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Sbject

Experimental study on the cooling of PV solar panels using fins with innovative shapes

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Dedication

To the little girl I used to be, full of dreams and passions . I always dreamt of my graduation day. It seemed so far away, but thanks to the Lord, I made it. Despite all the problems and difficulties I went through, I would like to thank my parents, who supported me, believed in me, and prayed for me at every step of my life.

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Dedication

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TO MY DEAR MOTHER

No dedication can express my respect, my eternal love and my consideration for the sacrifices you have made for my education and well-being.

I thank you for all the support and love you have given me since I was a child, and I hope that your blessing will always be with me.

May this modest work be the fulfilment of your many wishes and the fruit of your countless sacrifices. May God, the Most High, grant you health, happiness and long life.

IN MEMORY OF MY FATHER

This work is dedicated to my father, who died too soon, and whose love, values and encouragement continue to accompany me despite his absence. I hope that, in the world that is now his, he will appreciate this humble gesture as a token of gratitude from a son who has always prayed for the salvation of his soul. May Almighty God have him in his holy mercy.

TO MY BROTHER AND SISTER

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MUSTAPHA

Résume

Cette étude expérimentale met en évidence l'efficacité de l'intégration d'ailettes de refroidissement passif dans les panneaux photovoltaïques (PV) pour améliorer à la fois la régulation thermique et la performance électrique. Deux configurations d'ailettes ont été testées dans des conditions extérieures réelles afin d'évaluer l'impact de la géométrie des ailettes sur la dissipation de la chaleur et la production d'énergie. Dans la première expérience, des ailettes verticales standard ont été montées sur la surface arrière du panneau photovoltaïque. Cette configuration a permis de réduire la température de 7°C à 9,5°C et d'augmenter la puissance jusqu'à 2,14 W, pour atteindre une puissance maximale de 53 W. L'amélioration du rendement a atteint 43,9 %, ce qui confirme l'avantage du refroidissement passif dans l'atténuation des pertes induites par la température. La deuxième expérience a utilisé une conception plus avancée avec des ailettes perforées en forme de croix. Cette configuration a démontré des performances supérieures, réduisant la température du panneau de 9°C à 14°C et augmentant la puissance de sortie jusqu'à 4 W, avec un maximum de 59 W. Le gain d'efficacité a atteint 53%, ce qui est environ 10% plus élevé que celui de la configuration à ailettes verticales. Les résultats démontrent que le refroidissement passif, en particulier avec des géométries d'ailettes optimisées, est une méthode simple, rentable et très efficace pour améliorer les performances des systèmes photovoltaïques. Ces améliorations sont particulièrement utiles dans les environnements à fort rayonnement, où les températures élevées des panneaux peuvent avoir un impact négatif sur le rendement énergétique et la longévité. Cette étude souligne le potentiel des conceptions innovantes en matière de gestion thermique et encourage la poursuite des recherches sur les solutions de refroidissement passives et hybrides afin d'améliorer l'efficacité énergétique solaire.

Mots-clés : énergie solaire, Refroidissement passif, panneau photovoltaïque sans ailettes, panneau photovoltaïque avec ailettes. Ailette de croix avec des perforations.

Abstract

This experimental study highlights the effectiveness of integrating passive cooling fins into photovoltaic (PV) panels to improve both thermal regulation and electrical performance. Two fin configurations were tested under real outdoor conditions to assess the impact of fin geometry on heat dissipation and energy output. In the first experiment, standard vertical fins were mounted on the back surface of the PV panel. This setup resulted in a temperature reduction ranging from 7°C to 9.5°C and a power increase of up to 2.14 W, reaching a peak output of 53 W. The efficiency improvement reached up to 43.9%, confirming the benefit of passive cooling in mitigating temperature-induced losses. The second experiment employed a more advanced design with cross-shaped perforated fins. This configuration demonstrated superior performance, reducing the panel temperature by 9°C to 14°C and increasing power output by up to 4 W, with a maximum of 59 W. The efficiency gain reached 53%, which is approximately 10% higher than that of the vertical fin setup. The findings demonstrate that passive cooling, especially with optimized fin geometries, is a simple, cost-effective, and highly efficient method for enhancing PV system performance. These improvements are particularly

valuable in high-radiation environments, where elevated panel temperatures can negatively affect energy yield and longevity. The study underscores the potential of innovative thermal management designs and encourages further research into both passive and hybrid cooling solutions to advance solar energy efficiency.
Keywords: solar energy, passive cooling, finless photovoltaic panel, photovoltaic panel with fins, Cross fin with perforations.

الملخص

لتحسين كل من التنظيم الحراري (PV) سلط هذه الدراسة التجريبية الضوء على فعالية دمج زعانف التبريد السلبية في الألواح الكهروضوئية والأداء الكهربائي. تم اختبار تكوينين للزعانف في ظروف خارجية حقيقية لتقييم تأثير هندسة الزعانف على تبديد الحرارة وإنتاج الطاقة. في التجربة الأولى، تم تركيب زعانف عمودية قياسية على السطح الخلفي للوحة الكهروضوئية. أدى هذا الإعداد إلى انخفاض في درجة الحرارة يتراوح بين 7 درجات مئوية و 9.5 درجة مئوية وزيادة في الطاقة تصل إلى 2.14 واط، لتصل إلى ذروة إنتاج تبلغ 53 واط. بلغ تحسن الكفاءة ما يصل إلى 43.9٪، مما يؤكد فائدة التبريد السلبي في التخفيف من الخسائر الناجمة عن درجة الحرارة. استخدمت التجربة الثانية تصميمًا أكثر تقدمًا مع زعانف مثقبة على شكل صليب. أظهر هذا التكوين أداءً فائقًا، حيث خفض درجة حرارة اللوحة بمقدار 9 درجات مئوية إلى 14 درجة مئوية وزاد إنتاج الطاقة بما يصل إلى 4 واط، بحد أقصى 59 واط. بلغ معدل الكفاءة 53٪، وهو أعلى بنحو 10٪ من معدل الكفاءة في التكوين ذي الزعانف العمودية. تُظهر النتائج أن التبريد السلبي، خاصة مع هندسة الزعانف المُحسّنة، هو طريقة بسيطة وفعالة من حيث التكلفة وعالية الكفاءة لتحسين أداء نظام الطاقة الكهروضوئية. هذه التحسينات ذات قيمة خاصة في البيئات عالية الإشعاع، حيث يمكن أن تؤثر درجات حرارة الألواح المرتفعة سلبًا على إنتاج الطاقة وعمرها الافتراضي. تؤكد الدراسة على إمكانات التصميمات المبتكرة لإدارة الحرارة وتشجع على إجراء مزيد من الأبحاث في حلول التبريد السلبي والهجين لتعزيز كفاءة الطاقة الشمسية.
الكلمات المفتاحية: الطاقة الشمسية، التبريد السلبي، الألواح الكهروضوئية بدون زعانف، الألواح الكهروضوئية ذات الزعانف زعنفة متقاطعة مع ثقوب.

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Notation	**Unite**	**Meening**
PV		Photovoltaic
DC	**A**	Direct current
AC	**A**	Alternative current
$\boldsymbol{V_{total}}$	**V**	The total voltage of the generator,
$\boldsymbol{C_n}$		**The** number of cells in series
$\boldsymbol{V_{cell}}$		The voltage of a single cell.
$\boldsymbol{\overrightarrow{\varphi}}$	**W.m^{-2}**	Flux
$\boldsymbol{\varepsilon}$		Body emissivity
σ	**W.m^{-2}.K^{-4}**	Stefan constant
$\dot{Q}$**conv:**	**W.m^{-2}**	Convective heat flux
$\boldsymbol{T_{without\ fins}}$	**°C**	Temperature without fins
$\boldsymbol{T_{with\ fins}}$	**°C**	Temperature with fins
$\boldsymbol{T_{ambiant}}$	**°C**	Ambiant Temperature
P	**W**	Power
V	**V**	Tension
I	**A**	Current
η	**%**	Solar panel efficiency

General introduction

General introduction

Among the various renewable energy sources available today, solar energy stands out as one of the most promising, sustainable, and accessible solutions for addressing both the global energy demand and the escalating climate crisis. Its widespread availability, minimal environmental impact, and relatively low maintenance make it particularly well-suited for deployment across diverse geographic regions, from urban centers to remote rural areas. In particular, the simplicity of installation and the pollution-free nature of photovoltaic (PV) systems position solar energy as a key contributor to future energy transitions worldwide.

However, despite these clear advantages, PV systems face a number of technical challenges, one of the most critical being the rise in panel temperature during operation, especially under high solar irradiance conditions. This is particularly problematic in hot and arid regions, such as the Algerian Sahara and the Arabian Gulf, where ambient temperatures often exceed 40°C. Under such conditions, solar panels tend to absorb excessive heat, leading to a marked decline in conversion efficiency, increased thermal stress on panel materials, and ultimately, a reduction in the operational lifespan of the entire system.

In response to these challenges, the present study explores a passive thermal management strategy aimed at enhancing the thermal performance of photovoltaic modules without relying on active or energy-consuming components. Specifically, it investigates the use of cooling fins as a means to improve heat dissipation from the back surface of the PV panels. To that end, two experimental setups were developed and tested under real outdoor conditions, on separate days and under slightly differing environmental factors such as ambient temperature and solar irradiance.

The first experimental configuration involved a comparison between two identical photovoltaic panels: one equipped with conventional vertical fins, and the other without any fins. The objective was to assess the impact of this simple fin geometry on panel temperature, electrical output, and overall efficiency. The results indicated a notable reduction in operating temperature, which in turn led to measurable improvements in power generation and voltage stability.

In the second experiment, the study introduced a more advanced and aerodynamically optimized design featuring cross-shaped fins with perforations, intended to further enhance airflow and thermal convection. As with the first experiment, this modified panel was compared to a finless reference panel, with both setups operated under full-day outdoor conditions from 8:00 AM to 5:00 PM. Environmental and electrical parameters were closely monitored, including surface temperature, ambient conditions, solar irradiance, voltage, current, power output, and real-time efficiency.

The data collected from both experiments revealed significant performance differences between the finned and non-finned panels. In particular, the cross-perforated fin design demonstrated superior thermal regulation, with temperature reductions ranging from 9°C to 14°C, compared to a 7°C to 9.5°C reduction achieved by vertical fins. These thermal improvements translated into higher power outputs and enhanced energy conversion efficiency. Furthermore, the inclusion of passive cooling elements contributed to greater electrical stability, reduced heat-induced degradation, and the potential for extended system lifespan.

From a broader perspective, these findings underscore the effectiveness, affordability, and practicality of implementing passive cooling techniques in PV systems. By avoiding complex mechanical systems or additional energy inputs, passive strategies like fin integration provide a low-cost, low-maintenance solution for improving PV performance in high-temperature environments. This is particularly valuable in developing countries and remote regions where energy resources are scarce and environmental conditions are harsh.

In response to these challenges, the present study investigates a passive cooling strategy based on the integration of heat-dissipating fins on the back surface of PV panels. This work is structured into four chapters, each addressing a key aspect of the study:

- Chapter I: General Concepts of Renewable Energy

This chapter presents an overview of renewable energy sources, with a particular focus on solar energy. It highlights global energy challenges and the strategic role of clean technologies in the energy transition.

- Chapter II: The Process of Photovoltaic Conversion

This section explores the fundamental physical principles underlying photovoltaic conversion, including the operation of solar cells, efficiency factors, and the influence of temperature on performance.

- Chapter III: Environmental Impact of Solar Panels

This chapter discusses the environmental implications of PV technology, considering both the benefits (e.g., reduction in greenhouse gas emissions) and potential impacts during production, operation, and disposal.

- Chapter IV: Installation Process and Results

This final chapter focuses on the experimental methodology, the design of the cooling systems, and the analysis of the data collected during testing.
In conclusion, this study offers compelling evidence that the strategic use of passive cooling components especially those optimized in shape and structure can lead to significant gains in thermal control, electrical performance, and system longevity. It reinforces the need for continued research and innovation in both passive and hybrid cooling technologies, which will be essential for ensuring the reliability and efficiency of future solar energy systems, particularly in the face of growing climate extremes.

Chapter I
General concepts of renewable energy

Introduction

The sun is an endless source of energy that is important to our planet's climate and ecosystems. By studying the solar spectrums and radiations, we can fully understand how sunlight eventually reaches Earth and considerably affects any environment.

For a very long time, man has sought to use this energy emitted by the sun, to reduce dependence on fossil fuels, it is to go beyond simply satisfying certain energy needs and it is to mitigate the overall ecological effect. As the world moves towards cleaner energy, solar energy is a fully sustainable and very promising solution.

Today, photovoltaic technology, is a revolutionary way to harness solar energy and turn it into electrical power. The foundation of PV technology is the photovoltaic effect, which states that when specific materials are exposed to sunlight, they produce an electrical current. This chapter provides a thorough overview of the fundamental ideas behind photovoltaic technology by examining the fundamentals of solar radiation, the structure of semiconductors, and intricate mechanisms that enable the conversion of solar light into usable electrical energy.

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I.1 Solar energy

I.1.1 The sun

The Sun is a gigantic, shining star that forms the center of our Solar System. It is largely made up of hydrogen and helium and is involved in the nuclear process of converting hydrogen into helium at its core, thereby producing prodigious quantities of energy in the form of light and heat. It is this energy that powers life on Earth, drives the Earth's climate, and induces the many types of weather. The Sun is estimated to be about 4.6 billion years old, having a structure made up of layers: these include the core, radiative and convective zones, the visible photosphere, the chromosphere, and the corona. Its magnetic behavior gives rise to sunspots and flares that affect a distance well over that of the Earth itself, forming the heliosphere that enfolds the Solar System.

The Sun's diameter is 1,391,960 kilometers, or about 109 times larger than that of the Earth; its energy, light, and heat supply make life on Earth quite possible.

Solar energy is produced in the center of the Sun, where temperatures are at about 15.57 $\times 10^6$ °C and pressures at 340 billion times sea-level atmospheric pressure. At these values, thermonuclear reactions may occur, in which four protons, or hydrogen nuclei, fuse together to form one helium nucleus, termed an alpha particle. Its mass would be about 70 percent compared with the combined mass of the four initial protons. The discrepancy in the mass and energy of this process is converted into energy within the Sun and conveyed through massive convection currents to its surface, where it is ultimately released as light.

The energy that is generated in the great depths of the Sun requires nearly a million years to reach the surface. The chemical reactions in the core of the Sun convert seven hundred million tons of hydrogen into helium per second; this process consequently generates five million tons of pure energy. [1]

I.1.2 Advantages

- Energy independence is the fact that the fuel, solar radiation, is renewable and free of charge.
- The system produces the necessary energy to serve the purpose
- More reliable and less vulnerable to the risk of power failure
- Flexible systems that can be expanded easily, allowing installations to be increased later in size to meet the Provisions for expansion customer's winning demands.
- Selling surplus production generates financial compensation or profitable turnover to pay back the initial investment costs.
- It requires little maintenance, allowing it to be up and running at a low expense to the user.

- Very few or almost no noise is produced by these systems**.** [1]

I.1.3 Disadvantages

The production of solar panels depends on cutting-edge technology, requiring significant research and development expenditure, thus generating significant installation costs. Their performance, or even their profitability, is still relatively limited. Domestic installations require a backup system. The cost of installation is high.

I.1.4 The solar spectrum

The solar spectrum consists of the radiation energy emitted by the source of sunlight in wavelengths from ultraviolet to visible light down to the infrared. It is perhaps the most essential energy source for life on Earth: powering photosynthesis, heating, and generating energy through solar conversion. It briefly reports the nature and aspects of the solar spectrum, its measurement, and its significance as described below. [2]

I.1.4.1 Definition and constituent parts of the solar spectrum

The solar spectrum is the electromagnetic radiation emitted from the Sun, in the range of X-rays to radio waves. Most of the energy from the Sun comes through the visible and infrared regions. The spectrum comprises three broad portions:

- **Ultraviolet (UV):** Wavelengths shorter than 400 nm have high-energy photons (3–5 eV).

Ultraviolet rays can be categorized into three types:

1. UVA: They can pass freely through the atmosphere and reach the Earth's surface. [2]

2. UVB: These are shorter and more difficult to pass through the atmosphere than UVA. Therefore, they reach the atmosphere at quicker times of the day near the equator than towards higher latitudes. [2]

3. UVC: They are very short in wavelength and cannot penetrate through the atmosphere. They are absorbed by the ozone layer. [2]

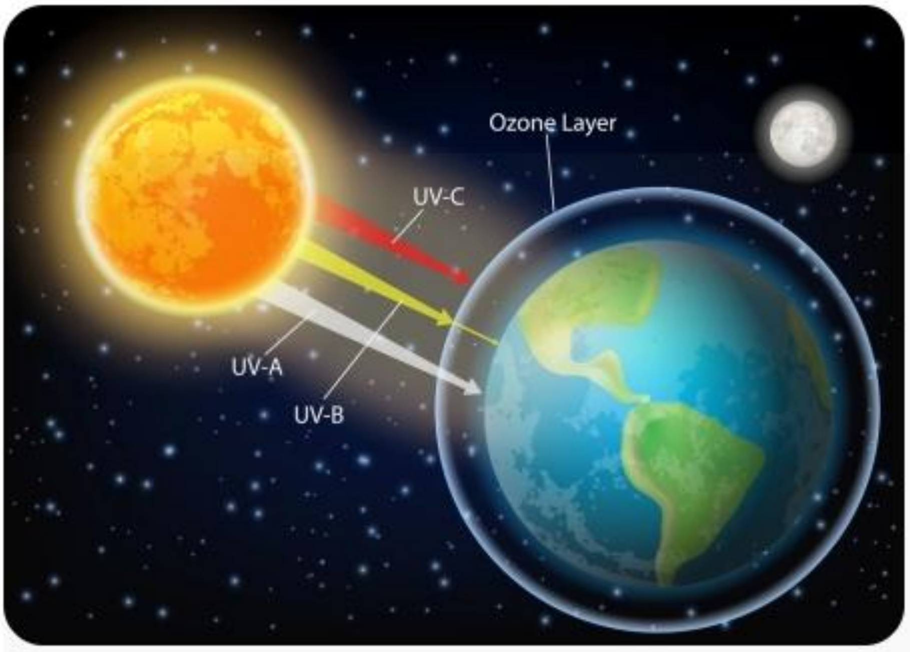

Figure I. 1: Types of ultraviolet [2]

- **Visible:** This portion extends between 400 nm and 750 nm, where photons with energies of 1.8–3 eV reside. This region carries nearly half of the Sun's total energy output. [3]
- **Infrared (IR):** Longhouse wavelengths longer than 1000 nm with the lowest energy of photons (0.35–1.8 eV). [3]

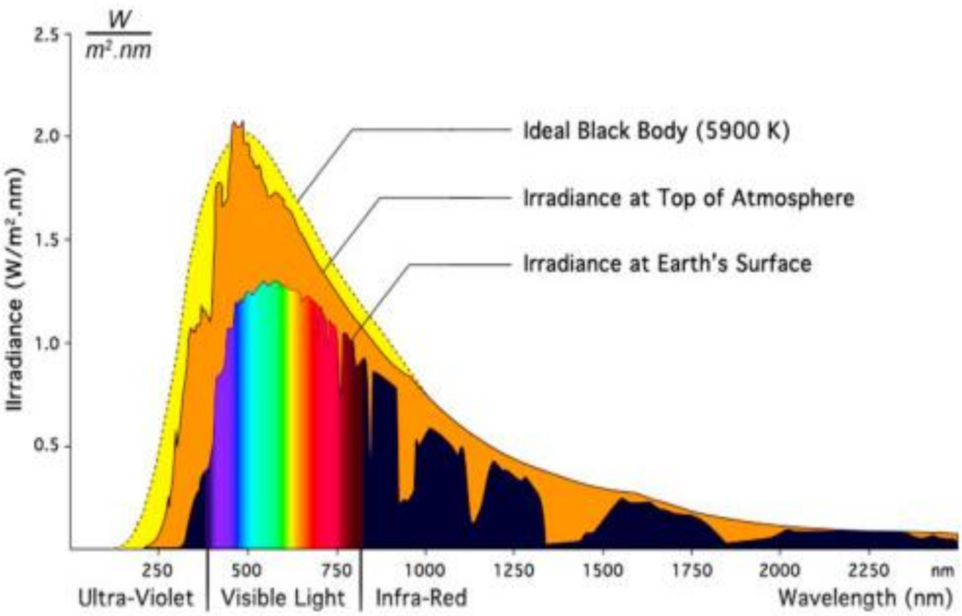

Figure I. 2: Solar spectrum with its types*[3]*

The solar spectrum is suitably influenced by core temperature (15 million K) and the surface temperature of the Sun, being about 5700 K, which approximates it as blackbody radiation. [3]

I.2 Solar radiation

Solar radiation is the manifestation of electromagnetic energy produced by the Sun, covering wavelengths from X-rays to radio waves. This is the main source of energy for the climate system and life on Earth. The total solar irradiance (TSI), or "solar constant," is about 1361 W/m² at the top of Earth's atmosphere. [4]

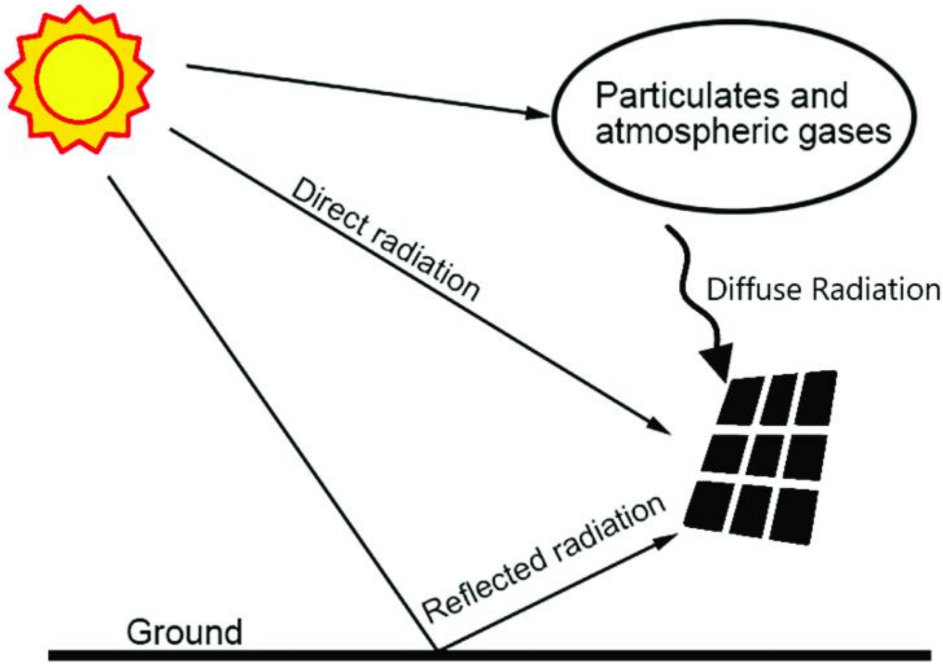

Figure I. 3: Types of Solar radiation *[5]*

I.2.1 Direct Solar Radiation

Radiation that travels unimpeded from the Sun to the Earth and forms sharp shadows. It is predominant on clear days and of great importance for concentrated solar power systems used to measure this energy such as the pyrheliometer or the pyranometer. [6]

I.2.2 Diffuse solar radiation

Atmospheric particles, clouds, or pollution scatter radiation. This doesn't produce sharp shadows and is predominant on cloudy days. Horizontal surfaces receive the most diffuse radiation. [7]

I.2.3 Reflected Solar Radiation

Radiation bounced off the surface of the Earth (e.g., snow, water, sand) due to the albedo effect. Fresh snow reflects as much as 90% of UVB radiation, thereby putting one at risk of exposure. [8]

I.2.4 Global Solar Radiation

Global irradiation is the total amount of solar energy, in a time unit, per unit area received on a horizontal surface, involving direct sunlight, diffuse (scatter) radiation by the atmosphere, and reflected light. Key contributory factors include:

- **The solar constant**: ~1,361 W/m^2 at the outer layer of Earth's atmosphere, the total energy output of the Sun.
- **Air mass (AM):** The path length through which sunlight passes in the atmosphere and increases as the solar angle decreases. Most common standard for solar panel testing (zenith angle ~48°), representing ~1.5 times the atmospheric thickness
- **Solar elevation**: Is controlled and affected, to mention the least, by time of day, latitude and season, making air mass varied as well as energy intensity.
- **Atmospheric circumstances**: Clouds, aerosols, and pollution scatter or absorb sunlight, reducing direct radiation.
- **Surface albedo**: The reflection ratio of the ground or environment (for example, snow reflects better than grass, etc.).
- **Altitude**: It lowers atmospheric filtering at higher heights; hence it increases solar energy reception.

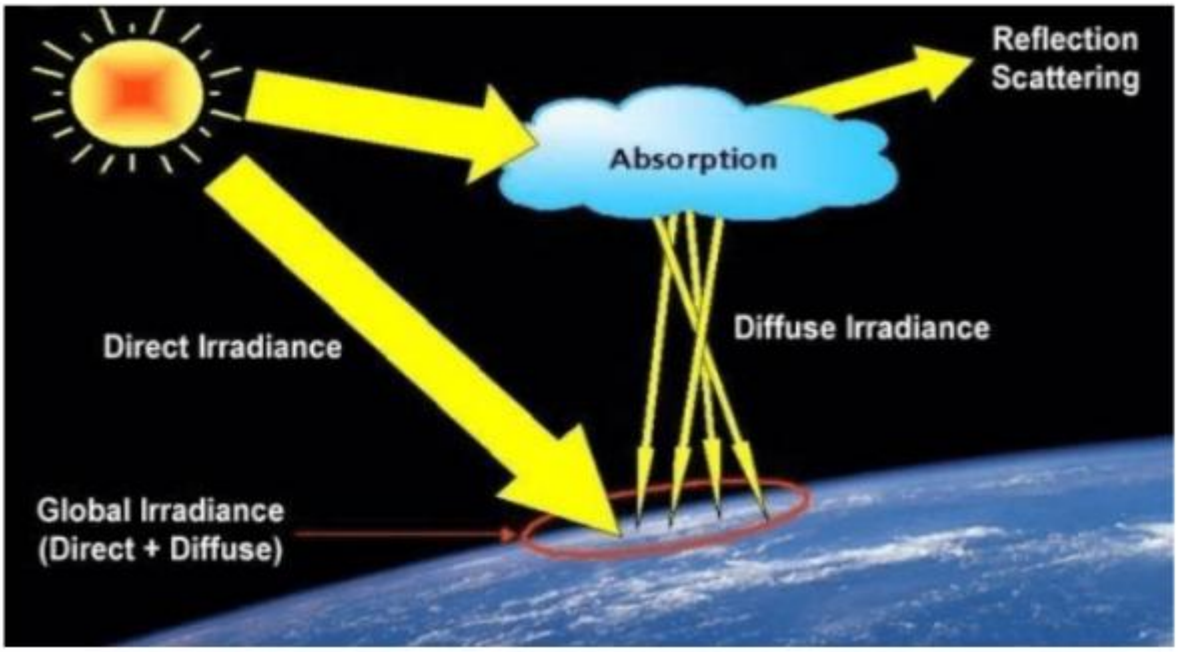

Figure I. 4: Components of global radiation (direct, diffused, and reflected radiations) [8]

Direct radiation usually dominates under clear skies (shorter atmospheric path), while cloudy conditions tend to enhance diffuse radiation. Their cumulative effect is what sets the net solar energy input into an area about the solar constant, whose attenuation is modulated by air mass and atmospheric interactions. [9]

I.3 Different technologies for converting solar energy

I.3.1 Photovoltaic solar energy

The world's desert regions (the Great Sahara, the southwestern United States, Australia, and South Africa) receive up to 2,900 kWh/m2/year of direct radiation, offering high potential for solar energy production.

The Maghreb countries have a high solar potential. Satellite measurements of solar radiation by the German Space Agency (DLR) show unusual levels of solar radiation of around 1200 kWh/m2/year in the north of the Great Sahara. In contrast, maximum solar radiation levels in Europe are around 800 kWh/m2 and are limited to the southern part of the continent. [10]

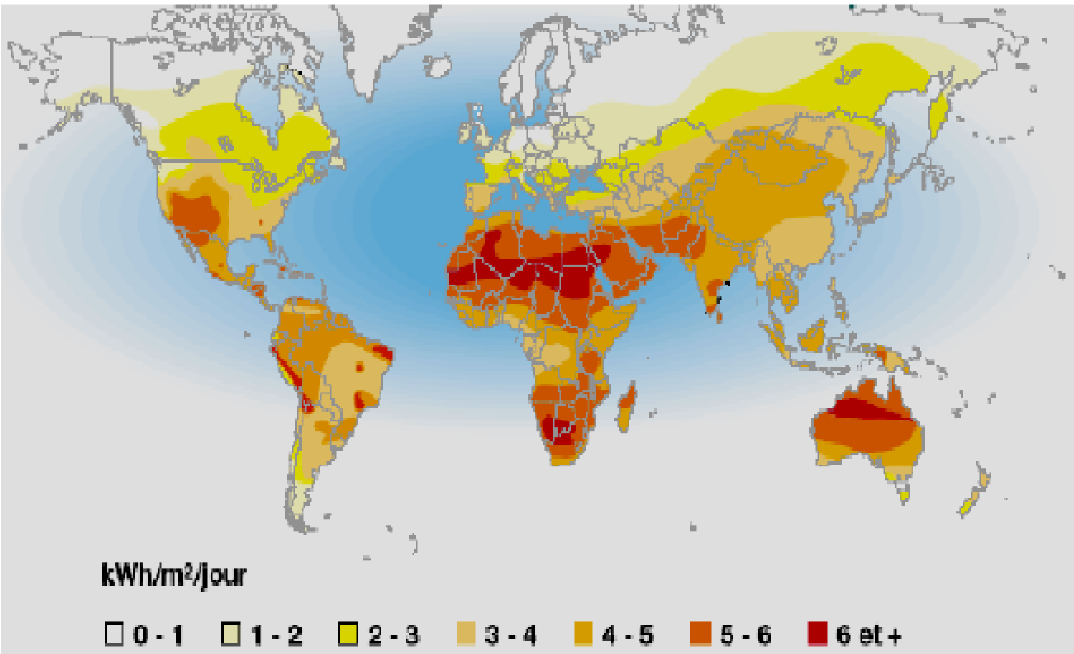

Figure I. 5: World map of average annual sunshine *[10]*

I.4 Sunshine in Algeria

In Algeria, solar energy has the most potential for renewable energy. It receives about 1,700 KWh/m2/year in the north and 2,263 KWh/m2/year in the south due to its 2,000 hours of sunshine annually, which can reach 3,900 hours on the high plateaux and in the Sahara. That's about 2,200 KWh/m2/year on average.

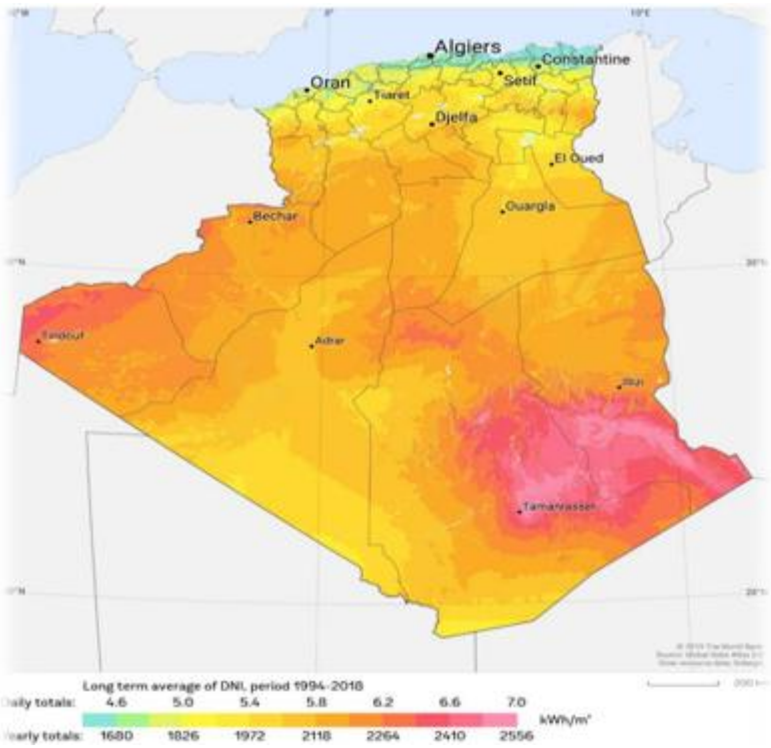

Figure I. 6: Solar potential in Algeria *[11]*

Over the majority of Algeria, the energy received daily on a one cubic meter horizontal surface is on the order of 5 kWh/m2/year, or around 1700 KWh/m2/year in the north and 2650 KWh/m2/year in the south. [11]

Table I. 1: Solar potential in Algeria *[11]*

Regions	Coastal region	highland	Sahara
Area (%)	4	10	86
Average duration of sunshine (hours/year)	2650	3000	3500
Average energy received ($KWh/m^2/year$)	1700	1900	2650

I.5 Renewable energy in the world

The share of renewables declined from 20.82% of global electricity generation in 1985 to 18.09% in 2005. One of the main reasons for this decline was the increasing share of fossil fuel and nuclear power generation as they captured a larger share of the global energy market. Since then, the share of renewables has steadily and significantly increased to reach 30.24% in 2023. This gradual rise has been supported by greater efforts towards climate change mitigation, technological advances in renewable energy, and favorable policies from governments. Immediately after 2010 in particular, the trend accelerated, showing a significant upward trend in the annual average, especially from 18.71% in 2010 to 30.24% in 2023. Significant increases have also occurred in some recent years, not least in 2020 when the proportion of renewables reached 28.08%, largely due to increased awareness of climate change and a shift towards investment in green infrastructure. These trends emphasize the gradual but determined transition to a sustainable energy mix**.** [12]

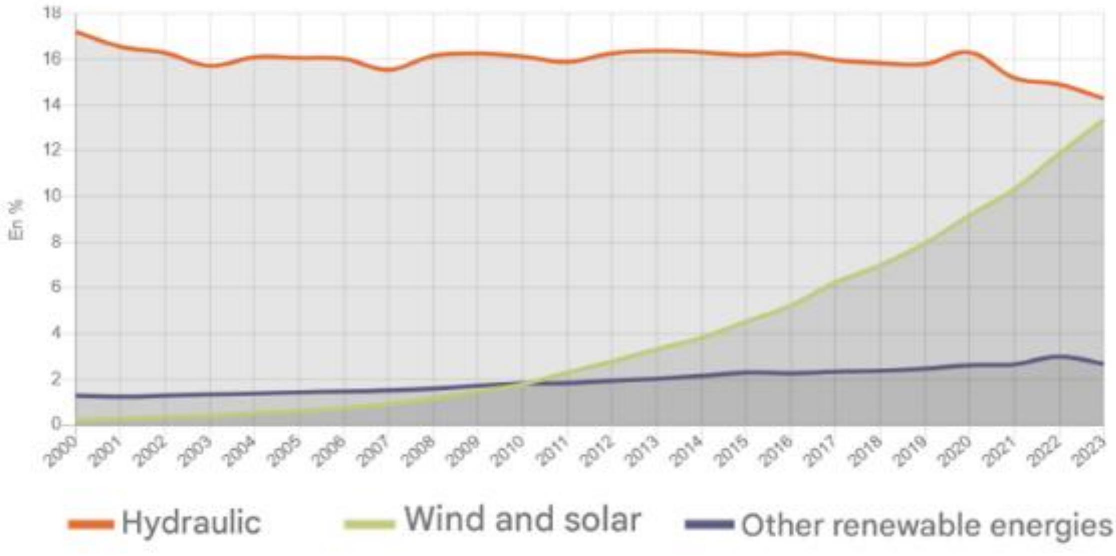

Figure I.7: Share of renewable energy in the global electricity mix in (%) [13]

I.5.1 Thermal solar energy

Direct thermal energy or solar heating is another type of solar energy technology that captures and uses the heat of the sun directly. While photovoltaic (PV) systems harness sunlight to create electricity, direct thermal systems employ solar collectors—including flat-plate panels, evacuated tubes, or air-based collectors—to absorb solar radiation and transfer the heat to a working fluid (usually water, air or a heat-transfer liquid such as glycol)

This fluid is later heated and circulated through either a system to heat water, warm indoor spaces, or to utilize in industrial processes. These systems can be either active, distributing heat through the use of pumps or fans, or passive, relying on natural convection. Among these applications, solar water heating is a prevalent use of solar energy in which water is heated for residential, industrial, and swimming pool use. Another use is solar space heating, where heated air or liquid circulates through floors, radiators, or ventilation systems to maintain indoor comfort. . [13]

Figure I.8: Thermal solar energy [14]

I.5.1.1 Advantages

- Harnessing the Sun – Solar thermal energy depends on sunlight, a plentiful and endless energy source.
- Save Money—After it's set up, it provides free heating, which helps cut down on electricity and gas bills.
- Effective Use – It turns sunlight into heat well, losing very little energy, so it’s often better for heating than solar panels.
- Good for the Planet – It doesn’t release any harmful gases, helping to lower our carbon footprints.
- Long-lasting – These systems are built to last, often functioning for over 20 years with just a little upkeep.
- Versatile Uses – They can heat water, warm up spaces, support industrial operations, and even generate power through methods like Concentrated Solar Power.
- Energy Freedom – They lessen the need for fossil fuels and help keep energy prices steady.
- Heat Storage – Thermal storage options, like hot water tanks, make it possible to save heat for later use, even when the sun isn’t shining.

I.5.1.2 Disadvantages

- High Start-Up Costs – Installing solar systems can be pricey, but you’ll save money on energy bills as time goes by.

- Weather Sensitivity – On cloudy days or during long winters, the efficiency of solar systems drops, especially in areas that don't get much sun.
- Space Requirements – You need enough roof or land area for solar panels to gather sunlight effectively.
- Maintenance Is Necessary – Though it's not too demanding, you do need to check your system occasionally to avoid leaks or rust and keep it running well.
- Limited Use at Night – Without proper storage, solar thermal systems can't generate heat after dark, so you'll need some backup heating options.
- Regional Challenges – These systems are less effective in colder places with little sunlight or where clouds are common.
- Complications for Large Projects – While they work well for homes and small businesses, expanding to meet the needs of larger industries requires a lot of infrastructure and investment.

I.5.2 Thermodynamic solar energy

Thermodynamic solar energy, or CSP = Concentrated Solar Power, is primarily used in large power plants as opposed to residential due to its complexity and infrastructure requirements. CSP systems function by employing mirrors or reflectors that focus sunlight on a central receiver where the solar energy is transformed into high-temperature heat. This heat is then converted into steam which drives turbines connected to generators which create the electricity. Unlike photovoltaic (PV) panels that directly convert sunlight into electricity, Concentrated Solar Power (CSP) relies on the thermodynamic process that converts solar heat into mechanical energy for electricity generation. An important advantage of CSP systems is that they can include thermal energy storage, which typically uses molten salts or other heat-storing materials, permitting electricity generation when the sun does not shine. This makes CSP an effective solution for ensuring a stable and continuous power supply. CSP plants are commonly found in regions with high solar radiation, such as deserts, and play a crucial role in large-scale renewable energy production, reducing dependence on fossil fuels and lowering carbon emissions.. [13]

Figure I.9: Thermodynamic solar energy [15]

I.5.2.1 Advantages

- It uses the abundant and infinite energy from the sunshine
- Energy storage ability--CSP system can store thermal energy (that is, molten salt), and make power supply without sun, so electricity is stable.
- High efficiency for large-scale applications–Its power plants produce electricity more efficiently than solar panels.
- Reduces the strict reliance on coal-burning electricity substations and moves towards cleaner power sources.
- **Potential for Hybrid Systems** – Can be integrated with other energy sources like natural gas for continuous power production.

I.5.2.2 Disadvantages

- **High Initial and Maintenance Costs** – The construction and upkeep of CSP plants are expensive due to labor costs and advanced infrastructure requirements.
- **Limited Employment Opportunities** – While CSP plants create jobs, they are often located in remote, non-urban areas, where poverty can persist despite employment opportunities.
- **Impact on Land-Use Patterns** – Labor costs and plant construction influence economic land-use patterns, especially in regions where CSP is developed.
- **Challenges of Desert Climates** – CSP plants are typically located in deserts, where the environment does not support land-intensive activities like farming or ranching.

- **Seasonal Efficiency Fluctuations** – The efficiency of CSP plants can decline due to seasonal changes, affecting energy production.

I 5.3 Photovoltaic solar energy

Photovoltaic (PV) technology captures sunlight and converts it into electrical energy through the use of panels comprised of numerous solar cells that are constructed from semiconductor materials. As sunlight strikes these solar cells, it produces an excitation within the electrons, causing them to become unbound which, in turn, produces a flow of electrons through an external circuit. Theoretically, in the case of a home or business, if we add more PV panels, we are able to collect and generate more energy than before. PV energy presents excellent possibilities for the future; but, whether PV energy will be beneficial or not, depends on the specific structure of the panels and the types of solar cells, which will discussed in greater detail in the next chapter. [13]

Figure I. 10*:* Photovoltaic solar panel [56]

Conclusion

In this first chapter, we have attempted to study solar energy with an introduction to the Sun, its advantages, and disadvantages. We have had a very concise definition of the solar spectrum and its parts; then we talked about solar radiation itself and various technologies for the conversion of solar energy, which include thermal, photovoltaic, and thermodynamic systems. Following this, we introduced the concept of solar insolation, focusing on that of Algeria; finally, the issue of increasing energy consumption in Algeria was addressed.

Chapter II
The Process of Photovoltaic Conversion

Introduction

In this chapter, we will explore photovoltaic conversion, starting with a context and a historical overview. Then, we will delve into photovoltaic conversion with the basics of solid materials, concerning semiconductors, conductors, and insulators.

In succession, we will move to define photovoltaic panels and manufacture photovoltaic panels. After that, doping in silicon will be phosphorylated, explaining "N" doping, "P" doping, and the PN junction. Then, we will discuss the arrangement of photovoltaic cells into solar panels, including aspects of series and parallel connections and the concept of energy band. Finally, we will carry out the advantages and disadvantages of photovoltaic plants, in terms of the benefits sides and limitations.

II.1 Photovoltaic convection

II.1.1 Definition

Photovoltaic is the direct conversion of sunlight into electricity using semiconducting materials, which leads to the photovoltaic effect first described by Alexander-Edmond Becquerel in 1839. [16]

When photons from sunlight strike a semiconductor material, usually silicon, some electrons are dislodged from their atomic bonds, creating electron-hole pairs within the material. The unique electric field set up within the semiconductor structure, which is frequently enhanced through deliberate doping with elements such as phosphorus and boron, pushes these charge carriers onto the conductive electrodes, and DC is produced. While modern PV cells tout efficiencies of 15% to 22% under standard test conditions, advanced multi-junction cells in laboratories have already broken above the 47% threshold efficiency by stacking layered materials for a wider capture of the sunlight spectra. Applications of PV are indeed broad: these range from rooftop solar panels for residential and commercial energy concentration, large PV farms to be incorporated directly into national grids, specialized uses in spacecraft, as well as remote, off-grid applications. Global adoption of PV has soared in the past decades, purely due to falling prices (over 80% decrease since 2010), alongside policies promoting the inclusion of renewables to propel renewables to an almost 30% share of global electricity generation by 2023. Notwithstanding all the merits it brings along, PV faces a number of challenges, such as limitations to energy storage, resource constraints in materials such as silver and high-purity silicon, and also environmental concerns on panel recycling.

Next-generation technologies in focus include perovskite solar cells, organic photovoltaic, and quantum dot systems, which are resoundingly promising for higher efficiencies, lower production costs, and greater flexibility. As underlined by the International Energy Agency, by the year 2050, PV will contribute to the largest share of the total electricity in the world because of its role in fighting climate change and thus ushering in sustainable energy transitions. [17]

II.1.2 History

Recording the history of photovoltaics is a sign of glint of human brilliance melding fortuitous discovery with unending innovation. The following is a chronological view of that evolution, from scientific curiosity toward a global renewable energy pillar:

From 1839: The story started when Edmond Becquerel, a 19-year-old French experimental physicist, was working in his father's laboratory. While investigating electrolytic cells, he found that light exposure would generate voltage in materials like silver chloride. While somewhat rudimentary, the discovery of the photovoltaic effect was the first step to exploit sunlight for electricity. Becquerel's findings were published in “the Comptes Rendus de l'Académie des Sciences”, stored in obscurity for decades while waiting for the tools and materials to set them free. [16]

Beginning in 1954, Bell Laboratories engineers Daryl Chapin, Calvin Fuller, and Gerald Pearson achieved a landmark breakthrough: they fixed the purity of silicon and produced a p-n junction to unveil the first practical solar cell with 6% efficiency. The cell presently powered rural telephone systems and satellites such as Vanguard I (1958), thus laying the groundwork for silicon's dominance. Chapin said later, "We turned a scientific oddity into a practical device. [18]

1970s–1980s: Solar energy receives a notice from the entire world during the oil crises of the 1970s. This saw governments turning on the money shower for PV research, be it NASA’s Skylab (1973) with its solar panels or Japan’s Sunshine Project (1974) and, of course, the U.S. Solar Energy Research Institute (1977) in pursuit of efficiency gains. The solar cells had an efficiency close to 15 percent by the early 1980s, and the first grid-connected systems were introduced in California. However, with the admissible prices still prohibitively expensive, solar was very much seen as a “future technology. [19]

The 2000s–2010s saw a manifestation of expansion in global solar. The feed-in tariff in Germany in 2000 and the mass production of solar panels in China by the early 2000s had reduced panel costs by as much as 80%. The efficiencies of silicon have surged beyond 20%, while thin-film technologies, such as the cadmium telluride panels produced by First Solar, offered lightweight alternatives. By 2010, solar had moved from a niche industry to one of the mainstream, with global capacity exceeding 40 GW. [20]

The 2009s–2020s The perovskite paradigm shift began shortly after an equally radical detonation of the global research race with cheap, light, and tunable-to-light spectra band-gap materials ripped into unchartered waters. From 3.8% efficiency in 2009, Tsutomu Miyasaka's team mixed up dye-sensitized cells, ganging up understanding by 2023, as confirmed by OxfordPV, that over 33.9% efficiency enabled perovskite-silicon tandem cells that were more easily produced than fossil fuels and sustained challenges of stability and scalability right into the 2020s. Breakthroughs like the MIT encapsulation technique extended perovskite's life to 30 years by 2024. [21]

As of now, photovoltaics supply 5.4% of global electricity, facing innovations that push boundaries. Multi-junction cells, which stack III-V semiconductors, mostly gallium arsenide, have achieved a new record of 47.6% efficiency. This breakthrough, set by NREL, is expected to bring about a revolution in space and desert applications. AI-technology: Machine learning-optimizing the angles of the photocells and the integration into the grid improves energy yield by 20% in 2024 (Fraunhofer ISE).

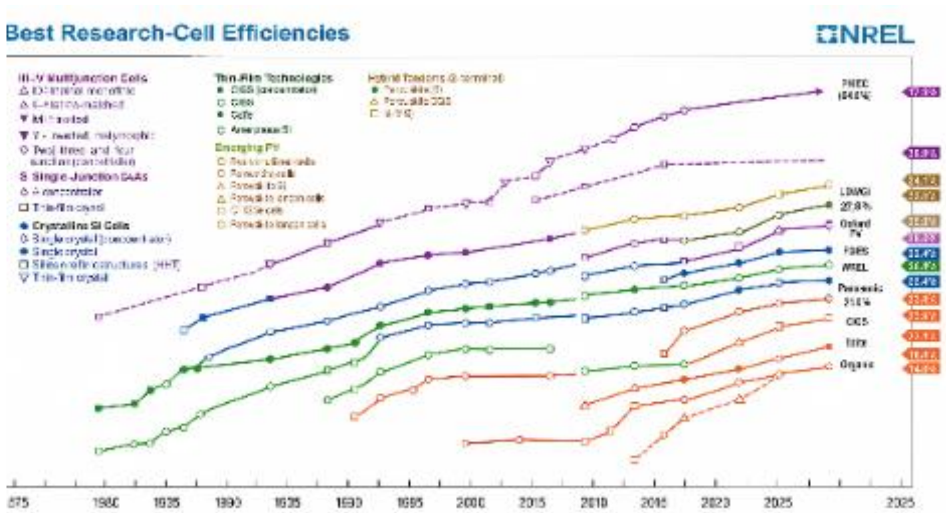

Figure II 1: Evolution of best research photovoltaic cell efficiencies across different technologies (1975–2025, NREL) [22]

Sustainability is key: for instance, the EU has formed the Circular Solar Alliance intending to reclaim by 2030 around 95% of the panel materials. [22]

II.1.3 Solid materials

In solid-state materials, the photovoltaic technology assumes a central role, meaning that the material itself holds electric potential when interacting with sunlight via the photovoltaic effect. Crystalline silicon, either monocrystalline or polycrystalline, will continue to play a dominant role as the semiconductor used due to its relative high efficiency, stability, and rather high established manufacturing processes. In addition to silicon, thin-film technologies that utilize such materials as cadmium telluride (CdTe) or copper indium gallium selenide (CIGS) provide users an opportunity for flexibility,

less material per solar panel, as well as cost-effectiveness, which provides a wide variety of applications. Emerging materials like perovskites are also attracting interest, with their tunable optical properties and potential efficiency, but practical issues regarding their stability over time and on a large scale remain. Progress in solid-state materials research still fuels innovations in terms of photovoltaic performance, rated efficiency, and compatibility with different environments, contributing to the sustainability of solar energy options and accessibility in terms of renewable energy infrastructure. [23]

II.1.3.1 A semiconductor

A semiconductor is a material that is in-between a conductor, such as copper, and an insulator, such as glass, in size of conductivity. Its unique behavior arises from the interaction of its band structure with temperature-dependent properties.

- At 0 Kelvin, the semiconductor resembles an insulator since, from band theory, there is a filled valence band and an empty conduction band separated by a band gap energy typical to materials; for titanium dioxide, for example, this presumably would be in the form of ~1 eV. Hence, no electrons available possess enough energy to cross over this difference.
- At room temperature (300 K), thermal agitation provides sufficient energy to excite a small fraction of electrons from the valence band to the conduction band. This creates Electrons filling the almost empty conduction band. Holes (positively charged vacancies) in the almost full valence band.

However, given that conduction is the proportionality with the density of free electrons and holes, there is very poor conductivity as comparatively few electrons have been excited. [24]

The primary material currently in use is silicon shown in figure 4. It is, for the most part, found in very large quantities on Earth, accounting for almost 28% of the Earth's crust. It is mainly found in nature as silicon oxide ($SiO2$), which is the principal component of sand. Thus, it is very abundant and cheap. [25] Some of its properties are given in the table below.

Table II.1: Characteristics of Silicon *[25]*

Symbol	property	value
SI	Atomic Number	14
	Atomic Mass	28.086 g/mol
	Density	2330 kg/ m^3
	Melting Point	1 683 K (1 410 °C)
	Boiling Point	2 628 K (2 355 °C)

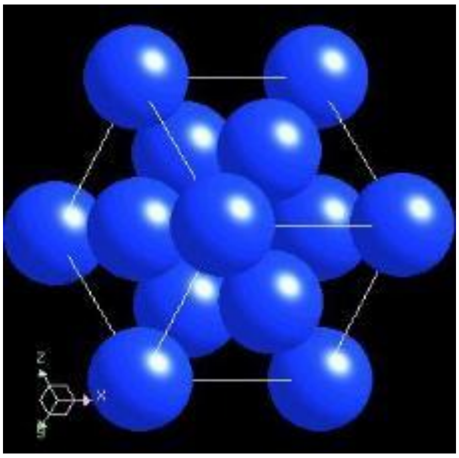

Figure II 2: The solid state structure of silicon’s diamond [25]

II.1.3.2 A conductor

Conductors are substances that allow the easy passage of electric charge through themselves with very low resistance, making them important in the transmission of energy in electric systems. These traditionally include metals such as copper, aluminum, and silver.

Copper is an excellent conductor of electricity; it is durable and has been used as a standard for wiring,

Aluminum is used much more for the transmission of power; it has the additional benefit of being lighter and cheaper than copper, even if its conductivity is lower.

Silver is a better conductor overall; however, it is only employed in specialized applications due to its high cost.

Further advances in materials science are being made in the area of superconductors; these materials are so good that when dropped below certain critical temperatures, they exhibit a zero electrical resistance situation that may allow for revolutions in energy efficiency and system performance. [26]

II.1.3.3 An insulator

The functions of insulating materials in photovoltaics are dual: passivation of cell surface and protection from environmental damage. In particular, thin films of either SiO_2 or Si_3N_4 are applied upon the surface of silicon solar cells to "passivate" it, which means reducing the density of the surface defects that could otherwise act as recombination centers for electrons and holes. This protects the cell from the surface defects that recombine the charge carriers before contributing to the output current, thereby increasing the efficiency of the cell. Apart from that, polymers such as ethylene-vinyl acetate (EVA) are utilized as special encapsulants to protect the delicate photovoltaic layers. These polymers cover the cell to keep it mechanically stable while protecting it from moisture, UV radiation, and fluctuations in temperature. Such encapsulation contributes a great deal in prolonging the life of the solar cells while, at the same time, ensuring their performance over long periods under extreme outdoor conditions. [27]

II.2 Photovoltaic panels

II.2.1 Definition

Photovoltaic (PV) panels function by converting sunlight into electricity through the wind-like photovoltaic effect. The substance in question is typically a semiconductor, usually silicon, which gets scattered on exposure to sunlight, providing excited electrons, hence generating mobile carriers of charge in the form of electrons and holes that create current. These PV modules are an interplay of many cells confined together into producing a unique module; these modules are highly reliable because of the presence of protective layers, such as tempered glass, usually by encapsulating them in EVA, and backed with a back sheet for support toward lifetime performance and durability. Beyond those, there are still anti-reflection coatings and passivation films on the surface of most PV panels that increase their efficiency by limiting surface losses. It is precisely because of this that they have found application in practically every niche, from residential rooftops to, again, very large solar farms, and have become very important also in the global transition to renewable energy. [28]

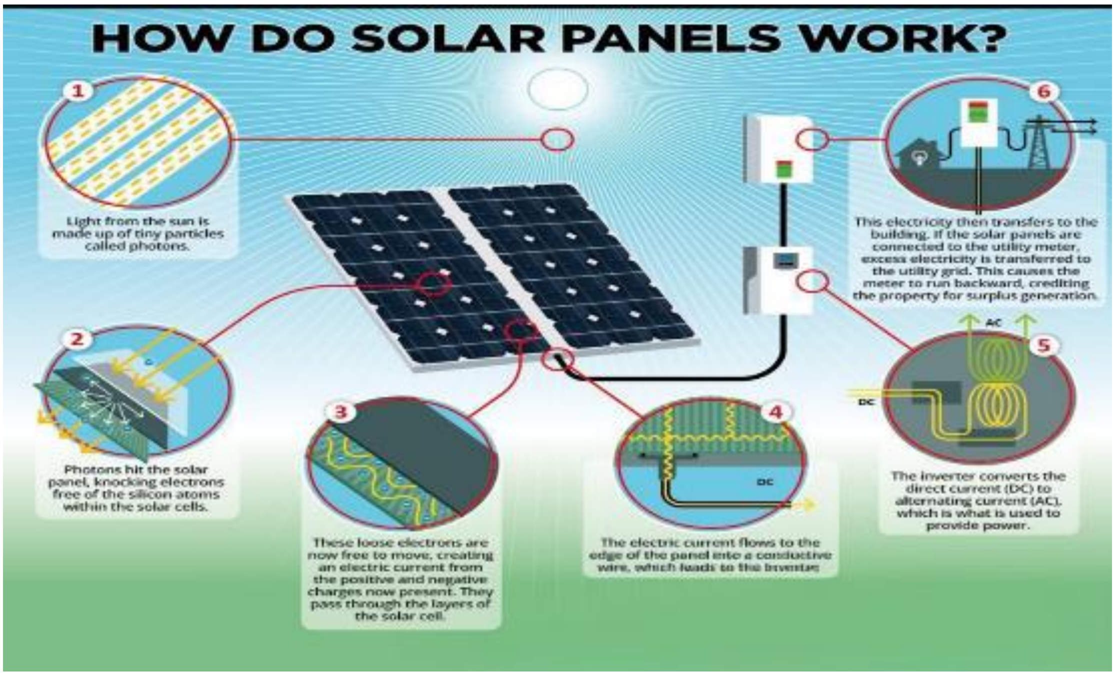

Figure II.3: "How Solar Panels Work: A Simple Visual Guide" *[29]*

II.2.2 Manufacturing of photovoltaic panels

The manufacturing process involves several key steps:

- **Silicon Purification**: Silicon was purified through chemical procedures that produced high-purity material to manufacture solar cells to be usable in the metallurgical industry.
- **Ingot Formation**: The purified silicon was melted and then made into ingots of varied sizes and forms; it may be cylindrical or rectangular. It is prepared with the use of methods like the Czochralski process "Single-crystal growth technique"; this means the ingot will guide a uniform crystal structure in generation, which would make for better electricity.
- **Wafer Slicing**: These ingots are sliced into wafers with the help of diamond-embedded wire saws. After slicing, these wafers are polished to eliminate surface defects that have been created during slicing and are further coated with some coating that will later be used to form a smooth surface.
- **Doping**: The formation of a p-n junction needed to generate an electric field comes with the doping of wafers with phosphorus or boron. It involves putting the wafers in a diffusion furnace, where they are heated up and exposed to gaseous doping agents.
- **Texturization**: The texturization of wafers is done to produce low surface reflection and have a better light absorption. The surface of the wafers is typically treated by etching them in a chemical bath, creating some kind of pyramidal structure that traps more sunlight.
- **Anti-Reflective Coating**: The anti-reflective coating is a layer, usually of silicon nitride, deposited onto the wafer surface by plasma-enhanced chemical vapor deposition (PECVD). This coating reduces light reflection so that a larger number of photons can enter the cell and be used to produce electricity.
- **Application of Metal Contacts**: Fine grid lines of silver are screen-printed on the wafer's front surface to collect electrons while a continuous aluminum layer is applied in the back. The contacts are then fired into a furnace to make them firmly electrically attached to the substrate.
- **Formation of the Solar Cell**: The wafers are now functional solar cells. Each cell is tested in terms of its efficiency and electrical characteristics to establish that strict quality standards are followed.

- **Module Assembly**: Individual solar cells are connected using metal ribbons and arranged in a matrix design. This is placed on a matrix between a front glass layer and a back encapsulation layer, usually made out of EVA for the protection of the module from environmental effects.
- **Lamination and Framing**: The module was built mainly through lamination, which sealed off the cells, preventing any moisture from getting in. The next step is adding a protective aluminum frame, which is very important because it strengthens the module structure and makes it a lot easier to mount.
- **Testing and Quality Control**: Extensive testing of the final modules is done, including electroluminescence and flash tests, to check performance, longevity, and all other aspects required by the standards in one industry of decision-making. [30]

Figure II.4: The Solar Panel Manufacturing Process: From Silica to Energy Systems *[57]*

II.2.3 Silicon doping:

Silicon is a semiconductor widely used in electronics due to its unique electrical and physical properties. In its crystalline form, silicon has low conductivity at ambient temperature. Its electrical properties can be greatly modified by doping - adding specific impurities to the crystal lattice. Semiconductors have a small band that can be correlated, and if the electrons have enough energy they will spend time in this band. The lower the band, the less energy is needed. Interestingly, from a technical and device energy consumption perspective, it takes 1.12 volts (or 1.79×10^{-19} J) of energy to place a valence electron in the conduction band of a silica crystal, the most common type of semiconductor. This is very low energy, for the use of today's semiconductors. [31]

II.2.3.1 N doping:

N-type doping means dope Silicon with elements with 5 valence electrons (pentavalent) such as phosphorus(P), arsenic(As), and Antimony(Sb) Since silicon has four valence electrons, adding a pentavalent element manifests an extra electron that can move about the crystal structure. The free electrons become charge carriers, which allows electrical current to pass more freely and increases the material's conductivity. This form of doping is known as N-type because electrons (which are negatively charged) allow current to flow. [31]

II.2.3.2 P doping:

P-type doping is the process whereby a trivalent element, like boron, gallium, or indium, which has three valence electrons, is introduced into silicon. Silicon, being tetravalent in nature, forms a vacancy (or "hole") when a trivalent element is added because in this case, there is one unoccupied bonding site (deprived of the electrons), usually considered to have lost one electron. Usually, electrons from nearby atoms try to fill up this hole, which creates the image of the moving holes in that area. The present holes act as the positive charge carriers, and it is through that tunnel through which electrical current is flowing. Since holes convey positive charges and thus make the current flow, this process is called P-type doping. [31]

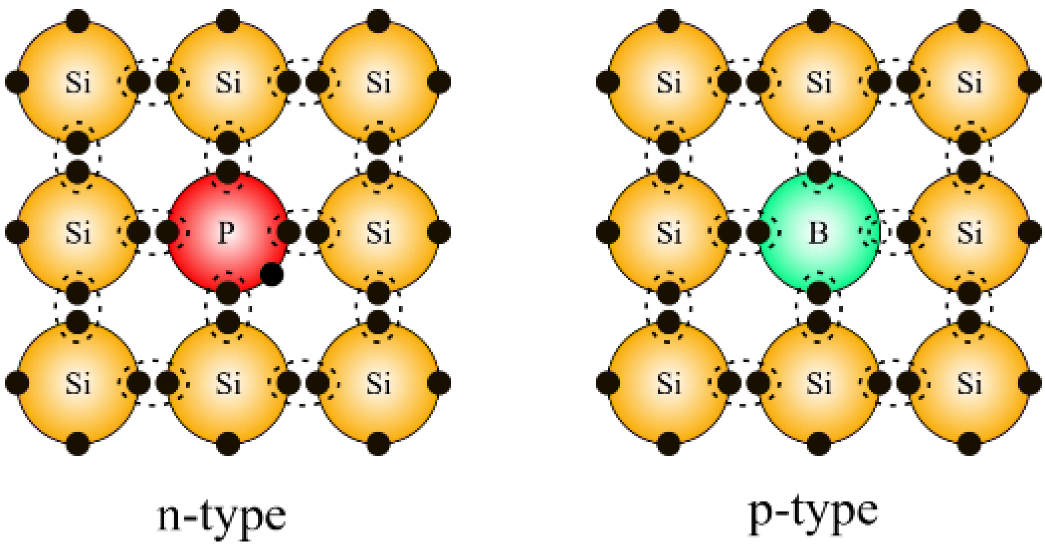

Figure II.5: Silicon doping with n-type and p-type *[32]*

As a result, these two methods of doping a semiconductor are antagonistic: one adds an electron to the semiconductor crystal, while the other removes one. It is possible to create electrical components like diodes or transistors by combining two materials that have been doped differently. For the time being, silicon is a semiconductor because it does not allow current to flow when its valence electrons are excited. To do this, an electrical tension must be applied while maintaining a minimum material seuil. Doping N (negative) or P (positive) can be used to slightly alter the stress threshold as well as other semiconductor properties. Finally, it should be noted for the sake of culture that silicon is not the only semiconductor that exists. Before him, the semi-conducting qualities of germanium were already utilized in the first transistors. Since then, other compounds have also been found. Although there are many others, the two most well-known of them are gallium arsenite and indium nitrite. Today, silica is widely used mostly due to its abundance on land—it makes up about 25% of the earth's crust—and ease of extraction and use.

In effect, this creates an electrical field that blocks potential at the central zone level. This area becomes isolated and is known as the P-N junction. As a result, the electrical field created tends to repel electrons toward zone N and holes toward zone P. As a result, an electron from the silicon's valence cushion is attached when the doped N zone is exposed to light, leaving a hole in parallel. Under the influence of the electrical field produced by the P-N junction, the electron diffuses toward the edge of zone N and the trou moves toward the edge of zone P. A current is created when a conductor connects the two faces of these two zones because the electron will fill the hole. A photovoltaic cell comprises a doped N tranche positioned on top of a doped P tranche. [31]

II.2.3.3 P-N jonction

The **connection PN** is a connection between a semiconductor of type P wherein traces are positioned as major-potential carriers and a semiconductor of type N wherein electrons are major-potential carriers. When the two semiconductors are brought together, electrons on the N-side diffuse inward into the region P, and the traces move towards the inverse direction to form a **zone of discharge** overflowing with mobile charges. This area, for example, converts into an electrical field that prevents further diffusion, thus providing a balanced electrostatic. When ['polarizing directly'] one applied tension reduces the potential barrier and allows current to flow to that gate;

when ['polarizing inverted'] this barrier is increased to block nearly the entire current from being emitted. [31]

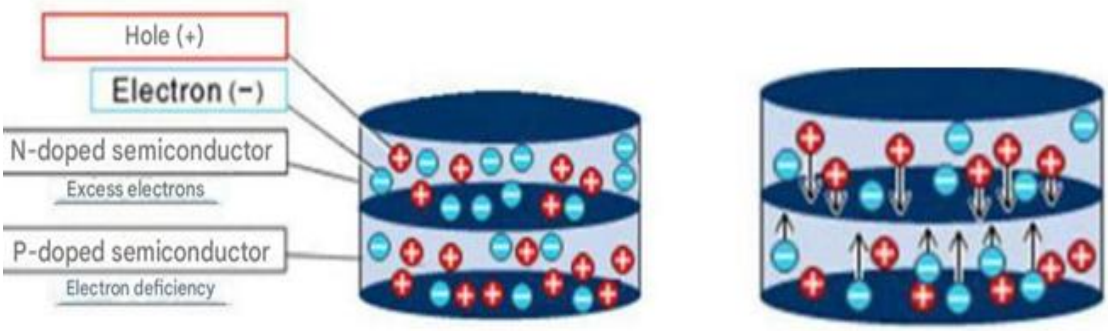

Figure II.6: Semiconductor doping, movement of electrons and holes *[31]*

II.3 The photovoltaic cell

II.3.1 Definition

The photons of light hitting the semiconductor material in the solar cell cause electrons to be freed from the semiconductor, collecting the free electrons, which are then used as electric current. [33]

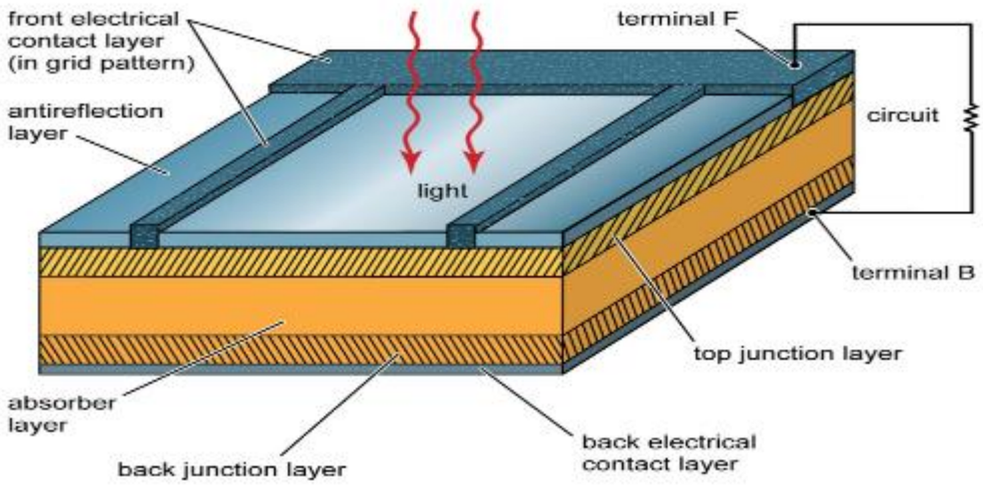

Figure II.7: Diagram of a solar cell structure [33]

II.3.2 The structure of the photovoltaic cell

A photovoltaic cell consists of a thin plate measuring 125 mm² or 156 mm² on the front and two metallic conductors that form an electrical contact. Its thickness is about one millimeter. Most photovoltaic cells are made of silicon. A photovoltaic cell is composed of:

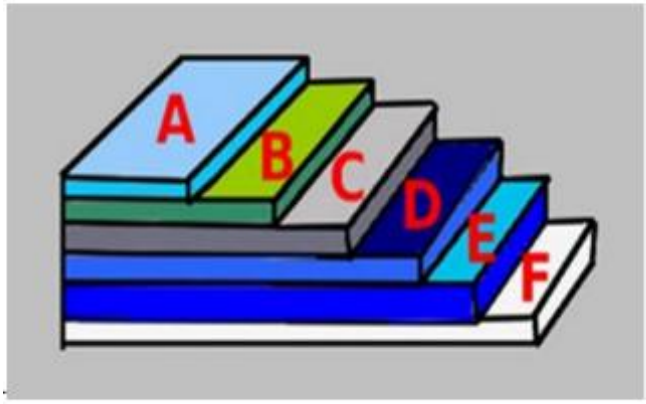

Figure II.8: Photovoltaic cell structure *[61]*

A:Glass

B: Anti-reflective coating

C Conductive grid

D : N-doped semiconductor

E : P-doped semiconductor

F : Conductor

II.3.3 Operating Principle

When sunlight hits the semiconductor absorber:

- **Photon Absorption**: Photons of sufficiency energy are absorbed and the energy excites electrons from the valence band to the conduction band, creating electron-hole pairs.
- **Charge Separation**: The built-in electric field at the p–n junction drives electrons toward the n-type layer and holes toward the p-type layer.
- **Current Generation**: These separated charges are collected by the electrical contacts to generate direct current (DC). For the majority of practical applications, this DC power is finally inverted to alternating current (AC) at an inverter. [34]

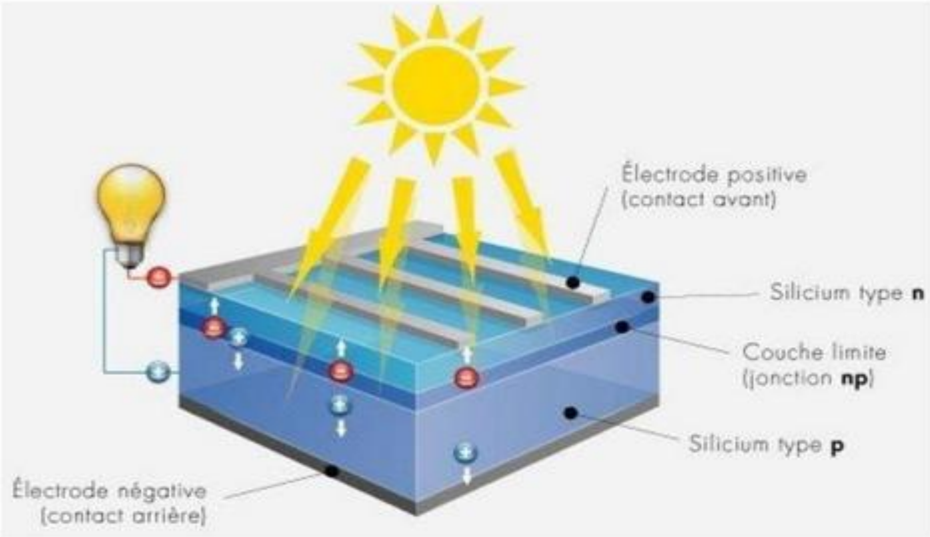

Figure II. 9: The components of solar photovoltaic panel *[58]*

II.4 The photovoltaic effect (light, photovoltaic cell, direct current)

II.4.1 Type of photovoltaic cells

II.4.1.1 Multi-junction Cell:

Multi-junction cells consist of multiple layers which allow them to convert various parts of the solar spectrum and to achieve the highest conversion efficiency.

- Advantages: Unmatched efficiency
- Disadvantages: No commercial application yet
- Energy Aspect: The record laboratory efficiency is around 40% (at an equivalent of 240 suns)
- Economic Aspect: Designed for use in space, this style of cell is currently not commercially viable. [35]

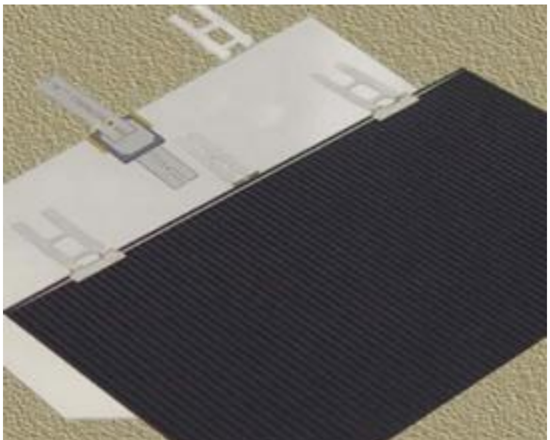

Figure II.10: Multi-junction Cell *[35]*

II.4.1.2 Monocrystalline Silicon Cell:

During the cooling process, molten silicon solidifies into a giant crystal. The large crystal is then sliced into thin slices to create the cells themselves which usually have a consistent blue coloring.

- Advantages: Very good performance (on the order of 150 Wp/m²), Long lifespan (around 30 years)
- Disadvantages: Expensive, Lower performance in low light
- Energy Aspect: Commercial module efficiency ranges from 12% to 20%.
- Record laboratory efficiency is around 25%.
- Economic Aspect: Expensive [35]

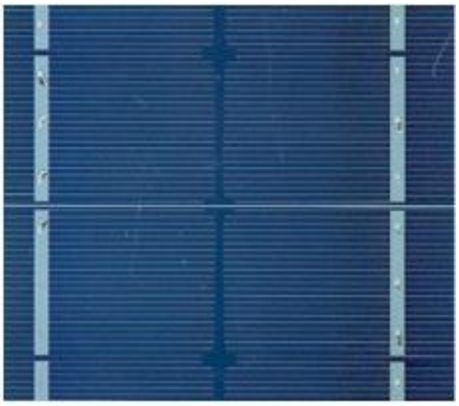

Figure II.11: Monocrystalline Silicon Cell *[35]*

II.4.1.3 Polycrystalline Silicon Cell:

When silicon cools, it creates multiple crystals. These cells are blue like a monocrystalline cell, but they are more inconsistent, as the varied crystals create patterns that become visible.

- Advantages: Good performance (on the order of 100 Wp/m²), Long lifespan (around 30 years), Less expensive than monocrystalline cell
- Disadvantages: Lower performance in low-light
- Energy Aspect: Commercial module efficiency ranges from 11% to 15%
- Laboratory efficiency records approximately 20%.
- Economic Aspects: Currently, this type of cell offers the best quality-to-cost ratio. [35]

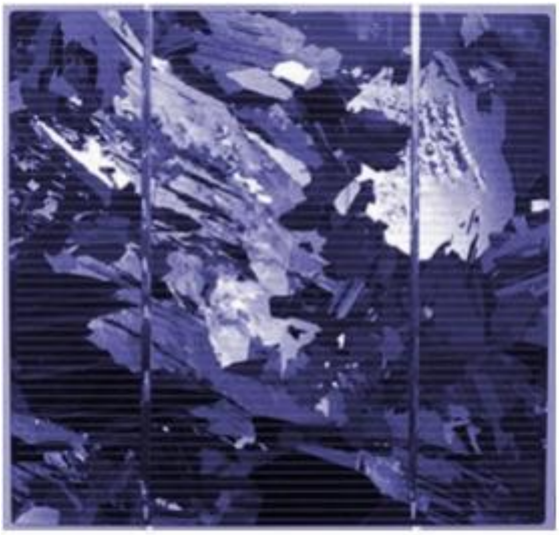

Figure II.12: Polycrystalline Silicon Cell *[35]*

II.4.1.4 Non-silicon Thin-Film CIS Cell:

CIS cells form part of a new generation of thin-film solar cells based on copper indium selenide (CIS). The raw materials used to manufacture CIS cells are easier to obtain than the silicon used in traditional photovoltaic cells. In addition, their energy conversion efficiency is the highest to date of thin-film photovoltaic cells.

- Advantages: Higher efficiencies than thin-film photovoltaic cells ,Does not require silicon ,Does not involve toxic materials and Flexible substrate construction is possible.
- Disadvantages: Thin films require larger surface areas for yield characteristics found in thicker materials.

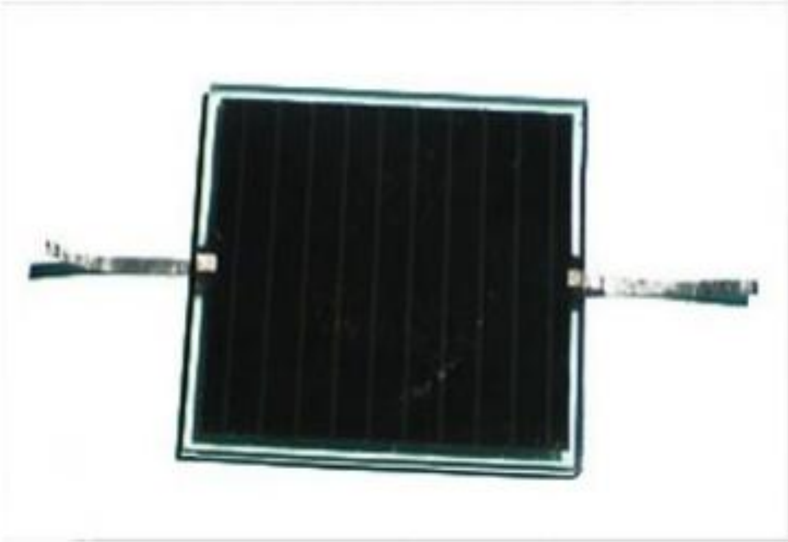

Figure II.13: Non-silicon Thin-Film CIS Cell *[35]*

- Energy Aspects: Commercial module efficiencies range from 9% to 11%, and record laboratory efficiencies range about 19.3%. [35]

II.4.1.5 Amorphous Silicon Thin-Film Cell:

In the fabrication process, silicon is transformed into a gas that is then applied to a glass substrate. The resultant cell is a very dark gray or brown color. This type of cell is used in calculators and so-called "solar" watches.

- Advantages: Operates under low irradiance, less expensive than the other types of cells, increased temperature tolerance compared to other types of cells
- Disadvantages: Low efficiency under full sunlight (~ 60 Wp/m²); thin-film cells require more area, to deliver the same output as that required for the thicker cells, Short lifespan (~10 years); the decrease in performance during .expected lifespan will be significant.
- Energy Aspect: Commercial efficiency of modules: 5% to 9%,

- Laboratory record efficiency: nearly as high as 13.4% [35]

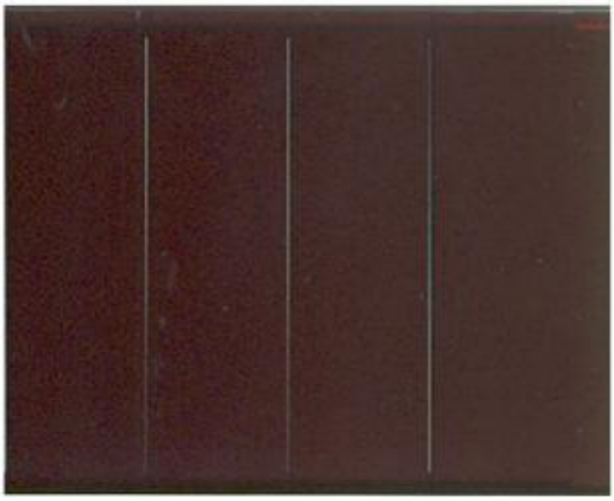

Figure II.14: Amorphous Silicon Thin-Film Cell *[35]*

II.4.2 Association of cells (the solar panel)

When the electrical cells are connected in series, the positive terminal of one cell is connected to the negative terminal of the other. In this type of arrangement, the total voltage (or potential difference) across the series is equal to the sum of the voltages of the individual cells. But the current through each cell is equal, since there is only one path for the current to flow. This type of connection is useful if a higher voltage is needed than that provided by a single cell. For instance, three 1.5V cells in series give a total of 4.5V. One disadvantage of a series connection is that if one cell fails (for example, due to a broken internal contact), the entire circuit is interrupted.

On the other hand, when cells are connected in parallel, all the positive terminals are connected together, and all the negative terminals are connected together. In this connection, the voltage remains the same as that of a single cell, but the total current capacity is the sum of the currents that can be delivered by each cell. This configuration is ideal when the application requires either more operating time or greater current output, but not higher voltage. A virtue of parallel connection is redundancy—if one cell fails, the others can still deliver power, with circuit operation maintained.

Practically, series and parallel combinations are often used to achieve wanted levels of voltage and current, especially in battery packs for consumer electronics, electric vehicles, and renewable energy systems.

II.4.2.1 Series grouping

The photovoltaic generator's (GPV) tension can be increased by connecting Cn (cell number) in series. The same current is then passed through the cells, and the characteristic that results from the series grouping is obtained by adding the elemental tensions of each cell. The electrical characteristics of a series of Cn cells are summarised in the equation :

$$V_{total}=C_n.V_{cell} \tag{II.1}$$

Where:

- V_{total} is the total voltage of the generator,
- $C_n$is the number of cells in series,
- V_{cell} is the voltage of a single cell.

Since the cells are in series, the current I through the entire generator remains the same as the current through a single cell:

$$\mathbf{I_{total}=I_{cell}} \tag{II.2}$$

This association system is often the most widely used for commercial photovoltaic modules. Since the surface of cells becomes increasingly significant, the current generated by a single cell increases steadily as technology advances, yet its tension stays relatively low.

Thus, the series linkage enables the ensemble's tension to rise, increasing its overall power. Commercial panels made of first-generation cells are often created by connecting 36 cells in series (Vco, = $0.6V \times 36 = 21.6V$) in order to get an ideal panel tension that is close to that of a 12V battery tension.

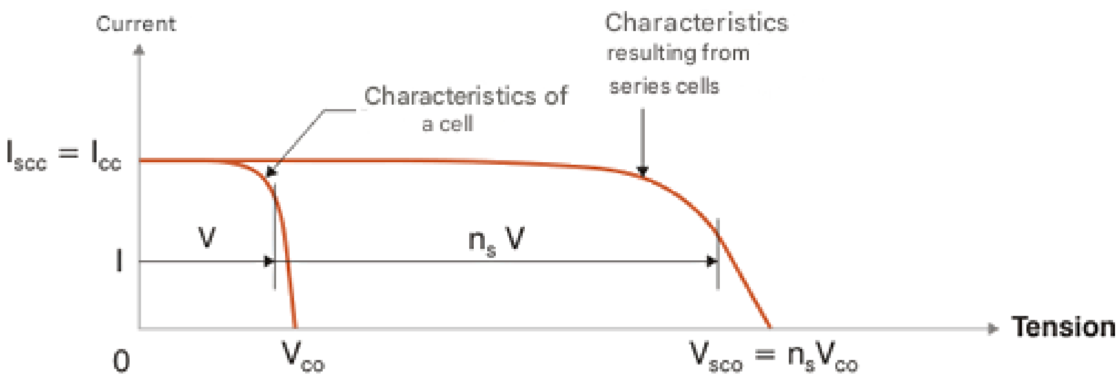

Figure II.15: Series grouping *[36]*

II.4.2.2 Parallel grouping

Forming a parallel association of Cn (cell number), is feasible, which increases the generator's output current. The characteristic that results from a grouping of identical cells connected in parallel is obtained by adding currents. The cells are subjected to the same stress. recapitulates the electrical characteristics of a parallel association of Cn cells. The electrical characteristics of a photovoltaic generator (GPV) composed of Cn cells connected in parallel can be summarized by the following equations

$$V_{total}=V_{cell} \quad (II.3)$$

$$I_{total}=C_n.I_{cell} \quad (II.4)$$

Where:

- V_{total} is the total voltage of the generator,
- I_{total} is the total current delivered by the generator,
- C_n is the number of cells connected in parallel,
- V_{cell} and I_{cell} are the voltage and current of a single cell.

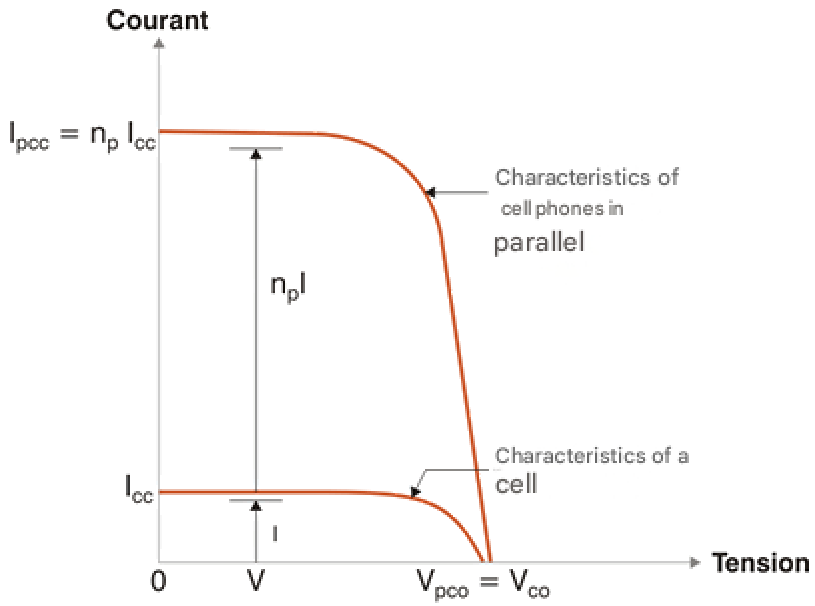

Figure **II.16:** Parallel grouping *[36]*

II.4.2.3 Mixt association:

A mixed combination of solar cells combines series and parallel connections to optimise energy conversion. The cells are grouped in series strings for voltage amplification, then these strings are connected in parallel for current amplification. This optimises the efficiency of the photovoltaic system and avoids the impact of partial shading or individual outages. In this way, a mixed combination ensures better adaptation to energy needs while guaranteeing stable, high-performance production.

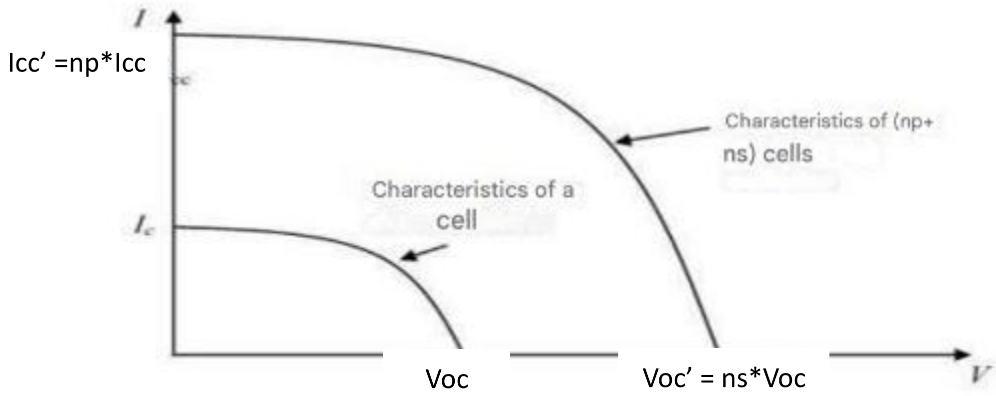

Figure II.17: Mixt association *[36]*

II.5 Advantages and disadvantages of solar photovoltaic

II.5.1 Advantages

Sustainable and Renewable: Unlike fossil fuels, solar energy is an abundant resource. Eco-friendly [34, 37]:

- It emits no greenhouse gases during operation.
- Lowers Electricity Bills: Energy costs can be decreased for both businesses and homeowners.
- Low Maintenance: Solar panels have a lifespan of 20 to 30 years and require minimal upkeep.
- Energy Independence: This reduces reliance on imported fuels and the electrical grid.
- Scalability and Versatility: It can be integrated into buildings or installed on rooftops and open spaces.

- Employment Creation: The solar industry generates jobs in manufacturing, installation, and maintenance.
- Grid Support: By sending excess electricity back to the grid (net metering), additional revenue can be generated.

II.5.2 Disadvantages:

- High Initial Cost: The cost of equipment and installation can be high.
- Problems with Intermittency: At night or on overcast days, solar panels are unable to produce electricity
- Cost of Energy Storage: Energy storage batteries can be expensive and space-intensive.
- Space Requirements: Large installations require a lot of roof or land space.
- Efficiency Restrictions: Only 15–22% of sunlight is converted into electricity by PV panels.
- Impact on Manufacturing: Energy and some hazardous materials are used in the production of panels.
- Location-Dependent: The production of solar energy differs according to climate and geographic location.
- Recycling Challenges: Recycling and disposing of panels at the end of their useful lives can be difficult.

Conclusion

In this chapter, we examined the evolution of photovoltaic technology from the historical timeline and semiconductor and conductor principles to an understanding of the solar panel manufacturing process. In this specific context, we examined how processes of doping silicon and making N, P, and PN junctions have resulted in what is known today as a modern PV cells system.

In the next chapter, we will be focusing on heat transfer and the effect of temperature on the performance of solar panels, further clarifying another important aspect of solar energy conversion.

Chapter III Environmental impact on solar panels

Introduction

There are many environmental aspects that affect the performance of solar panels, with dust and temperature being affected the most. The performance of the solar panels decreases when the temperatures are too high, the energy efficiency falls to lower levels and the lifespan of the product is reduced. Dust that collects on the surface of the solar panel modules limits any incoming solar radiation, as well, and limits heat transfer. When dust and temperature are looked at as a combination, they affect the solar panel system to a much larger extent. Due to all of this, understanding the processes of heat transfer is extremely important for proper management and the addition of some fins to increase the convective heat transfer and at the same time limit dust buildup, while still considered experimental, has potential, which would also lead to increased solar panel output.

III.1 Important Factors that Affect Solar Panel Temperature

Multiple environmental and design factors affect the operating temperature of solar panels:

- **Ambient Temperature**: The heat gain of solar panels is directly related to ambient temperature. Solar panels, on average operate 20 °C to 40 °C hotter than the ambient temperature.
- **Solar Irradiance**: As the solar intensity increases, so too does the temperature of the solar panels. Panels in peak sunlight can reach between 50 °C to 65 °C.
- **Wind Speed**: Wind is a fundamental cooling element performance in solar panels. Wind lowers temperature and panels; and although any amount of wind can reduce temperature, even just a light breeze of one meters/second can lower the panel temperature by 5 - 11 °C, while making it more efficient.
- **Mounting Position :** Solar panels that are mounted on rooftops typically operate at higher temperatures than solar panels that are mounted on the ground, or in a standard rack, because of the limited air flow capturing around the panels; this important, as the difference in operating temperature is typically 5 °C to 10 °C.
- **Color and Materials of the Panel**: In most applications, solar panels that have dark frames, and/or heat absorbing materials, tend to arb more thermal energy once the light has turned off. A good example would be a black framed panel that could be 1 °C to 3 °C hotter than a silver framed panel.
- **Panel Efficiency**: The more efficient a solar panel is at converting solar energy to electricity, the less heat is wasted energy. As expected, highly efficient panels trend 2 °C to 5 °C cooler than lower efficiency and performing panels.

- **Time of Day:** The time of day is related to maximum temperatures; typically, panels experience maximum temperatures 1 - 2 hours after maximum solar radiation is experienced, normally early afternoon.
- **Location**: The local weather, geographic location, and altitude can all affect the climate surrounding your solar panels. [37]

Two other key factors that significantly impact solar panel performance are dust buildup and overheating.

III.2 Dust Impact on Solar Panel

Dust composition, particle size, and accumulation characteristics will vary considerably based on geographic place and environmental context. In dry, arid regions, for example, deserts tend to have fine, wind-transported (e.g., quartz or silica) sand particles with high light-scattering intensity and are strongly electrostatically bound to surfaces. Meanwhile, urban or industrial engineered environments will accumulate soot or other pollution particles (e.g., sulfate) with the same high intensity but also absorb some sunlight, compounding the loss in efficiency.

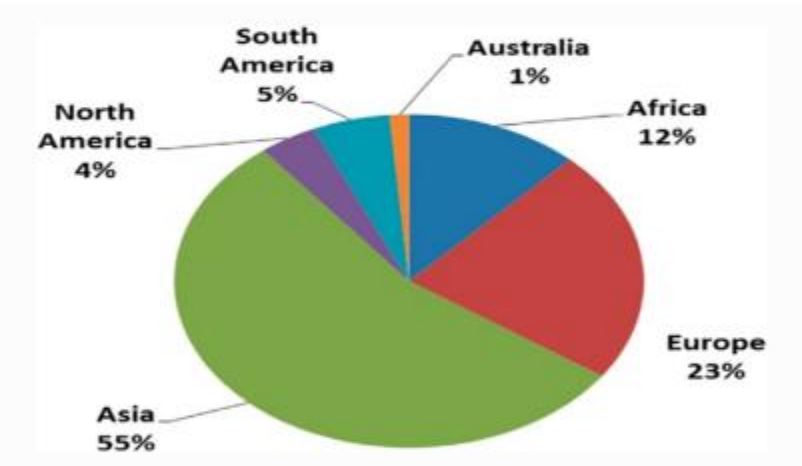

Figure III.1: Regional Contributions by Percentage to Research on Dust Effects in PV Panels *[40]*

These particles can be visible or invisible, contained in the air mass or settled onto surfaces like a solar panel. The dust accumulation on solar panel surfaces must be quantified to determine how the deposit of dust impacts solar panels. Usually, it is quantified by determining the thickness of the dust accumulation.

Most scientists express dust accumulation in grams per square meter and relate the solar panel power loss to the concentration of dust (g/m^2). The amount of dust that accumulates on various surfaces is location-sensitive. [38]

III.2.1 Dust Characteristics

Dust Characteristics and Behavior Relative to Locations/Places: The study outlines the physical characteristics (size, shape, composition, electrical charge) of dust particles, which depend upon the source of the dust (naturally occurring dust, pollution, emissions from people) and the conditions of the environment (humidity, wind speed, terrain). [39]

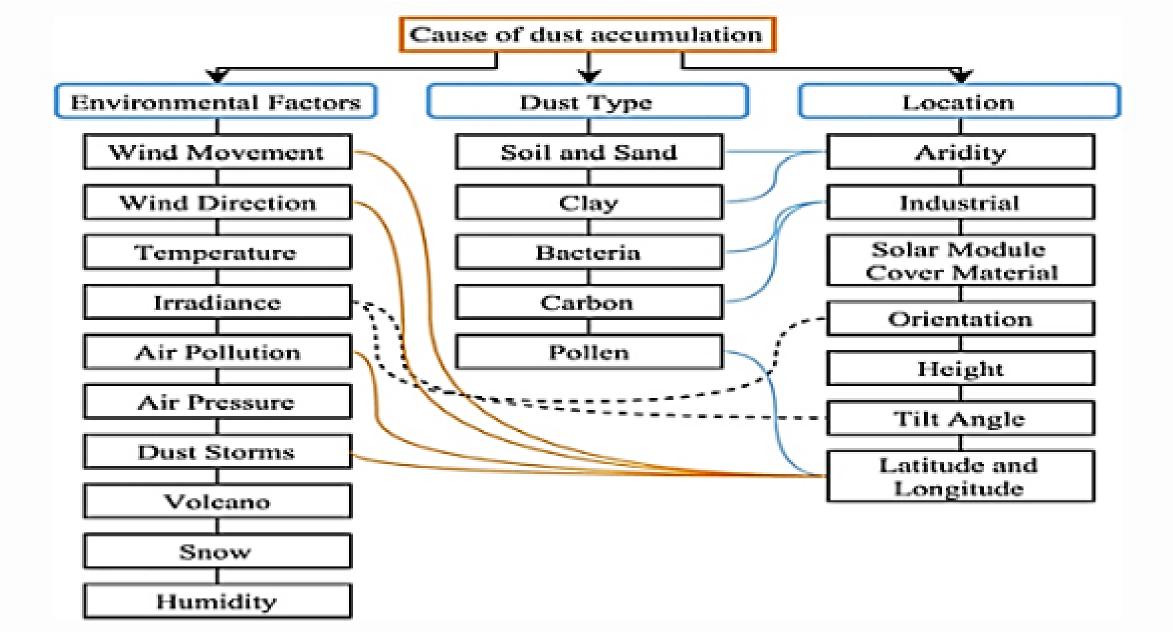

Figure III.2: Causes for dust on PV panels *[40]*

III.2.2 Mechanisms of Mitigation and Cleaning Technique

We offer an exhaustive summary of the intervention techniques and cleaning methods that have been investigated to mitigate the effects of dust build-up and high temperatures on the performance of solar panels. The interventions discussed include passive interventions, which include heat dissipating materials and surface coatings, and active interventions such as mechanical cleaning systems and electrostatic dust removal. The table below lays out the interventions in a structured manner, including details about how they operate, advantages, disadvantages and that their applicability in different environmental conditions. [40]

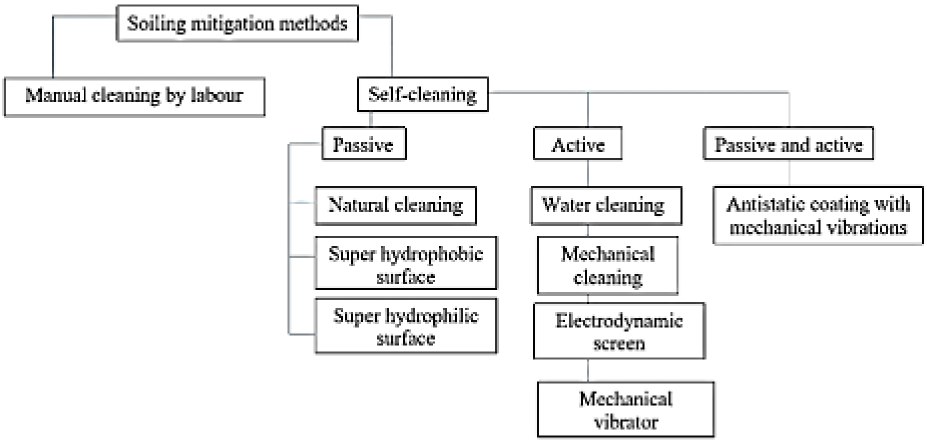

Figure III.3: Different soiling mitigation techniques *[40]*

III.2.2.1 Manual cleaning of PV panels

Cleaning solar panels by hand, water, and labor is costly, takes time, and is risky and water-ready in desert countries (e.g., Mena, Asia). Because water and the workforce are excessive for mega solar parks, it is not feasible and a need for scalable, less water-intensive alternatives. [40]

Figure III.4: (a) Water cleaning of PV panels by a labor and (b) using the Heliotex technology *[40]*

III.2.2.2 Active Methods of Mitigation:

Electrodynamic screening (EDS) cleans photovoltaic panels using electrostatic forces to mobilize and remove dust. In this method, an electric field, generally created as an "electric curtain" on the panel surface, drives dust particles that have obtained opposite charges to move in an orderly fashion until they are completely removed. This method uses a very low amount of energy, typically less than 1 Wh/m^2 for each cleaning cycle, removes dust within a few minutes under dry ambient conditions, and is effective at restoring panels' efficiency without needing a power supply or cleaning agents. [40]

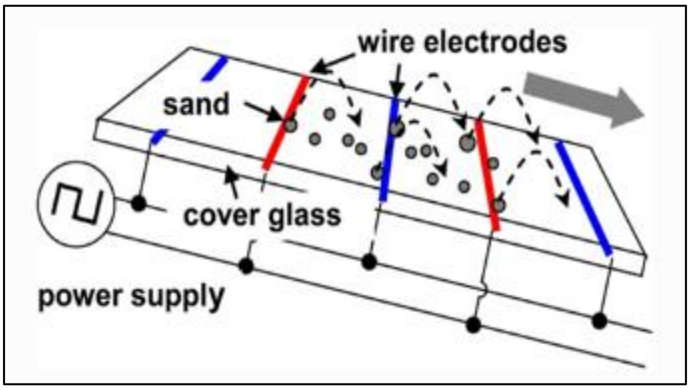

Figure III.5: Schematic Overview of an Electrostatic Sand Removal System Employing Standing Waves and Gravity on Solar Panels. *[40]*

III.2.2.3 Robotic Systems

Robots are outfitted with brushes (usually made of silicone rubber) that perform daily cleaning in desert regions to prevent dust from cementing on surfaces.

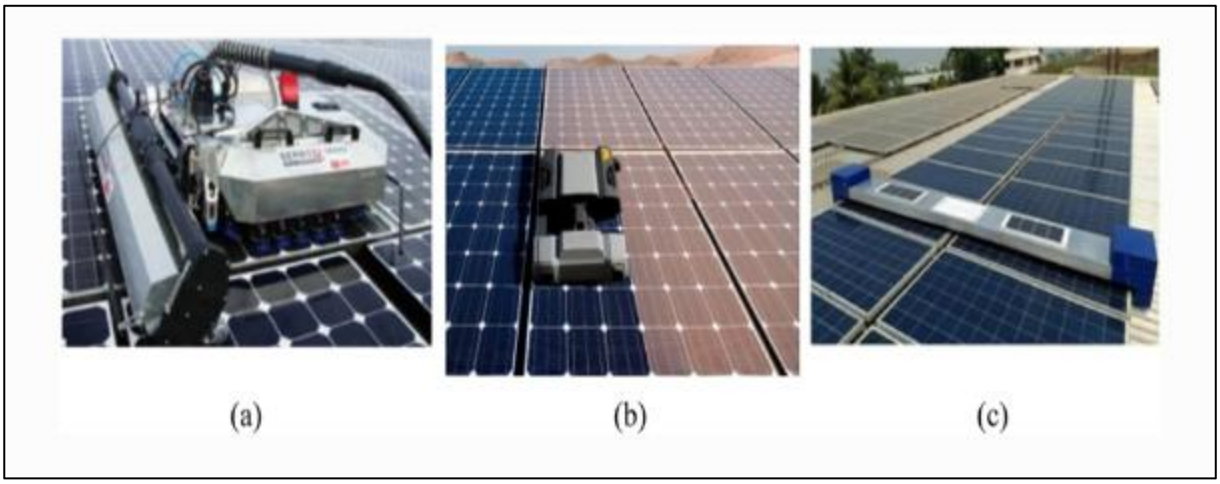

Figure III.6: PV panel dry cleaning using robot with a brushes, b suction bots, and c small solar cells for charging its batteries and self-running *[40]*

III.2.2.4 Passive strategies

Electrodynamic screening (EDS): is a method for cleaning photovoltaic panels using electrostatic forces to move and remove dust. In this method, an electric field—in the form of an "electric curtain"—is generated on the panel surface to drive dust particles (which gain opposite charges) to move in a systematic manner until they are fully removed. EDS can remove dust, requires very little energy (generally less than 1 Wh/m^2

per cleaning cycle), and can do so quickly under dry ambient conditions, returning panel efficiency without requiring additional power supply or cleaning agents. [40]

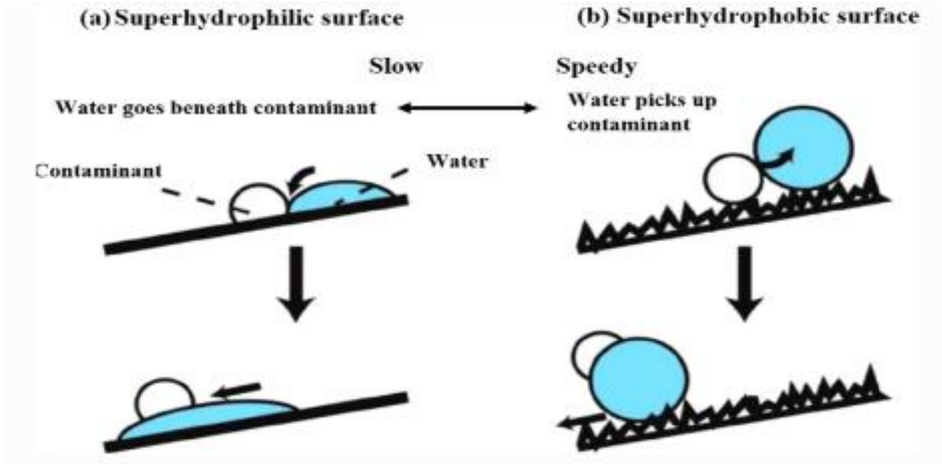

Figure III.7: The self-cleaning mechanism of the hydrophilic (left) and hydrophobic surfaces (right) *[40]*

III.3 Heat impact on solar panel

Temperature has a significant impact on the efficiency of solar panels: the higher the temperature, the lower the efficiency. Solar panels do not work better with heat, as is sometimes believed, because they convert light, not heat, into electricity. Above 25°C, their efficiency drops by 0.3 to 0.5% per additional degree, due to the increase in internal resistance. As a result, in very hot conditions, a sheet can lose up to 10 to 15% of its efficiency.

III.3.1 What is heat

Heat is energy created by the kinetic movement of molecules and atoms in matter. Thermal energy, or heat, is defined as the energy associated with the random movement of particles in a substance. The standard unit of heat is the joule (J), though other energy units such as the calorie (Cal) and British Thermal Unit (BTU) are also utilized depending on the context

Table III.1: Table showing some energy units *[41]*

Joule(J)	Kcal	British thermal unit (Btu)
1	**2.39×10^{-4}**	**9.478×10^{-4}**
4184	**1**	**3.966**
1055	**0.252**	**1**

III.3.2 What is heat transfer?

Heat transfer, described as the transfer of thermal energy, occurs when thermal energy moves from one system to another because a temperature difference exists. This transfer of thermal energy proceeds from a system at a higher temperature to a system at a lower temperature, per the second law of thermodynamics. [42]

We resume the three modes of heat transfer by this Schematic diagram of heat transfer models:

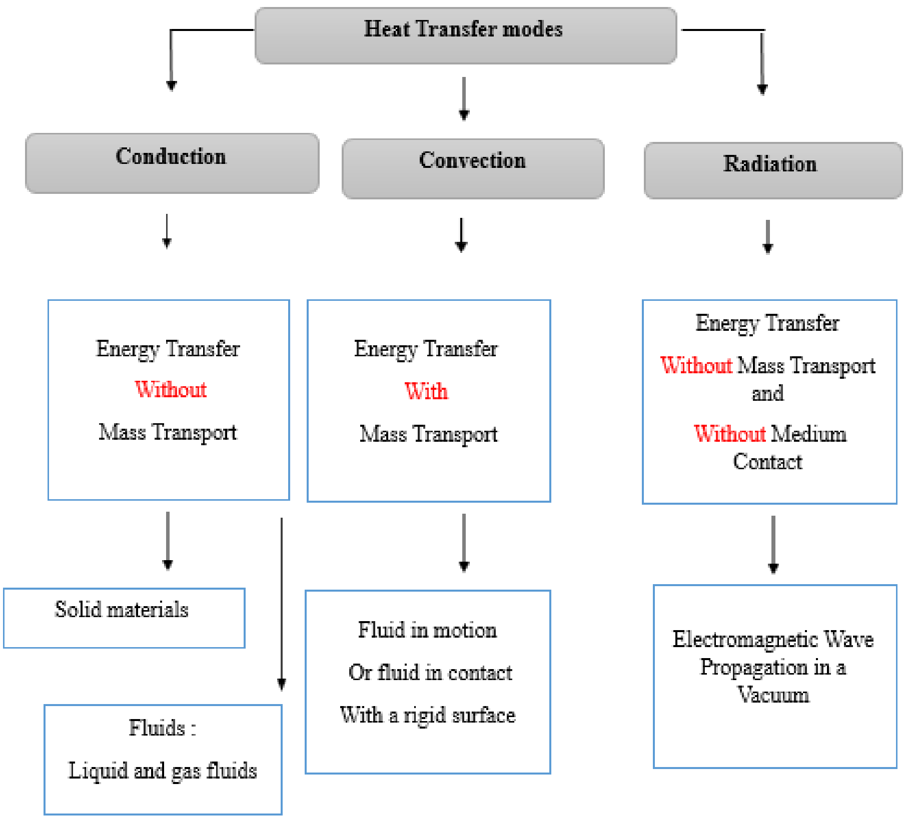

Figure III.*8*: Heat transfer models

III.3.3 Heat exchanged by conduction - Fourier's law

This transfer mechanism is governed by a phenomenological law established by Joseph Fourier in 1822, which states that the flux density modified by conduction is proportional to the temperature gradient. This law is known as Fourier's law. [42]

$$\vec{\varphi}=-\lambda.\overrightarrow{\nabla}.T \text{ in W/m}^2 \qquad \text{(III-1)}$$

The sign (-) used in this law reflects the fact that heat flows from hot areas to cold areas (in the opposite direction to the temperature gradient).

Thermal conductivity, expressed in W/m/K, is the proportionality coefficient, or λ. It depends on the type of body being examined and is generally influenced by temperature. It reflects a material's ability to transfer heat by conduction.

Examples at room temperature;

λ glass wool = 0.04 W/m/K

λair = 0.026 W/m/K (still air is a very good insulator)

λ glass = 1.2 W/m/K

λcopper = 390 W/m/K

Furthermore, if λ is large, the temperature gradient will be even more feasible for a given heat flux. In some situations, it can be assumed that the temperature distribution inside a body with high thermal conductivity is nearly uniform for moderate fluxes.

III.3.4 Heat exchanged by convection - Newton's law

This transfer mechanism is governed by Newton's law, which states that the density of heat flow between a solid and a fluid in equilibrium is proportional to the temperature difference that gives rise to it. [42]

If $T_p > T_\infty$:

$$\vec{\varphi}=h(T_p-T_\infty)\,\vec{n} \qquad \text{(III.2)}$$

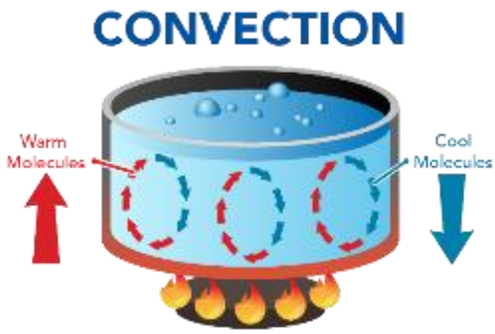

Figure III.9: The heat flux density exchanged between a solid wall and a fluid [43]

It is very difficult to determine this coefficient precisely because it depends on several factors (fluid, type of fluid, surface condition, etc.).

III.3.5 Heat exchanged by radiation - Stefan's law

Through the use of electromagnetic waves, heat can be transferred via radiation between two bodies at different temperatures that are separated by a semi-transparent environment or a vacuum. This process does not require any support equipment. This transfer mechanism is governed by Stefan's law. For example, a small body placed within a closed enclosure [41].

$$\varphi = \varepsilon . \sigma . (Tp^4 - Tc^4) \quad \textbf{(III.3)}$$

ε:Body emissivity ($0< \varepsilon \leq 1$)

σ:Stefan constant

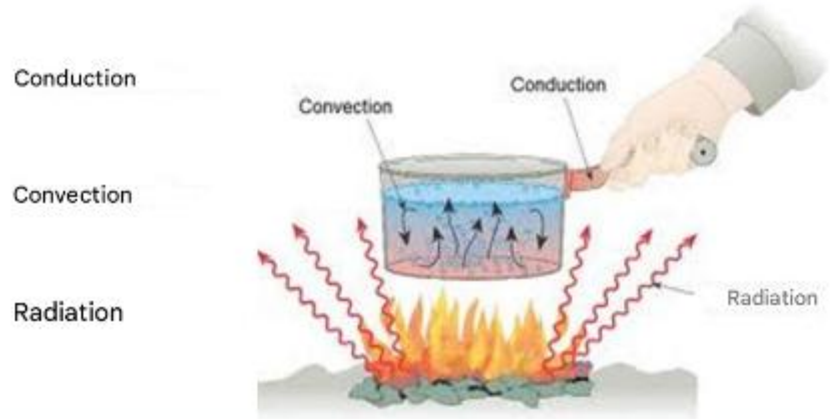

Figure III. 10: Heat exchange types *[44]*

III.3.6 How is heat transferred?

We call two objects in thermal contact to be in thermal equilibrium when they are at identical temperatures and neither object is gaining or losing heat between them. If the objects are not in thermal equilibrium, heat energy will flow from the hotter object to the cooler object. The second law of thermodynamics tells us that heat can never spontaneously flow from a cooler object to a hotter object without work being done to accomplish that flow. [41]

III.3.7 Cooling technologies:

Every power system requires a cooling mechanism to be installed particularly the PV panel. Numerous systems have been developed to lower the temperature of the photovoltaic panel to prevent performance degradation, which is mostly caused by temperature increases. [45] The suggested systems are divided into two categories: The active systems and the passive systems

III.3.7.1 Passive systems for cooling PV panels:

Passive cooling systems provide an efficient way to mitigate heat in both day-to-day and high-temperature situations without using electric power or complex mechanical systems. All passive cooling systems utilize some form of natural physical processes for passive heating and cooling, such as air flow, heat loss via radiation, or the absorption and temporary storage of thermal energy in the case of heat sinks. Passive systems offer all of these methods to lower some of the PV module thermal loads, reducing energy consumption sustainably and effectively.

Passive PV cooling systems don’t use fans, water pumps, or other electronic controls, so they are generally a simpler system and are inherently more robust and less expensive than active systems. Passive systems can be incorporated into the installation design, whether it’s a rooftop, ground-mounted, or BIPV system. Some of the advantages of passive systems is that there are minimal maintenance requirements associated with passive systems; there are no moving parts to wear out, and there is less chance of mechanical failure.

The use of passive cooling is especially important in very hot climates or very high direct solar irradiance areas. PV systems operate less efficiently under high thermal loads, and thermal loads can range from thousands of watts in a small-scale PV system to tens of thousands of watts in a utility-scale installation. The contribution of passive cooling can be significant - increased PV energy output (kWh); improved economic performance of the PV system over its lifetime, and improved environmental sustainability. Passive cooling can allow the PV panels to operate closer to their design temperature range, thus maximizing the thermal efficiency of the passive cooler.

III.3.7.1.1 Holes cooling :

The effectiveness of this method has been demonstrated by research conducted by M.S. Abd Elhady et al. [46], who discovered that the panel loses 25% of its rendering at a temperature of 75°C, primarily in northern Africa and the golf countries. The process of cooling by natural convection between the PV cells and the surrounding air. The holes are located in the panel's neutral zones (which do not contain any PV cells), demonstrating that the size and name of these holes affect the cooling quality. They can achieve an 8°C difference, which is equivalent to 8% efficiency. The difference between the perforated and non-perforated panels is 13C°, and the maximum values are recorded at midday. They noticed that the panel temperature dropped from 66C° to 53C°. [46]

Table III.2: Experimental results for panels with holes *[46]*

Number of holes	Holes density= $\frac{\text{Number of holes}}{\text{Panel's area}}$	Average Temp. T	Decrease in Temp., $\Delta T = T_{no\,holes} - T_{holes}$
0 (No holes)	**0**	**70°C**	**0°C**
3	11.5 hole/m^2	58°C	12°C
6	**23 hole/m^2**	**54°C**	**16°C**
9	34.5 hole/m^2	52°C	18°C
12	**46 hole/m^2**	**51°C**	**19°C**

Table (III.2) shows the experimental values, which prove that the holes contribute to reducing the temperature of the panels. It can be seen that the higher the density of the holes, the lower the temperature.

III.3.7.1.2 Limiting the overheating of a PV panel using a beam splitter

This approach is also passive. It relies on a feature of silicon technology. As we know, silicon panels do not absorb the entire spectrum of the sun; they only absorb the visible part of the spectrum, which is the operational part of the spectrum that helps produce electricity.

This method involves using a spacer to block the solar spectrum, allowing only the part of the spectrum that contributes to the photovoltaic effect to pass through before it reaches the panel's surface. [47]

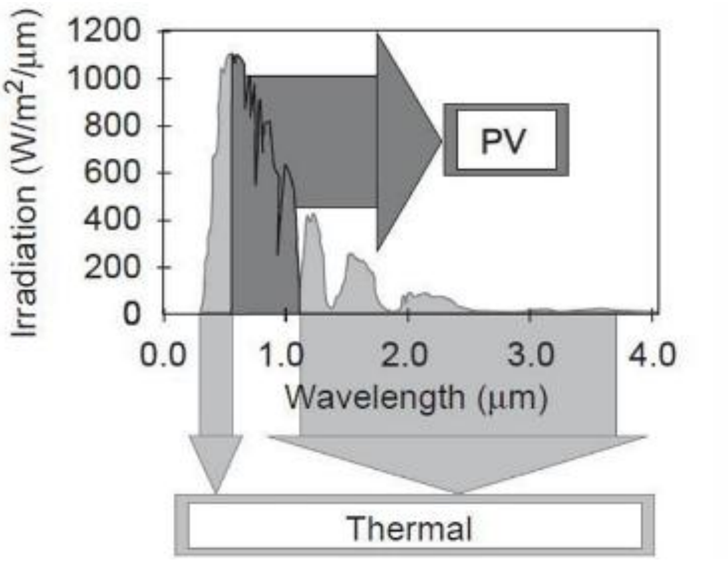

Figure III.11: Curve representing the separation of the solar spectrum into a PV part and a thermal part *[47]*

Figure (III11). shows that the thermal component of the spectrum is larger than the photovoltaic component. This explains the quick reheating of PV panels, alternatively, this spectrum will be very helpful when a thermal concentrator is integrated, resulting in what is known as a hybrid PVT system.

III.3.7.1.3 Thermal regulation of the PV module using a phase change material PCM

The purpose of using a material with phase change (PCM) integrated into PV modules is to keep their temperatures close to ambient. The idea is for the PCM to absorb excess heat until it reaches its foundation (for instance, the sel paraffine. Huang et al. designed the experimental prototype and conducted a numerical study that was validated through experimentation. They have created a cooling unit for a PV panel by employing an PCM in a rectangular enclosure.

Experimental tests of this system behind a PV produced encouraging results: under a heat flux of 750 W/m2 and an ambient temperature of 20°C, its temperature is maintained at 36°C for 150 minutes for the configuration without ailettes and at 30°C for 150 minutes for a configuration with four fins. Additionally, it has a radiation of 1000W/m² and an ambient temperature of 25°C. The module's temperature is maintained at 40°C for 80 minutes, with a fusion temperature PCM of 32°C.

To properly distribute the heat flux, fins are included. One crucial parameter is the number of fins; the more fins there are, the more effective the system is. The PCM type also plays a key role in this technology, Research studies have varied the kind of PCM and have seen a minimum temperature of 10C° with a radiation of $1000W/m^2$ for five hours. [45]

III.3.7.2 Active systems for cooling PV panels

Active systems for cooling photovoltaic (PV) panels are defined as systems that utilize external energy or mechanical components to increase the cooling process. Active PV cooling systems are made to bring the temperature of PV panels down and are demonstrated to improve performance and life of the panels. Once PV panels reach a certain temperature, they can no longer efficiently convert sunlight into electricity and this is when active cooling comes into play.

It usually include pumps, fans, heat exchangers etc. that will circulate a cooling fluid (air or liquid) across or behind the panels. Consequently, active cooling systems consume energy. However, while they consume energy to operate and are therefore not standalone solutions, the production of electricity from a cooler panel typically offsets energy use.

III.3.7.2.1Forced ventilation

Force of ventilation: Convection can be equally and actively improved by an air force flow. For instance, this latter can be created by simply adding one or more ventilators (Figure III.11). This kind of arrangement has demonstrated cooling up to 15 °C The interest in this type of device is naturally limited by its integration issues as well as its high electrical consumption. [48]

Figure III. 12: Forced Ventilation system *[48]*

III.3.7.2.2Cooling PV panels with a thermal collector (PV/T)

Thermal collector cooling is an efficient method that provides two benefits. It enables the simultaneous generation of both electrical and thermal energy, but at a higher cost. Each panel needs to have a heat collector installed behind it. Researchers who created hybrid solar-thermal systems have long addressed the issue of heating photovoltaic panels. In 1976, Martin Wolf [49] conducted the first study on photovoltaic thermal panels (PV/T). This study was followed by a number of other studies that consistently included PV/T panels.

There is a small distinction between PV/T and PV panel cooling, which is the recovery of heat from PV panels using hot, sanitary water.

Due to this, installing PV/T systems is still considered too expensive today.

It is anticipated that by adjusting to needs, cooling systems will increase the performance of PV panels.

III.3.7.2.3. Panel water spray cooling:

This method also has a double benefit: it cleans and cools at the same time.

Some of the works include:

The Suni-Brain system

In France, one company has commercialized and installed this system for clients, who have all reported improved performance. The company is called SUNI Brain, a French startup. It has conducted studies showing that the panel can reach surface temperatures of up to 100 degrees centigrade (that's in France) without the need for a cooling system.

Extreme weather conditions put photovoltaic cells under mechanical stress. This system not only ensures that performance is maximized through cooling and cleaning but also enables the life of the PV panels to be extended. This system is divided into 30 states.

The basic idea is to circulate water across the surface of the panel using pumps and vessels that return to the storage tank (closed loop). Minimal energy is required to circulate the collected rainwater.

SUNI Brain is a fully autonomous (automated) system that operates in four steps:

- Rainwater harvesting
- Storage of rainwater in a storage tank
- The panels can be arranged if required.

Data recording for maintenance projects has shown that this system can guarantee a 20-25% increase in yield. [42]

Figure III. 13: SUNI Brain sprinkler cooling system *[42]*

The cooling system designed by CDER.

Existing cooling systems include the cooling and cleaning system developed by a research team in Algeria: Mohamed Fathi et al. [50]

cleaning system developed by a research team in Algeria: Mohamed Fathi et al [50]

The prototype created by the Bousmail Unit of Development of Renewable Energy, EPST CDER, ensures water circulation throughout the entire face surface prior to the photovoltaic panel. This latter is constructed using a 12V pump that is controlled by an electrical armoire, and this depends on the temperature. The system is equipped with a charge regulator to control and secure the 150 Ah battery's electrical storage. A filter with a 12L distillation water reservoir is installed to prevent the buildup of a calcaire or other couche. To continuously monitor the temperature change, a thermocouple matrix is installed on the panel. The temperature data on the front and rear faces are stored in the computer. [50]

The experiment is conducted during an average summer day with 870W/m2 of radiation [50]. After 40 minutes of exposure, the temperature rises to 70°C on the front face. The adopted refrigeration cycle lasts 30 minutes, during which time the water circulates for 6 minutes. It enables lowering the face temperature to 40°C and stabilising it. The pompe becomes reactive after 24 minutes. The performance increased by 2% during the cooling cycle. The excess energy generated covers the power consumption that will be shared by a series of PV panels. The measured difference between a cooled and a heated panel is 15W. [50]

The goal of this initial prototype is to optimise cooling, which lowers the energy used by the pump.

- The panel used: 150W of 1.08m2 reference PS-M605-150 its manufacturer

Philadelphia Solar company.

- The pump used: DC 12V Santoprene®diaphragm pump, reference 8000-443-136

with a power of 38.4 W.

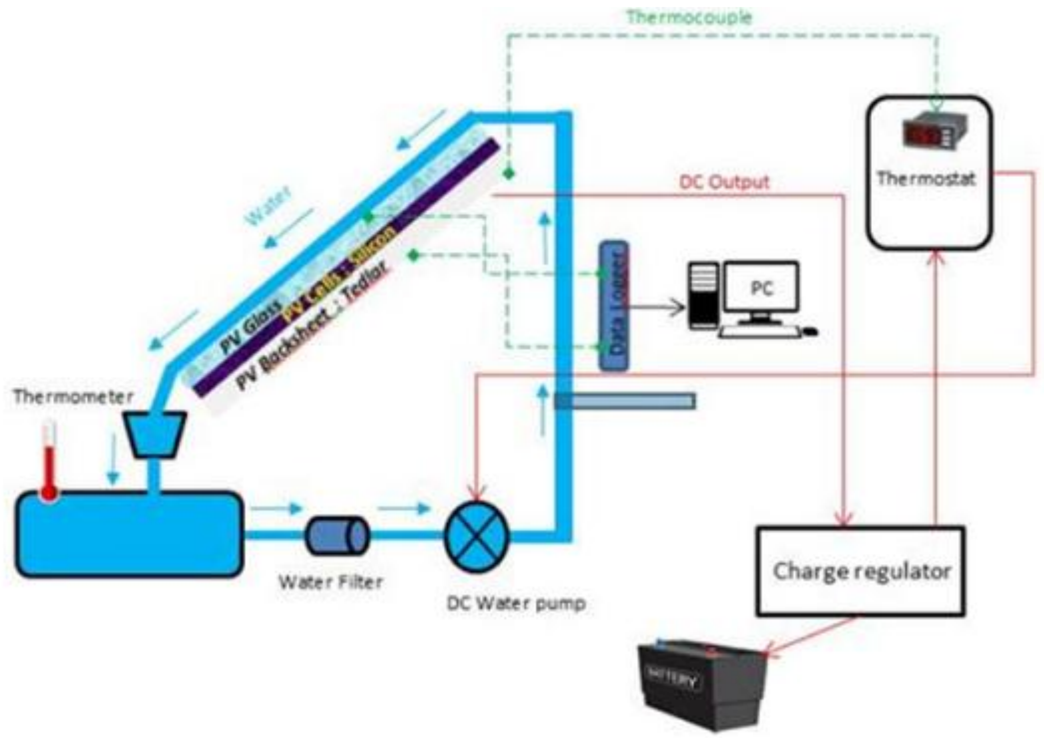

Figure III. 14: Descriptive diagram of the system designed by CDER *[50]*

III.4 Fins cooling

III.4.1 Definition

Fins are extending surfaces that are used to enhance the rate of heat transfer by decreasing the surface temperature at a specific surface temperature or enhancing the rate of heat transfer for a specific surface temperature. When fins are employed on a surface, the convection heat transfer between the surface and the fluid it is surrounded by is significantly increased. In most engineering uses, particularly where large amounts of heat need to be dissipated from relatively small surface areas, fins play a crucial role. Fins work by increasing the surface area effectively, thereby allowing more efficient dissipation of heat in order to obtain a steady-state condition. Among the most common types are straight fins like rectangular and triangular fins. Triangular fins are particularly useful since they offer the same heat transfer as rectangular fins but with significantly less volume of material. This makes them highly useful, offering maximum heat transfer per unit mass with ease in manufacturing. [42]

III.4.2 Fins types

Fins are a key component of thermal management systems in applications such as electronics, photovoltaics, and industrial equipment to aid in heat dissipation. Fins are extended surfaces designed to transport thermal energy away from hot components and into the surrounding ambient environment so that these components can operate in safe and efficient temperature ranges.

Fins provide a greater effective surface area to enable heat transfer. The heat transfer effectively enlarges the interface available for conduction at a heated surface (typically a post or component) and the ambient air. The fin promotes convection natural or forced, and, in either case, assists with moving and exchanging thermal energy away from the hot surface and into the ambient environment. The combination of the fin's geometry, orientation, spacing, and material affects their ability to transfer heat. The thermal fluid mechanics of the air between facility components and the fins, such as the convective heat transfer coefficient, will depend upon many factors. Often, small changes to the geometry, orientation, and configurations can substantially alter fin performance. Although the designs may seem simple, fins are the result of accurate engineering optimizations. In the design of fins, often convective heat transfer must be improved at the potential cost of weight, cost, vibrant strength, and manufacturability. Passive systems, which rely solely on natural convection, require a specific balance to obtain the desired performance since no fans or pumps are present. The only cases available for improved heat transfer in passive systems depend upon natural airflow and thermal gradients.

Selecting the right fin geometry in cases such as heat exchangers, power electronics, and solar panels can greatly increase energy efficiency and system life. Also, since they are "silent," passive, and reliable devices, fins are often the key components in systems that need low maintenance and off-grid energy independence.

Fins can be broadly classified as: Longitudinal fin, Radial fin, Pin fin

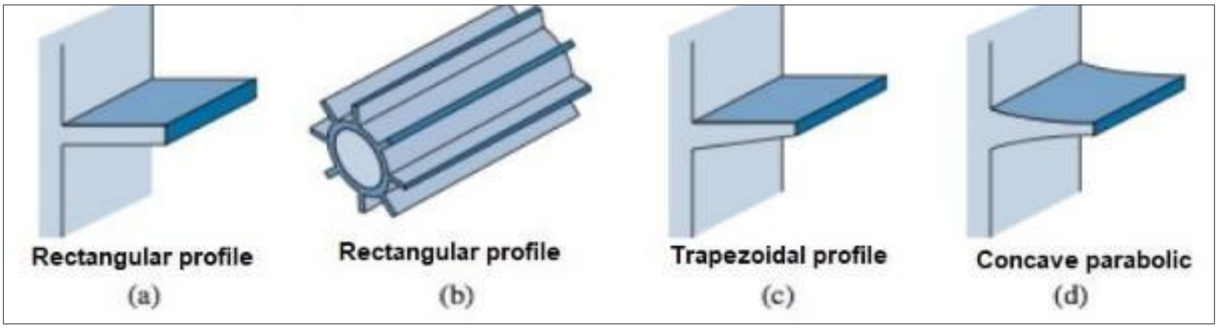

Figure III. 15: : Longitudinal fin [51]

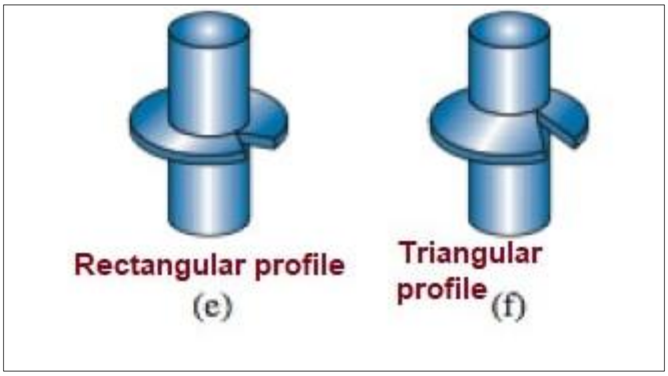

Figure III. 16: Radial fin [51]

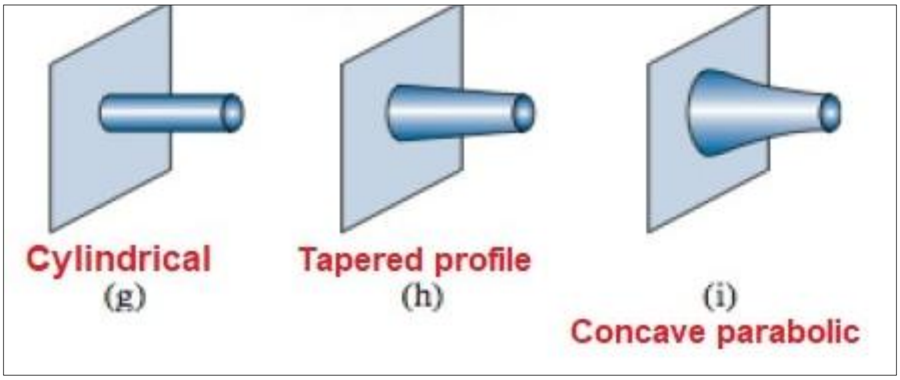

Figure III. 17: Pin fin[52]

III.4.3 Fins materials

Fins are critical components in solar air collectors as they enhance heat transfer by increasing the surface area in contact with the working fluid (usually air). The choice of fin material significantly affects the collector's thermal performance. Typically, materials with high thermal conductivity such as copper and aluminum, are preferred. Copper offers excellent thermal conductivity but is more expensive and heavier. Aluminum, while slightly less conductive, is lightweight, cost-effective, and corrosion-resistant, making it a popular choice in many designs. In some cases, galvanized steel or coated steel fins are used for their durability and mechanical strength, though they are less efficient in heat conduction. The selection of fin material must balance thermal performance, cost, weight, and durability depending on the intended application and operating environment.

III.4.4 Heat transfer

The rate of heat transfer from a surface at a temperature Ts to the surrounding medium at T∞ is given by Newton's law of cooling as [51]:

$$\dot{Q}conv=h.As.(Ts-T\infty) \qquad \textbf{(III.4)}$$

Where,

As: is the heat transfer surface area.

h: is the convection heat transfer coefficient

Ts: surface temperature and

T∞: are fixed by design considerations,

The rate of heat transfer can be accelerated in two ways:
Increase the convection heat transfer coefficient (h) by installing a pump or fan or by replacing the current one with a larger one, although this method may or may not be feasible. Furthermore, it could not be sufficient.
Increase the surface area (As). The alternate method is to connect fins—extended surfaces made of highly conductive materials like aluminum—to the surface. A thin metal sheet is extruded, welded, or wrapped on a surface to create finned surfaces. By exposing a greater surface area to convection and radiation, fins improve heat transfer from a surface. [51]

III.4.5 Fin efficiency

Fin efficiency is the extent to which a fin transfers heat compared to the ideal case of perfect efficiency where the whole fin is at the base temperature. It indicates the efficiency of the fin in actual conditions, where the fin length experiences temperature drops.

The efficiency of a fin will always be less than one because it is not the case in real life that the temperature of a fin is constant along its length—at the base, the fin is hottest; it gets cooler nearer to the tip. Because heat travels from hot areas to cooler surroundings, the cooler portions of the fin (the portions farther from the base) will not transfer heat as readily. If the entire fin had a temperature that remained the same as the base, then it could transfer the maximum amount of heat possible (i.e., ideal case). However, since the fin temperature cannot stay the same as the base, the heat transferred will always be less than the ideal value, which means that efficiency will always be less than one, as efficiency is defined as the ratio of actual heat transferred to ideal heat transferred [51].

$$\eta = \frac{T_{without\ fins} - T_{with\ fins}}{T_{without\ fins} - T_{ambiant}} \quad \textbf{(III.2)}$$

Were:

$T_{without\ fins}$: Temperature without fins

$T_{with\ fins}$: Temperature with fins

$T_{ambiant}$: Ambiant Temperature

III.5. Advantages and disadvantages of fins:

III.5.1 Advantages

- Enhanced Heat Transfer
- Economical Cooling
- Ease of Design and Mounting
- Universal Application
- No Moving Parts
- Energy-Efficient:

III.5.2 Desadventages

- Limited Effectiveness at High Convection Rates:
- Extra Weight and Space
- Complex Manufacturing (for Some Types): difficult to manufacture.
- Dust and Dirt Accumulation:
- Reduced Efficiency with Ineffective Thermal Contact:
- Cost of Material

Conclusion

This chapter covered the effects of dust and heat on the performance and efficiency of solar panels. We also looked into numerous ways to boost their efficiency. Cooling fins are one of the most promising and cost-effective heat-reduction technologies available. As a result, in the following chapter, we will put this method to the test by applying it to actual solar panels and evaluating its performance.

Chapter IV
Installation process and results

Introduction

In the above chapters, we have already outlined the key issue of temperature rise in photovoltaic (PV) systems and its negative impact on energy conversion. Although solar panels under standard test conditions are highly effective, they can degrade performance when placed in particularly hot climates. As outlined above, when the panels' temperature exceeds 25 °C, the output from the panel is expressed by an approximate decrease of 0.3%-0.5% (for each degree increase), primarily due to internal resistance rise and voltage attenuation. Thus, all temperature-dependent decreases of conversion efficiency add an extra burden to the issue of maximizing solar energy harvest, hence of paramount importance in areas affected by solar radiation during an extended period and high intensity.
Chapter 4 will consider the practical use of a passive cooling method to assist in the thermal regulation of the solar panel (or array). Each of these systems relies on passive effects or permanent fixtures on the components with a simple support. Passive cooling methods are different from active methods (active cooling systems to regulate the temperature of the module require energy input and moving parts) in that passive cooling does not require energy to operate and simply relies on alterations in the physical characteristics that dissipate and lower heat emission without consuming energy. In this study, we proposed a passive cooling method using metallic fins that are attached to the back surface of the solar panel. These fins increase the sun's surface area to dissipate heat (compared to a flat surface) and allow for a greater heat exchange surface area with the surrounding air, which promotes effective natural convection and radiation.

In this chapter, we present the experimental setup, the tools used, and the procedures implemented to evaluate the effectiveness of the proposed passive cooling strategy. Two experiments were designed and carried out under real outdoor conditions to compare the performance of different photovoltaic panel configurations. The first experiment involved the comparison of two identical PV panels—one equipped with vertical fins and the other without fins. The second experiment examined the performance of a panel fitted with cross-shaped perforated fins, compared to a panel without fins. Throughout the tests, several key variables were measured: surface temperature, electrical output (voltage, current, power), and environmental conditions (ambient temperature and solar irradiance). These measurements were taken using thermocouples and a multimeter over a defined period.

The main objective of this study is to quantify the improvements in thermal and electrical performance resulting from passive cooling using newly designed fins, and to assess whether this simple and low-cost modification can effectively enhance solar panel efficiency in practical applications.

IV.1 Description of geographical features

The comparative testing of the two solar panels, one fitted with fins and one standard, was done under the sky outside the i2E center, at Abou Bekr Belkaïd University in Tlemcen, a city in northwest Algeria at an average elevation, 843 m above sea level, in a climate that is Mediterranean semi-arid, which is characterized by hot and dry summers and mild and wet winters, and has an impact on the performance of photovoltaic installations.

An important factor when trying to maximize solar energy production in this area is for the solar panels to be at the correct tilt angle. Research has shown that in Tlemcen, the optimal tilt for photovoltaic panels is between 32°and 37° pointed South, which enables the panels to capture the maximum solar radiation throughout the year. This configuration impacts the energy efficiency of the installation, which is vital to being able to compare different designs of solar panels to the desired level of accuracy.

In conclusion, the location of the experiment provides good geographic and seasonal conditions to investigate the performance of solar panels, because of the high altitude in Tlemcen with optimum sunlight exposure, adding weight to the results that were achieved. [52]

Figure IV. 1: Geographical location

IV.1.1 Optimizing Photovoltaic Efficiency

When we think about performance studies, we know that monocrystalline silicon panels have the highest commercial efficiencies (max 24 %) due to their high purity and uniform structure. However, we also know that performance is highly dependent on the environment;

In general, the higher the temperature, the lower the panel's output because the vast majority of PV cells performance degrades, on average, 0.3 percent and 0.5 percent for every degree Celsius (°C) over standard test conditions. Solar angle is another important characteristic that affects the amount of sunlight the panel absorbs,Shading can severely reduce output (in some cases, these panels may <10 % output).

IV.1.2 Passive cooling techniques (fins)

Thermal fins is a device that lowers the temperature of photovoltaic modules, specially designed to do that, and that takes no extra energy, thus maximizing efficiency and lifespan of the panels. The fins are typically made of aluminum, which has extremely high thermal conductivity. The fins are mounted directly on the back of the solar panel. Because they are fins, this will increase the areas exposed to ambient air, thus enabling natural convection that will release heat away from the plate. This method could decrease the module temperature by 5 to 15°C, as well as increase electrical efficiency because the performance of solar cells will decrease due to heat; and the fins will work better in hot climates, plus they would be inexpensive.

Part one (experience one): Vertical fins installation and results

IV.2 Materials and Equipment

IV.2.1 Solar panels (1 with fins, 1 without)

IV.2.1.1 Solar panel without fins

The SolarPro model is a PV module, mono-crystalline panel capable of producing a peak power output of 50 W, while suitable performance for our system depends on actual field conditions.

Also, Peak Power output is measured under standard test conditions, which relate to standard test conditions. See our Leaflet for reference (1000 W/m² irradiance, 25 °C, AM 1.5).

The panel has a maximum P-MPP current of 2.70 A at 18.24 V and open circuit voltage short circuit current ratings of 21.8 V and 2.97 A, respectively.

Designed for reliability in off-grid applications for solid-state devices, this panel is lightweight and simple to mount. While it is user-friendly, as with all photovoltaic modules, it needs to be treated with care, and not perform installation or service operations in wet conditions.
When properly installed and maintained (to prevent shading and soiling), it will provide stable electrical DC power, which requires little or no maintenance for small-scale solar electric systems.

Figure IV. 2: Solar panel

IV.2.1.1 Solar panel with fins

The module is still the same electrical specifications; we just placed some fins on the back to lower its operating temperature. We mounted fins of different shapes and sizes on the back of our second panel. We used a small amount of silicone adhesive to secure 16 fins to the back of one of the panels; the thermal conductivity of silicone is negligible

Figure IV. 3: Stick fins on solar panel

This table presents the various sizes and quantities of fins that were utilized:

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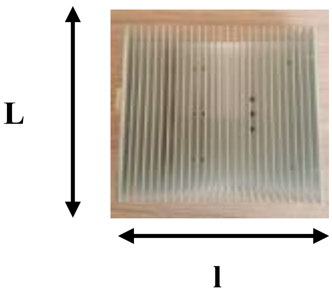
Table IV. 1: Presentation of the various sizes of fins that were utilized

Fins	The back of the fins	Sizing
		**l =10 cm L=14 cm 4 pieces**
		**l=10cm L=10cm 8 pieces**
		**l=10cm L = 12cm 2pieces**
		**l = 10cm L= 29 cm 2 pieces**

We put our sensors in position (x, y) to measure temperatures. We then took pictures of those locations, using a thermal camera to visualize and analyze the temperatures distributions.

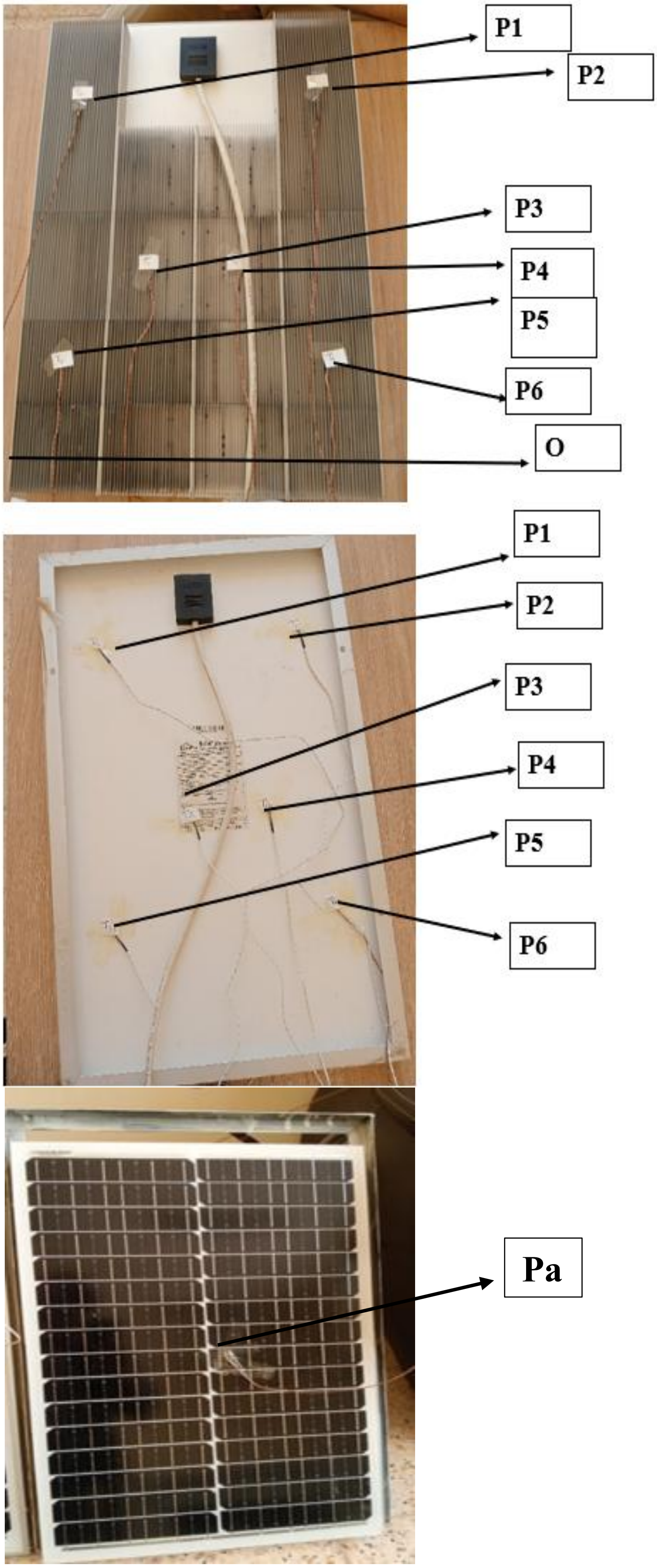


Figure IV. 4: : Temperateur sensors

Table IV. 2: : Sensors positions

Point	O,X (cm)	O,Y (cm)
Pa (Ta)	20	30
P1 (T1)	5	51
P2 (T2)	35	51
P3 (T3)	15	25
P4 (T4)	25	27
P5 (T5)	5	15
P6 (T6)	35	15

IV.2.2 Battery

The NP12-18Ah is a 12 V, 18 Ah valve-regulated lead-acid (VRLA) battery from NPP Power Vietnam Co., Ltd. It is suitable for both cyclic and standby (float) applications. The recommended floating voltage for continuous float service is 13.6–13.8 V, while for cyclic (deep-cycle) application, the recommended voltage is 14.5–15.0 V. The initial charging current should not exceed 5.4 A.
With a Note:
Short-circuiting terminals should be avoided.
The battery should never be disassembled
Any environment with temperatures exceeding 55 °C should be avoided.
Finally, incineration and disposal by fire should be strictly avoide

Figure IV. 5: Battery

IV.2.3 Solar charge controller

P2410 is a solar charge controller with advanced three-stage PWM charging technology. This is a small, stand-alone solar power system. This is a basic and typical model for solar power control applications. It is widely used worldwide with various types.

Figure IV. 6: : Solar controller

IV.2.4 Solarimeter

The TM-206 is a portable solar power meter which measures solar radiation in either Watts per square meter (W/m²) or British Thermal Units per square foot per hour (BTU/ft²·h) up to a maximum range of 0–2000 W/m² (0–634 of BTU/ft²·h).
It has a cosine-corrected sensor so it can measure the expected value when compensating for the angle of incident light .The unit has a 3½-digit LCD display and has updates of 0.25 seconds for measurements providing stability and speed while testing.

Figure IV. 7: Solar meter

Application: Solar Panel Alignment: Measuring incident radiation at numerous angles can very quickly establish the optimum tilt and orientation for photovoltaic panels

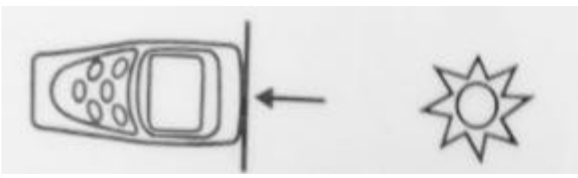


Figure IV. 8: Solar meter alignment

IV.2.5 Multimeter

A digital multimeter (DMM) is an electronic measurement tool that brings together multiple measurement functions into one option. The ASTONIA M890C+ is a general purpose DMM and is often used by technicians, electricians in a wide variety of situations.
Some of the options include:

- ❖ Voltage (V), which measures both AC (V~) and DC (V—) voltages.
- ❖ Current (A), which measures both AC and DC current.
- ❖ Resistance (Ω) which measures the resistance (R) in ohms.
- ❖ Capacitance (Cx) which measures capacitors.
- ❖ Transistor Testing (hFE) for NPN and PNP guess transistors.
- ❖ Temperature (TEMP °C) is for taking temperature measurements with a thermocouple probe.
- ❖ Auto Power Off for battery saving for inactivity.

Ports (bottom):

1) 20A MAX for high current measurements.
2) mA is for low current (up to 200mA) measurements.
3) COM, ground or common reference.
4) V/Ω is for voltage resistance, diode, and temperature measurements.

Figure IV. 9: Multimeter

IV.2.6 Thermal camera

A thermal imager (or a thermal camera) is a diagnostic device that gives you the ability to visualize and obtain surface temperature measurements of a target area by measuring infrared radiation (heat) emitted by the surface. This FLUKE thermal imager is handheld, rugged, and made for industrial, electrical, and HVAC applications.

Key Features:

- Display screen- A visual representation of the target area, with the temperature gradients visualized using color mapping.
- Control buttons (F1, F2, F3, and Power):
- Control buttons are used for navigating through the screen for viewing, saving images, changing settings, and turning the thermal imager ON/OFF.
- Trigger (most likely on the back of the handle) , Used to take images with the thermal imager.
- Rubberized grip- handle is ergonomic for comfortable handling and secure when in the field.
- Wrist strap- Helps prevent the unit from being accidently dropped when in use.
- FLUKE Quality- The FLUKE Company is known for their durability, accuracy, and simple and easy interface.

Applications:

- Electrical Inspections: Use it for checking overheated devices, faulty connections, and overloaded circuits.

- Mechanical Diagnostics: Use it to check for worn bearings in relation to elevated temperatures, friction overheating, and inefficient motors.

- HVAC: Use it for checking for insulation, air leaks, and to check temperature distributions.

- Building Inspections: Can be used for indicating water damages, mold risk areas, and thermal bridging.

Figure IV. 10: Thermal camera

IV.2.7 Thermocouple

A thermocouple operates by the Seebeck effect where a loop of two different metals creates a thermoelectric voltage when it is held at different temperatures at its junctions. A thermocouple serves as a sensor to measure temperature, consists of two different types of metals, and connects at one end. When the junction of the two metals is heated or cooled, a voltage is produced that can be correlated back to the temperature.
We used fourteen thermocouple (Type K) probes to monitor surface and edge temperature under varying heat-transfer conditions. In two groups of six, twelve sensors were put on the back of the panel. One group was put on the back of the bare panel (without fins) and the other group was put on small aluminum heat-sink fins to facilitate

convective heat transfer. Two thermocouples were also placed on the front faces, one bare and one finned, to record inlet-side temperature profiles.

Figure IV. 11: Thermocouple

IV.2.8 The lamps

This is a DC lamp, rated at 55 watts and 12 volts, and is typically found in automotive applications where it is applied in load rating tests, but can also be used to test and simulate loads in photovoltaic (solar power) systems.
Application in a PV System:
Resistive Load for Testing:

- We have used the load lamp as a resistive load to determine how the PV panels, batteries and charge controllers perform.
- When connected to the system, the load lamp draws a constant current (approximately 4.6 A = 55W / 12V), closely simulating actual loads.
- It is also useful to analyze battery performance under load, this allows us to monitor battery performance at the stated discharge rate and simulate typical load rates commonly found in households.
- A great way to confirm if our PV panel is producing enough voltage and current under ideal sunlight to justify energizing your load.

We used two of these lamps connected in parallel

Figure IV. 12: Lamps

IV.3 Prototype Design and Implementation

The prototype contains two photovoltaic (PV) modules one with fins and the other one without fins by an inclination 37° attached to a solar charge controller to manage the power to a 12V battery. A range of measuring instruments, including a multimeter, a thermal camera, and a solar irradiance meter are included to enable monitoring of the electrical and thermal parameters.

The PV module was tested in both configurations (with and without cooled fins) to evaluate their performance effects. The entire prototype was designed for outdoor testing in order to capture real-world solar radiation characteristics.

Figure IV. 13: Prototype design

Figure IV. 14: Field implementation of the experiment

IV.4 Results interpretation

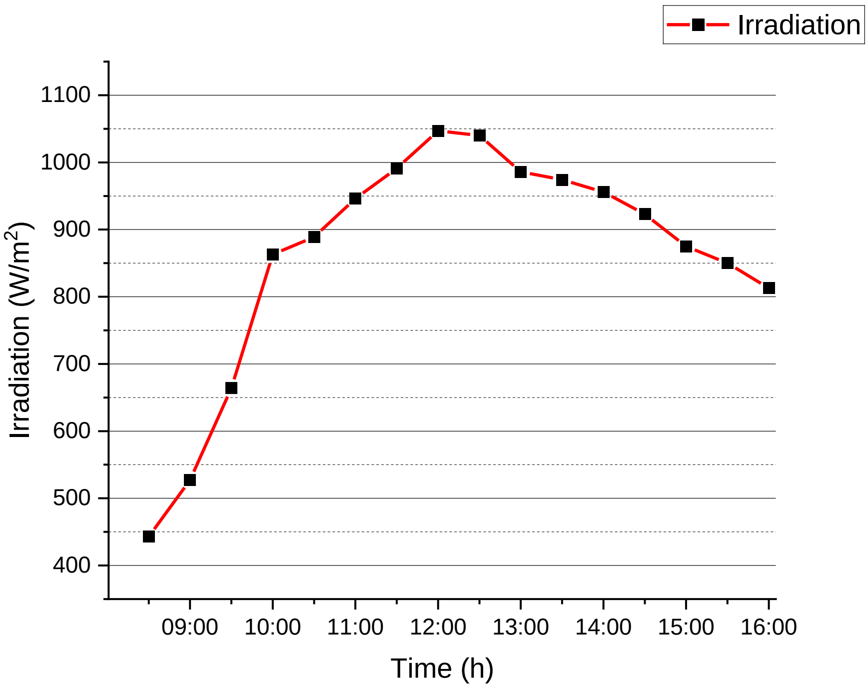
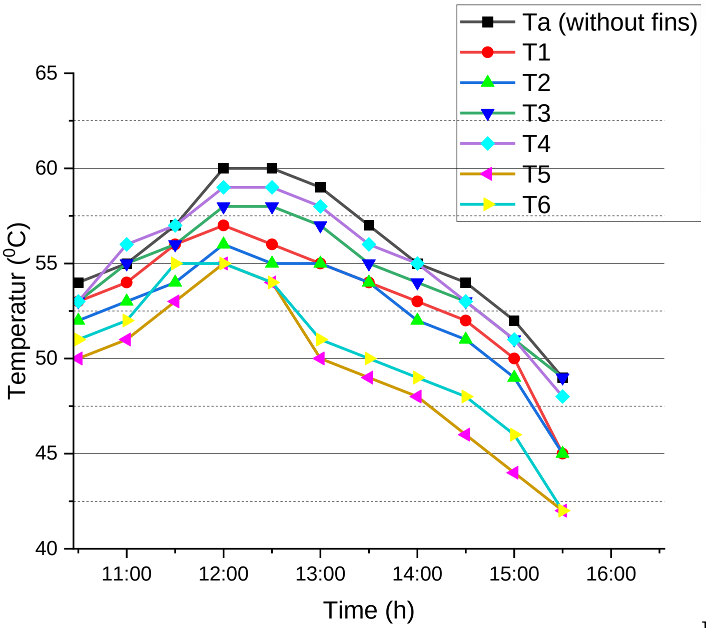


Figure IV. 15: Graph of irradiation on 01/06/2025 over time

The diagram (IV.15) illustrates the evolution of solar irradiance on 01/06/2025 from 8:30 am to 5 pm. Irradiance increases gradually in the morning until 12 noon, when the sun is at its zenith and irradiance is at its highest, reaching around 1047 W/m². It then gradually decreases to around 800 W/m² at 4 pm. This bell-shaped curve corresponds to a typically sunny day. The period of high irradiation, generally between 10 a.m. and 3 p.m., is the most favourable for photovoltaic energy production.



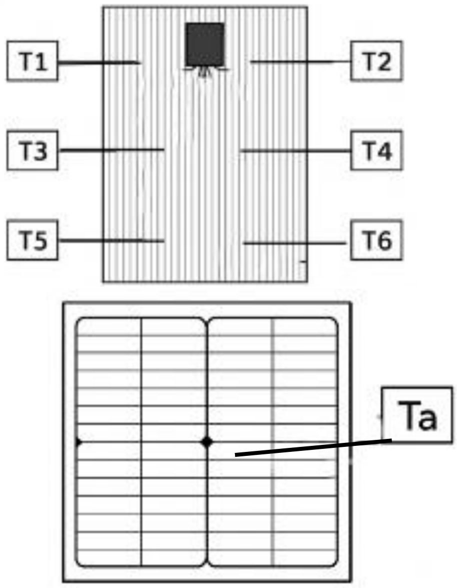


Figure IV. 16: Temperature sensors

Figure IV. 17: Graph of temperature without fins over time

The graph (IV.17) shows the evolution of temperatures on a finless solar panel during the period from 10:30 to 16:00. Curve Ta represents the temperature at the front of the panel (exposed to the radiation) and curves T1 to T6 are the measurements taken at the back of the panel at various points. We can already see that over time, the temperatures gradually decrease, probably due to the reduction in solar radiation, as does the temperature at the front surface. The temperature of the front surface (Ta) is much higher than the temperature of the rear surface, reaching a maximum of 60°C on average, clearly indicating the accumulation of heat on the exposed surface. Temperatures measured at the rear from T1 to T6 are generally similar, ranging from 60°C to 42°C.

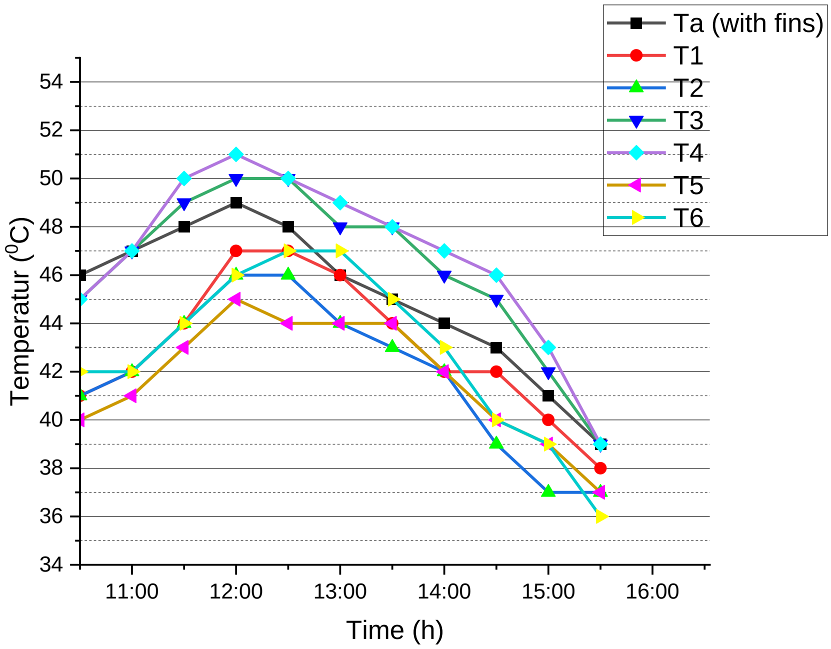
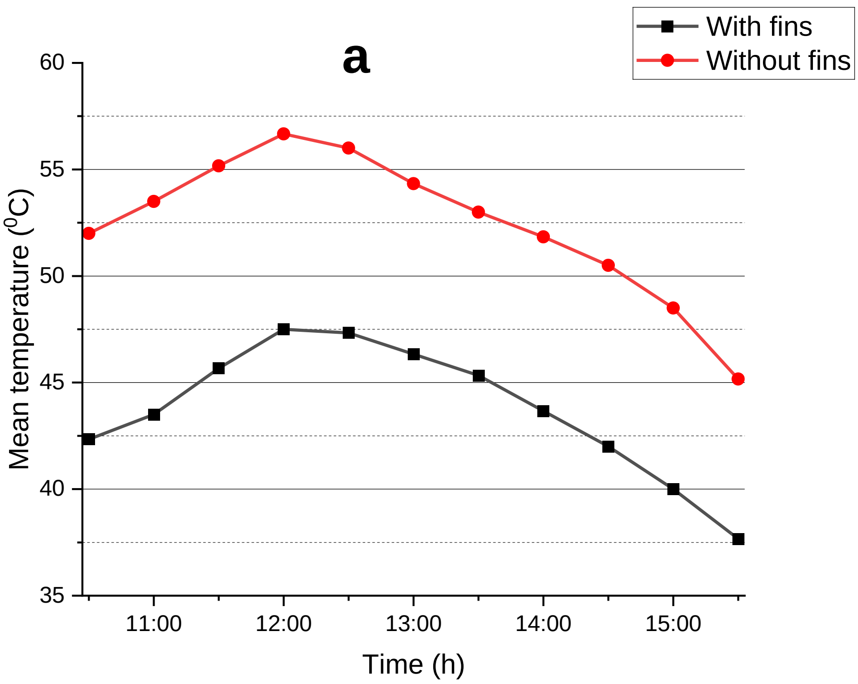


Figure IV. 18: Graph of temperature with vertical fins over time

The graph (IV.18) illustrates the gradual decrease in temperature of the photovoltaic panel over the period from 11:00 a.m. to 4:00 p.m. The surface temperature (Ta) and the temperature measured at the rear of the panel (at T1 to T6) show that Ta is warmer than the rear temperatures most of the time. The difference between the two shows the contribution of the fins to cooling the panel. The back temperatures are close enough to each other to indicate a homogeneous thermal distribution. Overall, passive fin cooling produces a good effect in terms of long-term temperature reduction for the panel, which is likely to perform better.



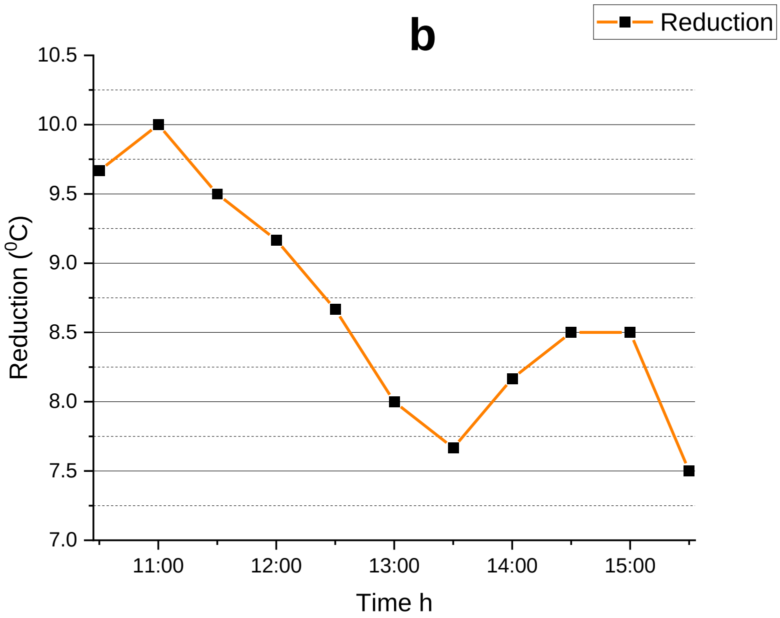


Figure IV. 19: (a)Graph of mean temperature with and without fins over time, (b) Change in temperature for PV panel with and without fins

The graph (IV. 19. a) shows the temperature evolution of two photovoltaic panels over time, from 10:30 AM to 4 PM, one of which has cooling fins (black curve), and the other does not (red curve)

At all times during this period, the temperature of the panel without fins is always greater than the panel with fins. For instance, at 11:30 and at 12:00 AM, the uncooled panel has a temperature of about 55°C and 56°C, respectively, while the panel with fins only approaches 45.5 and 47.5°C, respectively. This difference continues through all periods and even a little later in the day: at 3:30 PM, the temperature for the uncooled panel is about 45°C, and for the cooled panel it is about 37°C

The graph (IV.19.b) illustrates the temperature reduction variation of the PV panel with and without fins. The use of fins led to a significant temperature reduction, reaching up to 9.5°C at 11:30 AM, which represents a substantial improvement in thermal management.

This large temperature difference showing the significant temperature reduction from fins confirms the capability of passive cooling. As previously stated, the fins promote the heat exchange between the panel and the environment and also limit the overheating. This improved thermal control allows the photovoltaic system to operate within a more favorable temperature range to enhance the electrical performance and ultimately increases the efficiency of the PV system.

Conclusion

The graph indicates that photovoltaic panels with fins have a considerably lower average temperature than photovoltaic panels without fins. This difference shows that passive cooling works and allows better temperature regulation and, in turn, better performance of the photovoltaic panels.

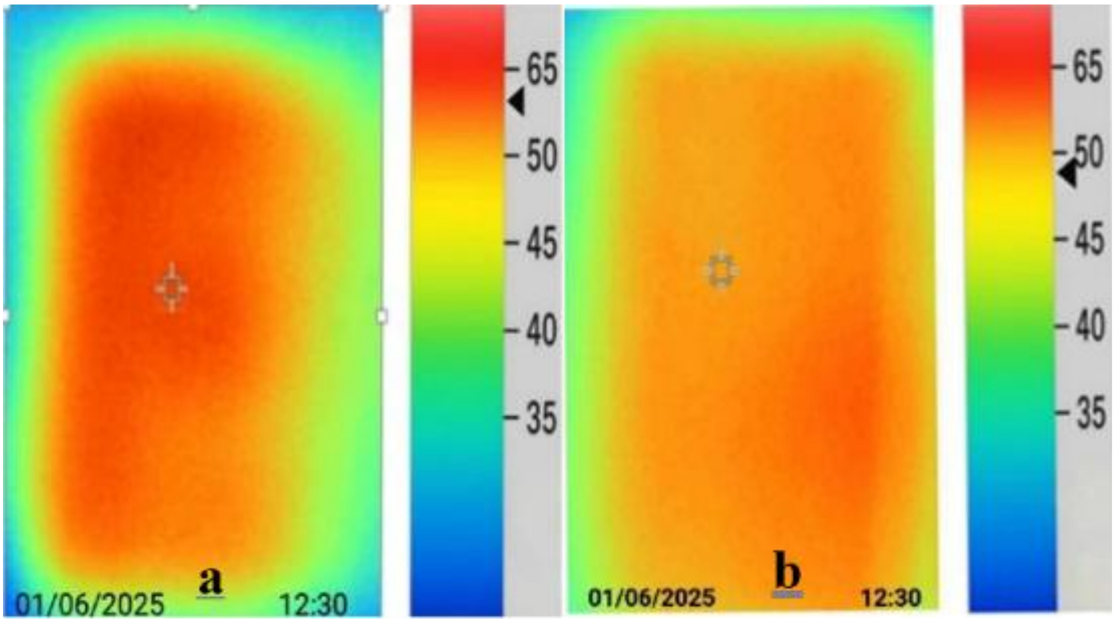


Figure IV. 20: Thermal camera image of PV panel, (a): Without fins, (b): With fins

The thermal image (IV.20) compares two photovoltaic (PV) panels subjected to the same sunlight conditions on 06/01/2025 at 12:30, one without fins (a) and the other with fins (b). The panel without fins (a) reaches a maximum temperature of around 59.9°C at its center, which is attributed to thermal concentration at the center of the panel and therefore to heat accumulation, whereas the panel with fins (b) has a much more even temperature distribution, with a maximum that drops to around 48°C, confirming passive cooling. This shows the efficiency of heat dissipation promoted by the fin. A lower operating temperature maintains better electrical performance and reduces the effects of premature ageing. These results demonstrate the benefits of integrating fins to improve the reliability and efficiency of photovoltaic installations, particularly in hot environments.

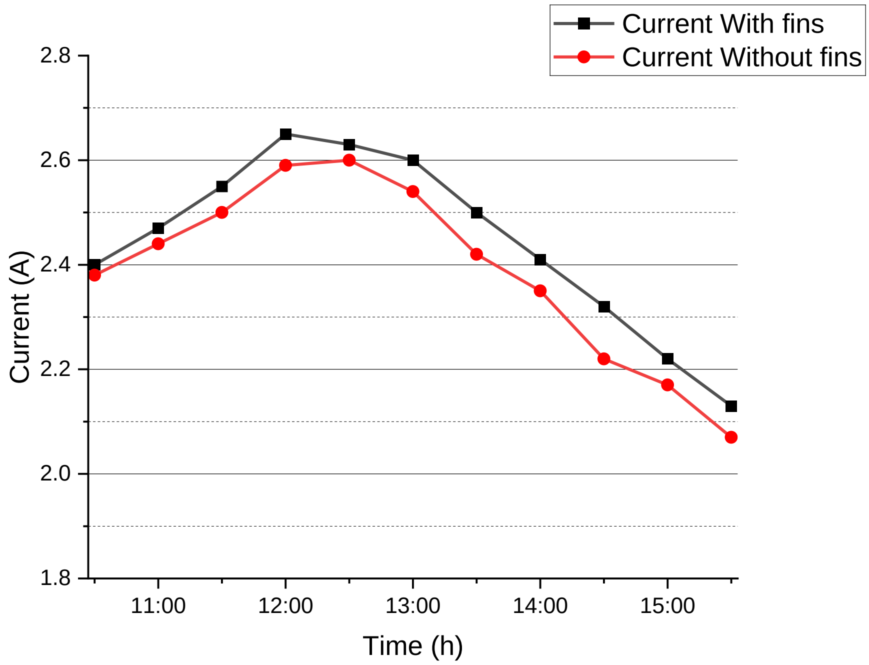


Figure IV. 21: Graph of current with and without fins over time

The graph (IV.21) shows the temporal changes in electrical current from photovoltaic panels and compares two setups, one with cooling fins and the other without. The data shows that both of the panels produced an increase in current from 11:30 through to about 13:00; both panels had peaked a measurement of just under 2.7 A. After the point of maximum solar input, the current produced began to drop off for both panels, likely due to rising operating temperature of the panels as the efficiency decreases as the temperature of the panels increase. The noticeable difference between the two comes from the yet one distinct measurement - the panel with the fins produced more current than the setup without the fins consistently during the measurement period. This indicated a better thermal management of the panel by the fins, helping provide a better heat dissipation mechanism to protect panel temperatures from thermal rise, allowing improved performance using electrical energy.

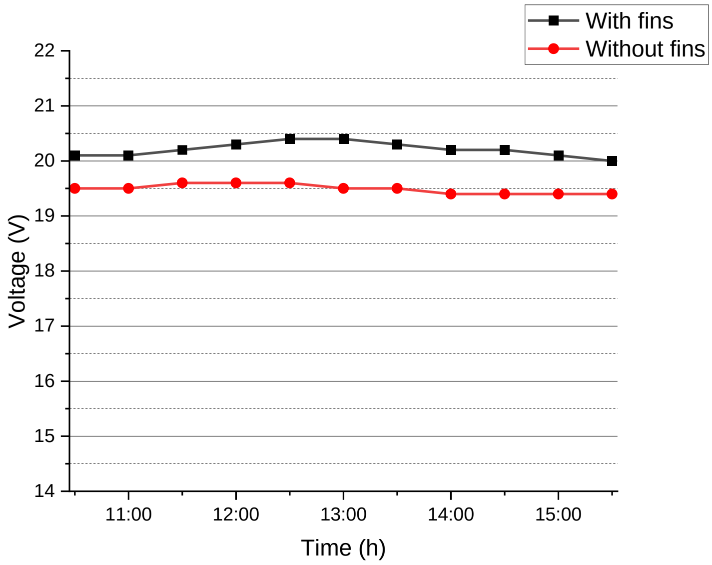


Figure IV. 22: Graph of voltage with and without fins over time

The graph (IV.22) below illustrates the output voltage evolution of a photovoltaic panel as a function of time for the respective day between 10:30 am - 4:00 pm. Two configurations were analyzed for the panel: with fins (black curve) and without fins (red curve). Throughout the experimental process, it can be seen that the output voltage for the panel with fins maintained a higher mean value (mean value of ~20.4 V) than the panel without fins (mean value of ~19.6 V). This indicates that the fins provided a form of passive cooling, which contributed positively to the electrical performance of the panel; it kept the temperature of the panel in a more acceptable thermal range while allowing for the operational efficiency of energy conversion to increase. Both configurations operate effectively under proper thermal management; however, the panel with fins produced a better electrical performance with a higher and more stable output voltage; as a result, it exhibited operational efficiency optimized not just by energy conversion, but also by thermal management.

Conclusion

Fins help improve heat dissipation and overall stability of the voltage output from the photovoltaic panel, leading to improvements in efficiency and performance of the system. This will give increased active cooling to the system passively

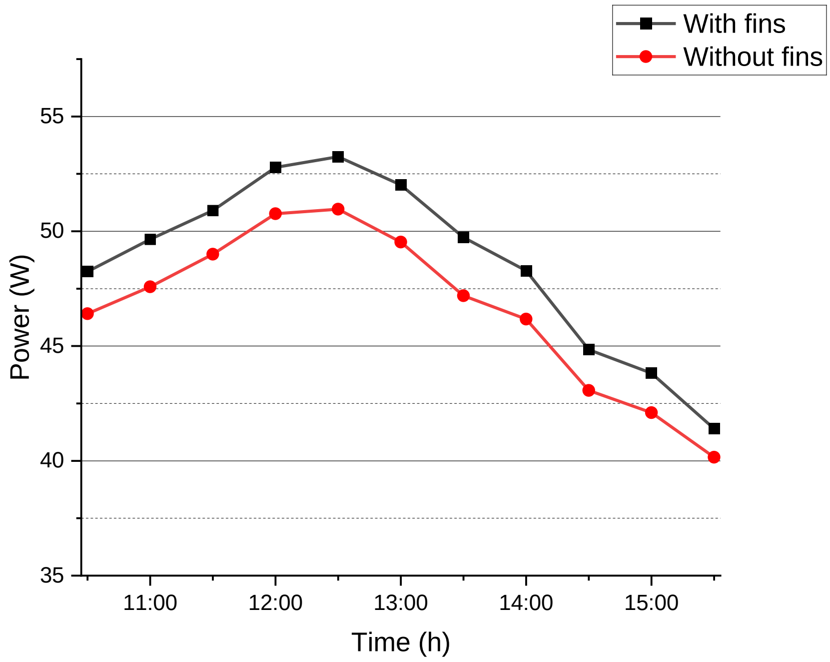


Figure IV. 23: Graph of the power with and without fins over time

The graph (IV.23) shows the change in power provided by solar panels between 10 a.m. and 4 p.m., taking into account the configuration with fins and without fins. It can be seen that the energy increases in the morning, peaking at noon, and then decreases throughout the day in both cases, due to the rise in temperature during the day and changes in sunlight. However, it can be observed that the curve of the finned panel always remains higher than that of the non-finned panel, especially after 12 p.m. When it's 53W of PV with fins, and 51W of PV without fins this indicates that the finned panel dissipates heat better than the non-finned configuration, limiting the drop in performance when the temperature is exceeded. It can be concluded that the finned panel produces more stable and higher power, providing better energy efficiency over the period covered by the study.

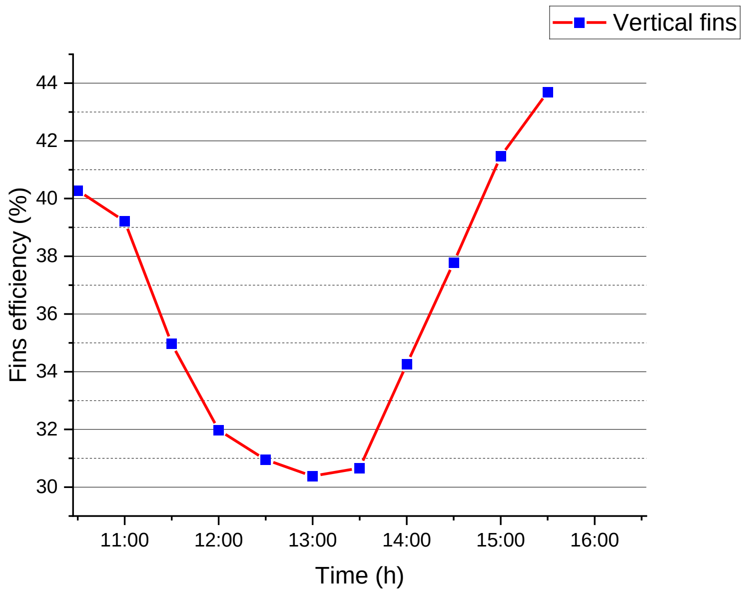


Figure IV. 24: Graph of fins' efficiency over Time

The graph (IV.24) shows the variations of fin efficiency (shown in chapter III), over the day; efficiency peaked at 10:30 am (41%) in the morning and declined as solar irradiation and panel temperature increased. The efficiency was approximately 31% during the midday hours of 12:00 to 13:30. This decrease in efficiency is to be expected, as passive cooling, which fins, can accomplish, is not functioning well in the middle of the day. This is because there isn't much of a temperature differential between the air and panel surface temperatures at this time, which makes fins less effective. The efficiency increases once more in the afternoon (after 13:30), reaching almost 43.9% by 15:30. The efficiency boost once more shows that the fins were better at dissipating heat and that the panel's performance improved as a result of lower ambient temperatures.

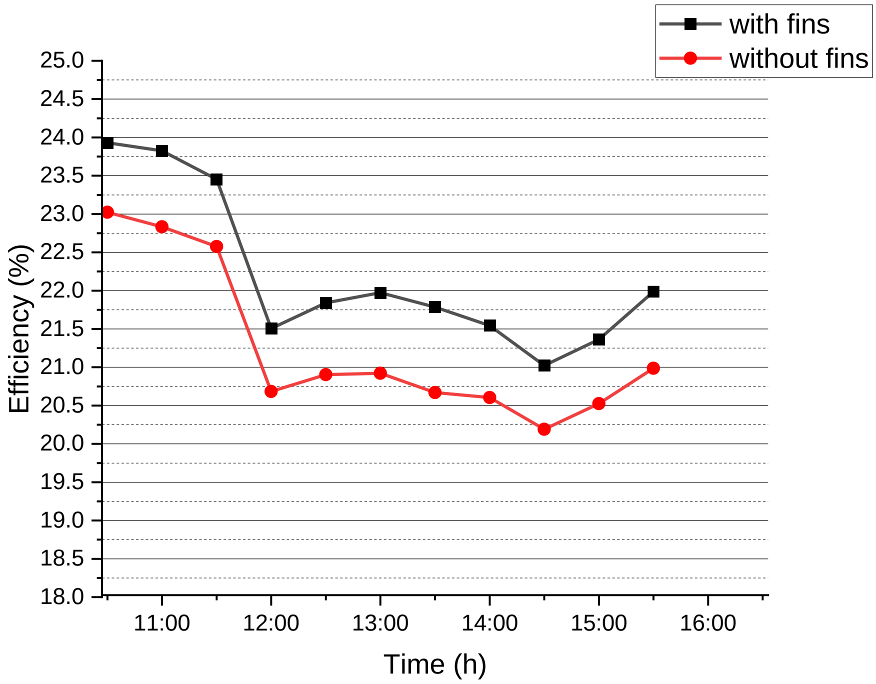


Figure IV. 25: Graph of efficiency with and without fins over time

The graph (IV.25) shows the evolution over time of the photovoltaic efficiency of two panel configurations: one equipped with cooling fins and the other without. Initially, both systems exhibit a gradual decline in efficiency, from around 24% and 23% at 11:00 to a minimum of approximately 20% and 21% at 13:00, coinciding with the peak period of solar radiation and temperature. This decrease is attributed to thermal stress, which negatively affects photovoltaic conversion efficiency. After 13:00, efficiency begins to recover as radiation decreases and panel temperatures drop. By the end of the observation at 16:00, efficiency with fins reaches about 22%, compared to 21% without them. These results confirm the positive impact of passive cooling strategies on maintaining and improving the performance of photovoltaic systems under fluctuating thermal conditions.

Part two (experience two): cross fins with holes installation and results

The second experiment took place on 17/06/2025. We implemented a new fin system, a cross-shaped fin system with perforations (holes) on the back side of the photovoltaic panel. The perforations were committed to enhancing the airflow into the cross fins and provided passive cooling. The fin system was constructed of the same material as the previous test. The panel was still a 37° inclination angle. The goal of the fins was to create a greater surface area for heat dissipation while still having the same environmental and structural parameters for a direct comparison of performance with Experiment one.

Figure IV. 26: New fins shape (cross fins perforated)

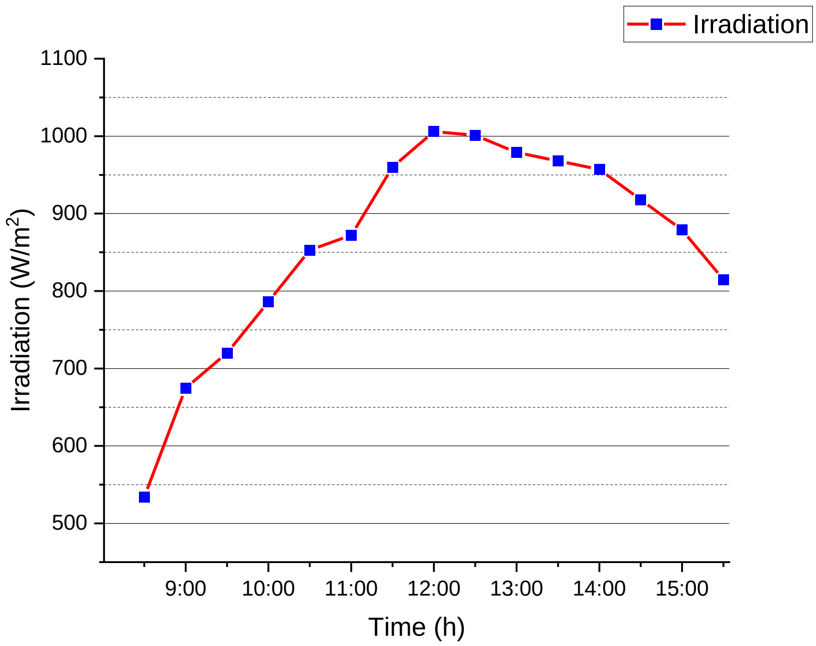


Figure IV. 27: Graph of Irradiation over time, day 17/06/2025

The figure (IV.27) shows how sun irradiance changes between 8:30 am and 5 pm on 17/06/2025. The irradiance progressively rises during the morning until midday, when the sun is at its zenith and the irradiance reaches its maximum, approximately 1006 W/m². At 5 p.m., it then progressively drops to about 815 W/m². Generally, photovoltaic energy generation is most effective during the high-irradiation period, which occurs between 10 a.m. and 3 p.m.

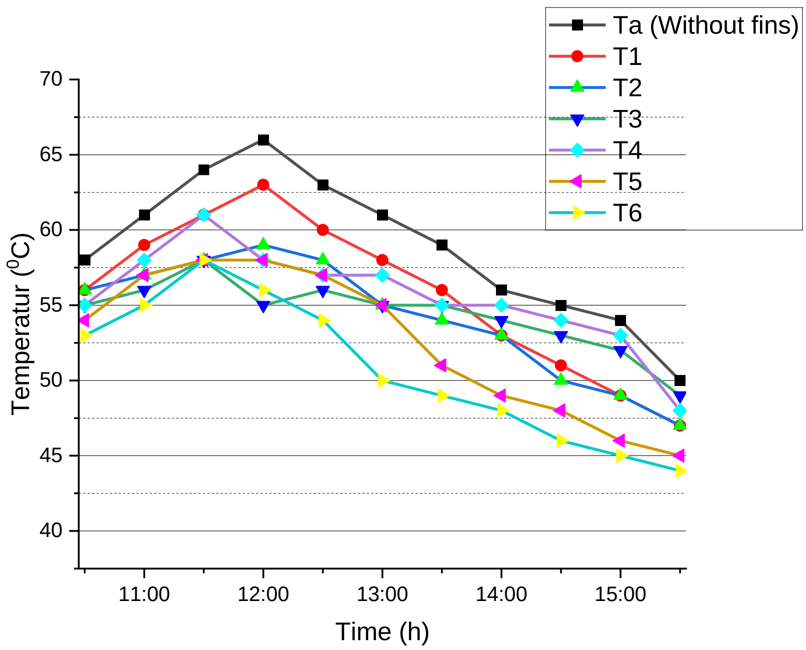


Figure IV. 28: Graph of temperature without fins over time

The graph (IV.28) represents the temperature evolution of a solar panel without fins. The measurements made at various positions at the rear of the panel are represented by the curves from T1 to T6, while the Ta curve shows the temperature at the front of the panel (exposed to radiation). We can already observe that as time passes, the temperature at the front surface and overall temperatures steadily drop as a result of less solar energy. With an average temperature of 66°C, the front surface's (Ta) temperature is significantly higher than the back surface's, amply demonstrating the buildup of heat on the exposed surface.

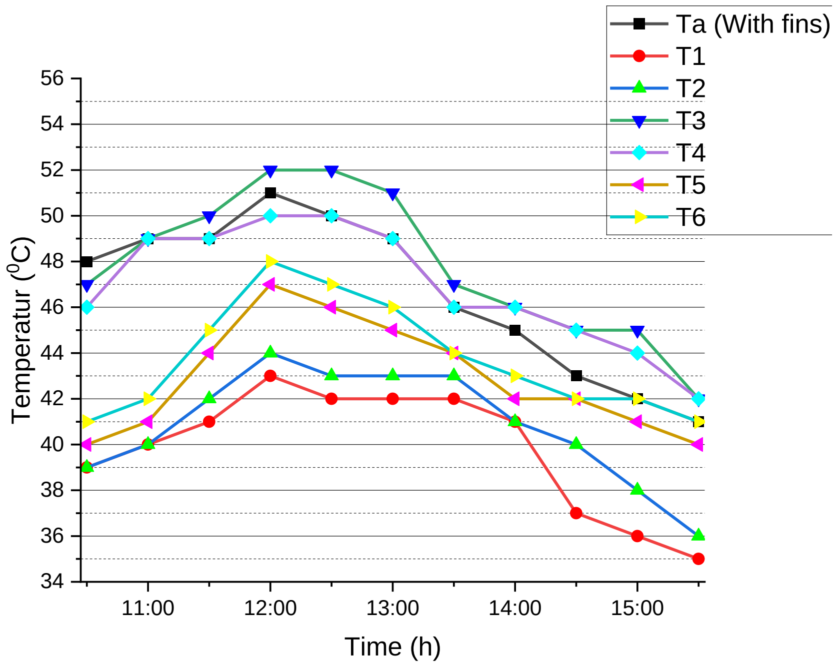


Figure IV. 29: Graph of temperature with cross fins over time

The graph shows the temperature changes of the solar panel with fins from 10:30 am to 4 pm. The temperature recorded at the back of the panel (at T1 to T6) and the surface temperature (Ta) indicate that Ta, T3, and T4 are almost similar, around 51°-52°C, and are often warmer than the back temperatures (T1, T2, T5, and T6). The backside temperatures exhibit a homogeneous thermal distribution because they are sufficiently close to each other. In terms of long-term board temperature reduction, passive fin cooling generally has a favorable effect. A comparison reveals that the temperatures at all measured points on the panel are lower than those recorded for the PV system without fins.

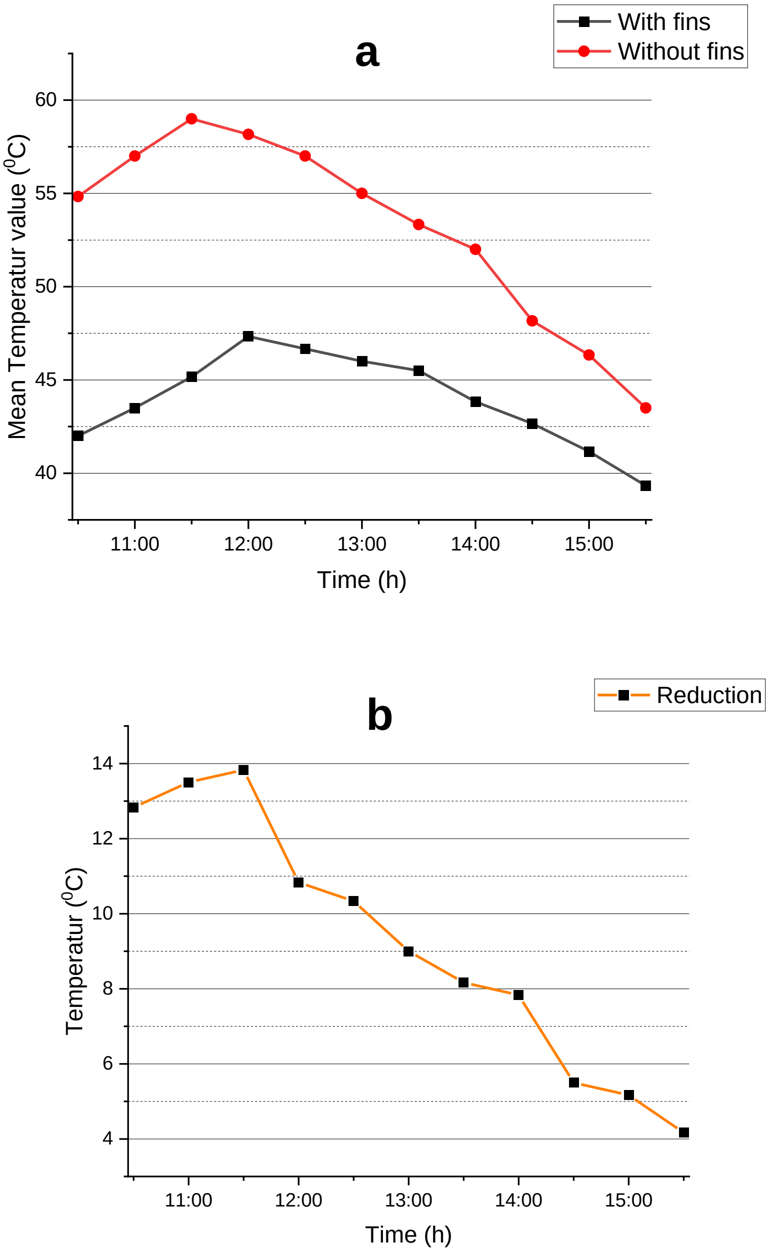
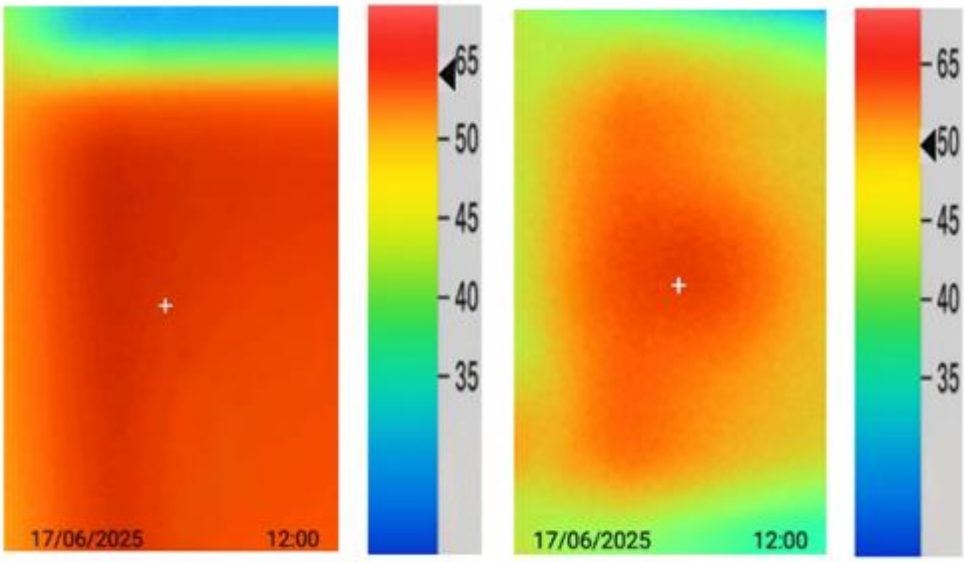


Figure IV. 30: (a)Graph of mean temperature with and without croos fins over time, (b) Change in temperature for PV panel with and without fins.

The graph (IV.30.a) shows the average surface temperatures of finned and unfinned photovoltaic panels during the day. Both finned and non-finned panels heat up significantly during the cool morning hours, peak during the midday when the sun is at its highest, and then cool down in the late afternoon as the sun's radiation weakens. However, we note that at 11:30 and at 12:00 AM, the uncooled panel has a temperature of about 59°C and 57.8°C, respectively, while the panel with fins only approaches 45°C and 47°C, respectively. This difference continues through all time periods and even a little later in the day: at 3:30 PM, the temperature for the uncooled panel is about 48°C and for the cooled panel it is about 39°C. This observation also highlights the importance of fins in contributing to cooling through natural convection, helping to dissipate heat and reduce convective heating on the photovoltaic panel.

The graph (IV.30.b) illustrates the temperature reduction variation of the PV panel with and without fins. The use of fins led to a significant temperature reduction, reaching up to a difference of about 14 °C at 11:30 AM, which represents a substantial improvement in thermal management.



a b

Figure IV. 31: Thermal camera image of PV panel, (a): Without fins, (b): With cross fins

The thermal images in Figure (IV.31) complement the comparison of the surface temperatures of two photovoltaic (PV) panels that were both exposed to the same environmental conditions, respectively, at noon on 17/06/2025. Image (a), associated with the panel without fins, shows a similar uniform thermal distribution (red coloration), indicating a surface temperature around 65.7°C. Image (b), associated with the panel with cross fins, has a heterogeneous distribution with many colder regions (green and yellow), particularly towards the edges. with a maximum of around 51°C. This pattern indicates increased heat dissipation due to the cross fins, which resulted in a cooler average surface temperature.

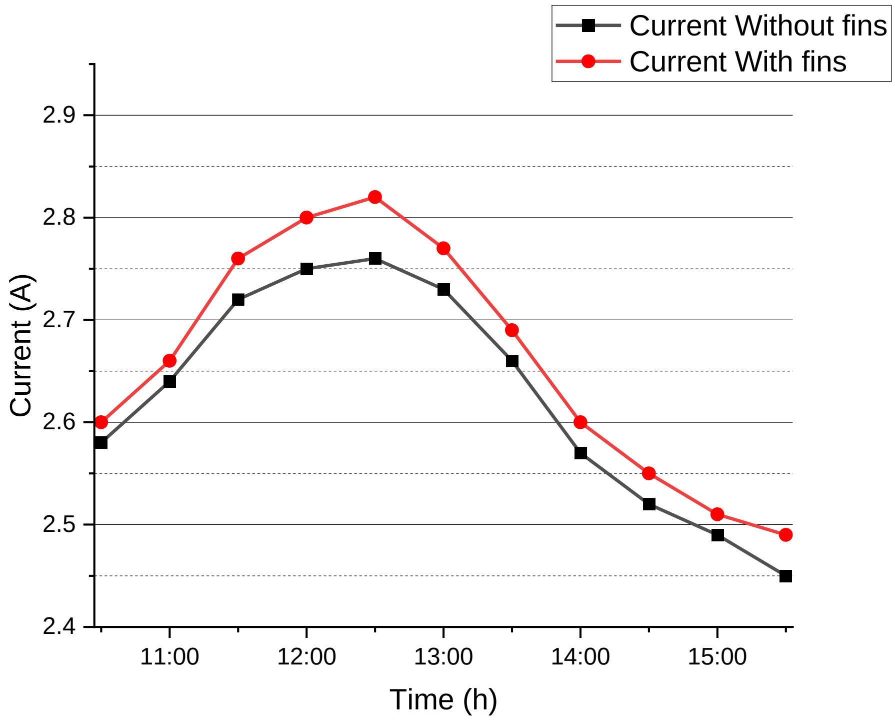


Figure IV. 32: Graph of current with and without fins over time

The graph (IV.32) shows the evolution of the electrical current over time. In both cases, the current peaks between 11:30 a.m. and 13:00 p.m., when the panel with fins reaches 2.82A, its maximum value, and without fins reaches 2.77A, then gradually decreases to its lowest level between 3:30 and 4 p.m. However, the current of the finned panel is slightly higher than that of the unfinned panel between 11 a.m. and 1 p.m. This may be due to thermal lag, the panel heats up faster without fins, so if the panel temperature rises with the ambient temperature, the fins improve heat management, dissipating heat more efficiently..

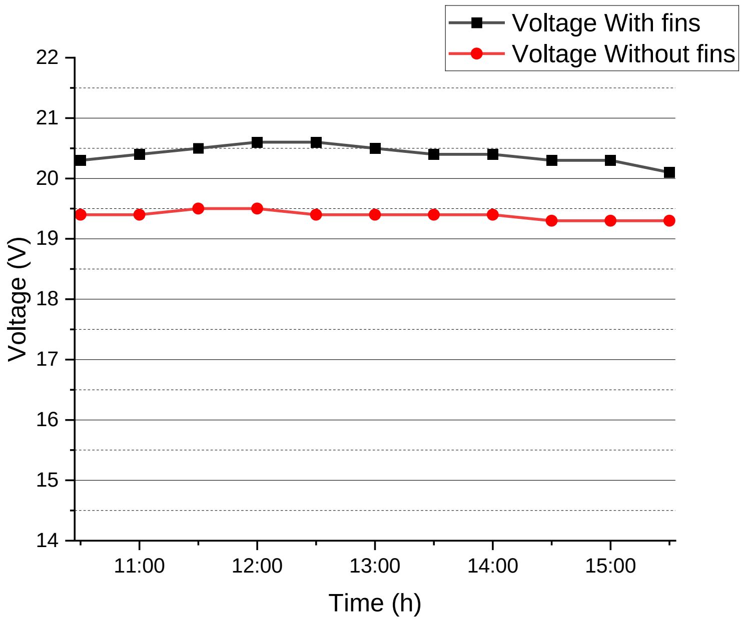


Figure IV. 33: Graph of voltage with and without fins over time

The graph (IV.33) shows the output voltage of a photovoltaic panel between 10:30 a.m. and 4:00 p.m. for two setups: with and without fins. The panel with fins consistently delivered a higher voltage, averaging 20.6 V compared to 19.6 V without fins. This demonstrates the effectiveness of passive cooling in maintaining optimal panel temperature, reducing thermal losses, and improving energy conversion efficiency. Despite identical environmental conditions, the finned panel showed better and more stable electrical performance, highlighting the importance of thermal management in photovoltaic systems.

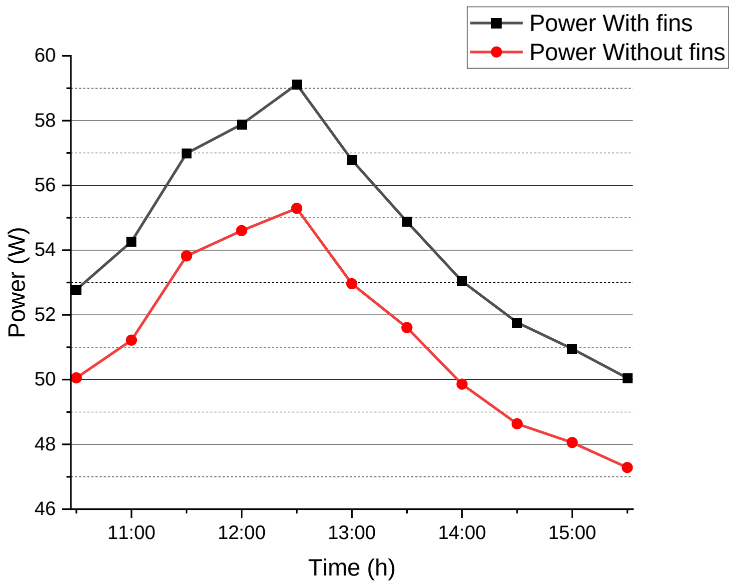


Figure IV. 34: Graph of power with and without fins over time

The graph (IV.34) shows the change in power (measured in watts) delivered by a solar panel between 10 a.m. and 4 p.m., taking into account the cases of the panel with fins and the panel without fins. It can be seen that the power increases in the morning, peaking at noon, and then decreases throughout the day in both cases, due to the rise in temperature during the day and changes in sunlight. However, it can be observed that the curve at 12:30 p.m. it is evident that the fin-equipped panel's curve consistently stays higher than the fin-less panel's, especially after midday. When it's 59W of PV with cross-fins, and 55W of PV without fins. It can be concluded that the finned cross panel produces more stable and higher power compared to exp.1, providing better energy efficiency over the period covered by the study.

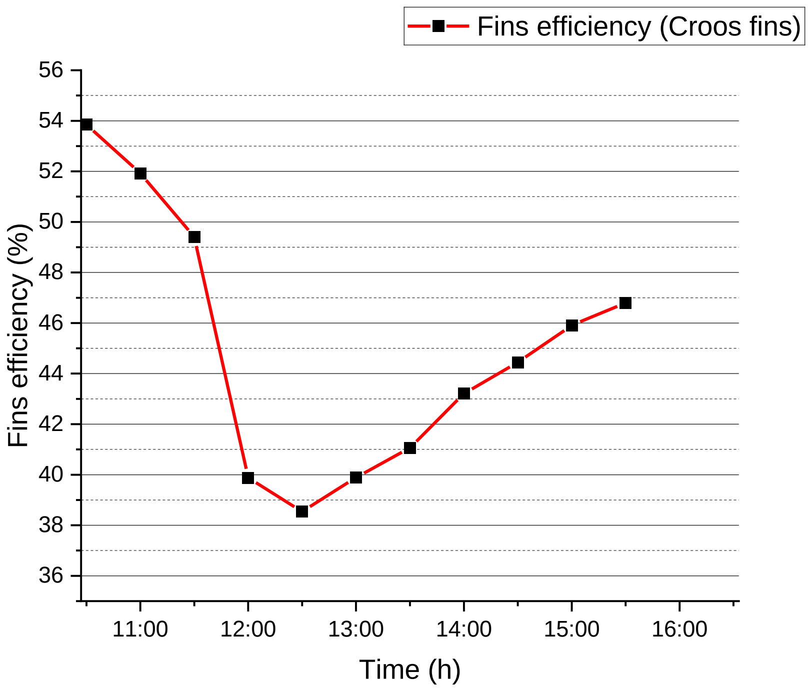


Figure IV. 35: Graph of fins' efficiency over time

The plot (IV.35) demonstrates the variations of a photovoltaic panel with cross fins efficiency throughout the day. The efficiency was high in the morning and peaked at 54% (10:30) but decreased with increased solar irradiance and panel temperature. In the middle of the day (12:00 - 13:30), the efficiency was lower, around 37%. This efficiency drop is expected because passive cooling, as may be achieved via fins, is not really working at mid-day, which should not be unexpected since at this time, there is little temperature gradient between the panel surface temperature and air temperature, under which conditions fins cannot work as effectively. In the afternoon (after 13:30), the efficiency rises again, reaching about 47% by 15:30. The increase in efficiency again indicates that the fins had improved capability to dissipate heat and the panel performance improved because ambient temperatures decreased. Overall, this plot shows a realistic U-shaped curve associated with photovoltaic systems where passive cooling via fins was applied.

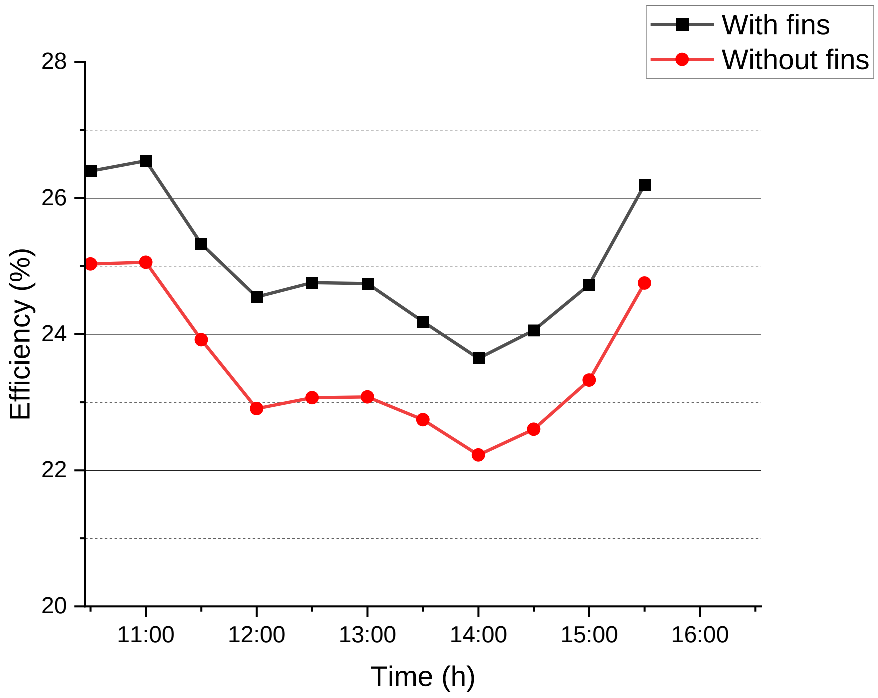


Figure IV. 36: Graph of PV panel efficiency with and without fins over time

The graph (IV.36) shows the change in photovoltaic efficiency of both solar panels, one with cooling fins (black line) and one without cooling fins (red line), from 10:30 AM–4 PM.

Throughout the entire day, the panel with fins was consistently more efficient than the panel without fins. Between 12:00 PM and 2:30 PM — the period of high Solar irradiance and peak sunlight — both panels experienced a reduction in efficiency, which can be expected since the temperature of the panel cells was increasing due to significant solar irradiance inputs.

However, the efficiency differential indicates the fins were performing a function of passive thermal management, effectively reducing the negative influence of temperature on electrical performance. The finned panel was, on average, 1–2% more efficient than the non-finned panel, supporting the use of fins for passive cooling to improve photovoltaic performance in a real environment.

Conclusion

This final chapter presents a detailed overview of the geographical characteristics of the study area, followed by a description of the materials and methods used in our experimental work. We then presented and analyzed the graphical results comparing two configurations: one photovoltaic panel equipped with cross-fins and another without fins.

Our experiments demonstrated that attaching fins to the rear surface of a photovoltaic panel (with an area of less than 1 m^2) can significantly enhance both heat dissipation and electrical performance. In the first experiment, vertical fins were used, resulting in a noticeable performance improvement. In the second experiment conducted on a different day under slightly varying ambient conditions, we tested a newly engineered fin design featuring a cross-shaped structure with perforations. This configuration yielded even better results.

General conclusion

General conclusion

The outcomes of this experimental study provide compelling evidence for the effectiveness of integrating passive cooling fins into photovoltaic (PV) systems as a means of improving both thermal regulation and electrical output. Two experimental configurations were developed and implemented under real outdoor conditions to assess the impact of different fin geometries on the performance of PV panels. The aim was to quantify the gains in thermal dissipation and power production, and to explore whether simple, low-cost physical modifications could provide meaningful improvements in solar panel efficiency.

In the first experimental setup, we investigated the use of conventional vertical fins attached to the back surface of a PV panel, comparing the results to those of an identical panel without any fins. The data collected during this experiment revealed a significant reduction in panel surface temperature, ranging from 7°C to 9.5°C. This reduction in temperature contributed directly to an increase in electrical output, with power gains recorded between 0.45 W and 2.14 W, and a maximum output of approximately 53 W. This corresponds to an efficiency improvement of up to 43.9% attributed to the finned configuration. The electrical performance also showed measurable improvement in terms of voltage and current: the voltage peaked at 20.4 V compared to 19.6 V for the panel without fins, while the current reached 2.6 A as opposed to 2.59 A. Overall, the efficiency increase ranged from 0.2% to 1.8%, depending on the time of measurement and solar conditions. These results confirm that passive cooling via vertical fins can provide a meaningful boost to panel performance by mitigating temperature-induced efficiency losses.

In the second experimental configuration, a more innovative and aerodynamically enhanced fin design was tested. This design featured cross-shaped fins with perforations, intended to further improve airflow and heat transfer from the back surface of the panel. The tests, although carried out on a different day under slightly varying ambient conditions, yielded even more promising results. The temperature reduction was more pronounced, ranging from 9°C to 14°C relative to the reference panel without fins. The power output also improved significantly, with an increase of 2.7 W to 4 W, reaching a peak of around 59 W. This represents a fin-induced performance gain of up to 53%, which is approximately 10% higher than the gains observed with vertical fins. Over the entire measurement period, the panel with cross-perforated fins consistently maintained a 2% higher efficiency than the finless reference panel. In terms of electrical parameters, the voltage reached 20.6 V (compared to 19.5 V for the finless panel), and the current peaked at 2.82 A, compared to 2.77 A without fins. These enhancements underscore the benefit of optimizing fin geometry to achieve better passive thermal regulation.

The superior results obtained with the cross-perforated fin configuration highlight the importance of design innovation in passive cooling strategies. While both configurations provided measurable improvements, the second design demonstrated a greater capacity for heat dissipation and energy recovery, proving that even small design adjustments can lead to significant performance differences.

Overall, this study demonstrates that passive cooling using fins especially when thoughtfully engineered offers a practical, low-cost, and highly effective method for enhancing the performance of PV systems. The improvements in temperature management and electrical output are particularly relevant in regions with high solar irradiance, where elevated panel temperatures can severely impact energy yield and system longevity. These findings not only validate the effectiveness of fin-based cooling but also encourage further exploration of advanced passive and hybrid cooling solutions, which may combine material science, structural design, and environmental adaptation to push the boundaries of solar energy efficiency.

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