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An Experimental Study on the Performance of a Photovoltaic Panel Using Cooling Systems

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Appreciation

First, we thank Almighty God for giving us the strength and patience to complete this work.

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Abstract:

This work presents an experimental study on the performance improvement of a photovoltaic panel using a passive cooling system. Photovoltaic modules operating in hot and arid regions are strongly affected by high temperatures, which reduce output voltage, electrical efficiency, and overall energy production. For this reason, thermal regulation represents an important factor for improving the reliability and performance of PV systems under desert climatic conditions.

The study was carried out under real outdoor conditions in Ghardaïa, Algeria, using two identical 100 W monocrystalline photovoltaic panels. One panel was used as a reference module without cooling, while the second one was equipped with a perforated finned aluminum plate mounted on the rear surface. Temperature, solar irradiance, and electrical parameters were measured and compared in order to evaluate the effect of the proposed cooling system.

The experimental results showed that the aluminum cooling system significantly reduced the operating temperature of the photovoltaic panel. The maximum temperature decreased from 65.54°C for the reference panel to 52.46°C for the cooled panel, corresponding to a reduction of approximately 13.08°C. This thermal improvement contributed to better operating conditions and enhanced electrical performance. Therefore, the proposed passive aluminum cooling system can be considered a simple, low-cost, and effective solution for improving photovoltaic panel performance in hot desert environments.

Keywords: Photovoltaic panel; Passive cooling; Aluminum fins; Temperature reduction; Electrical performance; Ghardaïa; Desert climate.

الملخص:

تتناول هذه الدراسة تجربة عملية لتحسين أداء اللوح الكهروضوئي باستعمال نظام تبريد سلبي. تتأثر الألواح الكهروضوئية العاملة في المناطق الحارة والجافة بدرجات الحرارة المرتفعة، مما يؤدي إلى انخفاض الجهد الكهربائي والمردودية الكهربائية والإنتاج الطاقوي العام. لذلك تُعد عملية التحكم الحراري عاملاً مهماً في تحسين موثوقية وأداء الأنظمة الكهروضوئية في الظروف المناخية الصحراوية.

أُجريت هذه الدراسة في ظروف خارجية حقيقية بمدينة غرداية، الجزائر، باستعمال لوحين كهروضوئيين متماثلين من نوع أحادي البلورة بقدرة 100 واط. استعمل اللوح الأول كمرجع دون تبريد، بينما زُوِّد اللوح الثاني بصفيحة ألومنيوم مثقبة مزودة بزعانف ومثبتة على الجهة الخلفية للوح. تم قياس درجة الحرارة والإشعاع الشمسي وبعض الخصائص الكهربائية ومقارنتها من أجل تقييم فعالية نظام التبريد المقترح.

أظهرت النتائج التجريبية أن نظام التبريد بالألومنيوم ساهم في خفض درجة حرارة تشغيل اللوح الكهروضوئي بشكل ملحوظ، حيث انخفضت درجة الحرارة القصوى من 65.54 درجة مئوية في اللوح المرجعي إلى 52.46 درجة مئوية في اللوح المبرد، أي بانخفاض قدره حوالي 13.08 درجة مئوية. وقد ساهم هذا التحسن الحراري في توفير ظروف تشغيل أفضل وتحسين الأداء الكهربائي للوح. وعليه، يمكن اعتبار نظام التبريد السلبي المعتمد على الألومنيوم حلاً بسيطاً ومنخفض التكلفة وفعالاً لتحسين أداء الألواح الكهروضوئية في البيئات الصحراوية الحارة.

الكلمات المفتاحية: اللوح الكهروضوئي؛ التبريد السلبي؛ زعانف الألومنيوم؛ خفض درجة الحرارة؛ الأداء الكهربائي؛ غرداية؛ المناخ الصحراوي.

Résumé :

Ce travail présente une étude expérimentale sur l'amélioration des performances d'un panneau photovoltaïque à l'aide d'un système de refroidissement passif. Les modules photovoltaïques fonctionnant dans les régions chaudes et arides sont fortement affectés par les températures élevées, qui réduisent la tension de sortie, le rendement électrique et la production énergétique globale. Pour cette raison, la régulation thermique représente un facteur important pour améliorer la fiabilité et les performances des systèmes photovoltaïques dans des conditions climatiques désertiques.

L'étude a été réalisée dans des conditions réelles en extérieur à Ghardaïa, en Algérie, en utilisant deux panneaux photovoltaïques monocristallins identiques de 100 W. L'un des panneaux a été utilisé comme module de référence sans refroidissement, tandis que le second a été équipé d'une plaque en aluminium à ailettes perforées montée sur la surface arrière. La température, l'irradiance solaire et les paramètres électriques ont été mesurés et comparés afin d'évaluer l'effet du système de refroidissement proposé.

Les résultats expérimentaux ont montré que le système de refroidissement en aluminium réduisait significativement la température de fonctionnement du panneau photovoltaïque. La température maximale est passée de 65,54 °C pour le panneau de référence à 52,46 °C pour le panneau refroidi, ce qui correspond à une réduction d'environ 13,08 °C. Cette amélioration thermique a contribué à de meilleures conditions de fonctionnement et à une amélioration des performances électriques. Par conséquent, le système de refroidissement passif en aluminium proposé peut être considéré comme une solution simple, peu coûteuse et efficace pour améliorer les performances des panneaux photovoltaïques dans les environnements désertiques chauds.

Mot-Clé: Panneau photovoltaïque; Refroidissement passif; Ailettes en aluminium; Réduction de température; Performance électrique; Ghardaïa; Climat désertique.

Table of Contents

Table of Contents:

Appreciation	I
Abstract:	II
Table of Contents:	IV
List of Figures:	VI
List of Tables:	VIII
General Introduction.....	1
Chapter I: Generalities PV Systems	
I.1 Introduction	4
I.2 What is photovoltaic?.....	4
I.2.1 Global Renewable Energy and Photovoltaic Potential.....	5
I.2.2 The Photovoltaic Market and Cost Evolution	6
I.3 Solar cell.....	6
I.4 The Effect of Temperature on Photovoltaic Panel Efficiency:	7
I.5 Working Principle of a Photovoltaic (PV) Panel	8
I.6 Types of photovoltaic technology	8
I.6.1 Monocrystalline silicon photovoltaic panels:	8
I.6.2 Polycrystalline silicon photovoltaic panels:	9
I.6.3 Amorphous (“thin-film”) silicon photovoltaic panels:	9
I.7 Enhancement of Thermal Conductivity	10
I.7.1 Effect of Fin Geometry on Cooling Efficiency	10
I.7.2 Rectangular/Square Fins.....	11
I.7.3 Cylindrical (Pin) Fins:	11
I.7.4 Triangular/Trapezoidal Fins	11
I.8 Energy Profile and Photovoltaic Initiatives in Algeria	12
I.8.1 Energy Production, Consumption, and CO ₂ Emissions Context.....	12
I.8.2 The Renewable Energy and Energy Efficiency Development Program (REEEDP)....	13
I.8.3 Current Implementation and Installed PV Plants in Algeria	14
I.9 Problem Statement: The Arid and Saharan Climate Challenge	15
I.10 Conclusion.....	16
Chapter II: Previous Studies	
II.1 Introduction.....	18
II.2 Traditional methods of cooling PV panels.....	18
II.2.1 Advanced Material-Based Cooling	18
II.2.2. Innovative Evaporative Techniques	19
II.2.3. Electronic and Hybrid Systems	19
II.3 Phase Change Material (PCM) Cooling	20
II.3.1 Radioactive Cooling Coatings.....	20
II.3.2 Passive Air Cooling (Natural Convection)	20
II.3.3 Active Air Cooling (Forced Convection).....	21
II.3.4 Direct Water Cooling (Spraying/Immersion).....	21
II.3.5 Phase Change Material (PCM) Cooling	22
II.3.6 Phase Change Material (PCM) Cooling.....	23
II.4. Phase Change Material (PCM) Cooling	23
II.4.1 Evaporative Cooling (Natural Materials).....	23
II.4.2 Thermoelectric Cooler (TEC) Modules	24
II.4.3 Hybrid and Nanofluid Systems	24
II.4.4 cooling using phase change materials (PCMs)	24
II.5. Water Cooling.....	25
II.5.1. Front surface water cooling.....	25
II.5.2 Back surface water cooling	26

Table of Contents

II.6 Cooling using Phase Change Materials (PCM)	27
II.7 Peltier	28
II.8 Fins.....	29
II.8.1. Definition	29
II.8.2. Selection of Fins.....	29
II. 9. Conclusion	30
Chapter III: Results and discussion	
III.1 Introduction	32
III.2 Description of the Experimental Setup.....	32
III.3 Different measurement equipment:	34
III.4 Conclusion.....	37
Chapter IV: Results and discussion	
IV.1 Introduction	39
IV.2 Experimental results and explanation.....	39
IV.2.1 Comparative experimental data under real operating conditions	39
IV.3 Temperature Analysis	43
IV.3.1 Temperature difference analysis between aluminum-cooled and reference panels ..	43
IV.3.2 Temperature trend of the aluminum-cooled panel	44
IV.3.3 Temporal evolution of aluminum panel temperature	45
IV.4 Analysis of Delta Voltage ΔV	46
IV.4.1 Open-circuit voltage evolution for the aluminum-cooled panel.....	46
IV.4.2 Reference open-circuit voltage evolution.....	47
IV.4.3 Comparative thermal and electrical performance.....	48
IV.5 Conclusion.....	50
General Conclusion:	53
Bibliography:.....	56

List of Figures

List of Figures:

Figure I. 1: Photovoltaic System [1].....	5
Figure I. 2: Global Cumulative Renewable Energy Capacity Evolution and Technology Mix Shares (2010–2019).....	5
Figure I.3: Historical Trajectory of Levelized Cost of Electricity (LCOE) and Cost Reduction Percentage for Commercial Photovoltaics vs. Alternative Renewable Technologies (2010–2019).....	6
Figure I. 4: The Effect of Temperature on Photovoltaic Panel Efficiency.....	7
Figure I. 5: Principle of Operation of Photovoltaic Solar Panels	8
Figure I.6: Monocrystalline silicon photovoltaic panels	9
Figure I. 7: Polycrystalline silicon photovoltaic panels.	9
Figure I. 8: Amorphous silicon photovoltaic panels.....	10
Figure I.9: Comparison of Fin Geometries for PV-PCM Cooling	11
Figure I.10: Correlation Curve Between National Electricity Consumption Growth and Cumulative Annual CO ₂ Emissions in Algeria (2010–2018).....	13
Figure I.11: Capacity allocation shares and technology distribution targets of the algerian renewable energy and energy efficiency development program (REEEDP) by 2030	14
Figure I.12: PV sites localisation of REEEDP	15
Figure I.13: Electrical Characteristic Curves I-V and P-V of a Crystalline Photovoltaic Module Showing Performance and Power Max P_{max} Degradation under Rising Cell Operating Temperatures 25 °C to 75°C.	16
Figure II. 1: Schematic of active PV/T cooling system with fluid circulation loop.....	20
Figure II. 2: Hybrid PV/T system featuring PCM and active nanofluid cooling channels.	20
Figure II.3: Exploded view of AE320M6-60 PV panel with attached aluminum heat sink plate [11].	21
Figure II.4: Bench setup of the PV/T air-cooled system showing the integration of data acquisition and solar monitoring instruments.....	21
Figure II.5: Thermal management of photovoltaic modules using a phase change material with internal fins.....	22
Figure II. 6: The Physical Model of PV-PCM with Fin Enhancement.	23
Figure II. 7: PCM in PV systems: Enhanced Performance	25
Figure II. 8: (A) Schematic diagram of the PV with cooling sprayers [15]	26
Figure II. 9: A view of Water spraying [16].....	26
Figure II. 10: System diagram [17]	27
Figure II. 11: Schematic diagram of water-based PV/T-PCM system (dimensions in mm) [18]	28
Figure II. 12: Peltier effet [19].....	28
Figure II. 13: Heat sink configuration on the back of the PV panel.....	29
Figure III.1 : Aluminum plate used in the cooling system prior to installation	33
Figure III.2: Aluminum plate equipped with vertical cooling fins mounted at the rear of the photovoltaic panel.	34
Figure III.3: Two 100W Monocrystalline Silicon Photovoltaic Panels.	35

List of Figures

Figure IV.1: Temperature comparison between the reference photovoltaic panel and the aluminum-cooled panel.	40
Figure IV. 2: Solar irradiance variation during the experimental measurement period.	41
Figure IV.3: Open-circuit voltage comparison between the reference photovoltaic panel and the aluminum-cooled panel.	42
Figure IV.4: Temperature comparison and Delta T between aluminum-cooled and reference panels.	43
Figure IV.5: Temperature trend of the aluminum-cooled photovoltaic panel.....	44
Figure IV.6: Temporal evolution of the aluminum panel temperature.....	45
Figure IV.7: Open-circuit voltage evolution for the aluminum-cooled photovoltaic panel.	46
Figure IV.8: Reference photovoltaic module open-circuit voltage evolution.	47
Figure IV.9: Comparative thermal and electrical performance of the reference and aluminum-cooled PV modules.....	49

List of Tables

List of Tables:

Table II.1: Classification of fins types.....	30
Table III.1: Experimental setup instrumentation and measurement ranges.	34
Table III.2: Electrical Characteristics and Technical Specifications of the PV Module.....	36
Table IV. 1: Comparative experimental data for reference and aluminum-cooled photovoltaic panels under different irradiance levels.....	39
Table IV.2: Comparative thermal and electrical performance between the reference and aluminum-cooled PV modules.	48

General Introduction

General Introduction

Solar energy is one of the most promising renewable energy sources due to its abundance, cleanliness, and suitability for electricity generation in remote and sunny regions. Photovoltaic systems convert solar radiation directly into electrical energy through semiconductor materials, making them widely used in both small-scale and large-scale applications. In Algeria, and particularly in the southern regions, the high level of solar irradiation offers an important opportunity for the development of photovoltaic energy.

However, the performance of photovoltaic panels does not depend only on the amount of received solar radiation. It is also strongly affected by operating temperature. Under hot and arid climatic conditions, the temperature of PV cells can rise significantly during the day. This increase causes a decrease in output voltage, reduces electrical efficiency, and may accelerate the degradation of the module materials. Therefore, improving the thermal behavior of photovoltaic panels is necessary for maintaining stable electrical performance and increasing energy production.

Several cooling techniques have been proposed to limit the negative effect of temperature on PV panels. These techniques include active cooling methods, such as water and forced-air cooling, and passive cooling methods, such as heat sinks, fins, and phase change materials. Passive cooling systems are particularly interesting because they are simple, inexpensive, do not require additional electrical energy, and can be adapted to desert environments.

Problem Statement

Photovoltaic panels installed in hot and arid regions such as southern Algeria are exposed to very high ambient temperatures and intense solar radiation. Although these conditions provide abundant solar energy, they also lead to a significant increase in PV cell temperature, which reduces electrical efficiency, decreases power output, and accelerates material degradation. Therefore, improving the thermal management of PV modules has become essential to ensure reliable and efficient energy production. In this context, the main question is:

How effective is a passive cooling system based on a perforated finned aluminum plate in reducing the operating temperature of photovoltaic panels and improving their electrical performance under the desert climatic conditions of Ghardaïa, Algeria?

Objectives of the Study

The main objective of this study is to experimentally evaluate the effect of a passive cooling system on the thermal and electrical performance of a photovoltaic panel under real outdoor conditions. More specifically, this work aims to compare the temperature evolution of a reference PV panel and an aluminum-cooled PV panel, determine the temperature reduction achieved by the cooling system, analyze the effect of cooling on electrical voltage stability, and assess the suitability of perforated aluminum fins as a simple and low-cost cooling solution for photovoltaic systems in desert climates.

Methodology

The experimental study was conducted using two identical 100 W monocrystalline photovoltaic panels. One panel was left without cooling and used as a reference, while the second panel was equipped with a perforated finned aluminum plate fixed to its rear surface. Measurements were taken under real climatic conditions in Ghardaïa. The main measured parameters included panel temperature, solar irradiance, and open-circuit voltage. The results obtained from the reference and cooled panels were then compared in order to evaluate the thermal and electrical impact of the proposed passive cooling system.

Structure of the Dissertation

This dissertation is divided into three chapters. The first chapter presents general concepts related to photovoltaic systems, including the working principle of PV panels, the main types of photovoltaic technologies, the influence of temperature on PV efficiency, and the solar potential of Algeria. The second chapter reviews previous studies and cooling techniques used for photovoltaic panels, with a focus on passive cooling systems, water cooling, phase change materials, Peltier modules, and fins. The third chapter presents the experimental setup, measurement equipment, obtained results, and discussion of the thermal and electrical performance of the cooled and reference photovoltaic panels. Finally, the general conclusion summarizes the main findings and highlights the effectiveness of the proposed passive aluminum cooling system.

Chapter I:
Generalities PV Systems

I.1 Introduction

Excessive consumption of traditional fossil energies resulted in an energy crisis and an increase in environmental concerns, and dense emissions from harmful greenhouse gases that cause global warming, threatening the security of people and the future of the world. Demands for renewable and clean energies have increased to reduce dependence on traditional fossil energies and reduce associated environmental concerns. Solar energy is the best source of renewable energy due to its cleanliness, accessibility, sustainability and unlimited potential. Photovoltaic conversion is direct conversion of electromagnetic energy (radiation)

into direct current electrical energy. The main ingredient in this conversion is solar photovoltaic cell. In this chapter, generalities of solar photovoltaic are shown.

I.2 What is photovoltaic?

Solar photovoltaic (PV) technology is a method of converting solar radiation directly into direct current (DC) electricity through the photovoltaic effect. The term "photovoltaic" combines "photo," derived from the Greek *phōs* meaning light, and "voltaic," referring to Alessandro Volta, a pioneer in electrical science

In a PV system, solar cells—typically made from semiconductor materials like crystalline silicon—absorb incident photons from sunlight. When these photons possess energy greater than the material's band gap, they excite electrons, dislodging them from their atomic bonds and creating electron-hole pairs. An internal electric field at the p-n junction drives these charge carriers in opposite directions, resulting in an electric current when the circuit is closed.

This process, while appearing straightforward, involves intricate quantum and solid-state physics. Solar PV devices are modular in nature and can be scaled from single cells powering calculators to large-scale solar arrays generating megawatts of electrical power for the grid.

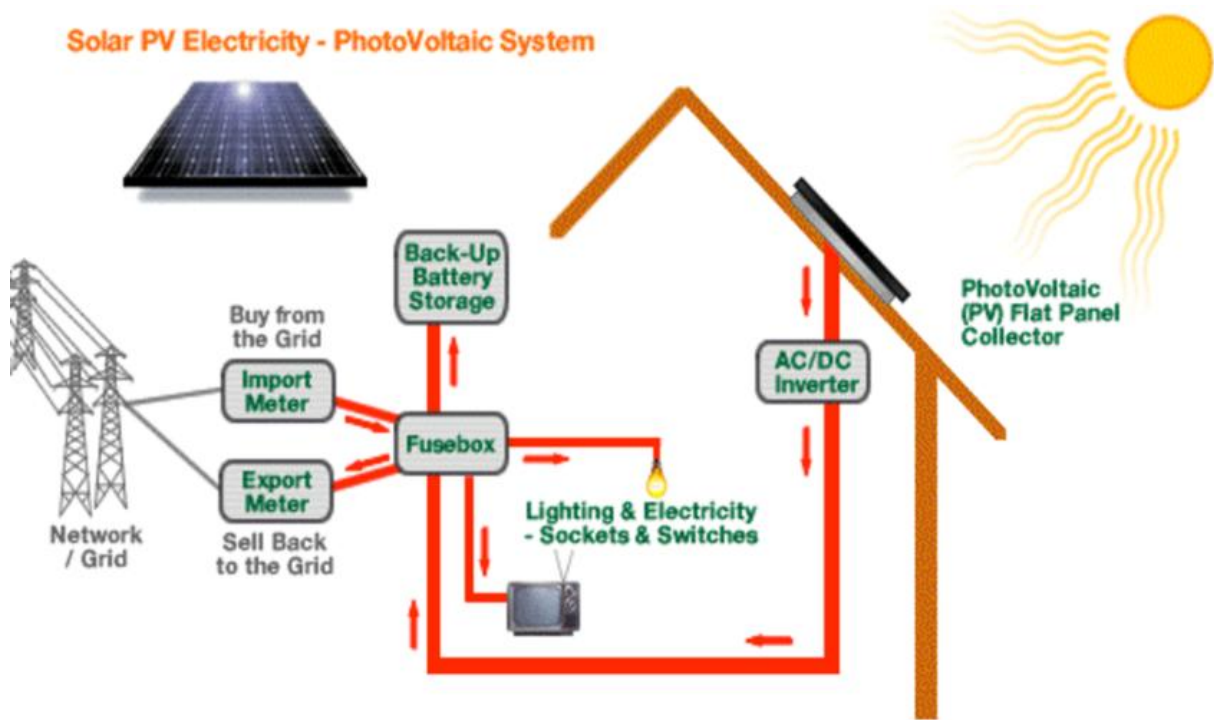


Figure I. 1: Photovoltaic System [1]

I.2.1 Global Renewable Energy and Photovoltaic Potential

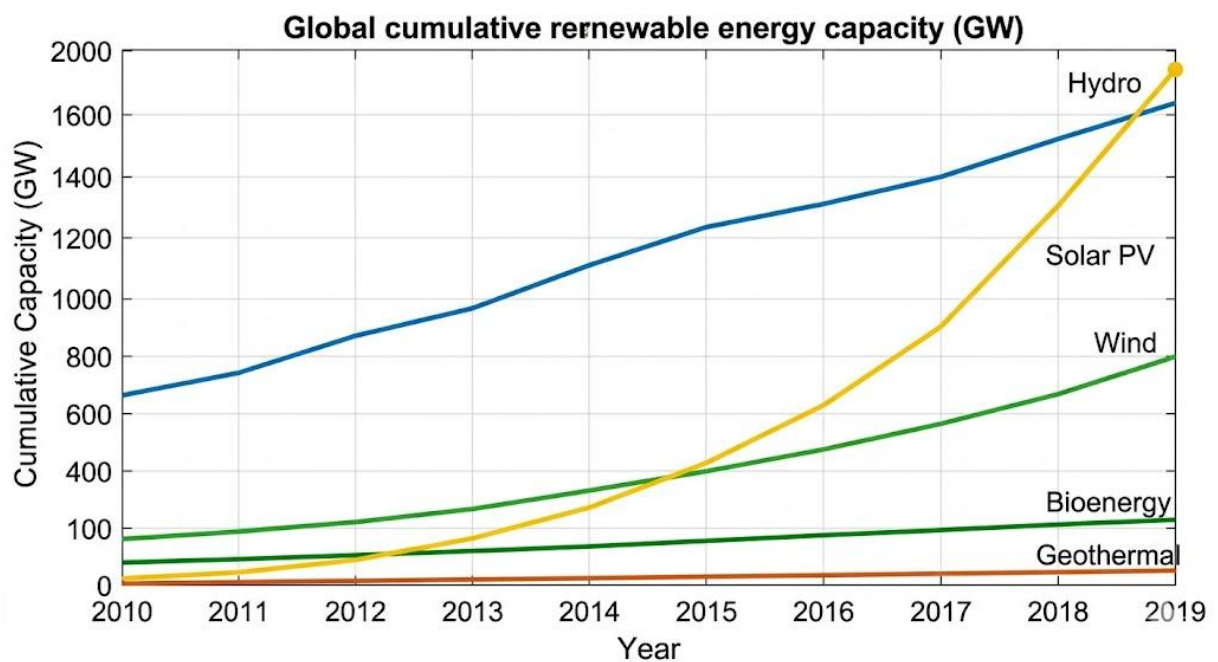


Figure I. 2: Global Cumulative Renewable Energy Capacity Evolution and Technology Mix Shares (2010–2019)

I.2.2 The Photovoltaic Market and Cost Evolution

The monumental expansion of solar photovoltaic infrastructure is fundamentally driven by a steep reduction in capital and operational deployment costs. This rapid decline is a direct consequence of mature manufacturing supply chains, developer experience, and material science refinements. Over a single decade (2010–2019), the levelized cost of electricity generated via solar PV dropped precipitously by 82%, plummeting from USD 0.378/kWh in 2010 down to USD 0.068/kWh in 2019. This represents the sharpest cost contraction among all renewable energy options, outperforming concentrated solar power (CSP) at a 47% reduction and onshore wind at 39% over the same timeframe. Consequently, solar PV has positionally established itself as the most economical framework for new utility-scale electricity generation globally, presenting immense potential to stimulate economic growth and introduce new industrial labor opportunities

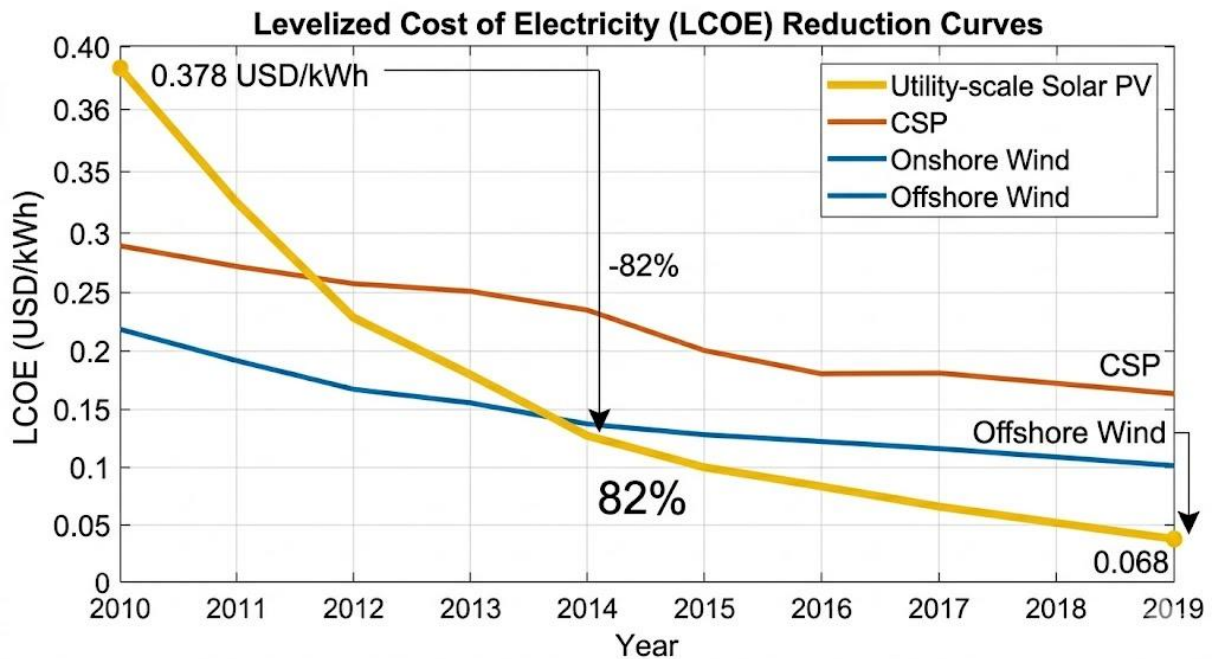


Figure I.3: Historical Trajectory of Levelized Cost of Electricity (LCOE) and Cost Reduction Percentage for Commercial Photovoltaics vs. Alternative Renewable Technologies (2010–2019)

I.3 Solar cell

Any device that directly converts the energy of light into electrical energy through the photovoltaic effect. The overwhelming majority of solar cells are fabricated from silicon—with increasing efficiency and lowering cost as the materials range from amorphous (monocrystalline) to polycrystalline to crystalline (single crystal) silicon forms. Unlike batteries

or fuel cells, solar cells do not utilize chemical reactions or require fuel to produce electric power, and, unlike electric generators, they do not have any moving parts.

I.4 The Effect of Temperature on Photovoltaic Panel Efficiency:

The efficiency of photovoltaic (PV) panels decreases as temperature increases because higher cell temperatures reduce the semiconductor bandgap and increase internal losses. As a result, the output voltage drops more significantly than the current increases, leading to an overall reduction in power. This relationship is typically shown as a downward-sloping curve, where efficiency is highest at lower temperatures (around 25 °C standard test conditions) and declines almost linearly as temperature rises, as mentioned in study achieved at ouargla in .

The effect of temperature and irradiance on the output power and efficiency of a PV module can be expressed mathematically as follows:

$$P_m = P_{m,STC} \cdot [1 + \gamma_{P_m}(T_{pv} - 25) + \delta \cdot \ln(I_r/1000)] \cdot (I_r/1000)$$

$$\eta_{pv} = \eta_{STC} \cdot [1 + \gamma_{P_m}(T_{pv} - 25) + \delta \cdot \ln(I_r/1000)]$$

where:

- P_m : maximum power (W)
- $P_{m,STC}$: power at standard conditions
- T_{pv} : cell temperature (°C)
- I_r : irradiance (W/m²)

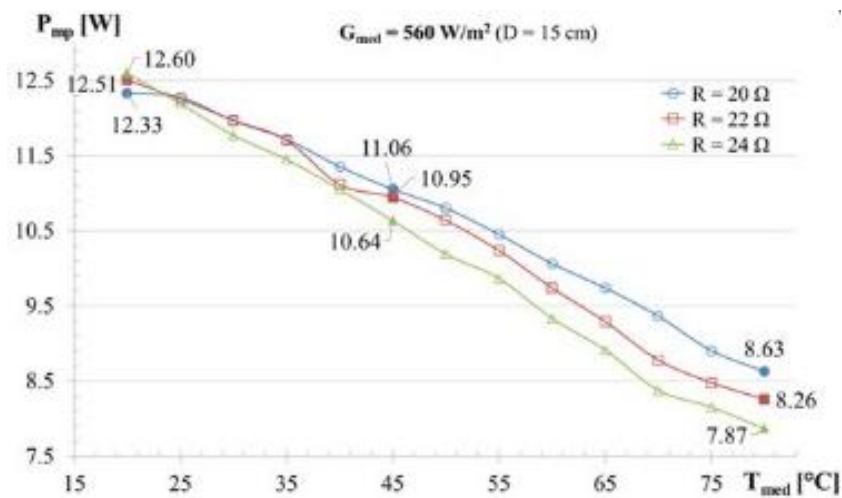


Figure I. 4: The Effect of Temperature on Photovoltaic Panel Efficiency

I.5 Working Principle of a Photovoltaic (PV) Panel

The working principle of a photovoltaic (PV) panel is based on the photovoltaic effect, where solar cells made of semiconductor materials such as silicon absorb sunlight and convert it into electrical energy. When photons from solar radiation strike the surface of the cell, they transfer their energy to electrons, causing them to become excited and move freely. This movement of electrons generates an electric current, while the built-in electric field within the cell creates a potential difference (voltage). When the cell is connected to an external circuit, the flow of electrons produces usable electrical power.

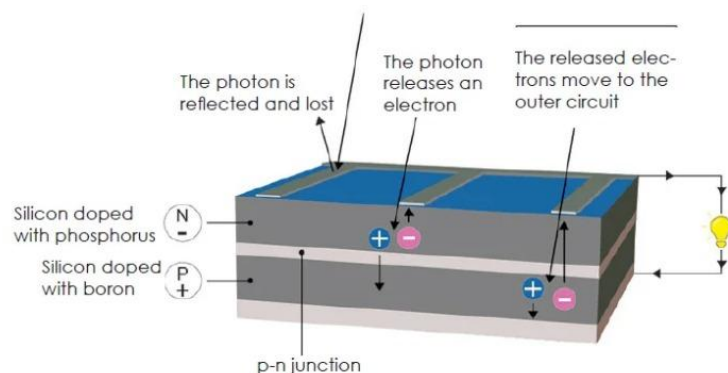


Figure I. 5: Principle of Operation of Photovoltaic Solar Panels

I.6 Types of photovoltaic technology

The solar PV panel is the main building block of a PV system. While these systems all tend to look I.6.1 Polycrystalline silicon photovoltaic panels: very similar, the PV technology at the heart of these panels can vary. These include:

I.6.1 Monocrystalline silicon photovoltaic panels:

These panels are manufactured using cells cut from a single, continuous silicon crystal, resulting in a highly ordered atomic structure. Monocrystalline technology is known for its high efficiency, often converting around 15% of solar energy into electricity. This superior performance is due to the high purity of the silicon used. However, the intricate and energy-intensive manufacturing process makes these panels more expensive than other types

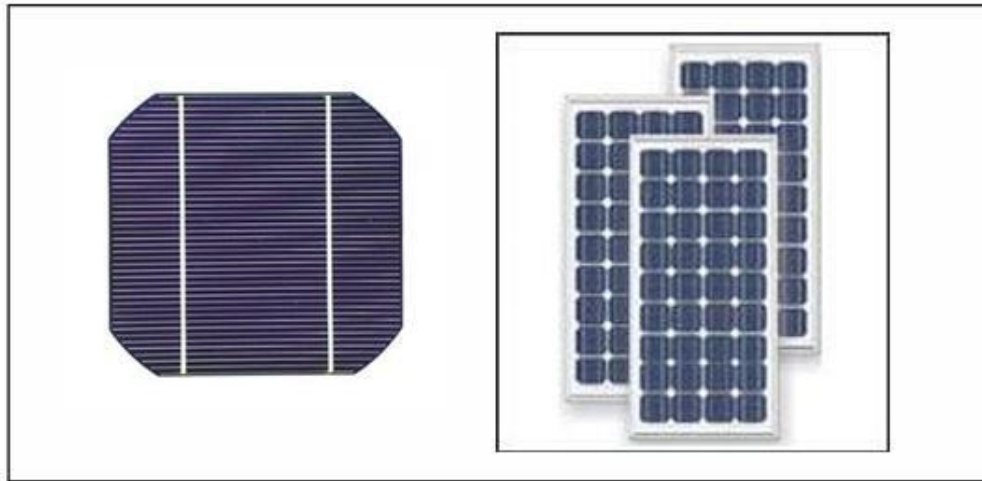


Figure I.6: Monocrystalline silicon photovoltaic panels .

I.6.2 Polycrystalline silicon photovoltaic panels:

Polycrystalline panels, also referred to as multicrystalline, are created by melting silicon and allowing it to solidify into large blocks. These blocks are then sliced into thin wafers and assembled into solar cells. This manufacturing method is less complex and more cost-effective compared to monocrystalline production. However, this simplicity comes with a trade-off: lower efficiency, typically around 12%, due to the less organized crystal structure

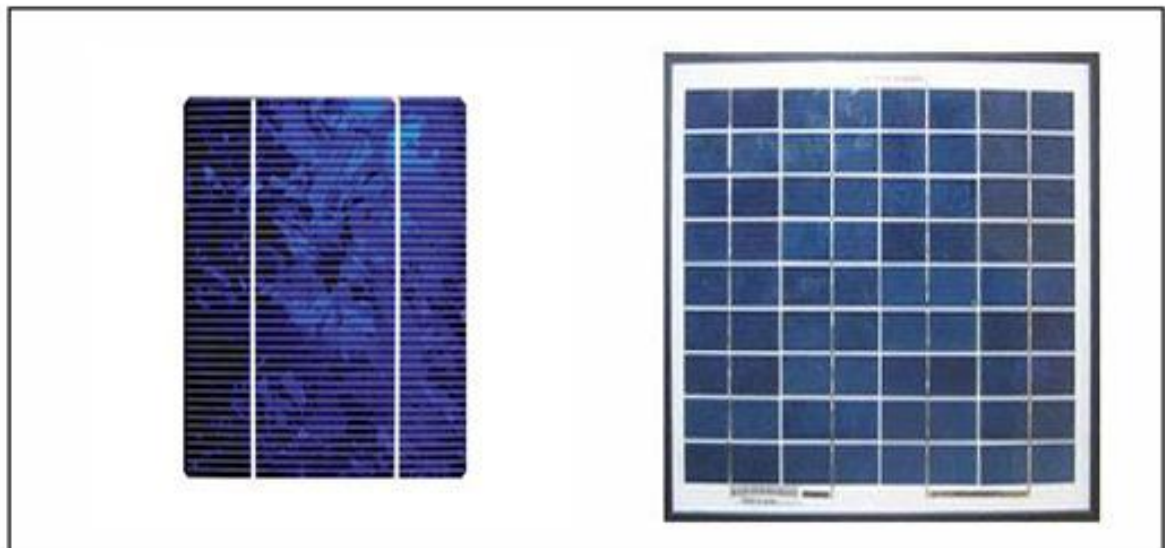


Figure I. 7: Polycrystalline silicon photovoltaic panels.

I.6.3 Amorphous (“thin-film”) silicon photovoltaic panels:

Amorphous silicon solar cells are a type of photovoltaic technology where a thin, non-crystalline layer of silicon is deposited onto a substrate. These cells offer enhanced light

absorption compared to crystalline silicon, enabling the production of thinner, more flexible solar panels. Due to their flexibility, they can be applied to a wide range of surfaces, including both rigid and curved ones. While their efficiency is lower—typically around 6%—they are cost-effective and easier to manufacture. This makes them particularly suitable for large-scale applications where low production cost is a priority, such as in building-integrated photovoltaics and large-area installations.

In addition to electrical performance, thermal management plays a crucial role in improving PV efficiency.



Figure I. 8: Amorphous silicon photovoltaic panels.

I.7 Enhancement of Thermal Conductivity

The Role of Heat Sinks (Fins) While Phase Change Materials (PCM) are excellent for latent heat storage, their primary drawback is low thermal conductivity (typically $0.2 \text{ W/m} \cdot \text{K}$ for paraffin wax). This limitation prevents the heat from the PV panel from reaching the core of the PCM quickly. To overcome this, Heat Sinks (metallic fins) are integrated into the PCM container to act as thermal bridges

I.7.1 Effect of Fin Geometry on Cooling Efficiency

The geometry and arrangement of fins significantly influence the melting rate and temperature distribution within the PCM. The most common geometries include:

I.7.2 Rectangular/Square Fins

These are the most widely used due to their ease of fabrication. They provide a large surface area for heat conduction, helping to maintain a uniform temperature across the back of the PV panel.

I.7.3 Cylindrical (Pin) Fins:

These offer a high surface-area-to-volume ratio. Their circular geometry promotes better natural convection within the liquid PCM as it melts, which can lead to faster heat dissipation compared to longitudinal fins.

I.7.4 Triangular/Trapezoidal Fins

These are designed to optimize material use (weight reduction) while maintaining high thermal performance near the heat source.

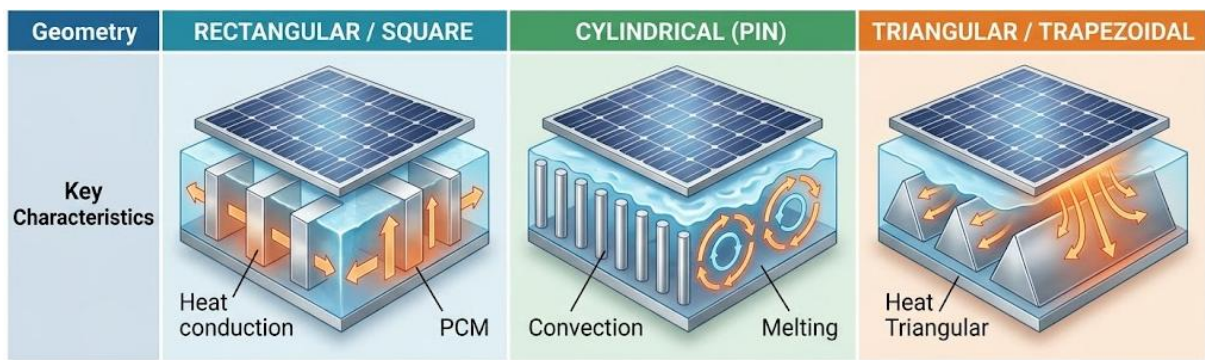


Figure I.9: Comparison of Fin Geometries for PV-PCM Cooling

Fin Geometry	Key Characteristics	Primary Advantages	Impact on PCM Performance
Rectangular / Square	Most widely used geometry.	Ease of fabrication.	Provides a large surface area for heat conduction and maintains a uniform temperature across the PV panel.
Cylindrical (Pin)	Circular geometry with a high surface-area-to-volume ratio.	Promotes better natural convection within the liquid PCM.	Leads to faster heat dissipation compared to longitudinal fins as the PCM melts.
Triangular / Trapezoidal	Optimized shape for material efficiency.	Significant weight reduction.	Maintains high thermal performance specifically near the heat source.

Comparison of solar cells to batteries, fuel cells, and electric generators regarding chemical reactions and moving parts

I.8 Energy Profile and Photovoltaic Initiatives in Algeria

I.8.1 Energy Production, Consumption, and CO₂ Emissions Context

Algeria possesses significant, diversified primary energy assets, with global rankings in natural gas reserves matching vast operational fields of crude oil and condensate. Historically, commercial hydrocarbon production stabilized across most commodity streams until 2016, at which point gas extractions were scaled sharply to reach 92,106 K to by 2018 to offset liquid hydrocarbon constraints linked to OPEC output caps. Domestically, fossil fuels represent the absolute foundation of the national energy balance, with final consumption surging to 48.1 Mtoe in 2018 marking an abrupt 7.8% annual increase dominated by natural gas, liquefied petroleum gas (LPG), and refined petroleum distribution.

Concurrently, the domestic power sector has expanded massively to generalize household electrification, achieving a geographical coverage rate of nearly 99% across more than six million residential consumers managed under the national Sonelgaz grid. This universal electrification, combined with rising demographic density and changing socio-economic requirements, has driven a sharp upward trajectory in power demand. National electricity consumption expanded from 36.58 TWh in 2010 to 66.67 TWh in 2018, representing a compounding annual growth rate of roughly 10%. Because conventional power plants rely almost exclusively on fossil gas combustion, national carbon dioxide emissions have mirrored this growth, escalating from 95.5 Mt in 2010 to 137.3 Mt by 2018. This environmental strain necessitates an immediate strategic pivot toward sustainable energy integration to decouple economic progression from carbon-intensive power generation. [2]

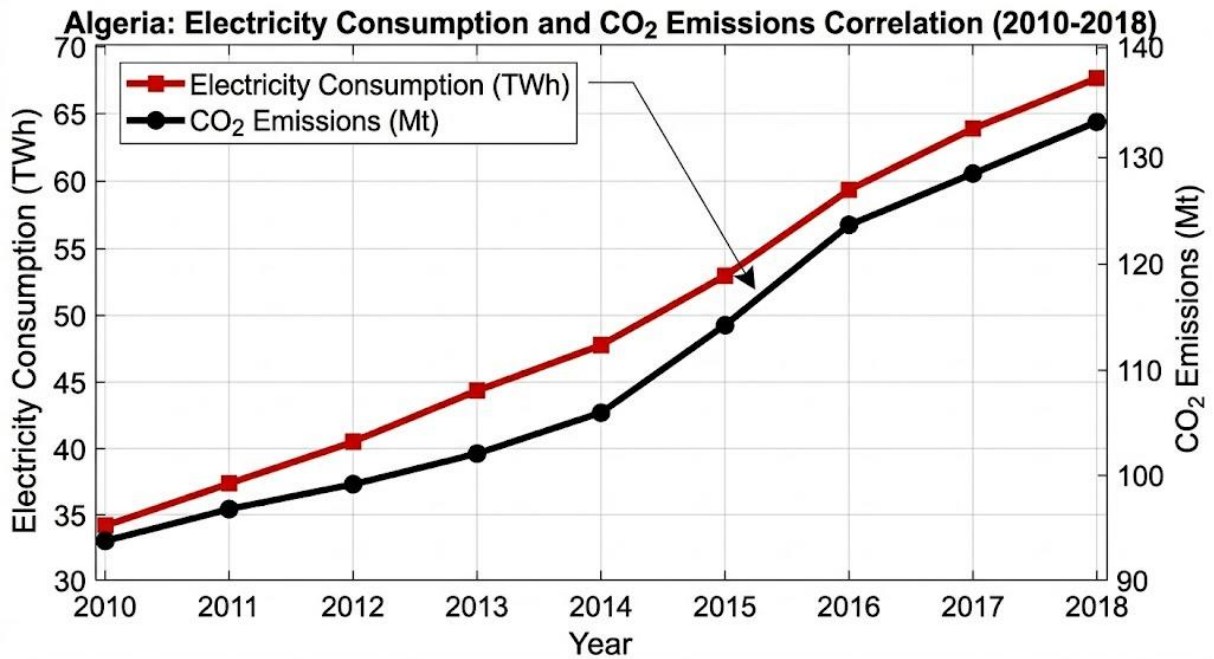


Figure I.10: Correlation Curve Between National Electricity Consumption Growth and Cumulative Annual CO₂ Emissions in Algeria (2010–2018).

1.8.2 The Renewable Energy and Energy Efficiency Development Program (REEEDP)

To counter environmental degradation and preserve domestic hydrocarbon assets for long-term export markets, the Algerian government launched the Renewable Energy and Energy Efficiency Development Program (REEEDP). The strategic blueprint targets a cumulative renewable capacity generation of 22,000 MW by the year 2030. Under this framework, 12,000 MW is allocated to satisfy escalating domestic grid demands, while the remaining 10,000 MW is intended for cross-border international energy exportation. Following a comprehensive strategic revision in 2015 to align with shifting global capital expenses, solar photovoltaic technology was designated as the primary pillar of the program. Out of the total 22,000 MW target, solar PV represents the dominant share at 13,575 MW (61.70%), far exceeding wind power at 5,010 MW (22.77%), concentrated solar power (CSP) at 2,000 MW (9.1%), and biomass/cogeneration configurations. [3]

Algeria Renewable Energy Program (REEEDP): Targeting 22,000 MW by 2030

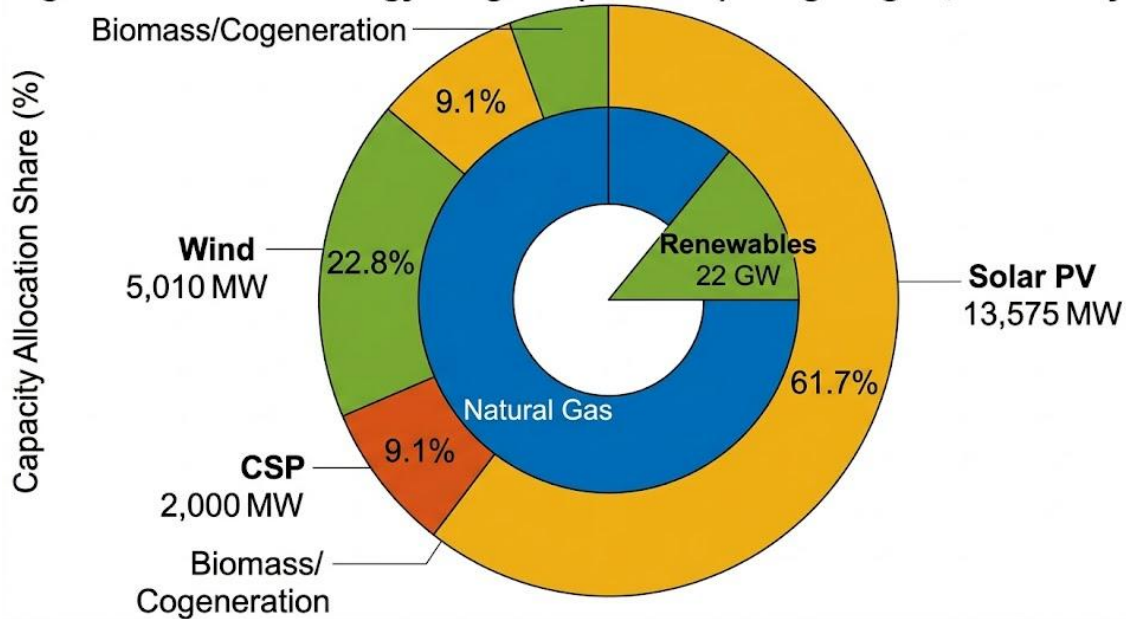


Figure I.11: Capacity allocation shares and technology distribution targets of the algerian renewable energy and energy efficiency development program (REEEDP) by 2030

I.8.3 Current Implementation and Installed PV Plants in Algeria

Despite clear long-term policy targets, the practical deployment of utility-scale projects on the ground has progressed at a slower rate than initially planned. By 2020, the original schedule of the REEEDP had not been fully met. The actual grid-tied renewable asset base remains predominantly dominated by a 343 MW utility-scale portfolio delivered by Shariket Kahraba wa Taket Moutadjadida (SKTM), a subsidiary of Sonelgaz. This operational baseline includes 22 solar PV installations spread across key wilayas, headlined by large plants in El-Khnag, Laghouat (40 MW), Ain-El-Ibl, Djelfa (33 MW), Ain-Skhouna, Saida (30 MW), and El-Hadjira, Ouargla (30 MW).

Additionally, the state energy firm SONATRACH integrated a 10 MW solar PV plant in Bir-Rebaa North (BRN) within the Ouargla wilaya as part of its SH2030 modernization strategy, which aims for 2,300 MW of self-generation solar assets by 2030. This brings the total completed capacity delivered across utility networks to approximately 354.1 MW. [5]

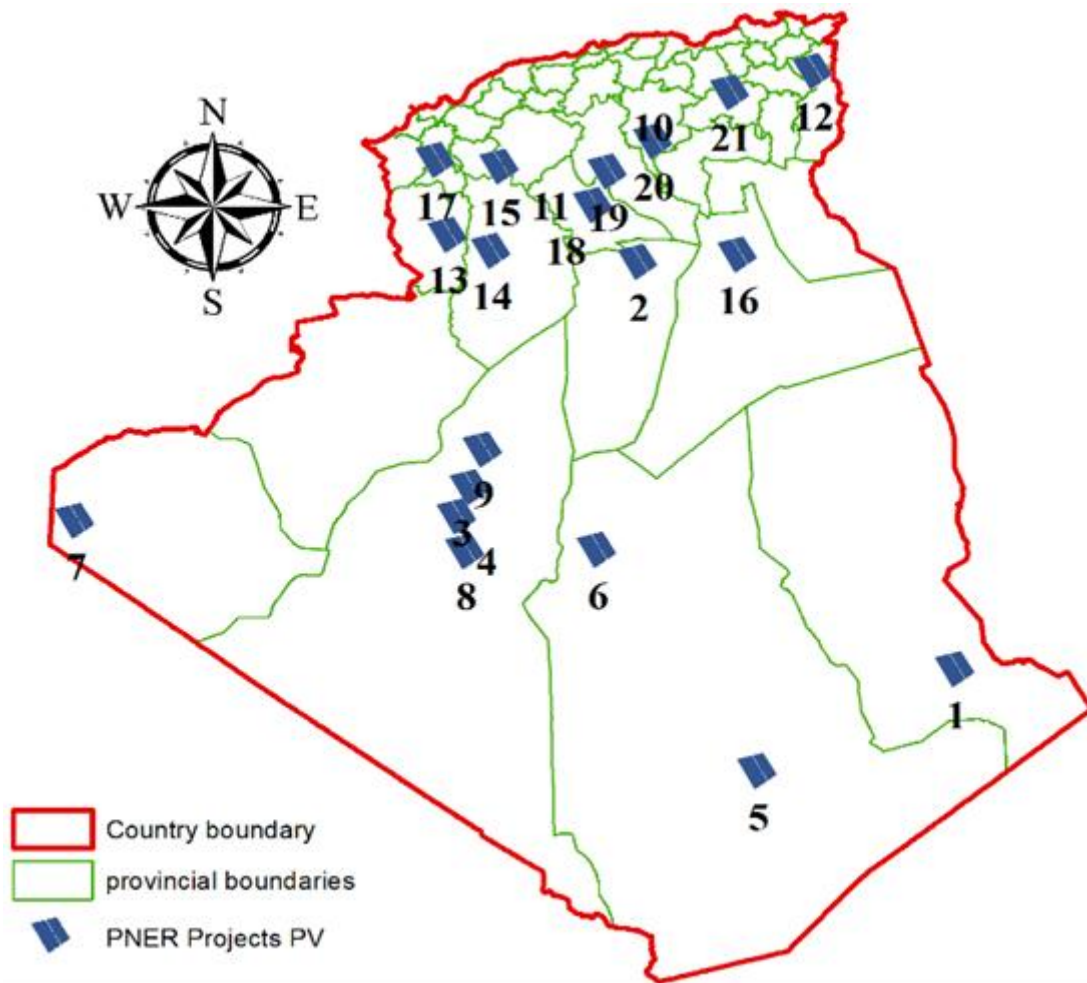


Figure I.12: PV sites localisation of REEEDP

I.9 Problem Statement: The Arid and Saharan Climate Challenge

A critical spatial analysis of Algeria's solar portfolio reveals that more than 75% of all installed operational PV capacities are purposefully located within the central and southern desert regions of the country, such as Laghouat, Djelfa, Adrar, and Ouargla. These installations are strategically positioned to leverage the peak solar irradiation densities and maximum clearing hours inherent to the Saharan environment. However, these identical geographic zones are defined by an extreme desert climate that imposes severe, interrelated degradation penalties on the performance, real-world conversion efficiency, and operational lifecycles of standard photovoltaic modules.

The primary environmental restrictions are twin-fold: severe atmospheric dust soiling and extreme thermal operating profiles. Desert solar plants face significant performance drops due to aggressive soiling from frequent sandstorms, which rapidly decrease the transmittance of front glass covers and limit power conversion. Concurrently, high ambient summer temperatures exceeding 45°C and peaking at a historical high of 51.3°C in Ouargla overheat standard crystalline silicon modules up to 75°C. Since crystalline silicon conversion efficiency

degrades linearly by 0.4% to 0.5% for every 1°C increase above standard test conditions, these extreme operating environments induce a severe drop in immediate power yields. [6]

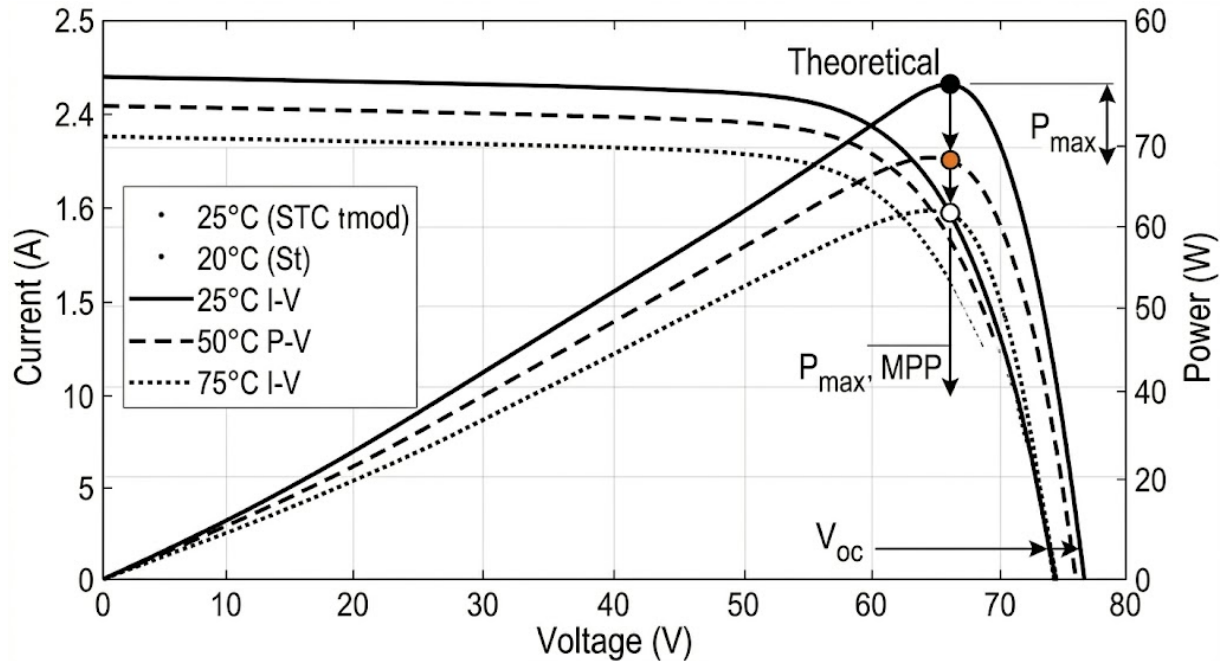


Figure I.13: Electrical Characteristic Curves I-V and P-V of a Crystalline Photovoltaic Module Showing Performance and Power Max P_{max} Degradation under Rising Cell Operating Temperatures 25 °C to 75°C.

I.10 Conclusion

This chapter has provided a comprehensive overview of the fundamental principles of photovoltaic (PV) technology and the solid-state physics governing $p-n$ junctions in converting solar irradiance directly into DC electricity. Despite a dramatic global reduction in the Levelized Cost of Electricity (\$LCOE\$) and Algeria's massive, world-class solar potential—particularly within its vast Saharan territory—extreme environmental operating conditions impose severe limitations on practical utility-scale deployments. The theoretical analysis confirms that excessive operating temperatures narrow the semiconductor bandgap and amplify internal losses, triggering a linear efficiency degradation of approximately 0.4% to 0.5% per °C above standard test conditions. To mitigate this catastrophic thermal voltage sag in arid zones, passive thermal management using Phase Change Materials (\$PCM\$) presents a robust solution for latent heat storage. Furthermore, to overcome the low thermal conductivity inherent to organic PCMs, integrating metallic heat sinks with optimized fin geometries (such as rectangular, cylindrical, or triangular designs) is essential to accelerate heat dissipation. These foundational concepts establish the necessary theoretical framework for the advanced experimental and numerical evaluations detailed in the subsequent chapters of this thesis.

Chapter II:
Previous Studies

II.1 Introduction

The global surge in energy demand, driven by rapid population growth and industrialization, has placed renewable energy technologies at the forefront of sustainable development. Among these, solar photovoltaic (PV) technology is a leading solution, harnessing a virtually unlimited resource to meet electricity needs while reducing greenhouse gas emissions. Despite their widespread adoption in solar farms, remote sites, and buildings, the efficiency of PV systems remains a critical challenge, typically ranging from only 15% to 20%.

The core issue lies in the physics of energy conversion. While PV panels absorb solar radiation to generate electricity, a significant portion of this energy often over 80% is converted into heat. This natural process leads to elevated operating temperatures that negatively impact the panel's performance, durability, and life span. Research indicates that for every one-degree Celsius rise in temperature, the power output of a solar panel can drop by approximately 0.41%. In arid and hot regions, where solar intensity is highest, panel temperatures can soar, leading to substantial energy losses and the risk of "hotspots" that can permanently damage the cells.

The importance of these cooling systems in daily life cannot be overstated. By maintaining optimal temperatures, cooling technologies ensure that solar installations, whether on a residential rooftop or a large-scale solar farm operate at peak efficiency. This translates to higher electricity yields, lower costs for consumers, and a more reliable power grid. Furthermore, advancements in low-cost, locally available materials, such as palm fibres or marble for evaporative cooling, make these technologies accessible for remote and developing areas. Ultimately, the continued development of PV cooling aligns with global sustainability goals by promoting the transition to cleaner, more efficient, and affordable energy for everyone [7].

II.2 Traditional methods of cooling PV panels.

II.2.1 Advanced Material-Based Cooling

- **Nanofluids:** This technique uses fluids containing nanoparticles (such as **Zn** or **Al₂O₃**) to improve thermal conductivity and heat transfer compared to conventional water or air.

- **Nano-Phase Change Materials (Nano-PCM):** An advancement over standard PCM, where nanoparticles are integrated into phase change materials to enhance their thermal properties and stabilization capabilities.
- **Radiative Cooling Coatings:** Special coatings, including **Sub-bandgap Reflection (SBR)** and **Mid-Infrared Emission (MIE)**, are applied to the panel's surface to reflect unwanted solar radiation and emit heat back into the atmosphere. [8]

II.2.2. Innovative Evaporative Techniques

- **Palm Fiber Cooling:** A novel method that uses locally available **palm fibers** wetted with water to provide evaporative cooling. This can be enhanced with **fan-assisted airflow** to accelerate heat removal.
- **Marble Cooling:** An experimental technique where **marble** is used as an evaporative carrier to regulate the temperature of the PV panel.
- **Cotton Wicks:** Utilizing **cotton wicks** submerged in water and attached to a finned surface to facilitate continuous passive evaporative cooling. [9]

II.2.3. Electronic and Hybrid Systems

- **Thermoelectric Cooler (TEC) / Peltier Modules:** These electronic devices use the Peltier effect to actively pump heat away from the PV panel toward a heat sink.
- **Microchannel and Pulsating Heat Pipes:** Integration of advanced heat pipe designs, such as Closed-Loop Pulsating Heat Pipes (CLPHP) or Microchannel Heat Pipes (MCHP), to transport heat more effectively than traditional cooling systems.
- **Liquid Immersion Cooling:** Submerging PV cells in a dielectric liquid (e.g., Dimethyl Silicon Oil) to ensure uniform temperature distribution and eliminate hotspots.
- **Porous Heat Sinks:** Using numerical modeling and optimization to design porous materials that improve heat transport and overall system efficiency.

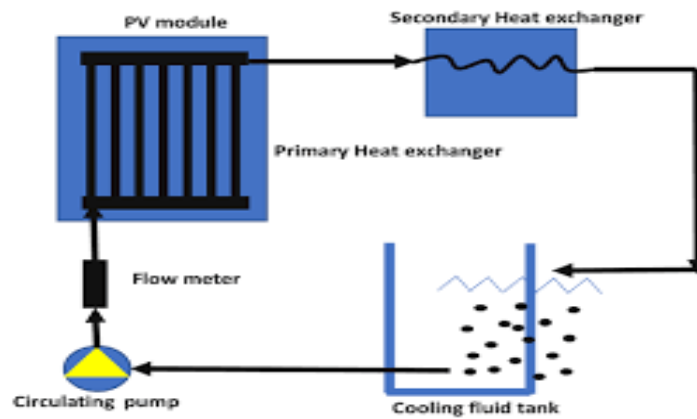


Figure II. 1: Schematic of active PV/T cooling system with fluid circulation loop.

II.3 Phase Change Material (PCM) Cooling

PCM modules are integrated onto the back of the panels. These materials absorb thermal energy as they melt, keeping the panel at a stable, cooler temperature during peak sunlight hours.

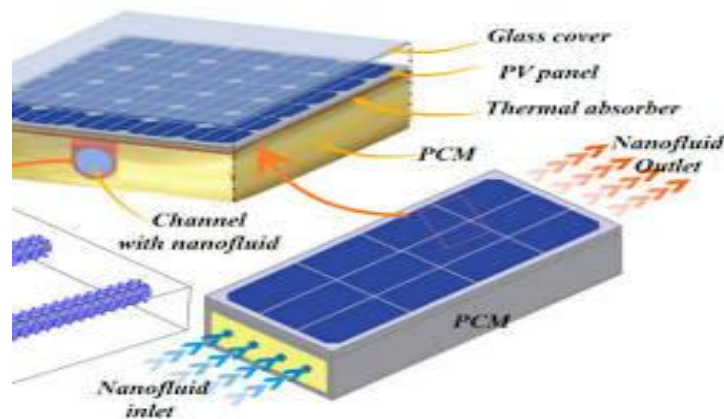


Figure II. 2: Hybrid PV/T system featuring PCM and active nanofluid cooling channels.

II.3.1 Radioactive Cooling Coatings

Innovative coatings are applied to the glass surface of the PV panel. They are designed to reflect sub-bandgap solar radiation and emit heat into the cold vacuum of space via the "sky window" (mid-infrared emission). [10]

II.3.2 Passive Air Cooling (Natural Convection)

This method relies on natural airflow without any electrical consumption. It often involves creating an air gap behind the panel or attaching aluminium heat sinks (fins) to increase the surface area for heat dissipation.

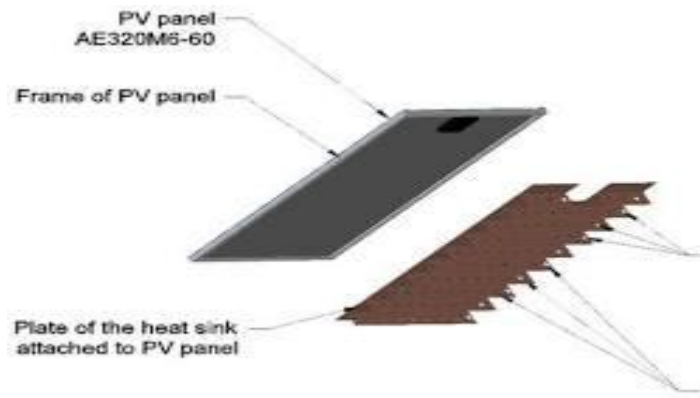


Figure II.3: Exploded view of AE320M6-60 PV panel with attached aluminum heat sink plate [11].

II.3.3 Active Air Cooling (Forced Convection)

In this traditional setup, fans or blowers are used to force air over the back surface of the panel. This significantly improves the heat transfer coefficient compared to passive methods but requires a small amount of power.



Figure II.4: Bench setup of the PV/T air-cooled system showing the integration of data acquisition and solar monitoring instruments

II.3.4 Direct Water Cooling (Spraying/Immersion)

One of the most established methods is spraying water directly onto the front or back surface of the panel. The water absorbs heat and can also help clean the panel surface, improving light absorption

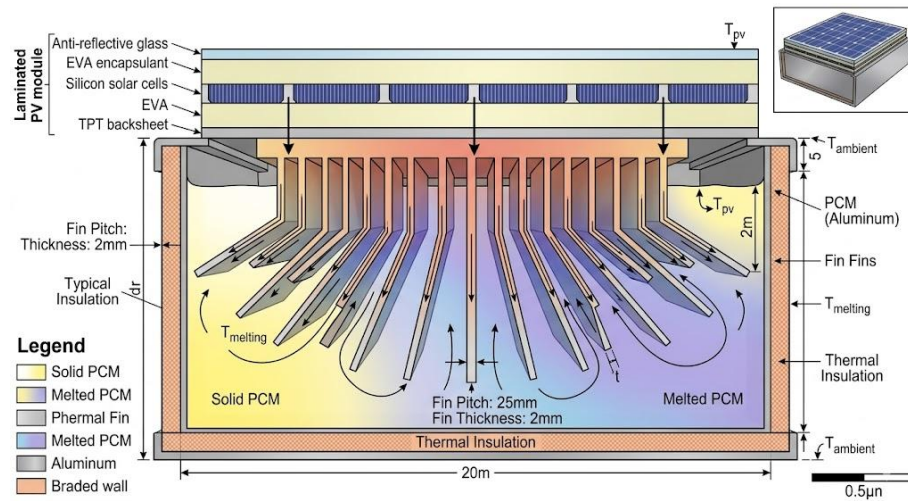


Figure II.5: Thermal management of photovoltaic modules using a phase change material with internal fins.

techniques, each utilizing unique materials and mechanisms to reduce operating temperatures and mitigate efficiency losses.

Table summarises the traditional methods of cooling PV Based on the image provided, here is the traced table detailing various solar panel cooling methods:

II.3.5 Phase Change Material (PCM) Cooling

Phase Change Materials (PCMs) represent a significant innovation in passive PV cooling. These materials, such as paraffin wax or metallic PCMs, are integrated into the back of a PV panel to absorb and store excess thermal energy as latent heat during the melting process. This process maintains the PV panel at a constant, lower operating temperature during peak solar radiation periods, effectively stabilizing its thermal performance.

Recent advancements in this field include the development of multi-PCM systems and the use of ribbed aluminum plates to enhance thermal conductivity. For instance, a bifacial PV-PCM system utilizing multiple PCMs and ribbed plates has been shown to reduce cell temperatures by approximately 13°C, leading to a 0.5% increase in electrical efficiency compared to non-cooled systems. Furthermore, the integration of nanofluids with PCMs has demonstrated even greater potential, with studies reporting thermal efficiencies exceeding 70% and significant reductions in average surface temperatures. Despite their effectiveness, the high cost of high-performance PCMs remains a challenge for widespread commercial adoption. [12]

II.3.6 Phase Change Material (PCM) Cooling

Phase Change Materials (PCMs) represent a significant innovation in passive PV cooling. These materials, such as paraffin wax or metallic PCMs, are integrated into the back of a PV panel to absorb and store excess thermal energy as latent heat during the melting process. This process maintains the PV panel at a constant, lower operating temperature during peak solar radiation periods, effectively stabilizing its thermal performance. [13]

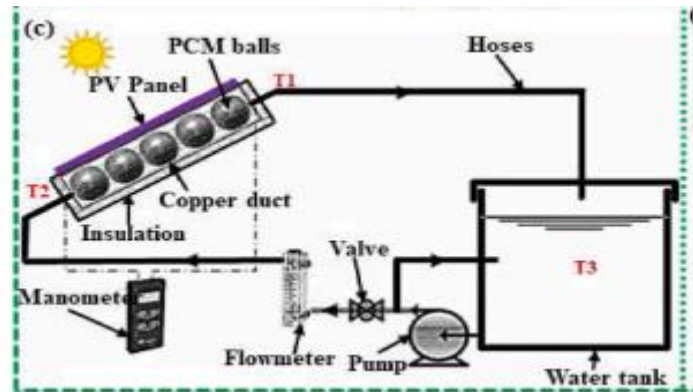


Figure II. 6: The Physical Model of PV-PCM with Fin Enhancement.

II.4. Phase Change Material (PCM) Cooling

- Diagrams in the reviews show the integration of PCM modules on the rear surface of PV panels. These figures typically illustrate the temperature reduction achieved when latent heat is absorbed during the material's phase transition.
- **Enhanced Heat Sinks:** Some figures depict PCM integrated with ribbed aluminum plates or fins (e.g., rectangular, perforated, or U-shaped) used to improve the low thermal conductivity of organic PCMs.
- **Nano-PCM Systems:** Illustrations show the comparison between standard PV panels and those using "nano-PCM" (PCM infused with nanoparticles), noting a visible 13°C temperature drop in experimental thermal maps.

II.4.1 Evaporative Cooling (Natural Materials)

- **Palm Fiber Setup:** In the experimental study conducted in arid zones, images show PV panels equipped with a cooling layout featuring palm fibres and marble.

- **Airflow Integration:** Diagrams illustrate a "fan-assisted" system where a brushless fan (typically 6x6cm) is positioned to distribute air over the saturated natural fibers to accelerate the evaporative cooling process.

II.4.2 Thermoelectric Cooler (TEC) Modules

- **TEC Installation:** The documents provide a specific "Solidworks" model and a "Real photo" of a thermoelectric cooling system fixed to a PV panel.
- **Peltier Effect Layout:** The diagram shows the peltier module sandwiched between the back surface of the PV panel and an aluminum heat sink. A 12V-DC fan is fastened to the heat sink fins to dissipate the heat pumped away from the panel.

II.4.3 Hybrid and Nanofluid Systems

- **PVT Component Diagram :** This figure depicts the internal components of a Photovoltaic/Thermal (PV/T) system, showing the channels where nanofluids (like TiO_2 -water) flow to extract heat.
- **Radiative Cooling:** An experimental prototype image shows panels treated with mid-infrared emission coatings designed to increase heat dissipation via radiation to the sky.

II.4.4 cooling using phase change materials (PCMs)

The integration of Phase Change Materials (PCM) into solar photovoltaic systems serves as an effective passive cooling strategy to counteract the reduction in electrical efficiency caused by high operating temperatures. Because solar cell efficiency typically decreases by approximately 0.4% to 0.5% for every degree Celsius rise above 25°C, PCM is attached to the rear of the panels to absorb excess heat through the process of latent heat storage. As the panel heats up, the PCM undergoes a phase transition usually from solid to liquid maintaining the PV cells at a lower, more stable temperature while storing large amounts of thermal energy without a significant increase in its own temperature. Although common PCMs like paraffin suffer from low thermal conductivity, which often necessitates the use of internal fins or metallic additives to enhance heat transfer, the system automatically "recharges" at night by releasing the stored heat and solidifying for the next day's cycle. This thermal regulation not only boosts power output by maintaining panel temperatures 10–20°C lower than standard modules but also extends the lifespan of the system by reducing long-term thermal stress.

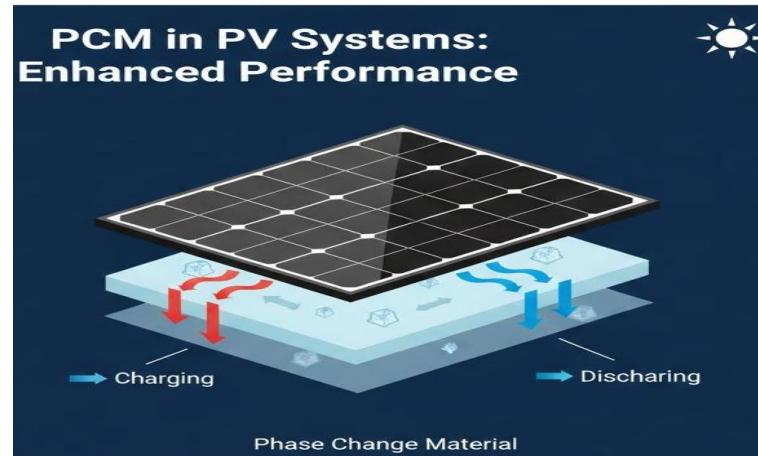


Figure II. 7: PCM in PV systems: Enhanced Performance

II.5. Water Cooling

II.5.1. Front surface water cooling

II.5.1.1. Definition

One of the best active cooling technologies that air the front side of solar panels with water guarantees that the surface temperature is even and it helps in the extraction of scattered dirt particles [14]. This technique can be a cause of approximately 9% increase in the power efficiency of solar panels where different cooling rates will depend on the velocity of water flow through the system.

In the paper released by (K. A. Moharram) and other authors, the study of the performance of PV panels was carried out using water cooling as means of lessening water consumption and the electrical power for cooling, in particular, desperate cases of extremely hot and arid places like desert areas [15]. They developed a spray jet-based cooling system in which the cooling starts at the point when the PV surface temperature has already reached the maximum allowable value, according to the model used Figure.II.10.

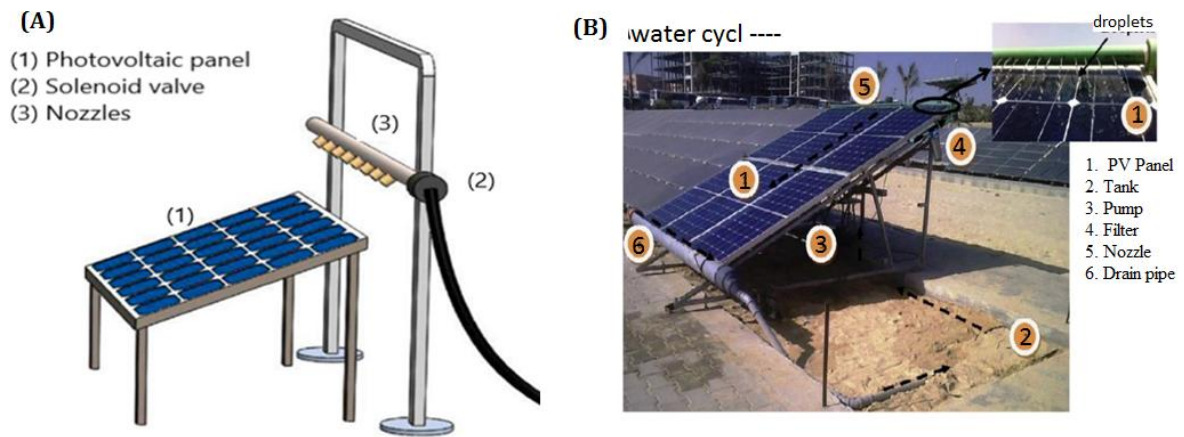


Figure II. 8: (A) Schematic diagram of the PV with cooling sprayers [15]

(B) Experimental system [15]

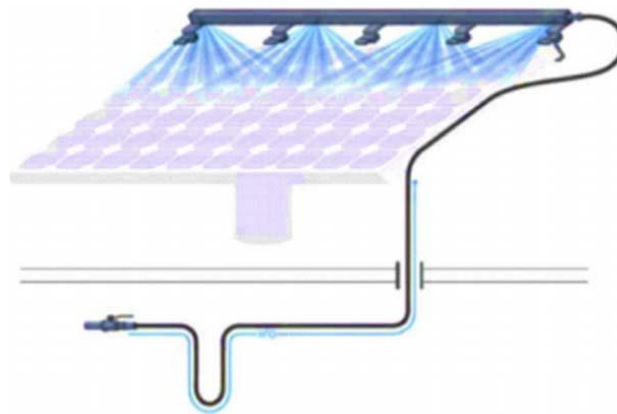


Figure II. 9: A view of Water spraying [16]

II.5.2 Back surface water cooling

Backside of the photovoltaic panels was cooled through the water by spraying, which was then gathered and directed to the receptacle. A re-circulatory mechanism containing borehole heat exchanger is used for clean water that is used to further increase the cooling effect of the system, and next, water is re-cycled through the panels so that they are cooled down again in addition to the other cooling methods.

Water cooling can also function on the lower side to improve heat conduction or as a protective shield. Yet, it is of less force than the cooling of the upper side in the temperature reduction. [17].

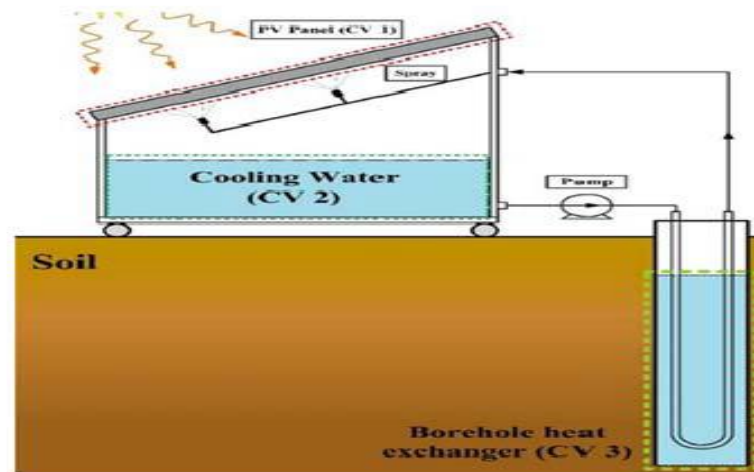


Figure II. 10: System diagram [17]

II.6 Cooling using Phase Change Materials (PCM)

The range of temperature within which a phase change material operates dictates its selection. These materials can be obtained both in laboratories and commercially, and they can be classified into three categories: inorganic, organic, and eutectic mixtures. Thermally, most of these materials do not possess the all-requisite features for storage which makes it critical to choose the most economical option that fulfills the required property for the system.

Utilizing phase change materials on the photovoltaic modules' rear side aid in keeping the temperature at the module's melting point. These materials can absorb a certain amount of heat during the phase change from solid to liquid and release the heat when reverting to solid, thus helping in thermal stabilization. Furthermore, the control of temperature regulation is to be done while considering the quantity of the material analysis and the time required for the analysis. Since the system is built to work under a varying climate, defining the properties of the material poses a significant challenge. Alternative approaches must be sought owing to the

system's continuous changes in solar radiation, external temperature, wind speed, and the substantial impact these parameters have on the corners of the photovoltaic module and the phase change material.

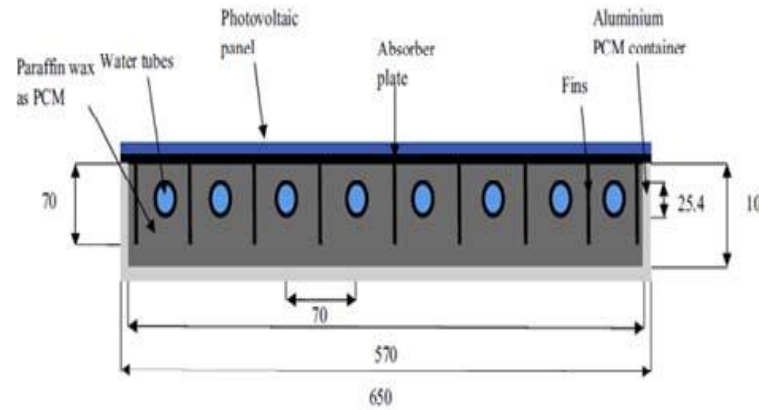


Figure II. 11: Schematic diagram of water-based PV/T-PCM system (dimensions in mm)
[18]

II.7 Peltier

Thermoelectric (T.E.) cooling is also a technology used to reduce the temperature of PV panels by converting excess heat into electrical energy. The system operates based on the Peltier effect, which allows the panel to be cooled using electrical energy. The fundamental principles behind thermoelectric cooling include the Peltier effect and the Seebeck effect. In a specific direction, the Peltier effect induces a thermal flow at an electrified junction, resulting in heating on one side and cooling on the other. The heating/cooling flow rate depends on

temperature differences and electrical voltage/current. Najafi and Woodbury [18] developed a model for P.V. cell cooling using a Peltier element, demonstrating the feasibility of integrating thermoelectric cooling for high-concentration PV cells. A study conducted by Borker et al [18] experimentally evaluated thermoelectric cooling in PV modules, revealing an efficiency improvement from 8.35–11.46% to 12.26–13.27%. Benghaneim et al observed that the temperature of PV cells decreased from 83°C to 65°C using TE modules. For reliability, the energy consumption of the T.E. module should be significantly lower than the electricity produced via cooling PV panels.

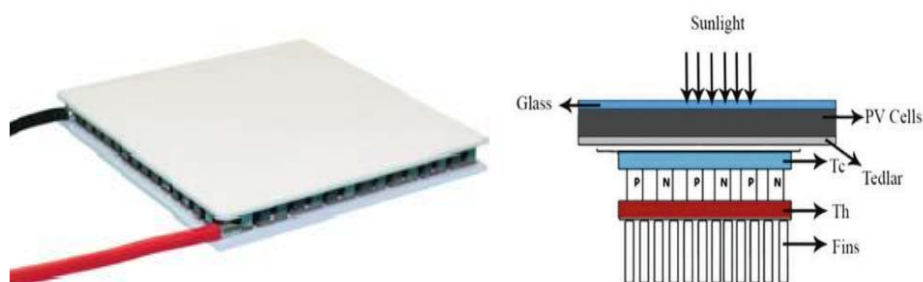


Figure II. 12: Peltier effect [19]

II.8 Fins

II.8.1. Definition

Fins is a term used to describe these parts or components which are used to enhance the cooling or heating capability of a device by providing additional surface area for heat transfer. Fins can be found in home heating radiators, car radiators, as well as in the microprocessors of electronic systems [20].

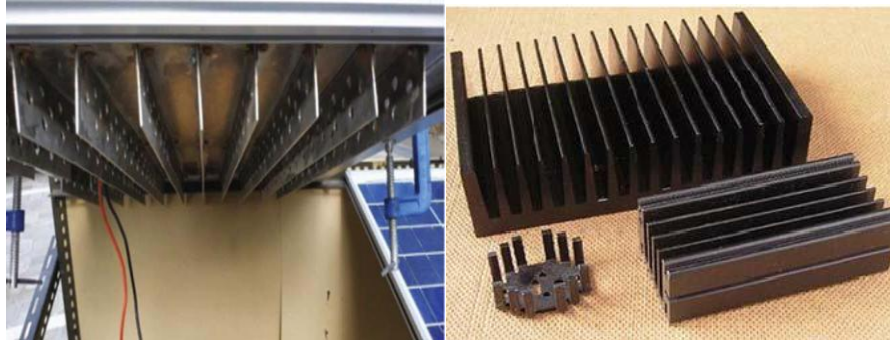


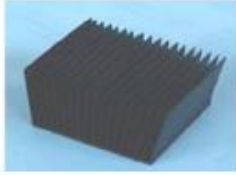
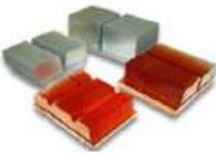
Figure II. 13: Heat sink configuration on the back of the PV panel

B, passive cooling systems by air .

II.8.2. Selection of Fins

Fins are fitted when large quantities of heat needs to be removed in small volumes such as car radiators, air cooled engine casings and evaporators in air conditioning systems. Fins are more effective with liquids than with gases because the former allows for greater convective heat transfer. Gases, even if they have a lower transfer rate, do benefit from the presence of fins. Compared to wider and more spaced apart fins, narrow and closely spaced ones perform better. While increased spacing yields better results, efficiency is lost due to pressure losses if the spacing is minimized too much. Furthermore, fin performance improves with higher thermal conductivity (λ). Fins are chosen based on a trade-off between cost, pressure losses and the rate of heat transfer [21].

Table II.1: Classification of fins types

Extruded	Stamped	Bonded	Folded Fin
			
Heated metal is forced through a profiled die	Metal stamped to form a particular shape	Individual fins are bonded with epoxy to a pre-grooved base	Fins are pre-folded and then brazed or soldered to a plate base
Single fin Assembly	Swaged	swaged	Skived
			
Individual pieces of fin and spacer material are stacked and then brazed to create the desired shape	Individual fins are placed in a pre-grooved base and then a roller or punch will swage the sides to the fins	Heated metal is compressed into a form mold to the desired shape	Fin are skived from a solid piece of Material, usually copper

II. 9. Conclusion

Throughout this chapter, we were familiarized with the basic principles and tactics in the thermal management of photovoltaic systems. It was explained how the temperature plays a crucial role in the efficiency and performance of the solar cell. We started by making an attempt to clarify the idea of cooling and then we indicated and detailed the main factions of methods of heat prevention in the solar panels. The goal was the broadest possible

presentation of ways to cool, e.g., air and water-based realizations, use of innovative materials like phase change material, thermoelectric module, and special items such as fins, heat pipes, and micro channel exchangers. Further, we showed other solutions such as radiative cooling, Nano fluid applications, evaporative systems, and spectrum filtering that is a signal of growth in the R&D of this sector. With these solutions in all, we pinpointed the need to marry the correct thermal management system with the photovoltaic system, with the aim of lengthening the life of the system, achieving the highest operational efficiency, and making the whole system convenient for the usage under different climatic conditions.

Chapter III:
Experimental Setup and
Methodology

III.1 Introduction

The performance of photovoltaic (PV) panels is strongly influenced by their operating temperature, especially in hot and arid regions such as southern Algeria. Under high solar irradiance and elevated ambient temperatures, the temperature of PV modules can increase significantly, leading to a reduction in electrical efficiency and power output. Therefore, the development of effective and low-cost cooling techniques has become an important research topic for improving the performance and reliability of photovoltaic systems.

This chapter presents the experimental implementation of a passive cooling system based on an aluminum plate equipped with cooling fins. The design, fabrication, and installation of the cooling device are described in detail. In addition, the experimental site, climatic conditions, photovoltaic modules, measuring instruments, and data acquisition system used during the tests are presented. The objective of this chapter is to provide a comprehensive description of the experimental methodology adopted to evaluate the effectiveness of the proposed cooling system under real Saharan operating conditions.

III.2 Description of the Experimental Setup

The experiment was carried out in the Wilaya of Ghardaïa, one of the desert regions in Algeria characterized by a high suitability for photovoltaic energy exploitation, due to its geographical location and its hot and dry climate, which ensures high levels of solar radiation throughout the year. The Temperatures in the region range between 22°C and 40°C during April and May, and can reach approximately 50°C in summer, especially between June and August, making it a harsh and ideal environment for testing the performance of solar systems. In addition, the flat terrain and the abundance of sand dunes contribute to continuous and direct exposure to sunlight.

The measurements were conducted in late May, specifically on the 5th and 6th of May 2026, under real climatic conditions, in order to evaluate the performance and efficiency of the photovoltaic system under high solar irradiance and elevated temperatures characteristic of the climate of Ghardaïa.

In this study, a passive and efficient cooling method for photovoltaic panels was adopted using aluminum plates equipped with fins, due to the high thermal conductivity of aluminum, which facilitates rapid heat transfer and effective dissipation to the surrounding environment. The fins

increase the surface area exposed to air, thereby enhancing heat exchange and improving the cooling performance.

The experiment was conducted on two identical photovoltaic panels with the same technical specifications to ensure accurate comparison. The proposed cooling system (finned aluminum plates) was applied to one panel, while the second panel was left unmodified to serve as a reference (control panel) for evaluating the effect of the cooling system.

This study was carried out in the backyard of the Thermodynamics Laboratory, within At the Unit of Applied Research in Renewable Energies (URAER) – Ghardaïa under real climatic conditions of the region, allowing an effective assessment of the cooling system performance in a desert environment characterized by high temperatures.



Figure III.1 : Aluminum plate used in the cooling system prior to installation

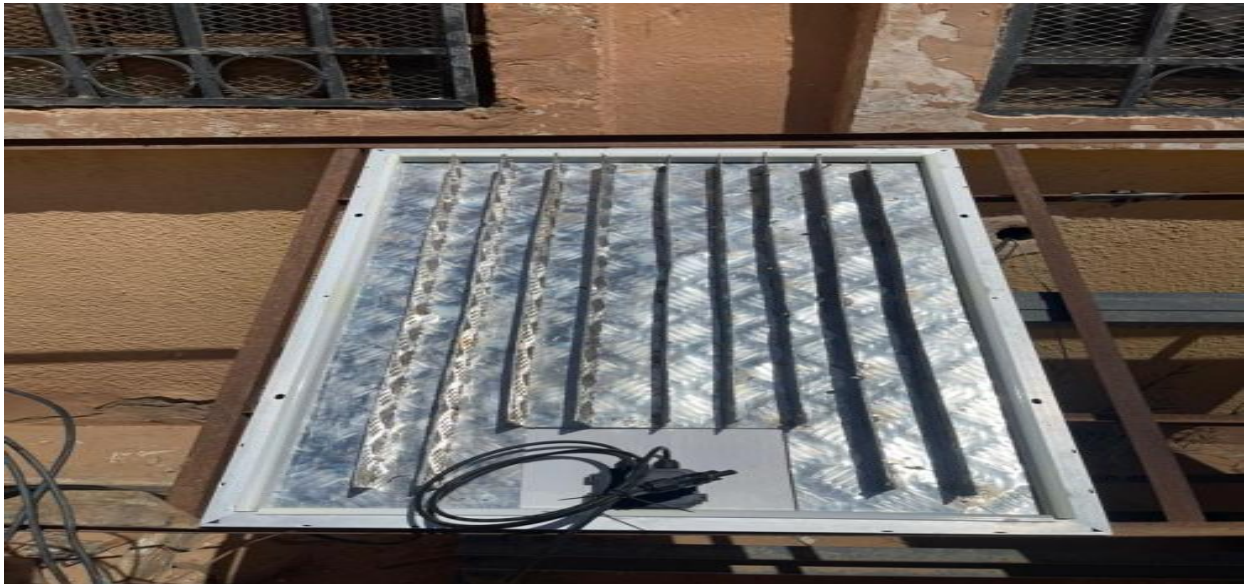
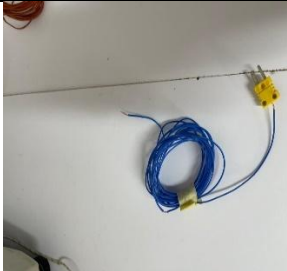


Figure III.2: Aluminum plate equipped with vertical cooling fins mounted at the rear of the photovoltaic panel.

III.3 Different measurement equipment:

A set of precise measuring instruments was used to collect data on the performance of photovoltaic panels under various cooling conditions. The main devices utilized in the experimental setup are presented as follows

Table III.1: Experimental setup instrumentation and measurement ranges.

Device Name	Figure	Measurement	Range	unit
DM750M Digital Multimeter		Voltage and Current	0-1000 V /0-10 A (approx.)	V/A
2 Thermocouple (Type K)		Panel surface and ambient temperature	-200 to 1372°C (approx.)	°C

Hand Pyranometer 4890.20		Solar irradiance	0-2000 W/m ²	W
Data Acquisition		Voltage-current – resistance-frequency	Data Acquisition/Switch Unit (GPIB, RS232; Serial Number: MY44050878) to determine the temperature values	
VFD –vacuum fluorescent Display -				



Figure III.3: Two 100W Monocrystalline Silicon Photovoltaic Panels.

Table III.2: Electrical Characteristics and Technical Specifications of the PV Module

Category	Specification	Value
General	Brand	YHSUNPRO Power
General	Reference	5150-008
Electrical Characteristics	Module Type	100M(36)
Electrical Characteristics	Maximum Power	100 Wp
Electrical Characteristics	Tolerance	±3%
Electrical Characteristics	Voltage at Pmax (Vmp)	19.10 V
Electrical Characteristics	Current at Pmax (Imp)	5.24 A
Electrical Characteristics	Open-Circuit Voltage (Voc)	22.82 V
Electrical Characteristics	Short-Circuit Current (Isc)	5.55 A
Physical Characteristics	Size	950 × 580 × 30 mm
Physical Characteristics	Weight	8 kg
Physical Characteristics	Cells	36 pcs, 182 monocrystalline silicon
Operating Data	Max. System Operating Voltage	1000 V
Operating Data	Maximum Over-Current Protection Rating	10 A
Operating Data	Module Application	Class A
Test Conditions	Standard Test Condition	1000 W/m ² , AM1.5, 25°C
Safety	Warning	Electrical hazard. This unit produces electrical power when exposed to light. Cover glass before opening terminal junction box.

III.4 Conclusion

This chapter presented the experimental methodology and the practical implementation of the passive cooling system developed for photovoltaic panels. The study was carried out under real climatic conditions representative of the Saharan environment, where high temperatures often negatively affect PV performance. The experimental setup included two identical photovoltaic panels, one operating with an aluminum finned cooling system and the other used as a reference panel.

A detailed description of the cooling device, measurement instruments, data acquisition system, and technical specifications of the photovoltaic modules was provided. These elements ensured reliable monitoring of the thermal and electrical behavior of the panels throughout the experimental campaign.

The experimental configuration established in this chapter forms the basis for the analysis presented in the next chapter, where the thermal and electrical performance of the cooled and uncooled photovoltaic panels will be compared and discussed in detail.

Chapter IV:
Results and discussion

IV.1 Introduction

The southern regions of Algeria, such as Ouargla and Ghardaïa, experience extreme summer temperatures that frequently exceed 45°C which severely penalizes the conversion efficiency of photovoltaic (PV) modules. To counteract this degradation, the structural design, configuration of the aluminum plate, and all preliminary training and baseline experiments on the cooling setup were successfully conducted at the University of Kasdi Merbah in Ouargla. However, due to the lack of a specialized continuous logging system locally, the experimental prototype was relocated to Ghardaïa. This strategic step was taken to utilize a comprehensive and fully integrated data acquisition system, allowing for the precise gathering of long-term thermal and electrical data necessary for rigorous academic analysis and performance study under real Saharan operating conditions. The system was experimentally tested under real climatic conditions in Ghardaïa during late May. Its thermal and electrical performance was compared with an identical PV panel operating without cooling. The results aim to evaluate the effectiveness of this simple and low-cost cooling solution for improving PV efficiency in hot and arid regions.

IV.2 Experimental results and explanation

IV.2.1 Comparative experimental data under real operating conditions

Table IV. 1: Comparative experimental data for reference and aluminum-cooled photovoltaic panels under different irradiance levels.

Scan	Time	110 <T1 temoin> (°C)	113 <Eclairement> (VDC)	115 <T alimimum> (°C)	116 <T2 temoin> (°C)	119 <Voc temoin > (VDC)	120 <Voc > (VDC) aluminium
1	5/4/2026 16:08:09:512	68,827	720,54346	52,418	65,54	21,591285	23,845605
2	5/4/2026 16:18:09:496	67,069	717,65089	48,414	38,789	21,771603	23,942537
3	5/5/2026 14:33:57:486	64,703	589,01371	48,857	53,305	21,263514	23,698041
4	5/5/2026 14:43:57:486	67,641	814,79432	49,903	57,286	21,768383	23,970629
5	5/5/2026 14:53:57:486	70,961	814,28551	51,915	59,665	21,601611	23,81396
6	5/5/2026 15:03:57:486	71,915	836,00183	52,465	58,283	21,600167	23,799304
7	5/5/2026 15:33:57:486	68,123	752,88647	49,795	55,505	21,736961	23,944536
8	5/5/2026 15:53:57:486	68,555	734,61163	50,869	56,336	21,649799	23,875584
9	5/5/2026 16:03:57:486	68,359	724,63991	50,701	55,769	21,658571	23,879803
10	5/5/2026 16:23:57:486	66,632	698,6669	48,95	54,757	21,796364	23,954862
11	5/5/2026 16:33:57:486	67,341	684,01775	50,491	56,026	21,692325	23,885466
12	5/5/2026 16:43:57:486	67,031	664,21447	49,973	54,442	21,678557	23,888242
13	5/5/2026 16:53:57:486	65,898	647,83861	49,274	52,798	21,697877	23,935875
14	5/5/2026 17:03:57:486	64,858	627,55254	49,324	51,87	21,723192	23,937652
15	5/5/2026 17:13:57:486	64,187	604,75657	48,567	48,521	21,724303	23,97507

The table presents the results of temperature and voltage measurements of photovoltaic panels under different levels of solar irradiance, which ranged from 589 to 836 W/m². The results show

that the aluminum-equipped panel recorded lower temperatures, ranging from 48.41 to 52.47°C, compared to the reference panel, whose temperature ranged from 64.19 to 71.92°C. This indicates the effectiveness of aluminum in dissipating heat. This reduction in temperature had a positive impact on electrical performance, as the open-circuit voltage (Voc) of the aluminum-equipped panel ranged from 23.70 to 23.98 V, compared to 21.26 to 21.80 V for the reference panel. These findings confirm the inverse relationship between temperature and voltage, where reducing the operating temperature contributes to improving the performance and efficiency of the photovoltaic panel.

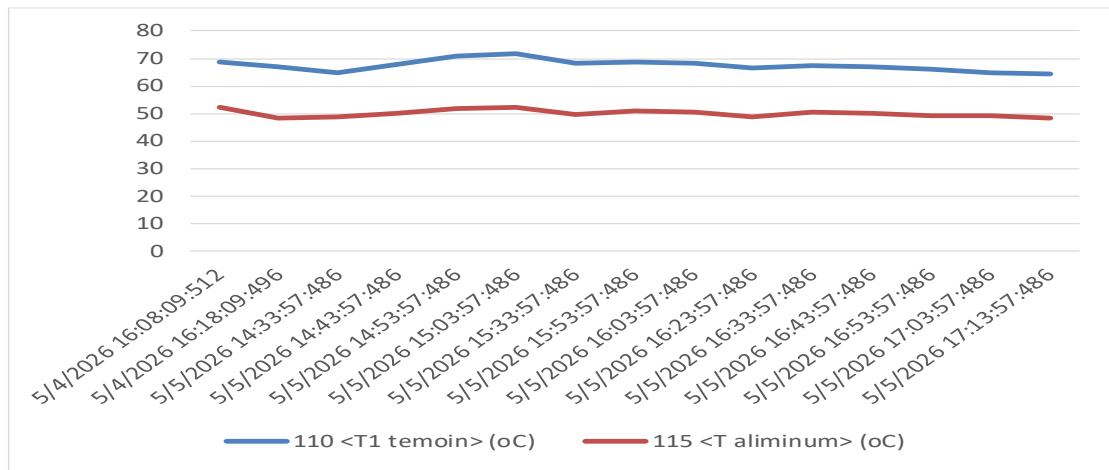


Figure IV.1: Temperature comparison between the reference photovoltaic panel and the aluminum-cooled panel.

The figure presents a comparison between the temperature of the reference photovoltaic panel (T1 Reference) and the aluminum-cooled panel (T Aluminum) over a series of measurements. It can be observed that the temperature of the reference panel remained consistently higher, ranging from approximately 64°C to 72°C, whereas the aluminum panel recorded lower temperatures, varying between 48°C and 52°C.

Both curves follow a similar trend, increasing and decreasing according to the environmental conditions and solar irradiance levels. However, the aluminum panel maintained a temperature reduction of approximately 15–20°C compared to the reference panel throughout the measurement period. The highest temperatures for both panels were recorded around the middle of the experiment, after which a gradual decline was observed.

These results indicate that the aluminum cooling system was effective in dissipating heat and reducing the operating temperature of the photovoltaic panel. Lower operating temperatures are beneficial for photovoltaic systems because they help maintain higher electrical performance and improve the overall efficiency of the solar panel.

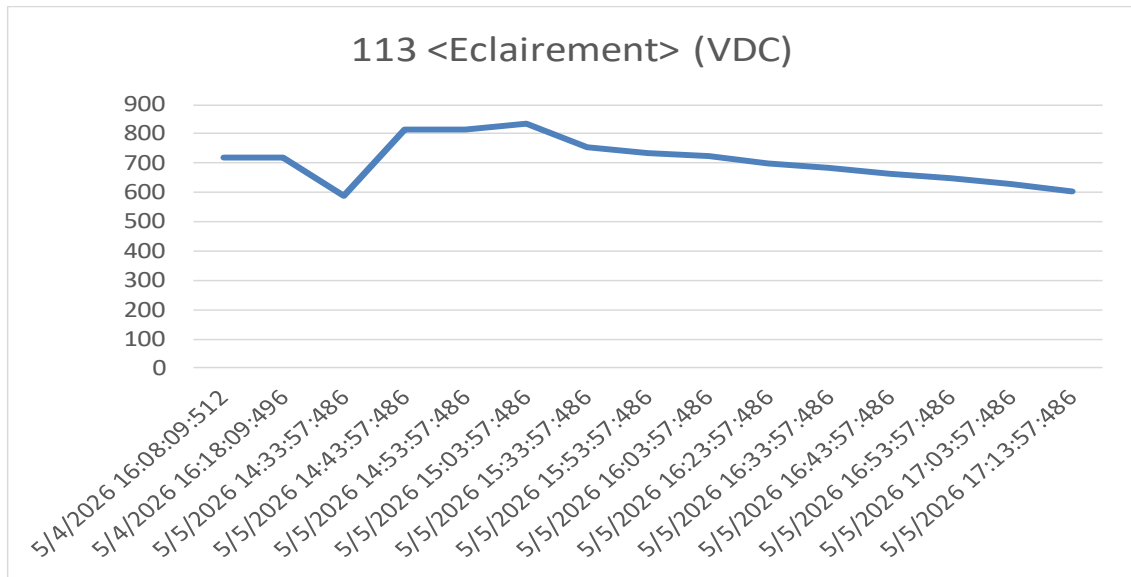


Figure IV. 2: Solar irradiance variation during the experimental measurement period.

The figure illustrates the variation of solar irradiance (Éclairement) during the measurement period. The irradiance values ranged from approximately 589 W/m² to 836 W/m², indicating fluctuations in solar radiation caused by changing weather conditions and solar intensity throughout the day.

At the beginning of the experiment, irradiance remained around 720 W/m², then dropped to its minimum value of about 589 W/m². Subsequently, it increased sharply, reaching a peak of approximately 836 W/m², which represents the highest level of solar energy received by the photovoltaic system. After this peak, irradiance gradually decreased, ending at approximately 605 W/m².

Overall, the graph shows a typical daily solar radiation pattern characterized by an increase toward midday followed by a gradual decline in the afternoon. These variations in irradiance directly influence the thermal and electrical performance of photovoltaic panels and should be considered when analyzing temperature and voltage measurements.

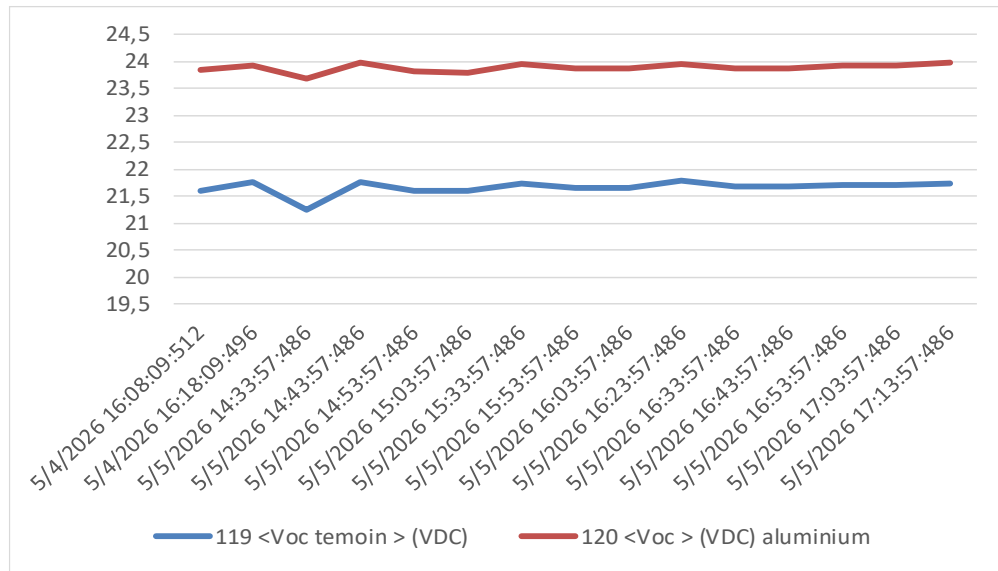


Figure IV.3: Open-circuit voltage comparison between the reference photovoltaic panel and the aluminum-cooled panel.

The figure compares the open-circuit voltage (Voc) of the reference photovoltaic panel (Voc Reference) and the aluminum-cooled panel (Voc Aluminium) throughout the measurement period. The results show that the aluminum panel consistently achieved higher voltage values, ranging from approximately 23.70 V to 23.98 V, whereas the reference panel recorded lower values between 21.26 V and 21.80 V.

Although both curves exhibit similar fluctuations in response to changing environmental conditions and solar irradiance, the voltage of the aluminum panel remained higher at all measurement points. The voltage difference between the two panels was relatively stable, averaging about 2.2 V.

This improvement can be attributed to the lower operating temperature of the aluminum panel. Since photovoltaic cell voltage decreases as temperature increases, the enhanced heat dissipation provided by the aluminum cooling system helped maintain a higher open-circuit voltage. Therefore, the figure confirms that thermal management using aluminum positively affects the electrical performance of the photovoltaic panel by increasing its voltage output and overall efficiency.

The data logger can be programmed to collect data at specified intervals. In this case, it is set to record data every 10 seconds

IV.3 Temperature Analysis

IV.3.1 Temperature difference analysis between aluminum-cooled and reference panels

Measurement No.	T Aluminum (°C)	T2 Reference (°C)	ΔT (°C)
1	48.857	53.305	4.448
2	49.903	57.286	7.383
3	51.915	59.665	7.750
4	52.465	58.283	5.818
5	49.795	55.505	5.710

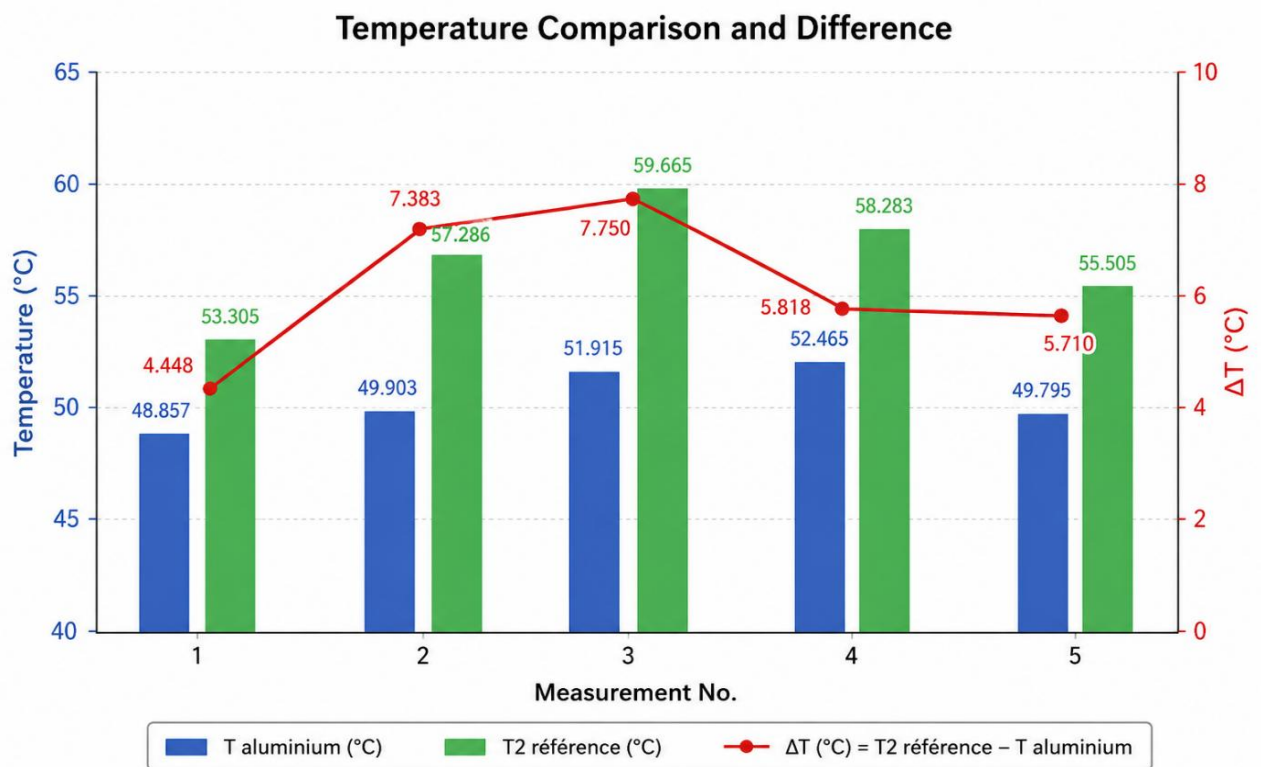


Figure IV.4: Temperature comparison and Delta T between aluminum-cooled and reference panels.

The figure compares the temperature of the aluminum panel (T Aluminum) with the reference panel (T2 Reference) and illustrates the temperature difference (ΔT) for five measurements. The results show that the aluminum panel consistently operated at lower temperatures, ranging from 48.857°C to 52.465°C, while the reference panel recorded higher temperatures, ranging from 53.305°C to 59.665°C.

The temperature difference (ΔT) varied between 4.448°C and 7.750°C, with the highest difference observed in Measurement 3 and the lowest in Measurement 1. This consistent

temperature reduction demonstrates the effectiveness of aluminum in dissipating heat and limiting temperature buildup on the photovoltaic panel.

Overall, the graph confirms that the use of aluminum improves the thermal behavior of the system by maintaining lower operating temperatures, which can contribute to enhanced photovoltaic performance and efficiency.

IV.3.2 Temperature trend of the aluminum-cooled panel

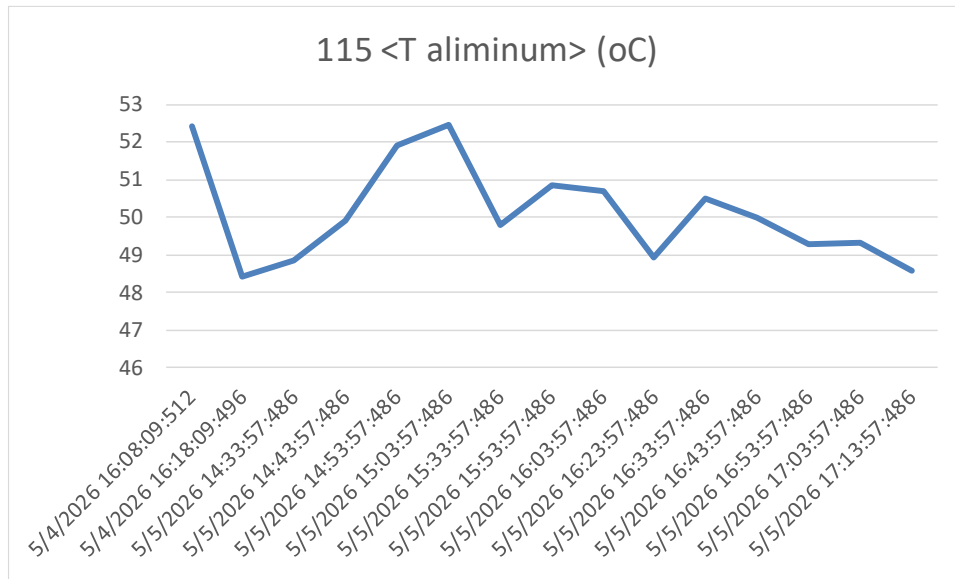


Figure IV.5: Temperature trend of the aluminum-cooled photovoltaic panel.

The graph illustrates the variation of the aluminum temperature over the recorded measurement period. The temperature fluctuates within a relatively narrow range, approximately between 48.4°C and 52.5°C, indicating a generally stable thermal behavior.

At the beginning of the monitoring period, the temperature was around 52.4°C, followed by a noticeable decrease to approximately 48.4°C. Subsequently, the temperature gradually increased and reached its peak value of about 52.5°C. After this peak, several moderate fluctuations were observed, with temperatures oscillating around 50°C.

Towards the end of the observation period, the temperature exhibited a slight downward trend, stabilizing near 48.6°C. Despite these fluctuations, no abrupt or extreme temperature changes were recorded, suggesting that the system operated under relatively stable conditions.

Overall, the data indicate that the aluminum temperature remained consistent throughout the measurement period, with only minor variations that may be attributed to normal process dynamics, measurement uncertainty, or environmental influences. This stability suggests effective thermal control and a relatively uniform heat distribution within the monitored system.

IV.3.3 Temporal evolution of aluminum panel temperature

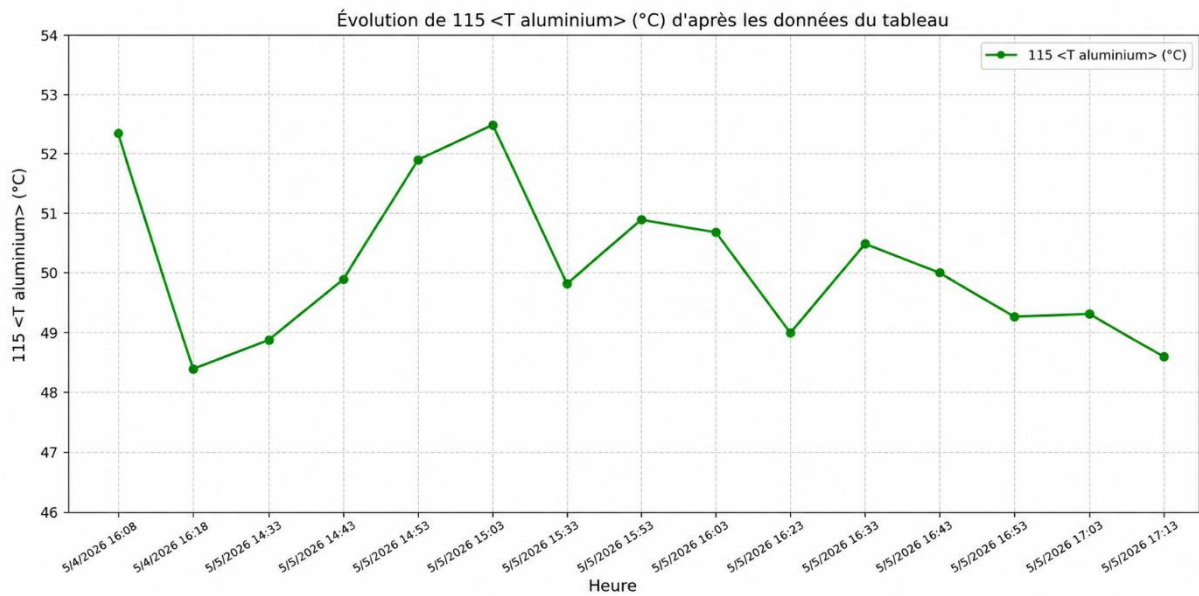


Figure IV.6: Temporal evolution of the aluminum panel temperature.

The graph illustrates the temporal evolution of the aluminum panel temperature throughout the monitoring period. The recorded temperatures ranged from approximately 48.4°C to 52.5°C, indicating relatively small fluctuations and a generally stable thermal behavior.

At the beginning of the measurement period, the aluminum temperature was about 52.4°C, after which it experienced a noticeable decrease to 48.4°C. Subsequently, the temperature gradually increased, reaching its maximum value of approximately 52.5°C during the early afternoon. This increase is likely associated with higher solar irradiance and enhanced heat absorption by the aluminum surface.

Following the peak temperature, the aluminum panel exhibited moderate oscillations around 50°C, reflecting normal variations in environmental conditions and solar radiation intensity. Although several short-term increases and decreases were observed, the overall fluctuations remained limited, demonstrating a relatively stable thermal response.

Toward the end of the monitoring period, the temperature showed a slight downward trend, eventually stabilizing near 48.6°C. This decline corresponds to the reduction in solar irradiance during the late afternoon and the consequent decrease in heat accumulation.

Overall, the results indicate that the aluminum panel maintained a stable temperature profile throughout the experiment. The limited temperature variation suggests effective thermal equilibrium with the surrounding environment and confirms that the aluminum surface responded consistently to changes in solar exposure without experiencing significant thermal instability.

IV.4 Analysis of Delta Voltage ΔV

ΔV measures the discrepancy in electrical potential between the reference cell and the cell equipped with an aluminium heat sink.

Where:

$V_{oc, Temin}$: Open-circuit voltage of the control sensor (in VDC).

$V_{oc, aluminium}$: Open-circuit voltage of the sensor mounted on aluminium (in VDC)

During the night (where irradiance is zero), ΔV stays close to a baseline, representing the inherent calibration difference between the two sensors.

We notice fluctuations in V that coincide with the sun's peak intensity (around 12h00 to 14h00). the curve shows ΔV narrowing or becoming more stable during high-heat periods, it proves that the cooling provided by the aluminium substrate is effectively preserving the electrical efficiency of the cell.

IV.4.1 Open-circuit voltage evolution for the aluminum-cooled panel

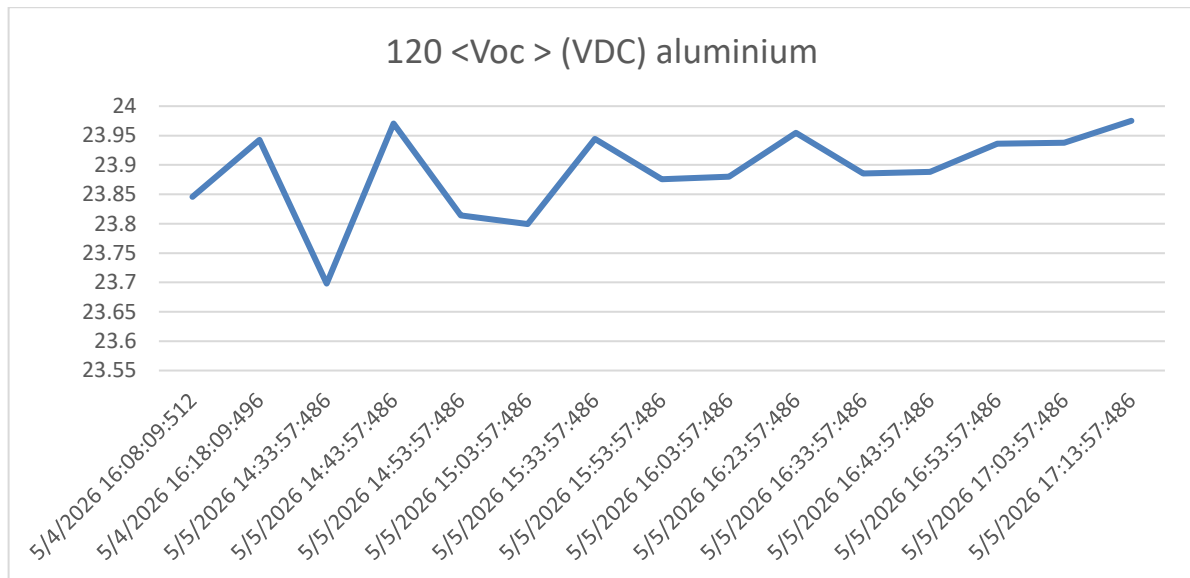


Figure IV.7: Open-circuit voltage evolution for the aluminum-cooled photovoltaic panel.

The graph presents the variation of the open-circuit voltage (Voc) measured for the aluminum sample during the experimental period. The recorded values range from approximately 23.70 V to 23.98 V, indicating very limited fluctuations and a high degree of voltage stability.

At the beginning of the measurements, the voltage was around 23.85 V and increased slightly to 23.95 V. A temporary decrease to approximately 23.70 V was then observed, representing the lowest value recorded during the test. Following this decline, the voltage recovered rapidly and fluctuated within a narrow interval around 23.85–23.96 V.

During the latter part of the experiment, the voltage showed a gradual upward trend, eventually reaching nearly 23.98 V, which corresponds to the maximum recorded value. The small amplitude of variation throughout the monitoring period suggests that the electrical performance of the aluminum sample remained highly stable.

Overall, the results demonstrate that the open-circuit voltage exhibited excellent consistency with only minor fluctuations. This behavior indicates stable operating conditions, reliable electrical characteristics, and the absence of significant disturbances affecting the aluminum sample during the measurement process.

IV.4.2 Reference open-circuit voltage evolution

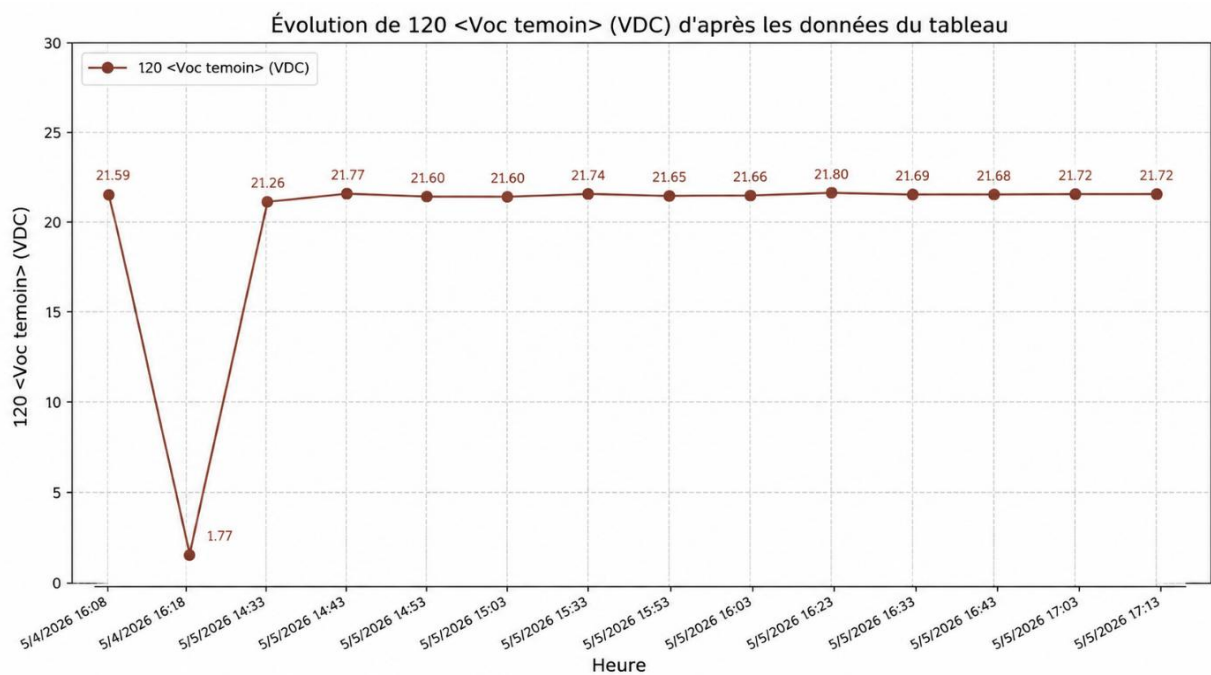


Figure IV.8: Reference photovoltaic module open-circuit voltage evolution.

The graph illustrates the variation of the reference photovoltaic module's open-circuit voltage (Voc Reference) during the measurement period. The recorded values ranged from approximately 21.26 V to 21.80 V, except for one unusually low value of 1.77 V, which appears to be an outlier or a temporary measurement anomaly.

At the beginning of the monitoring period, the voltage was 21.59 V, indicating normal operating conditions. A sudden drop to 1.77 V was observed in the second measurement. Since all

subsequent values returned immediately to the normal range, this decrease is likely attributable to a temporary shading event, a momentary interruption in the measurement process, or an instrumental error.

Excluding this anomalous value, the open-circuit voltage remained remarkably stable throughout the experiment, fluctuating within a narrow interval of approximately 21.26–21.80 V. The highest voltage (21.80 V) was recorded around the middle of the observation period, while the remaining measurements exhibited only minor variations.

The limited voltage fluctuations suggest that the reference photovoltaic module operated under relatively stable environmental conditions. Furthermore, the stability of the V_{oc} values indicates that the module maintained consistent electrical performance despite moderate variations in irradiance and temperature.

Overall, the results demonstrate excellent voltage stability for the reference PV module. Apart from the isolated abnormal reading, the open-circuit voltage remained nearly constant, confirming the reliability and steady operating behavior of the photovoltaic system during the experimental period.

IV.4.3 Comparative thermal and electrical performance

Table IV.2: Comparative thermal and electrical performance between the reference and aluminum-cooled PV modules.

Parameter	Reference PV Module	Aluminum PV Module	Difference	Effect
Average Temperature (°C)	54.99	49.66	-5.33 °C	Temperature reduction
Average V_{oc} (V)	21.68	23.89	+2.21 V	Voltage enhancement
Maximum Temperature (°C)	65.54	52.46	-13.08 °C	Improved heat dissipation
Maximum V_{oc} (V)	21.80	23.98	+2.18 V	Improved electrical performance

The comparison shows that the aluminum cooling configuration reduced the average operating temperature by 5.33°C and the maximum temperature by 13.08°C compared with the reference PV module. This thermal improvement was accompanied by an increase of 2.21 V in the average open-circuit voltage, indicating that the aluminum layer enhanced heat dissipation and contributed positively to the electrical performance of the photovoltaic module.

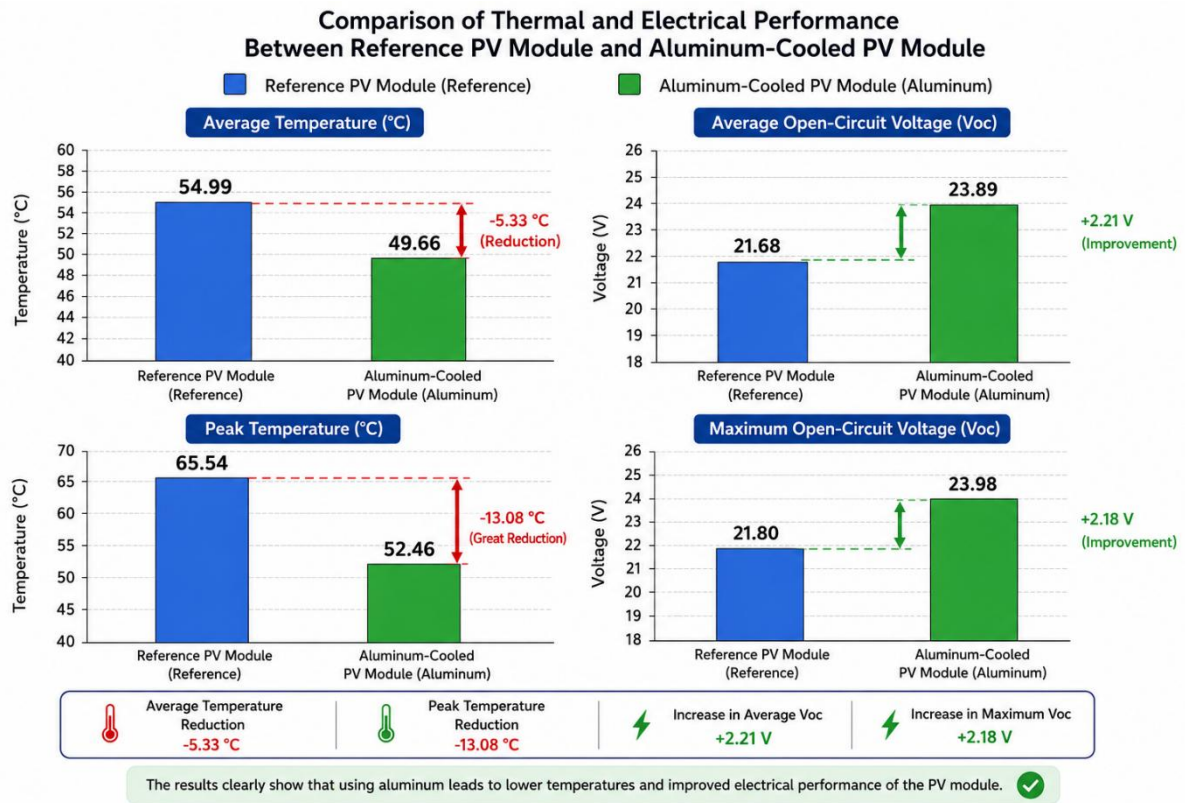


Figure IV.9: Comparative thermal and electrical performance of the reference and aluminum-cooled PV modules.

The figure compares the thermal and electrical performance of a reference photovoltaic (PV) module and an aluminum-cooled PV module. The results clearly demonstrate the positive impact of aluminum on both temperature regulation and electrical output.

Regarding the average operating temperature, the reference PV module recorded an average temperature of 54.99°C, whereas the aluminum-cooled module exhibited a lower average temperature of 49.66°C. This represents a reduction of 5.33°C, indicating that the aluminum layer effectively enhanced heat dissipation and reduced thermal accumulation within the PV module.

A more significant difference was observed in the peak temperature. The maximum temperature reached by the reference module was 65.54°C, while the aluminum-cooled module reached only 52.46°C. The reduction of 13.08°C confirms the excellent thermal management capability of aluminum and its effectiveness in limiting overheating under high solar irradiance conditions.

From an electrical perspective, the average open-circuit voltage (Voc) increased from 21.68 V for the reference module to 23.89 V for the aluminum-cooled module, corresponding to an improvement of 2.21 V. This increase is consistent with the well-known inverse relationship

between photovoltaic cell temperature and voltage, whereby lower operating temperatures contribute to higher voltage output.

Similarly, the maximum V_{oc} improved from 21.80 V in the reference module to 23.98 V in the aluminum-cooled module, resulting in a gain of 2.18 V. This finding further supports the beneficial effect of thermal control on the electrical performance of photovoltaic systems.

Overall, the comparison demonstrates that the incorporation of aluminum significantly reduced both the average and peak operating temperatures while simultaneously enhancing the open-circuit voltage. These results indicate that aluminum is an effective passive cooling material capable of improving the thermal stability and electrical efficiency of photovoltaic modules, thereby contributing to better overall system performance.

IV.5 Conclusion

This chapter presented a comprehensive experimental evaluation of the thermal and electrical performance of a photovoltaic (PV) module equipped with an aluminum cooling system compared to a reference PV module operating under the same environmental conditions. The analysis focused on key performance indicators, including module temperature, peak temperature, solar irradiance, and open-circuit voltage (V_{oc}).

The results demonstrated that the aluminum cooling configuration significantly improved the thermal behavior of the PV module. The aluminum-cooled module consistently operated at lower temperatures than the reference module, achieving reductions in both average and maximum temperatures. In particular, the peak temperature was reduced by more than 13°C, highlighting the effectiveness of aluminum as a passive heat dissipation material. This thermal improvement contributes to reducing thermal stress on PV cells and enhances their operational stability.

From an electrical perspective, the reduction in operating temperature was accompanied by an increase in the open-circuit voltage. The aluminum-cooled module exhibited higher average and maximum V_{oc} values than the reference module, confirming the strong relationship between temperature control and photovoltaic performance. These findings are consistent with the established principle that lower cell temperatures contribute to improved electrical efficiency.

The graphical analyses and comparative evaluations further confirmed the positive influence of aluminum on both heat management and electrical output. The observed improvements indicate

that integrating aluminum into photovoltaic systems can serve as an effective and low-cost passive cooling solution capable of enhancing module performance under real operating conditions.

Overall, the experimental results validate the proposed approach and demonstrate that aluminum cooling can effectively improve the thermal regulation and electrical characteristics of photovoltaic modules. Consequently, the adoption of aluminum-based cooling techniques may contribute to increasing energy yield, improving system reliability, and extending the operational lifespan of PV installations. These findings provide a valuable basis for future research aimed at optimizing passive cooling strategies for photovoltaic applications.

Based on the experimental investigation presented in Chapter IV, this study evaluates the thermal and electrical enhancement of monocrystalline silicon photovoltaic (PV) modules operating under the extreme desert climate of Ghardaïa, Algeria. High ambient temperatures severely penalize conversion efficiency due to the negative temperature coefficient beta inherent to semiconductor layers, which triggers significant thermal voltage sag in open-circuit voltage (V_{oc}). To mitigate these losses, a passive cooling system utilizing an aluminum plate substrate equipped with perforated vertical fins was mounted at the rear of the PV panel. Characterized by high thermal conductivity, the aluminum acts as an efficient heat sink. The integration of perforated fins expands the total convective surface area and promotes airflow turbulence, significantly augmenting the convective heat transfer coefficient (beta).

Experimental results demonstrate highly robust heat dissipation during peak solar irradiance. The reference control panel reached a critical degradation-prone thermal peak, whereas the modified module plateaued within a safe operational range. This critical thermal reduction successfully suppresses thermal stress and stabilizes the current-voltage (I-V) and power-voltage (P-V) characteristics. Consequently, this passive engineering solution recovers a significant portion of the energy yield that would otherwise be lost to heat.

General Conclusion

General Conclusion:

This dissertation presented an experimental study on the improvement of photovoltaic panel performance using a passive cooling system based on a perforated finned aluminum plate. The study was motivated by the negative effect of high operating temperature on photovoltaic modules, especially in hot and arid regions such as southern Algeria, where solar irradiance is high but thermal conditions can reduce electrical efficiency and accelerate material degradation.

The first chapter introduced the general principles of photovoltaic systems, including the photovoltaic effect, the main types of PV technologies, the influence of temperature on panel efficiency, and the solar energy potential in Algeria. It showed that although Algeria has favorable solar resources, the high temperatures recorded in desert environments represent a major technical challenge for photovoltaic installations.

The second chapter reviewed different cooling techniques used to reduce PV module temperature, including water cooling, air cooling, phase change materials, thermoelectric systems, and heat sinks. This review showed that passive cooling systems are particularly suitable for desert regions because they are simple, low-cost, reliable, and do not require additional electrical energy during operation.

The third chapter presented the experimental investigation carried out under real outdoor conditions in Ghardaïa. Two identical 100 W monocrystalline photovoltaic panels were used: one as a reference panel without cooling and the other equipped with a perforated finned aluminum plate fixed at the rear side. Temperature, solar irradiance, and open-circuit voltage were measured and compared in order to evaluate the thermal and electrical effect of the proposed cooling system.

The experimental results confirmed that the aluminum cooling system had a clear positive effect on the thermal behavior of the photovoltaic panel. The cooled panel operated at lower temperatures than the reference panel throughout the measurement period. The maximum temperature decreased from 71.91°C for the reference panel to 52.46°C for the aluminum-cooled panel, corresponding to a reduction of approximately 19.45°C. This demonstrates the ability of aluminum fins to dissipate heat and limit thermal accumulation on the rear surface of the PV module.

The reduction in operating temperature also improved the electrical behavior of the panel. The open-circuit voltage of the aluminum-cooled panel remained higher and more stable than that

General Conclusion

of the reference panel. The aluminum-cooled panel recorded voltage values ranging approximately from 23.70 V to 23.98 V, while the reference panel recorded values between about 21.26 V and 21.80 V. This confirms the inverse relationship between temperature and voltage in photovoltaic modules: when the temperature decreases, the voltage increases, leading to better electrical performance.

Overall, the results demonstrate that the use of a perforated finned aluminum plate is an effective passive cooling solution for photovoltaic panels operating in hot desert climates. The proposed system reduced the operating temperature, improved voltage stability, and enhanced the thermal and electrical performance of the PV module. Because of its simplicity, low cost, and absence of additional energy consumption, this cooling method can be considered a practical solution for improving photovoltaic performance in Algeria and similar arid regions.

Future work could focus on testing different fin shapes, materials, and plate geometries, as well as evaluating the long-term durability of the cooling system under real desert conditions. Further studies may also include measurements of current, output power, and efficiency in order to obtain a more complete evaluation of the energy gain achieved by passive aluminum cooling.

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