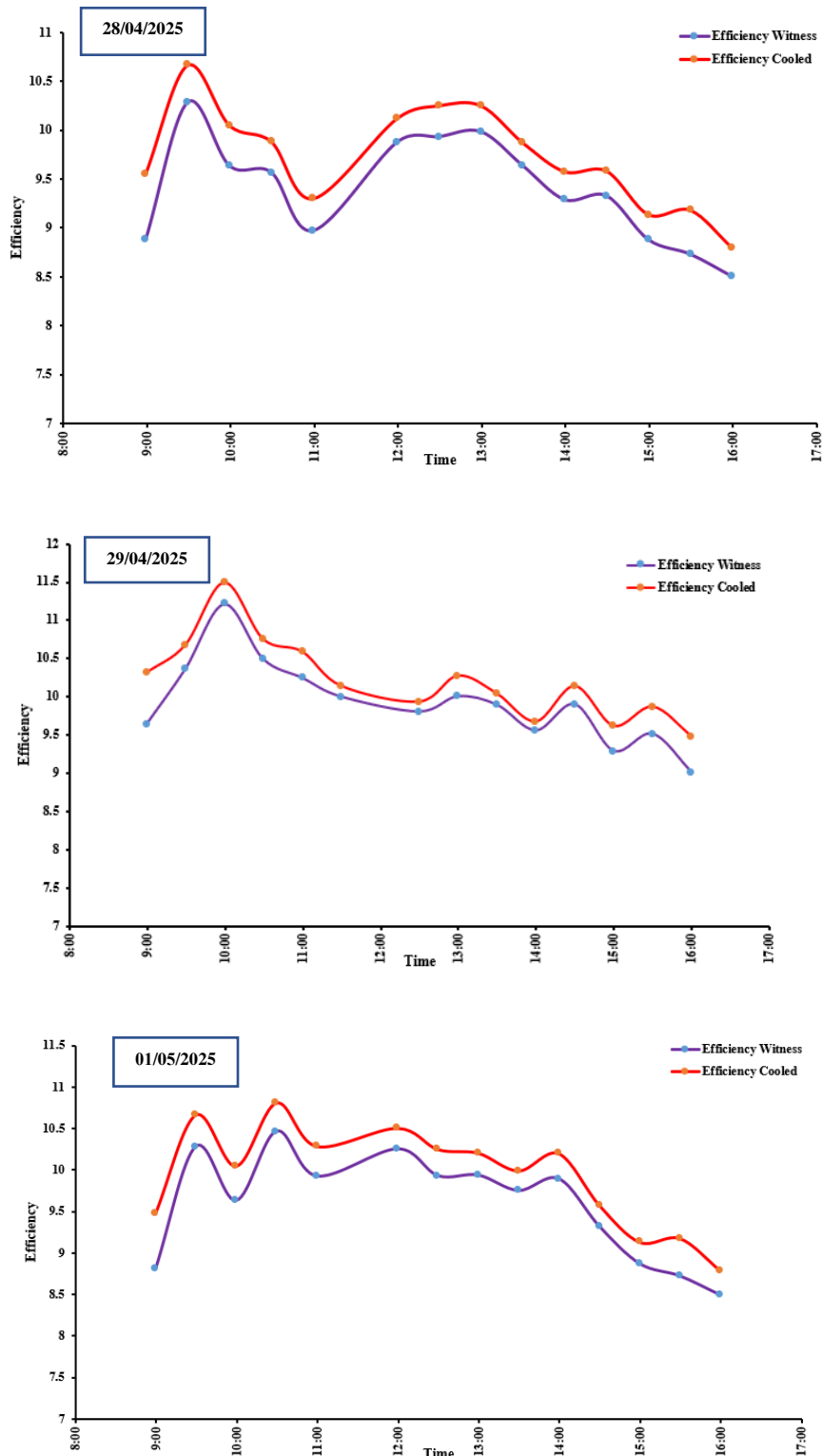


Figure IV.15 Effectiveness of Solar Panels

The efficiency curves presented in the graph of 28 and 29 April for two sunny days shown in **Figure IV.15** clearly show marked differences between the two solar PV modules. PV module

equipped with heat sinks, at consistently higher efficiency levels compared to reference module temperatures. This variation is most evident during the afternoon, and especially between 11:00 am and 2:00 pm, when solar radiation is at its peak.

Increasing the efficiency of a refrigerated unit is likely due to the ability of heat sinks to cool, which helps lower the temperature of the unit by improving heat dissipation. This cooling mechanism helps reduce the internal cell resistance, allowing the unit to perform better under intense sunlight. On the other hand, the reference unit, which lacks a heat sink cooling mechanism, shows a continuous decrease in efficiency as temperatures rise throughout the day.

In conclusion, the cooling effect of heat sinks greatly enhances the overall efficiency of photovoltaic energy, especially during periods of high solar radiation, which confirms the positive effect of thermal management on the performance of solar panels, and this is confirmed on the 29th. As for May 1, it was characterized by partial cloudy conditions. The recorded results show a noticeable convergence in the yield values between the panel equipped with heat sinks (Efficiency Cooled) and the control panel (Efficiency Witness), compared to previous sunny days, where the difference was more noticeable.

This convergence can be explained by a decrease in the intensity of direct solar radiation due to clouds, which led to a decrease in heat accumulation in both panels and thus a decrease in the thermal difference between them. However, the cooled panel continued to have a slightly higher yield than the control panel, confirming the effectiveness of the heat sink cooling system even in suboptimal conditions (weak sunlight).

The importance of this result is that heat sink technology remains useful across different fields

IV.7 Conclusion

The results consistently indicate that the use of heat sinks lowers the temperature of the PV modules, especially on days with high solar radiation. The temperature in the cooled module was significantly lower than the reference temperature on sunny days, sometimes reaching 9°C when the sun was at its peak. On partly cloudy days, the module managed to stay cooler, but the difference between the indoor and outdoor temperatures was smaller than usual.

When temperatures dropped, the electronic functions of the device also improved. Under strong sunlight conditions, the cooled PV module consistently had a higher peak power output than the

reference module. This improvement occurs because lower cell temperatures reduce the internal electrical resistance, helping the module operate more efficiently.

The research also showed that the effectiveness of passive cooling is highly dependent on wind speed. As wind speed increases, the thermal load increases, allowing heat sinks to lower the module temperature and improve its performance. Conversely, lower wind speeds reduce the effectiveness of heat sinks.

Overall, the results of this chapter demonstrate that heat sinks are a reliable and effective means of managing the heat of photovoltaic modules in warm, sunny locations. They keep the modules cool, prolong the system's lifespan, and thus enhance energy production, especially when the weather is hot and the air is moving. Therefore, they help PV systems operate and last longer, especially in locations exposed to sunlight. Even with changing weather patterns, this system's ability to regulate temperature demonstrates its potential for wider use in solar energy systems.

General conclusion

General conclusion

The thesis fully dealt with the high-temperature issues experienced by photovoltaic (PV) modules in Ouargla, Algeria. Analysis and experimentation done in this study bring new knowledge on improving the performance of PV systems by improving their thermal management.

It was found in the literature that using PVs in deserts, where very high temperatures and a lot of sunlight are typical, greatly decreases their efficiency and shortens their working life. When compared to other forms of cooling, using heat sinks is more practical since they function well, are reliable, and need little energy.

It was found through experiments that adding heat sinks to the back of PV modules reduces operating temperatures by as much as 9°C, even during times when sunlight is strongest, compared to such modules with no cooling. This improved thermal management made the plant's electrical output and efficiency better, regardless of what the climate was doing. Studies also pointed out that wind speed can boost the effectiveness of indoor cooling.

On the whole, using heat sinks for cooling is deemed a feasible approach to increase how well and how long PV modules function in hot areas. Such methods help energy yields to be maintained, rates of degradation to be lessened, and PV systems to last longer. Based on these findings, it seems useful to include passive thermal management in strategies to improve the efficiency of solar energy in Algeria and other places with the same environmental conditions.

Further research can explore hybrid cooling, test new materials for heat sinks, and conduct studies on larger PV systems under various environmental conditions. The learning from this research contributes to solar technologies that help the environment and create more efficient PV systems for changing climates.

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Abstract

This study focuses on the thermal management of photovoltaic (PV) modules in hot climates, with a specific focus on the Ouargla region in southern Algeria, where high ambient temperatures significantly reduce PV efficiency and system longevity. The core problem addressed is the accumulation of heat in PV panels, which can result in power losses of up to 25% due to the negative temperature coefficient of silicon solar cells. The objective of this work is to evaluate the effectiveness of a passive cooling technique using aluminum heat sinks mounted on the rear side of PV modules to reduce their operating temperature and improve electrical performance under real-world conditions. An experimental setup was designed and implemented, involving two identical polycrystalline PV modules—one equipped with heat sinks and the other serving as a reference without cooling. Thermocouples were installed on both modules to monitor surface temperature, and identical resistive loads were connected. Data were collected over three days (April 28, April 29, and May 1, 2025) under varying meteorological conditions (sunny and partly cloudy). The cooled panel consistently operated at 6°C to 10°C lower than the uncooled panel, with the maximum recorded temperature difference reaching 10.5°C under clear skies. The cooled panel also showed an increase in output power of up to 12% and an average improvement in electrical efficiency between 8% and 10%. Notably, the cooling system required no external energy, making it both passive and cost-effective. Furthermore, wind presence contributed to enhanced heat dissipation, especially at speeds above 3.5 m/s. In conclusion, the use of passive aluminum heat sinks significantly improved PV module performance in high-temperature environments. This simple and affordable method is suitable for large-scale applications in arid and semi-arid regions like southern Algeria, contributing to the development of more efficient and sustainable solar energy systems.

المخلص

تتناول تركيز هذه الدراسة على الإدارة الحرارية للألواح الكهروضوئية في المناطق ذات المناخ الحار، مع تسليط الضوء على منطقة ورقلة بالجنوب الجزائري، حيث تؤدي درجات الحرارة المرتفعة إلى انخفاض كبير في كفاءة الألواح وعمرها الافتراضي. وتعالج الدراسة مشكلة تراكم الحرارة داخل الألواح الشمسية، والتي قد تؤدي إلى فقدان في القدرة الكهربائية يصل إلى 25% نتيجة المعامل الحراري السالب لخلايا السيليكون. تهدف هذه الدراسة إلى تقييم فعالية تقنية تبريد سلبية باستخدام مشتتات حرارية من الألمنيوم، تم تثبيتها على الجهة الخلفية للألواح، بهدف تقليل درجة حرارتها وتحسين أدائها الكهربائي في ظروف تشغيل واقعية. تم إعداد وتنفيذ تجربة مخبرية باستخدام لوحين شمسيين متماثلين من نوع بولي كريستالين، أحدهما مزود بمشتتات حرارية والآخر يُستخدم كمرجع بدون تبريد. تم تثبيت مجسات حرارية على كلا اللوحين وربطهما بأحمال مقاومة متماثلة، وجمعت البيانات خلال ثلاثة أيام (28 و29 أبريل و1 ماي 2025) تحت ظروف مناخية مختلفة (شمسة وغائمة جزئياً). أظهرت النتائج أن اللوح المبرد عمل بدرجة حرارة أقل بمعدل يتراوح بين 6 إلى 10 درجات مئوية مقارنة باللوح المرجعي، وبلغ الفارق الحراري الأقصى المسجل 10.5 درجة مئوية في الأجواء الصافية. كما ارتفعت القدرة الكهربائية للوح المبرد بنسبة تصل إلى 12%، وتحسنت كفاءته الكهربائية بمعدل يتراوح بين 8% و10%. ومن الجدير بالذكر أن نظام التبريد لا يحتاج إلى مصدر طاقة خارجي، مما يجعله فعالاً ومنخفض التكلفة. كما ساهمت سرعة الرياح في تحسين التبريد، خاصة عند تجاوزها 3.5 م/ث. وبشكل عام، أثبتت هذه التقنية فعاليتها في تحسين أداء الألواح الكهروضوئية في المناطق الحارة، وتمثل خياراً بسيطاً وقابلاً للتطبيق على نطاق واسع في البيئات الصحراوية وشبه الصحراوية مثل جنوب الجزائر.

Résumé

Cette étude porte sur la gestion thermique des modules photovoltaïques (PV) dans les zones à climat chaud, avec un accent particulier sur la région de Ouargla, au sud de l'Algérie, où les températures ambiantes élevées réduisent considérablement l'efficacité des panneaux et leur durée de vie. Elle traite du problème central de l'accumulation de chaleur dans les modules PV, pouvant entraîner une perte de puissance allant jusqu'à 25 % en raison du coefficient thermique négatif des cellules en silicium. L'objectif principal de ce travail est d'évaluer l'efficacité d'une technique de refroidissement passif basée sur l'utilisation de dissipateurs thermiques en aluminium fixés à l'arrière des modules PV, afin de réduire leur température de fonctionnement et d'améliorer leurs performances électriques dans des conditions réelles. Une installation expérimentale a été mise en place avec deux modules photovoltaïques polycristallins identiques, l'un équipé de dissipateurs thermiques (panneau refroidi) et l'autre utilisé comme référence sans refroidissement. Des thermocouples ont été installés pour surveiller la température, et les deux panneaux ont été connectés à des charges résistives identiques. Les mesures ont été réalisées pendant trois jours (28 et 29 avril, et 1er mai 2025) sous diverses conditions météorologiques (ensoleillées et partiellement nuageuses). Les résultats ont montré que le panneau refroidi fonctionnait à une température inférieure de 6 à 10 °C, avec un écart thermique maximal de 10,5 °C par temps clair. Le panneau refroidi a présenté une augmentation de la puissance électrique allant jusqu'à 12 % et une amélioration de l'efficacité électrique moyenne de 8 à 10 %. Le système de refroidissement ne nécessitant aucune source d'énergie externe, il est entièrement passif et économique. La présence du vent a également amélioré la dissipation thermique, notamment à des vitesses supérieures à 3,5 m/s. En conclusion, l'utilisation de dissipateurs thermiques passifs a permis une nette amélioration des performances des modules PV dans des environnements à haute température. Cette méthode simple et abordable est adaptée à un déploiement à grande échelle dans les régions arides et semi-arides comme le sud de l'Algérie.