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**ENHANCING THE PERFORMANCE OF PHOTOVOLTAIC PANELS
THROUGH COOLING METHODS IN OUARGLA**

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لحمد لله رب العالمين، والصلاة والسلام على أشرف المرسلين سيدنا محمد وعلى
آله وصحبه أجمعين

بعد مسيرة بحث وعطاء، نحمد الله العلي القدير الذي وقّنا وأعاننا على إتمام هذا
العمل المتواضع، ويشرفنا أن نتقدم بجزيل الشكر وعظيم الامتنان إلى كل من
ساندنا طوال مشوارنا الدراسي

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المذكرة وإثرائها بملاحظاتهم العلمية القيمة

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والمعرفة

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أخي وأخواتي الأعزاء، كل باسمه.

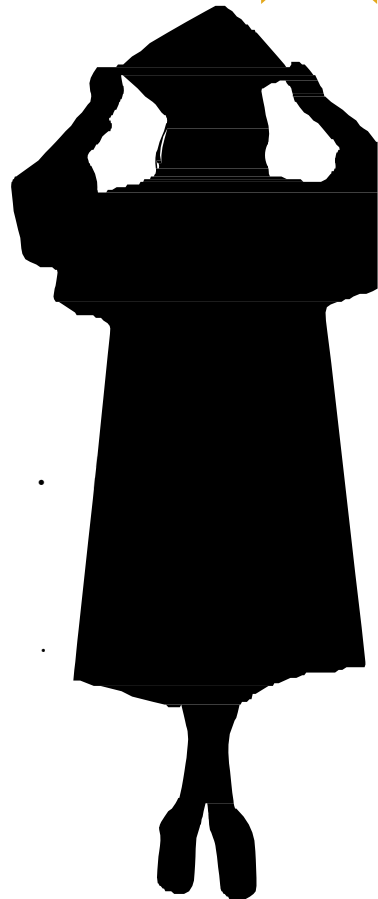
إلى الأرواح الجميلة التي رافقتني في دربي واختصرت لي مسافات التعب...
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Abstract:

This study evaluates the effectiveness of combining newspaper layers with burlap as a low-cost passive evaporative cooling system for photovoltaic (PV) panels under the hot climate of Ouargla. Experimental results showed clear superiority of the hybrid system compared with both uncooled and burlap-only panels. The proposed system achieved an average temperature reduction of 3.13 °C with a peak drop of 4.10 °C, leading to a mean power gain of 2.47 W and a maximum increase of 5 W. Compared with burlap alone, the hybrid structure provided an additional thermal reduction of 2.70 °C, a power enhancement of 2.48 W, and an open circuit voltage recovery of 0.16 V. The findings confirm that this eco friendly and inexpensive solution is effective for improving PV performance under severe thermal conditions.

Résumé:

Cette étude évalue l'efficacité de l'intégration du papier journal avec le tissu en jute comme système de refroidissement évaporatif passif et économique pour les panneaux photovoltaïques (PV) sous le climat chaud de Ouargla. Les résultats expérimentaux ont montré la supériorité du système hybride par rapport au panneau non refroidi et au jute seul. Le dispositif a permis une réduction moyenne de température de 3,13 °C avec un maximum de 4,10 °C, entraînant un gain moyen de puissance de 2,47 W et un gain maximal de 5 W. Comparé au jute seul, le système hybride a assuré une baisse thermique supplémentaire de 2,70 °C, une augmentation de puissance de 2,48 W et une récupération de tension de 0,16 V. Cette solution écologique et à très faible coût améliore efficacement les performances des panneaux photovoltaïques sous fortes contraintes thermiques.

الملخص

تهدف هذه الدراسة إلى تقييم فعالية دمج ورق الجرائد مع الخيش كوسيلة تبريد تبخيري هجينة ومنخفضة التكلفة للألواح الكهروضوئية في مناخ ورقلة الحار. أظهرت النتائج تفوق النظام الهجين مقارنة بال لوح غير المبرد والخيش المنفرد، حيث حقق انخفاضاً متوسطاً في درجة الحرارة بلغ 3.13 °C مع ذروة 4.10 °C، مما أدى إلى زيادة متوسط الاستطاعة بمقدار 2.47 W وأقصى ربح قدره 5 W. كما سجل النظام مقارنة بالخيش وحده خفضاً حرارياً إضافياً قدره 2.70 °C، وزيادة في القدرة بـ 2.48 W، وتحسناً في جهد الدارة المفتوحة بمقدار 0.16 V. تؤكد النتائج أن هذا النظام يمثل حلاً اقتصادياً وبيئياً فعالاً لتحسين استقرار وأداء الألواح الشمسية تحت الإجهاد الحراري المرتفع.

.1 Nomenclature

PV	Photovoltaic
I	Current
V	Voltage
I_{sc}	Short-Circuit Current
V_{oc}	Open-Circuit Voltage
P_{mp}	Maximum Power (W)
V_{mp}	Voltage at Maximum Power (V)
I_{mp}	Current at Maximum Power (A)
FF	Fill Factor
η	Conversion Efficiency
P_{max}	Maximum Electrical Power Output
P_{in}	Incident Solar Power
G	Solar Irradiance (W/m^2)
A	Surface Area of the Photovoltaic Panel (m^2)
EVA	Ethylene-Vinyl Acetate
DC	Direct Current
AC	Alternating Current
PCM	Phase Change Materials
PV/T	Photovoltaic Thermal System
Q_{cond}	Heat Transfer Rate by Conduction (W)
k	Thermal Conductivity ($W/m \cdot K$)
e	Thickness of Cooling Material Layer (m)
ΔT	Temperature Difference ($^{\circ}C$ or K)
Q_{conv}	Heat Transfer Rate by Convection (W)
h	Convective Heat Transfer Coefficient ($W/m^2 \cdot K$)
T_i	Surface Temperature ($^{\circ}C$ or K)
T_f	Surrounding Fluid Temperature ($^{\circ}C$ or K)
Φ	Porosity (%)
V_v	Volume of Voids (m^3)
V_t	Total Volume (m^3)
α	Thermal Diffusivity (m^2/s)
C_p	Specific Heat Capacity ($J/kg \cdot K$)
ρ	Density (kg/m^3)
ΔP	Average Power Output (W)
ΔV	Average Voltage (V)
DZD	Algerian Dinar

GENERAL INTRODUCTION

GENERAL INTRODUCTION

The increasing global demand for electrical energy, combined with growing environmental concerns and the progressive depletion of fossil fuel resources, has accelerated the transition toward renewable and sustainable energy systems. Among the various renewable energy sources, solar energy has emerged as one of the most promising alternatives due to its abundance, cleanliness, and wide geographical availability, particularly in arid and semi-arid regions such as southern Algeria.

Photovoltaic (PV) technology represents one of the most direct and effective methods for converting solar radiation into electrical energy. However, despite its significant advantages, photovoltaic systems remain highly sensitive to environmental operating conditions, especially temperature. Elevated panel temperatures lead to a reduction in electrical conversion efficiency, voltage output, and overall system performance. This issue becomes particularly critical in desert climates such as Ouargla, where high solar irradiance is accompanied by extremely elevated ambient temperatures.

To address this limitation, numerous thermal management strategies have been proposed in the literature, including active cooling systems, passive cooling techniques, and hybrid photovoltaic-thermal configurations. While active cooling methods often provide significant thermal improvements, they generally require additional energy consumption, complex mechanical components, and regular maintenance. Passive cooling techniques, in contrast, offer a simpler, more economical, and energy-independent alternative.

Recent studies have highlighted the effectiveness of evaporative cooling methods based on porous and absorbent materials capable of retaining moisture and promoting continuous heat dissipation through natural evaporation. Natural fibers such as jute have demonstrated promising cooling performance due to their high porosity and water absorption capacity. However, maintaining long-term moisture retention remains a practical challenge.

In this context, the present work proposes an innovative passive cooling approach based on a hybrid multilayer cooling configuration combining burlap fibers (jute) and recycled newspaper. The objective is to exploit the complementary physical properties of both materials in order to enhance water retention, prolong evaporative cooling duration, and improve the thermal regulation of photovoltaic panels under real desert climatic conditions.

The main objective of this research is to experimentally evaluate the thermal and electrical performance of the proposed passive cooling system under the climatic conditions of Ouargla. Specific objectives include analyzing temperature reduction, assessing electrical performance improvement, and determining the optimal multilayer configuration capable of achieving efficient and sustainable cooling.

This dissertation is organized into four main chapters.

Chapter 01 presents the theoretical background related to photovoltaic systems and the environmental factors affecting their performance.

Chapter 02 reviews previous studies on photovoltaic cooling techniques and identifies the research gap addressed by the present work.

Chapter 03 describes the experimental methodology, materials, mathematical modeling, experimental results, discussion, and evaluation of the proposed cooling system performance.

CHAPTER I

Generalities on Photovoltaic Systems

I.2 Introduction

The world is increasingly shifting toward the adoption of renewable energy sources in response to current environmental and economic challenges. Among these sources, solar energy is considered one of the most important due to its abundance and long-term sustainability.

This chapter aims to provide a clear overview of the fundamental concepts related to solar energy and photovoltaic systems. It begins with the general concept of solar energy and explains how solar radiation travels through the atmosphere. It then presents the basic physical principles governing the conversion of light into electricity. Finally, it discusses the engineering aspects of photovoltaic systems and examines how environmental and climatic conditions influence their performance, particularly in harsh environments.

I.3 Overview of Solar Energy

Solar energy is the electromagnetic energy generated by nuclear fusion reactions occurring in the core of the sun. It reaches the Earth in the form of light photons carrying an enormous amount of energy, which, if efficiently exploited, could satisfy humanity's energy needs thousands of times over [1].

I.3.1 Solar Thermal Systems

Solar thermal systems directly utilize the heat from the sun. Special collectors capture solar radiation and convert it into thermal energy, which is then transferred to fluids such as water or oil. This thermal energy can be used for various applications, including water heating and steam production for electricity generation. These systems are generally more suitable for applications requiring heat rather than electrical power [2].

I.3.2 Photovoltaic Systems

Photovoltaic systems convert sunlight directly into electricity. They operate using solar cells made of semiconductor materials, such as silicon. When sunlight strikes these cells, an electric current is generated through the photovoltaic effect. This technology represents the most widely used method for solar electricity generation and constitutes the main focus of this research [2].

I.4 Types of Solar Radiation

Solar radiation does not reach the Earth's surface uniformly. Its propagation is influenced by atmospheric conditions as well as the presence of gases and dust particles. Solar radiation is generally classified into three main types [1]:

- **Direct Radiation:** This refers to solar radiation that reaches the Earth's surface directly from the sun without being scattered. It represents the primary energy source for solar panels in desert regions characterized by clear skies.
- **Diffuse Radiation:** This occurs when sunlight is scattered by atmospheric particles or clouds. Photovoltaic panels are capable of utilizing this form of radiation effectively, unlike concentrated solar systems that rely exclusively on direct radiation.
- **Global Radiation:** This is the total sum of direct and diffuse radiation. It is considered the principal parameter used in the design of solar power plants for estimating the expected energy output at a specific location [2].

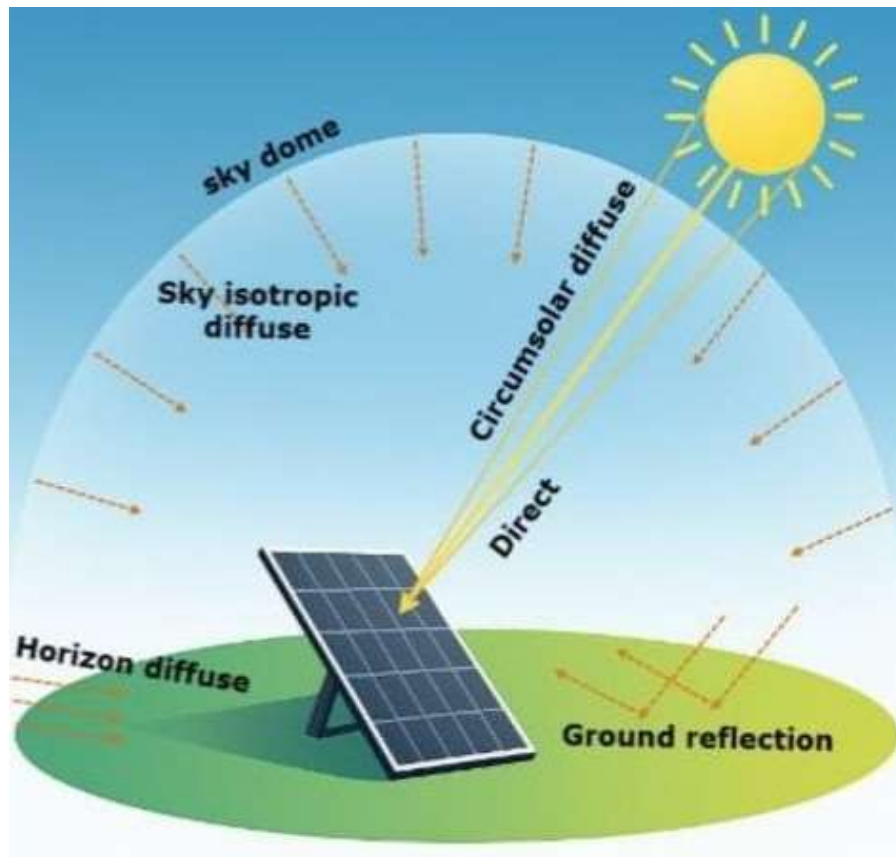


Figure I.1: Components of solar radiation on a tilted surface

I.5 Operating Principle and Electrical Characteristics

The conversion of solar radiation into electrical energy depends on physical processes occurring within the photovoltaic cell. The performance of the cell can be better understood through the analysis of its electrical characteristics during operation.

I.5.1 The Photovoltaic Effect

The process begins when sunlight, composed of photons, strikes the surface of the solar cell, particularly the p-n junction made of semiconductor material. When the incident photons possess sufficient energy, they release electrons from their atomic bonds, generating electron-hole pairs. The internal electric field present at the junction then separates these charges and directs them toward the external terminals, thereby producing direct current (DC) [3].

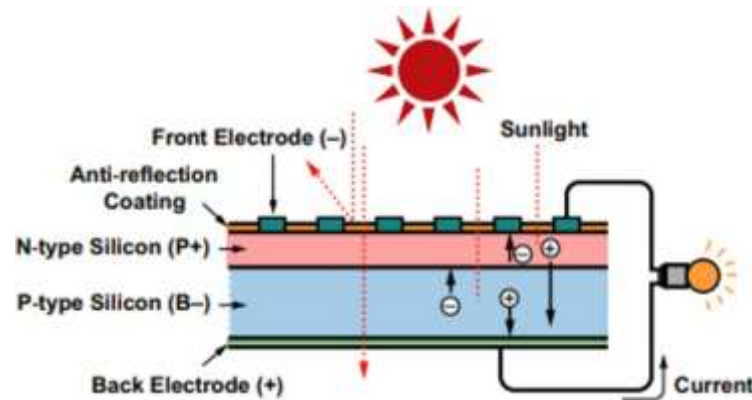


Figure I.2: Photovoltaic operating principle [4]

I.5.2 Electrical Characteristics and I–V Curve

The performance of a photovoltaic cell is commonly described using the current-voltage (I–V) characteristic curve. This curve illustrates the relationship between current and voltage under specific operating conditions and provides essential information for understanding the behavior and evaluating the performance of the photovoltaic cell [3].

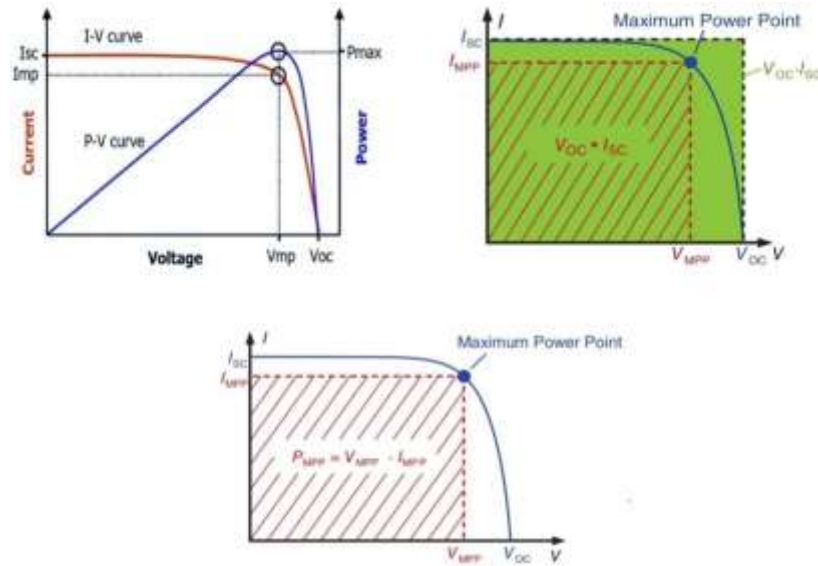


Figure I.3: Typical Current-Voltage (I-V) and Power-Voltage (P-V) characteristics of a PV cell [5]

From this curve, the main parameters used to evaluate cell performance can be defined as follows:

I.5.2.1 Short-Circuit Current (I_{sc})

This is the maximum current produced when the voltage is zero. It depends directly on solar irradiance [3].

I.5.2.2 Open-Circuit Voltage (V_{oc})

This is the maximum voltage produced when the current is zero. It is strongly influenced by temperature and generally decreases as temperature increases [5].

I.5.2.3 Maximum Power (P_{max} or P_{mp})

This represents the highest power that the photovoltaic cell can generate. It occurs at the maximum power point on the I–V curve and is calculated as:

$$P_{mp} = V_{mp} \times I_{mp} \quad (I.1)$$

Where:

- P_{mp} : Maximum power (W)
- V_{mp} : Voltage at maximum power point (V)
- I_{mp} : Current at maximum power point (A)

I.5.2.4 Fill Factor (FF)

The fill factor indicates the quality of the photovoltaic cell by comparing the actual maximum power to the theoretical maximum power. It is given by:

$$FF = \frac{V_{mp} \times I_{mp}}{V_{oc} \times I_{sc}} \quad (I.2)$$

Where:

- FF: Fill Factor (A dimensionless quantity that indicates the cell quality)
- V_{oc} : Open-circuit voltage (Measured in Volts, V)
- I_{sc} : Short-circuit current (Measured in Amperes, A)

I.5.2.5 Conversion Efficiency (η)

It is the ratio between the electrical power produced and the solar power received by the cell. It is calculated as:

$$\eta = \frac{P_{max}}{P_{in}} = \frac{V_{oc} \times I_{sc} \times FF}{G \times A} \quad (I.3)$$

Where:

- η : Conversion Efficiency (The ratio of electrical power produced to solar power received)
- P_{max} : Maximum electrical power output (Measured in Watts, W)
- G : Solar irradiance (Measured in Watts per square meter, W/m^2)
- A : Surface area of the photovoltaic panel (Measured in square meters, m^2)

Note: All the aforementioned characteristics are inversely affected by panel temperature; as temperature increases, photovoltaic performance degrades [6].

I.6 PV Hierarchy

In practical applications, photovoltaic panels are not used individually in large-scale systems. Instead, they are arranged in a hierarchical structure to achieve the required voltage and current levels for the intended application [7].

The hierarchical structure is organized as follows:

I.6.1 Cell

The photovoltaic cell is the smallest unit in a photovoltaic system. It generates a

relatively small voltage, typically around 0.6 V.

I.6.2 Module (or Panel)

A module consists of several solar cells electrically connected together. It is encapsulated to protect the cells from environmental conditions and to provide a higher electrical power output.

I.6.3 String

A string is formed by connecting multiple photovoltaic modules in series. This arrangement increases the total voltage generated by the system.

I.6.4 Array (or Field)

The photovoltaic array represents the final hierarchical level and is formed by connecting multiple strings together. It constitutes a complete system capable of generating a significant amount of electrical energy.

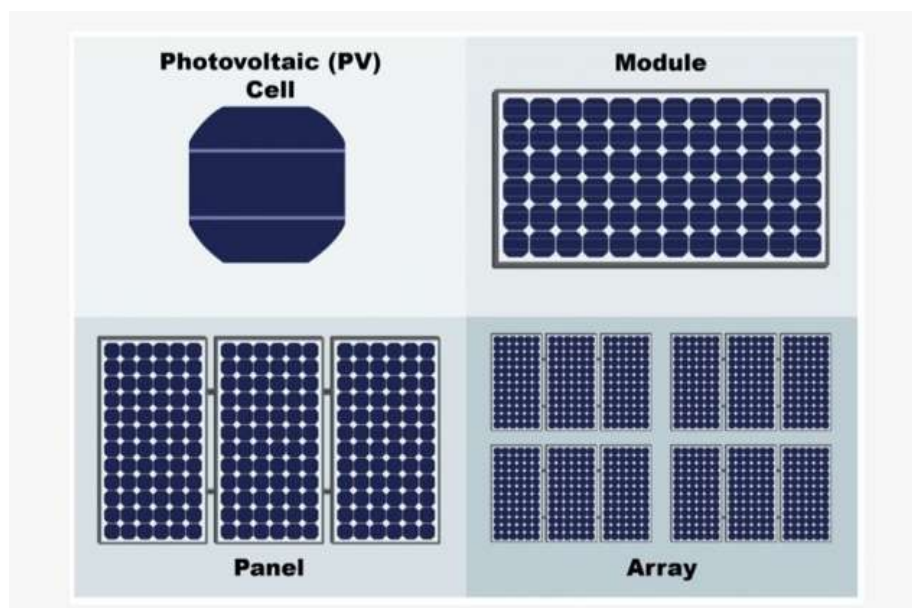


Figure I.4: The hierarchical structure of a photovoltaic system: from cell to array [8]

I.7 Photovoltaic Module Layers

To ensure high efficiency and long-term protection of photovoltaic cells, a solar module is composed of several integrated layers, each performing a specific functional role [6].

- **Aluminium Frame:** Provides structural support and mechanical protection for the entire photovoltaic module.

- **Tempered Glass:** Serves as the upper protective layer against environmental conditions while ensuring high solar transmittance.
- **Encapsulant (EVA):** A critical adhesive layer that protects the solar cells from moisture penetration and ensures structural cohesion.
- **Solar Cells:** The active semiconductor layer where the conversion of solar radiation into electrical energy occurs.
- **Back Sheet:** Provides electrical insulation and protects internal components from environmental degradation from the rear side.
- **Junction Box:** The electrical output terminal where the generated electricity is collected and directed toward the external load.

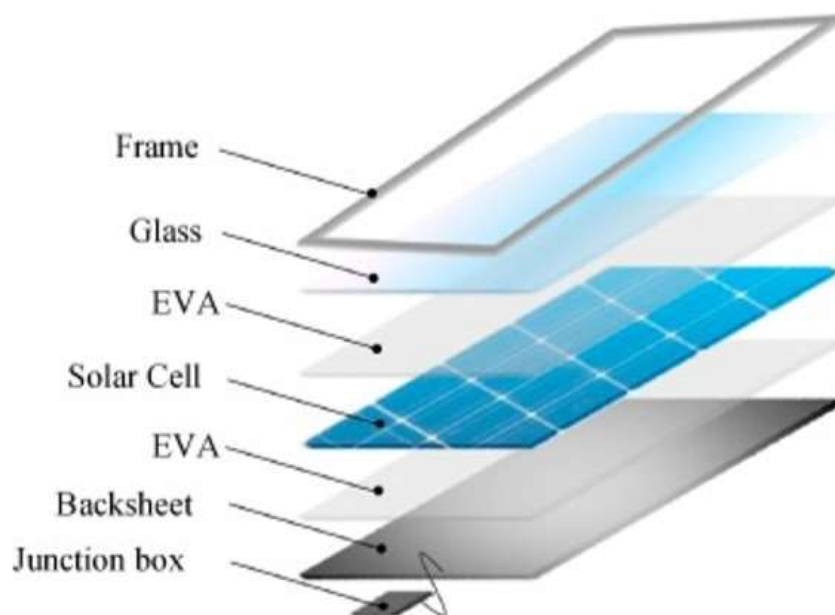


Figure I.5: Layers of a photovoltaic module [9]

I.8 PV System Components

To convert the generated electrical energy into usable power, the photovoltaic system requires the integration of several technical components [3].

- **Inverter:** Responsible for converting direct current (DC) into alternating current (AC) suitable for grid connection or electrical appliances.
- **Charge Controller:** Regulates the flow of energy and protects batteries from damage caused by overcharging.

- **Storage System (Batteries):** Ensures energy availability during periods of low solar irradiance or absence of sunlight.
- **Mounting Structures:** Mechanical support systems that maintain photovoltaic panels at the optimal orientation angle for maximum solar energy capture.

The complete integration of these components to provide usable electrical energy is illustrated in Figure I.6.

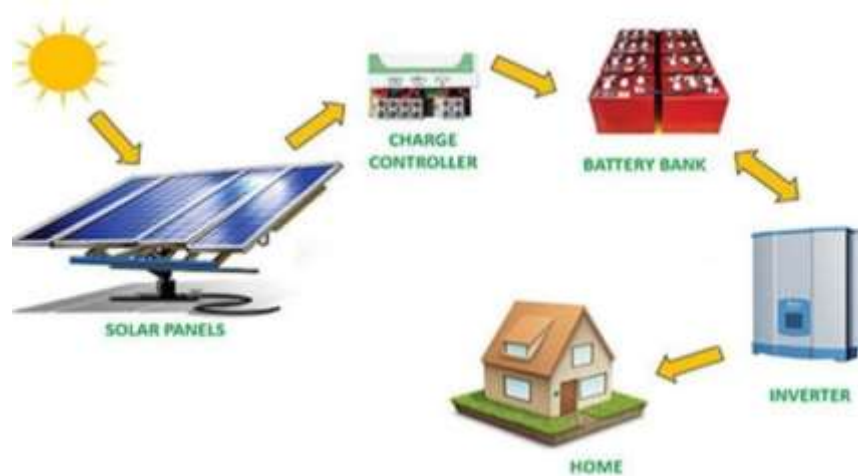


Figure I.6: Integration and connection of PV system components [10]

I.9 Types of PV Panels

Current commercial photovoltaic technology is mainly based on three principal types of solar panels, each differing in efficiency, manufacturing process, and cost [11, 12].

I.9.1 Monocrystalline Silicon

This type is characterized by high material purity and elevated conversion efficiency, often exceeding 20%. It is generally recognized by its dark black appearance.

I.9.2 Polycrystalline Silicon

Polycrystalline panels are known for their characteristic blue color and lower manufacturing cost. They are among the most widely used photovoltaic technologies for general applications.

I.9.3 Thin-Film Cells

Thin-film photovoltaic panels are lightweight and flexible. They also demonstrate comparatively better performance under high-temperature conditions than crystalline silicon panels.



Figure I.7: Major types of commercial solar panels and their technical characteristics [13]

I.10 Environmental and Climatic Factors Affecting Performance

The efficiency of photovoltaic (PV) systems is directly influenced by surrounding environmental and climatic conditions. Certain factors become particularly critical in arid and desert regions such as Ouargla.

I.10.1 Solar Irradiance and Angle of Incidence

The amount of electrical current generated by photovoltaic panels depends directly on solar irradiance (W/m^2). The angle at which sunlight strikes the panel surface also plays an important role. When solar rays reach the panel perpendicularly, a greater number of photons are absorbed while reflection losses are minimized. Therefore, adjusting the tilt angle according to the geographical latitude of the installation site is essential for maximizing energy capture [1].

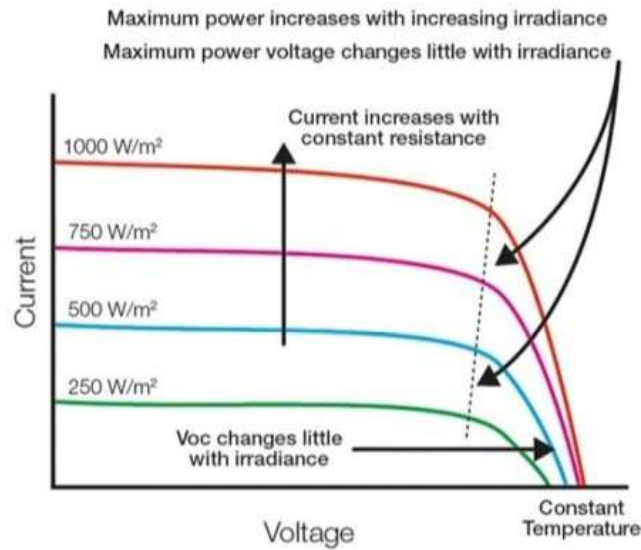


Figure I.8: Impact of solar irradiance variations on the I-V characteristic curve [14]

As illustrated in Figure I.8, increasing solar irradiance from 250 to 1000 W/m² results in a substantial linear increase in current, while the open-circuit voltage (V_{oc}) remains nearly unchanged. This confirms that the maximum power output is directly proportional to irradiance intensity.

I.10.2 Cell Temperature

Temperature is considered one of the most critical hidden factors affecting photovoltaic panel performance. As the cell temperature increases, electron movement becomes less efficient, and internal electrical resistance rises. This leads to a reduction in open-circuit voltage (V_{oc}).

Most photovoltaic panels experience a power loss ranging from 0.3% to 0.5% of their maximum power (P_{max}) for every degree Celsius above the standard test condition of 25°C. Consequently, the implementation of effective cooling techniques becomes essential [3].

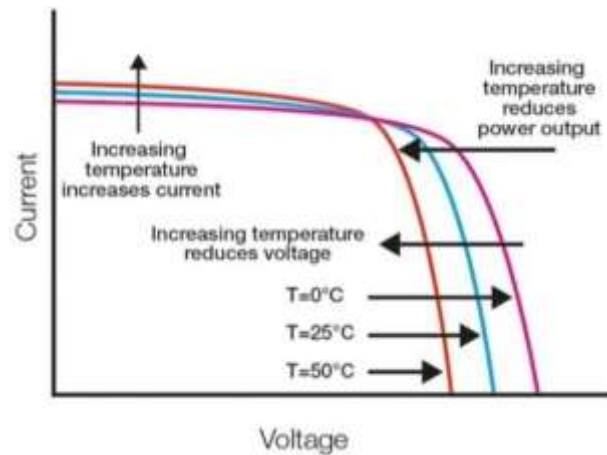


Figure I.9: Impact of cell temperature variations on the I-V characteristic curve [14]

Figure I.9 clearly demonstrates that increasing the cell temperature from 0°C to 50°C causes a significant voltage drop. This reduction is considerably greater than the slight increase observed in current, ultimately leading to a decrease in maximum power output and overall system performance.

Due to this negative thermal effect, identifying effective cooling strategies becomes a necessary step toward enhancing photovoltaic efficiency. This challenge constitutes the core motivation of the present study, where practical passive cooling techniques will be investigated experimentally to achieve improved performance.

I.10.3 Dust Effect

Dust is considered one of the major climatic factors affecting the efficiency of photovoltaic panels, particularly in desert environments. Dust accumulation on the glass surface creates an insulating layer that obstructs solar radiation from reaching the photovoltaic cells.

Experimental findings reported in previous studies indicate that dust accumulation over a period of 60 days resulted in a power reduction of approximately 7.67%. This negative effect becomes more pronounced with increasing dust density and longer exposure duration [15].

I.10.4 Shading and Clouds Effect

Shading, whether partial or total, resulting from passing clouds or surrounding physical obstacles, causes a sharp reduction in the short-circuit current generated by photovoltaic panels.

This environmental factor also distorts the I-V characteristic curve by reducing current intensity and limiting the ability of the cells to operate at their optimal capacity due to reduced direct radiation and increased diffuse solar radiation [15].

I.10.5 Wind Speed Effect

Experimental investigations confirm that wind plays a significant role in improving photovoltaic panel performance through forced convective cooling.

As wind speed increases, the surface temperature of photovoltaic cells decreases, which leads to an increase in voltage and, consequently, higher electrical power output.

Results obtained in the Ouargla region indicate a positive correlation between wind speed and conversion efficiency, as wind contributes to dissipating the excess heat accumulated due to intense solar radiation [16].

I.10.6 Relative Humidity Effect

Relative humidity is another climatic factor that can negatively affect photovoltaic performance in desert regions under certain conditions.

Elevated humidity levels contribute to the scattering of incoming solar radiation, thereby reducing the amount of energy reaching the panel surface.

Furthermore, increased humidity may promote condensation of water vapor on the panel surface, facilitating dust adhesion and the formation of muddy deposits that are difficult to remove naturally by wind action.

This ultimately leads to a deterioration in the overall energy performance of the photovoltaic system [16].

I.11 Conclusion

This chapter presented the fundamental principles governing photovoltaic systems, beginning with the photovoltaic effect and extending to the analysis of electrical characteristics through I-V and P-V curves.

The presented analysis clearly demonstrates that photovoltaic panel performance is not constant but is strongly influenced by environmental and climatic conditions, particularly solar irradiance and temperature.

Although solar radiation remains the primary source of energy generation, elevated temperatures, especially in desert climates such as Ouargla, constitute a major challenge due to their detrimental impact on voltage and overall power output.

Consequently, there is a clear need for simple, effective, and economically viable cooling solutions capable of operating under harsh environmental conditions.

For this reason, the following chapters will focus on the investigation and experimental evaluation of passive cooling techniques using locally available materials such as jute and

newspaper, with the objective of enhancing both the thermal and electrical performance of photovoltaic panels and improving their overall efficiency.

CHAPTER II

Previous Studies

II.1 Introduction

High operating temperatures significantly affect the performance of photovoltaic systems, which has motivated many researchers worldwide to investigate various cooling techniques to mitigate this negative impact.

This chapter presents a review of the principal previous studies that have examined both passive and active cooling methods for photovoltaic panels.

Through the analysis of these studies, this review aims to identify existing research gaps, particularly in arid regions such as Ouargla, and to establish the scientific basis for the proposed experimental investigation based on the use of simple, low-cost, and locally available materials.

II.2 Classification of PV Cooling Techniques

Photovoltaic cooling techniques can generally be classified into three main categories: passive cooling, active cooling, and hybrid photovoltaic-thermal systems.

II.2.1 Passive Cooling

Passive cooling relies on natural physical mechanisms to dissipate heat without requiring any external electrical energy.

- **Natural Air Cooling**

This technique enhances natural heat dissipation by improving airflow around the photovoltaic panel through structural modifications.

- ▷ Increasing the effective heat transfer surface area using thermal fins.
- ▷ Creating air channels behind the panels to promote natural ventilation.

- **Phase Change Materials (PCM)**

This cooling method employs special materials capable of absorbing latent heat during the phase transition process from solid to liquid state.

These materials store excess thermal energy and help regulate the operating temperature of photovoltaic panels.

- **Passive Evaporative Cooling**

Passive evaporative cooling is based on the use of porous and absorbent materials capable of retaining water and promoting continuous evaporation.

Examples include:

- ▷ Porous natural materials such as burlap.
- ▷ Cellulosic materials such as newspaper.

This technique depends on capillary action to maintain moisture within the cooling medium and allow natural evaporation, thereby reducing panel temperature.

II.2.2 Active Cooling

Active cooling requires external energy to operate mechanical equipment that enhances heat transfer and improves thermal management.

- **Active Water Cooling**

This approach uses water as a cooling medium through forced thermal exchange mechanisms.

Common methods include:

- ▷ Spraying water mist on the front surface of the photovoltaic panel.
- ▷ Forced water circulation through channels installed behind the panel.

- **Forced Air Cooling**

This method utilizes mechanical airflow generation to accelerate heat dissipation.

- ▷ Using electric fans to increase airflow behind the photovoltaic panel.

II.2.3 Hybrid Systems (PV/T)

Hybrid photovoltaic-thermal systems combine electricity generation with thermal energy recovery.

- **Photovoltaic Thermal Collectors (PV/T)**

These systems use a cooling fluid, such as water or air, to cool the photovoltaic panel while simultaneously recovering the extracted thermal energy for secondary applications such as space heating or water heating.

II.3 Previous Studies

II.3.1 Passive Cooling Techniques

Evaporative cooling is based on the use of the latent heat of water evaporation to remove excess heat from heated surfaces. This technique has demonstrated significant effectiveness in reducing the elevated temperature of photovoltaic cells, particularly under intense solar radiation conditions.

To better understand the development of this method and the diversity of materials used, several scientific studies have investigated its impact on both thermal and electrical performance [17].

Recent research has particularly focused on natural and low-cost materials as promising alternatives for improving evaporative cooling efficiency in photovoltaic systems.

II.3.1.1 Passive Hybrid Cooling of Photovoltaic Panels Using Clay and Marble Materials

A previous study presented an experimental approach to improve photovoltaic system performance through passive cooling techniques based on locally available porous and thermally conductive materials.

The study evaluated the effectiveness of clay and marble as cooling media integrated at the backside of photovoltaic panels. This design aimed to exploit the evaporative cooling capability of porous clay together with the high thermal conductivity of marble in order to reduce the operating temperature of solar cells.

The experimental findings showed that the hybrid cooling configuration combining clay and marble achieved the highest performance, reducing panel temperature by approximately 14.6°C.

This thermal improvement resulted in an increase in output power of about 15.6% and a noticeable enhancement in electrical efficiency compared to the conventional photovoltaic panel.

The study concluded that these materials represent an economical and sustainable cooling solution, particularly for hot climates, while recommending continuous wetting of the porous material to maintain stable cooling performance.

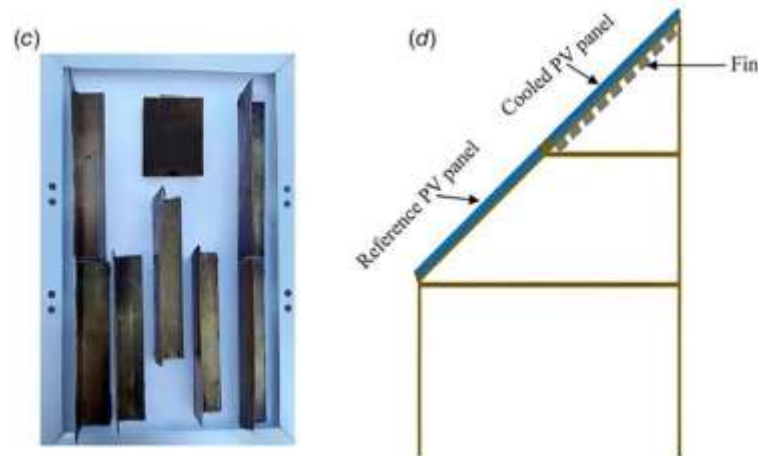


Figure II.1: Rear view of integrated solid cooling media and schematic configuration of the passive cooling system installed at the backside of the PV panel [18]

II.3.1.2 Cooling Using Natural Fibers (Palm Fibers)

Another study proposed an innovative and low-cost cooling method specifically adapted to desert environments through the use of palm fibers as a porous heat exchange medium.

This method consisted of placing a wet layer of palm fibers behind the photovoltaic panel. The retained moisture within the fibers enabled continuous evaporative cooling, which effectively removed heat from the solar cells.

As illustrated in Figure II.2, the experimental setup demonstrated the practical implementation of this cooling configuration.

The results showed that wet palm fibers reduced the operating temperature by approximately 8.5°C compared to the reference panel.

This thermal improvement positively affected electrical performance, resulting in an efficiency increase of approximately 7.2%.

The study concluded that palm fibers constitute a sustainable and effective alternative to industrial cooling materials due to their high thermal absorption capability and their abundant availability in the Ouargla region.



Figure II.2: Experimental setup of a photovoltaic cooling system using wet palm fibers in the Ouargla region [19]

II.3.1.3 Passive Evaporative Cooling of Photovoltaic Panels Using Wet Jute Fabric

A study presented an in-depth experimental investigation aimed at improving photovoltaic panel performance using a passive evaporative cooling technique based on water-wet jute fabric.

The study examined the thermal and electrical behavior of photovoltaic panels when a layer of wet jute fabric was installed at the backside of the panel.

This method takes advantage of the fabric's high water absorption capacity and its ability to distribute moisture uniformly, thereby enabling continuous evaporation and effective heat removal from the solar cells.

Experimental results revealed that wet jute fabric reduced the panel operating temperature by approximately 12 to 18°C during peak solar hours.

This temperature reduction led to an increase in output power and an improvement in electrical efficiency of approximately 14%.

The researchers highlighted that this method is simple, economical, and significantly less expensive than active cooling systems.

However, the technique requires a continuous water supply to maintain moisture content, which opens opportunities for further studies focused on improving water retention within the cooling medium [20].

II.3.1.4 Phase Change Materials (PCM)

A previous study presented an experimental approach to enhance the performance of photovoltaic thermal (PV/T) systems through the integration of phase change materials (PCM) as an advanced passive cooling technique.

This method consisted of placing PCM at the backside of the photovoltaic panel

in order to transform the conventional photovoltaic system into a hybrid configuration capable of generating both electrical and thermal energy.

As illustrated in Figure II.3, the PCM acts as a thermal storage medium that absorbs excess heat and prevents the photovoltaic cells from overheating beyond their optimal operating limits.

The experimental results demonstrated that integrating PCM into the PV/T system reduced the operating temperature of the panel by approximately 10.5°C.

This thermal improvement resulted in an increase in output power of approximately 10% and improved the stability of electrical efficiency compared to conventional photovoltaic panels.

The study concluded that this system represents an economical and sustainable solution for photovoltaic thermal management. It also recommended selecting phase change materials with suitable thermophysical properties according to climatic conditions in order to ensure efficient and continuous heat transfer.

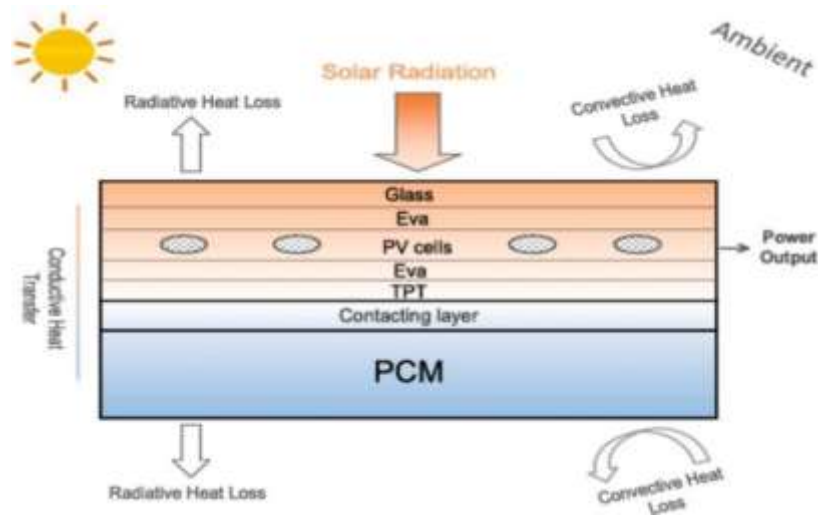


Figure II.3: 3D schematic representation of a photovoltaic thermal (PV/T) system integrated with phase change materials (PCM) [21]

II.3.2 Active Cooling Techniques

II.3.2.1 Active Water Spraying Cooling

A previous study analyzed the severe reduction in photovoltaic panel efficiency under arid climatic conditions, where natural cooling mechanisms are insufficient to counteract intense solar radiation.

The study adopted an experimental approach based on an active water spraying cooling system integrated into photovoltaic-thermal (PVT) systems, also referred to as Jet Cooling.

This system was designed not only to cool photovoltaic cells but also to recover waste thermal energy for additional applications, thereby combining improved thermal

management with enhanced energy utilization.

The experimental findings showed that this system reduced panel operating temperatures by approximately 10 to 20°C.

As a result, voltage stability improved, electrical efficiency increased by approximately 12% to 15%, and the maximum power output (P_{max}) increased significantly.

However, the study also identified practical limitations.

- ▷ Pump operation consumes approximately 5% to 10% of the generated electrical energy.
- ▷ Maintenance requirements can become difficult, especially in remote desert regions.
- ▷ Dependence on water availability reduces the system's practicality in arid environments.

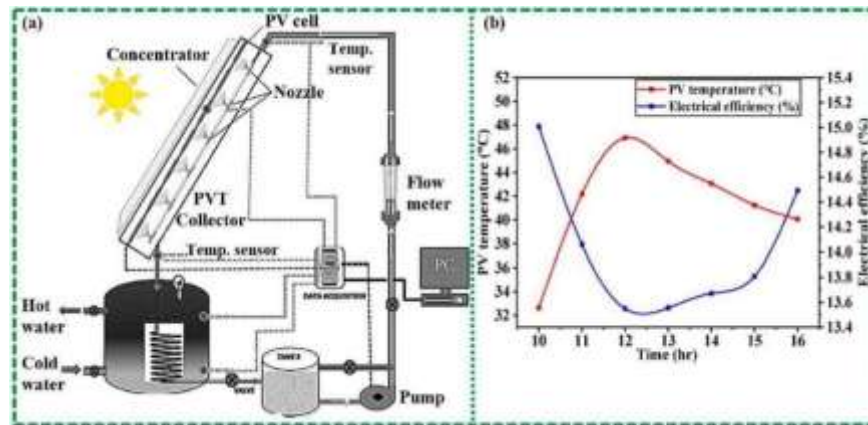


Figure II.4: Experimental setup of the active water spray cooling system and the impact of photovoltaic temperature on electrical efficiency [22]

II.3.2.2 Active Nanofluid Cooling

A previous study proposed an experimental cooling approach based on nanofluids characterized by high thermal conductivity to improve photovoltaic system performance.

The system used a nanofluid circulated behind the photovoltaic panels using an electric pump, as illustrated in Figure II.5. II.6

The objective of this configuration was to exploit the superior thermal conductivity of nanoparticles dispersed within the base fluid in order to absorb and remove heat from photovoltaic cells more efficiently than conventional water cooling.

The results demonstrated that nanofluid cooling significantly reduced panel temperature, leading to an increase in electrical efficiency ranging from approximately 12% to 14%.

The study concluded that nanofluid cooling represents an advanced technical solution for photovoltaic thermal management.

However, the researchers also emphasized that nanoparticle stability remains a major limitation for large-scale practical implementation.

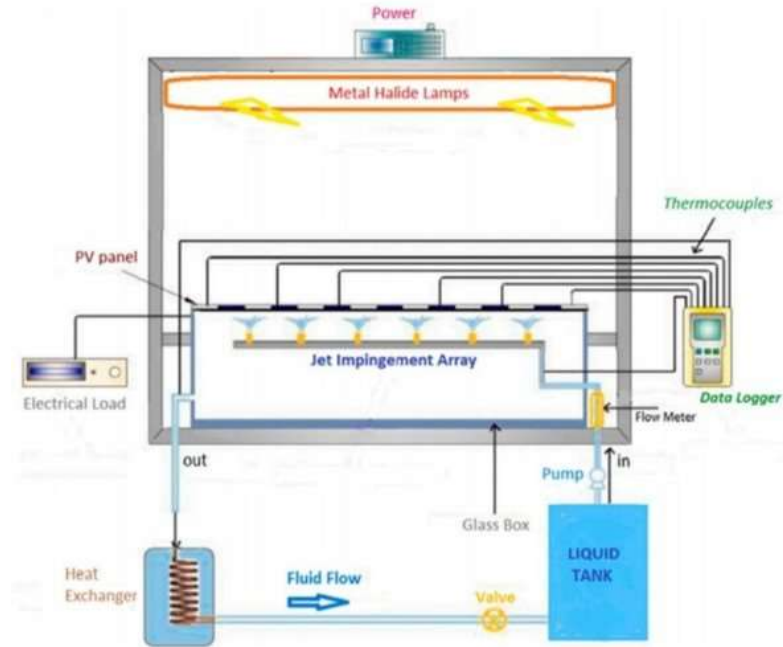


Figure II.5: Schematic diagram of an active nanofluid cooling system illustrating pump and reservoir configuration [23]



Figure II.6: Microscopic representation of nanoparticle dispersion within the base fluid for thermal conductivity enhancement [23]

II.3.2.3 Active Heat Pipe Cooling

A study presented an experimental cooling method designed to improve photovoltaic performance through the integration of active heat pipes.

The proposed system consisted of three principal sections:

- ▷ Evaporator section

- ▷ Adiabatic section
- ▷ Condenser section actively cooled by water

As illustrated in Figure II.7, this configuration exploits the exceptionally high thermal conductivity of heat pipes to ensure uniform temperature distribution and prevent localized overheating (hot spots).

Experimental results showed that this cooling technique reduced operating temperatures by approximately 15 to 25°C.

This thermal reduction improved electrical efficiency by up to 14%.

The study concluded that active heat pipe cooling offers excellent protection against thermal stress while recommending simplification of the mechanical design in order to reduce operating energy consumption.

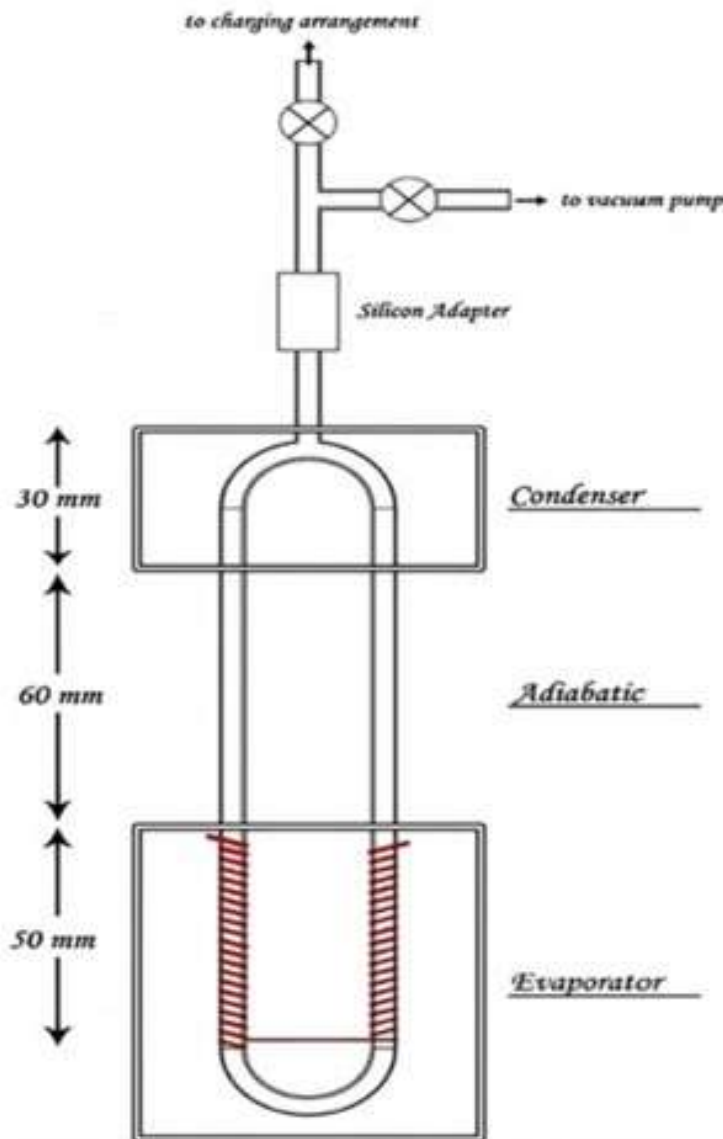


Figure II.7: Heat transfer mechanism within an integrated heat pipe showing evaporator, adiabatic, and actively cooled condenser sections [23]

II.3.2.4 Active Air Cooling

A previous study discussed active air cooling as an effective mechanical strategy for controlling thermal stress in photovoltaic panels.

This method is based on generating forced airflow behind the photovoltaic panel to remove accumulated heat.

As illustrated in Figure II.8, the study presented six different airflow configurations:

- ▷ Collector with thermal fins
- ▷ Collector with V-groove absorber plate
- ▷ Unglazed configuration
- ▷ Single-glazing system
- ▷ Double-glazing system
- ▷ Double-pass airflow system

The experimental results indicated that optimized active air cooling systems reduced panel operating temperature by up to 15.2°C.

This improvement resulted in an increase in electrical efficiency of approximately 4.2% compared to natural cooling.

The study also reported that although fan operation consumes part of the generated electrical energy, the energy gain achieved through improved photovoltaic performance significantly exceeds this consumption, resulting in a positive net power increase.

The researchers concluded that selecting the most suitable active air cooling configuration depends on balancing thermal performance, electrical performance, and surrounding operating conditions.

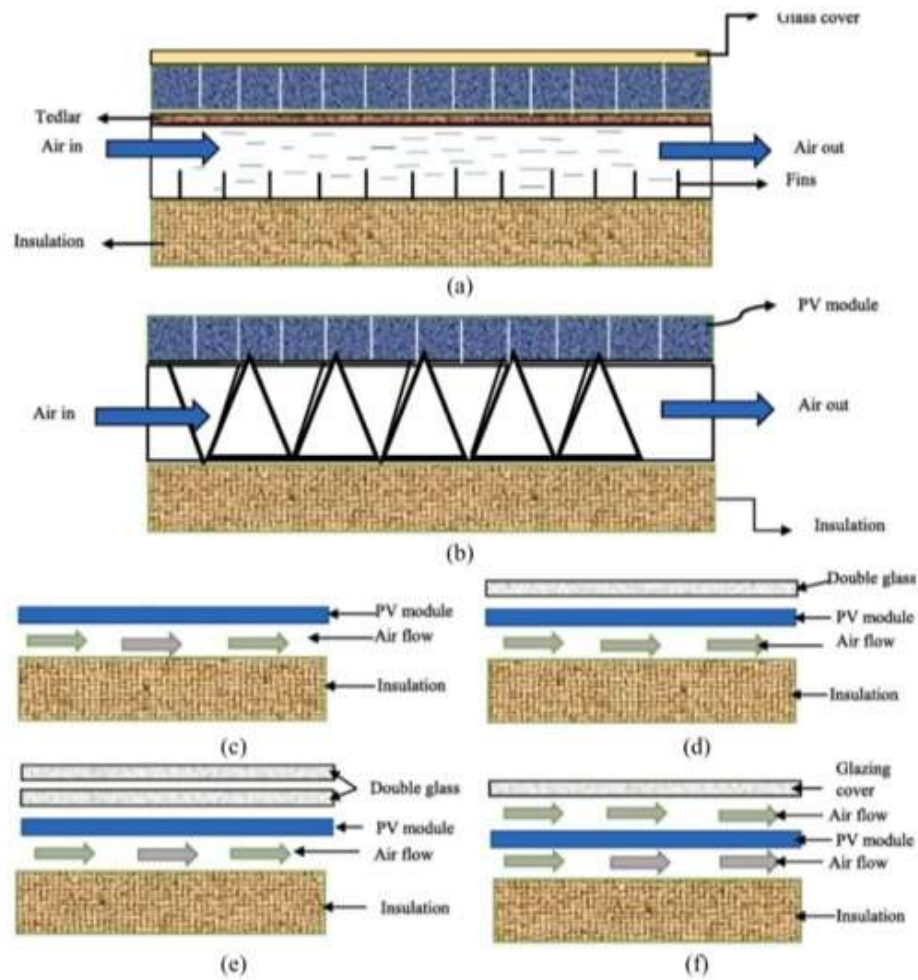


Figure II.8: Schematic configurations of active air cooling systems for photovoltaic panels [21]

II.4 Research Gap Analysis

Based on the review of previous studies, several important research gaps can be identified regarding photovoltaic cooling systems, particularly in hot arid environments.

Table II.1 presents a comparative summary of the main contributions of previous studies and the specific gap addressed by the present research.

Table II.1: Summary of the Research Gap Analysis

Reference	Main Contribution of the Study	Research Gap Addressed in This Work
Bayoumy et al. (2022)	Investigated different evaporative cooling methods for improving photovoltaic panel efficiency.	The present work investigates a new layered cooling configuration combining burlap and newspaper to determine the optimal number of layers (3–5) for prolonged cooling performance.
Ben-Amor et al. (2025)	Studied the use of natural fibers as evaporative cooling media for photovoltaic panels under Ouargla climatic conditions.	This study extends previous work by comparing natural fiber cooling with recycled newspaper as an additional moisture retention medium.
Jute Fabric Study (2025)	Demonstrated that wet jute fabric alone can effectively reduce photovoltaic panel temperature.	The present work investigates a hybrid multilayer system combining jute fabric with newspaper to improve moisture retention duration and cooling stability.
Togun et al. (2025)	Developed advanced photovoltaic thermal cooling systems with high thermal performance.	The present study focuses on a passive cooling approach that is structurally simple, energy-independent, and economically accessible.
Bukar and Wang (2025)	Recommended reducing the operational and installation cost of photovoltaic cooling systems.	This work addresses this recommendation by employing recycled newspaper materials to achieve an ultra-low-cost cooling solution.

II.5 Conclusion

The review of previous studies demonstrates that thermal management remains one of the most critical challenges affecting photovoltaic panel performance, particularly in hot desert environments such as Ouargla, where elevated temperatures directly reduce electrical efficiency.

Although numerous cooling techniques have been developed, there remains a clear need for solutions capable of combining effective thermal performance with economic feasibility.

Previous studies also reveal the strong potential of porous and cellulosic materials for improving evaporative cooling performance due to their water retention capacity and capillary transport properties, which enhance continuous evaporation.

However, limited research has investigated the combined use of such materials in hybrid configurations capable of achieving improved overall performance.

Based on these observations, the present research proposes a hybrid passive cooling

solution combining jute fabric and newspaper layers.

This concept seeks to exploit the high porosity of jute together with the fibrous structure of recycled newspaper in order to develop a more effective and sustainable cooling system.

This theoretical foundation prepares the way for the next chapter, where the proposed system will be experimentally evaluated under real climatic conditions.

CHAPTER III

Experimental Study and Performance Results Analysis of the Cooling System

III.1 Introduction

This chapter provides a comprehensive presentation of the experimental methodology developed and implemented to evaluate the performance of the proposed photovoltaic (PV) panel cooling system. It begins with an overview of the porous materials used and their characteristics, followed by the assembly procedure and the field data acquisition protocol. These experimental procedures constitute the fundamental basis for the analysis and discussion of the obtained results presented in this chapter, with the aim of assessing the technical effectiveness and economic feasibility of the proposed cooling system.

III.2 Geographic framework of the study (Ouargla region)

The experimental study was carried out at Kasdi Merbah University in the city of Ouargla, located in the southeastern part of Algeria. This region has a hot and dry desert climate. It is characterized by high solar radiation, often exceeding 1000 W/m^2 during peak hours, along with very high temperatures that can go above 45°C in summer. These harsh conditions lead to an increase in the temperature of photovoltaic panels, which negatively affects their performance. Therefore, Ouargla is considered a suitable location to test the effectiveness of the proposed cooling system using porous materials such as jute and newspaper.

III.3 Materials used and their physical properties

A combination of natural and organic materials was selected to develop the cooling system. This choice was made because these materials are available, low-cost, and have good thermal properties. The following table presents the main physical and thermal properties of the materials used in the experiment:

Table III.1: Physical and thermal properties of porous cooling materials

Property	Burlap Fibers (Jute)	Newspaper (4 Layers)	Reference
Thermal Conductivity (k)	0.038–0.055 W/m·K	0.034 W/m·K	[24]
Specific Heat Capacity (C_p)	≈ 2330 J/kg·K	1300–1600 J/kg·K	[25]
Capillary Height	High (12–15 cm)	Medium (5–8 cm)	[26]
Porosity (Φ)	80%–90%	60%–70%	[24]
Thermal Diffusivity (α)	Very Low	Low	[27]

III.4 Mathematical Modeling and Physical Analysis (Discussion)

The thermal performance of the cooling system placed at the back of the photovoltaic panel follows some physical laws. These laws explain why combining the used materials is important.

III.4.1 Heat transfer by conduction (Fourier's Law)

Heat moves from the back of the panel to the cooling medium according to the following relation:

$$Q_{\text{cond}} = k \times A \times \frac{\Delta T}{e} \quad (\text{III.4})$$

[28]

- Q_{cond} : Heat transfer rate by conduction (Watt).
- k : Thermal conductivity of the material (W/m·K).
- A : Surface area of the panel (m^2).
- e : Thickness of the cooling material layer (m).
- ΔT : Temperature difference between the panel and the medium (K).

Explanation based on the table:

We observe that newspaper has the lowest thermal conductivity value ($k = 0.034$ W/m·K), which makes it an excellent thermal barrier that prevents external heat from reaching the back of the panel. At the same time, its small thickness (e) helps transfer the

cooling effect produced by water quickly to the cells.

III.4.2 Evaporative and convective cooling (Newton's Law of Cooling)

Heat is removed through water evaporation and air flow behind the panel according to the following relation:

$$Q_{\text{conv}} = h \times A \times (T_i - T_f) \quad (\text{III.5})$$

[28]

- Q_{conv} : Heat transfer rate by convection (Watt).
- h : Convective heat transfer coefficient ($\text{W}/\text{m}^2 \cdot \text{K}$).
- A : Surface area of the panel (m^2).
- T_i, T_f : Surface temperature and surrounding fluid temperature ($^{\circ}\text{C}$ or K).

Explanation based on the table:

Jute is very important here because of its high capillary property. It keeps the surface wet for a long time, which increases the value of h and leads to continuous cooling.

III.4.3 Material structure and moisture storage (Porosity concept)

Porosity determines the ability of the material to retain water and allow air to pass through for evaporation:

$$\Phi = \frac{V_v}{V_t} \times 100 \quad (\text{III.6})$$

[24]

- Φ : Porosity (%)
- V_v : Volume of voids (pores) inside the material (m^3).
- V_t : Total volume of the material (m^3).

Explanation based on the table:

Jute has a very high porosity (about 90%), which allows it to store a large amount of water (acting as a moisture reservoir). Meanwhile, combining it with newspaper, which has a moderate porosity (60%–70%), ensures better water distribution in areas where the coarse jute fibers may not reach. This leads to more uniform cooling.

III.4.4 Thermal stability (Thermal Diffusivity)

Thermal diffusivity determines how fast the panel reacts to sudden temperature changes:

$$\alpha = \frac{k}{\rho \times C_p} \quad (\text{III.7})$$

[29]

- α : Thermal diffusivity (m^2/s).
- C_p : Specific heat capacity ($\text{J}/\text{kg}\cdot\text{K}$).
- ρ : Density of the material (kg/m^3).

Explanation based on the table:

Jute has the highest specific heat capacity ($C_p = 2330 \text{ J}/\text{kg}\cdot\text{K}$), which gives it a kind of thermal inertia. This allows it to absorb strong heat fluctuations, especially in hot regions like Ouargla. On the other hand, the newspaper helps balance this behavior due to its faster thermal response.

III.5 Description of the Experimental Cooling System

The cooling system developed in this study is based on the functional integration of jute fibers and newspaper layers. The aim is to use their physical properties to achieve sustainable evaporative cooling for photovoltaic panels.

III.5.1 Structure of the Cooling Unit

The system consists of two functional layers combined into one unit.

Four (04) layers of newspaper are placed in direct contact with the back surface of the photovoltaic panel. The cellulose fibers in the paper create a “micro moisture reservoir” that ensures uniform cooling across the panel surface.

These layers are covered by a layer of jute fiber. The jute acts as a structural support, providing the necessary tension to prevent the paper from tearing when wet. It also allows air to pass through, which is essential for the evaporation process.



Figure III.1: Cooling Unit Components: Newspaper Layers and Jute Fibers

III.5.2 System Assembly and Integration

To achieve maximum thermal efficiency, the assembly process starts by cleaning the back side of the photovoltaic panel to reduce thermal resistance.

The four paper layers are pre-wetted and carefully spread on the back surface to eliminate air gaps. Then, the jute layer is placed on top.

To improve stability and prevent slipping, the whole system is fixed using a metal mesh supported by small wooden plates. This structure is attached to the aluminum frame of the panel to ensure uniform pressure over the entire surface.

This setup keeps the system stable and fully attached to the panel, even under high temperatures and strong winds typical of Ouargla.



Figure III.2: System Assembly and Integration with the Photovoltaic Panel

III.5.3 Operating Principle

The system works based on passive evaporative cooling.

The jute layer is supplied with water regularly through a simple drip system to keep it saturated. Then, the water spreads naturally across the surface due to the capillary action of the jute fibers.

At the same time, the newspaper retains moisture near the panel surface for a longer period.

As the panel absorbs solar radiation, the water evaporates and absorbs latent heat directly from the back of the photovoltaic cells.

This reduces the panel temperature and prevents excessive heating, helping to maintain its electrical efficiency.

III.6 Experimental Setup and Measuring Devices

III.6.1 Specifications of the Photovoltaic Panel Used

In this experiment, monocrystalline silicon panels were used. These panels are known for their high efficiency in converting solar radiation into electricity.

The figure (3.4) below shows the technical characteristics of the panels under standard test conditions.



Figure III.3: Technical Specifications of the Photovoltaic Panel (Monocrystalline)

Table III.2. Electrical Characteristics of the Photovoltaic Module Used in This Study

Peak power (Pmax)	80 W
Open circuit voltage (Voc)	21.6 V
Max power voltage (Vmp)	17.2 V
Short circuit current (Isc)	5.0 A
Max power current (Imp)	4.66 A

III.6.2 Experimental Circuit and Measurement Protocol

III.6.2.1 Circuit Description and Connection

To evaluate the electrical performance of the PV panels under the specific climatic conditions of the Ouargla region, a complete measurement circuit was established. As shown in Figure (3.5), the PV panel is connected to a high-power rheostat which serves as a variable electrical load. This setup is designed to manually scan the current-voltage (I-V) characteristic curve, specifically to identify the operating point that yields the Maximum Power (P_{max}) under the available solar irradiance and thermal conditions.

An analog ammeter is connected in series to monitor the output current (I), while the digital multimeter is connected in parallel to measure the open-circuit voltage (V_{oc}) and

operating voltage (V). This configuration ensures precise data collection for calculating optimal electrical outputs and comparing the performance efficiency between cooled and uncooled panels at their peak production points



Figure III.4: The complete experimental measurement circuit setup

III.6.2.2 Summary of Measurement Instruments

The following table summarizes the technical specifications and the primary functions of the instruments used in this experimental setup:

Table III.3: Technical Specifications of the Measurement Instruments

Device Name	Figure	Measurement	Range / Scale	Unit
Rheostat		Variable Load	High Wattage	Ω
Analog Ammeter (PH 125)		DC Current	0–5	A
Digital Multimeter (DT-9205)		Voltage / Current	0–1000	V / A
Temperature Meter (PHYWE)		Surface and Ambient Temperature	Dual Channel	$^{\circ}\text{C}$

III.6.2.3 Detailed Description of Equipment

1. Rheostat (Variable Resistor)

A high-power rheostat was utilized to act as a manual control for the electrical load. By varying the resistance, we are able to capture corresponding current and voltage values for different loads, allowing us to pinpoint the specific coordinates where the panel operates at its Maximum Power Point ($P_{\max}$). This is a critical step for

evaluating how effectively the cooling methods enhance the overall efficiency of the panel.

2. Analog Ammeter (PH 125)

The analog ammeter (Model PH 125) provided a real-time visual reference for the current flow. Its robust design is particularly suited for steady-state measurements during outdoor field tests where digital displays might fluctuate due to rapid changes in solar irradiance.

3. Digital Multimeter (DT-9205)

This device was employed for its high input impedance and accuracy in measuring the DC voltage and current. It provides the necessary precision to detect subtle changes in electrical output caused by the variations in panel temperature during the cooling process.

4. Digital Temperature Meter (PHYWE)

Given the focus on thermal management, the PHYWE meter was critical for tracking temperature gradients. Using its dual-channel capability (T_1 , T_2), we were able to monitor the front surface of the panel and the cooling medium simultaneously, ensuring an accurate assessment of the evaporative cooling efficiency.

III.6.3 Comparative Methodology

This study is based on a step-by-step comparison method to evaluate the performance of the developed cooling system. Two identical panels were used, both fixed at a tilt angle of 30° , following these stages:

Stage 1 (Evaluation of the Developed System):

A direct comparison was made between the cooled panel (jute fibers + 4 layers of newspaper) and a reference panel operating without any cooling.

The goal of this stage was to measure the difference in temperature and electrical power between the developed system and the normal panel.



Figure III.5: Experimental Setup for Comparative Performance Evaluation between Cooled and Reference Panels

Stage 2 (Isolation of the Paper Effect):

In the next step, a comparison was made between a panel cooled with (jute + newspaper) and another panel cooled with jute only.

This stage aims to determine the added value of the newspaper and evaluate its role in improving moisture distribution and reducing panel temperature compared to using jute alone.

This two-step comparison method allows a clear analysis of each component of the cooling system and proves the effectiveness of combining jute and newspaper under Ouargla conditions.



Figure III.6: Experimental Setup for Comparative Performance Evaluation between burlap cooling and hybrid burlap and newspaper cooling

III.6.4 Data Collection Protocol

Measurements were carried out from 10:00 a.m. to 16:00 p.m. All readings were recorded manually every 30 minutes.

During each measurement cycle, the cooling layers were manually supplied with water to ensure continuous evaporative cooling.

III.7 Results and Discussion

To better understand the behavior and performance of photovoltaic panels, it was first necessary to study the climatic conditions during the experiments, since they strongly affect the thermal and electrical performance of the panels. The analysis focused on the variations of solar radiation, ambient temperature, and wind speed during the three experimental days (17, 18, and 19 May).

III.7.1 Climatic Conditions Analysis

III.7.1.1 Solar Radiation

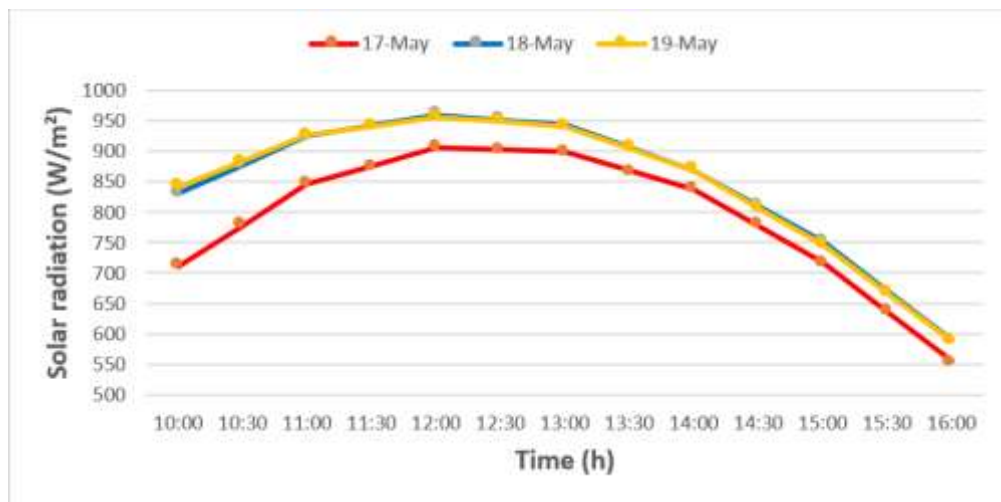


Figure III.7: Time Evolution of Solar Radiation during the Experimental Days

Comment:

The solar radiation curves showed a regular bell-shaped profile during the three days. The radiation values started at moderate levels in the morning, increased progressively until midday, and then decreased gradually in the evening.

On the first day (17 May), the lowest radiation values were recorded compared with the other days. The solar radiation started at about 710 (W/m^2), reached a maximum value of 915 (W/m^2) between 12:00 and 13:00, and then decreased to 555 (W/m^2) at 16:00.

For the second and third days (18 and 19 May), the radiation values were almost identical. The measurements started above $830 \text{ (W/m}^2\text{)}$, reached the same peak value of $965 \text{ (W/m}^2\text{)}$ at 12:00, and then gradually decreased to nearly $600 \text{ (W/m}^2\text{)}$ in the evening.

This similarity between the second and third days is very important for the experimental analysis because the panels received nearly the same solar energy input. Therefore, any difference observed later in the thermal or electrical performance can mainly be attributed to the effect of ambient temperature and the efficiency of the cooling system rather than to changes in solar radiation.

III.7.1.2 Ambient Temperature

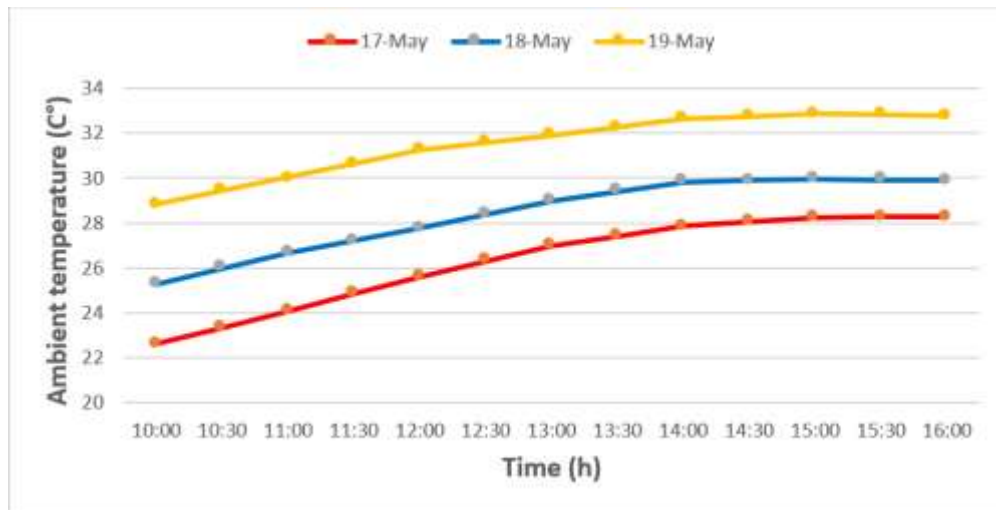


Figure III.8: Time Evolution of Ambient Temperature during the Experimental Days

Comment:

The ambient temperature curves showed a continuous and gradual increase from morning to evening due to the accumulation of solar heat during the day.

The first day (17 May) recorded the lowest temperatures of the study. The temperature started at $22.7 \text{ (}^{\circ}\text{C)}$ and reached a maximum value of $28.7 \text{ (}^{\circ}\text{C)}$ in the evening.

The second day (18 May) was warmer, with temperatures increasing from $25.3 \text{ (}^{\circ}\text{C)}$ in the morning to about $30.2 \text{ (}^{\circ}\text{C)}$ in the evening.

The third day (19 May) was the hottest day of the experiments. The temperature started from a relatively high value of $28.9 \text{ (}^{\circ}\text{C)}$ and continued increasing until it reached the highest value of the study, $33 \text{ (}^{\circ}\text{C)}$.

These results indicate a clear thermal difference between the three days, especially between the second and third days despite the similarity in solar radiation. This condition is useful for studying the influence of ambient temperature on photovoltaic panel efficiency. In general, high cell temperatures reduce the output voltage and the overall efficiency of

photovoltaic panels, which makes the evaluation of the cooling system more reliable under different thermal conditions.

III.7.1.3 Wind Speed

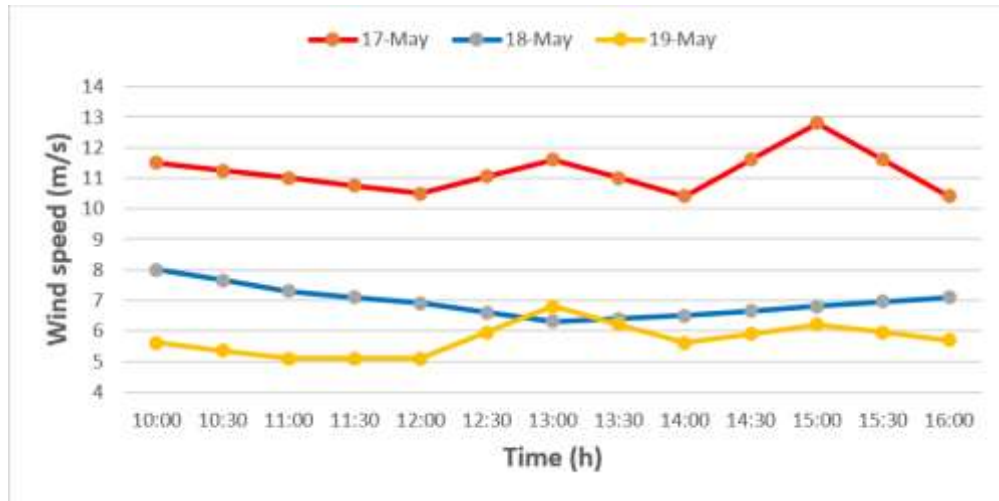


Figure III.9: Time Evolution of Wind Speed during the Experimental Days

Comment:

The wind speed measurements showed noticeable differences between the three days, which directly influenced the natural cooling of the panels by air convection.

The first day (17 May) was characterized by strong winds throughout the day. The wind speed varied from 11.5 (m/s) in the morning to a maximum value of 12.8 (m/s) at 15:00.

The second day (18 May) experienced moderate and relatively stable winds, ranging between 6.4 (m/s) and 8 (m/s).

In contrast, the third day (19 May) was generally calmer, with wind speeds around 5.6 (m/s), except for a slight increase at 13:00 when the speed reached 6.9 (m/s).

These climatic conditions help explain the thermal behavior of the photovoltaic panels. The strong winds during the first day improved the natural cooling process and reduced heat accumulation on the panel surface. On the other hand, the lower wind speed during the third day, combined with the high ambient temperature, created more severe thermal conditions for the panels. Therefore, the variation in wind conditions provided suitable experimental conditions for evaluating the effectiveness of the proposed cooling systems under different environmental conditions.

III.7.2 Study of Photovoltaic Panel Temperature Variations on the First Day (17 May)**III.7.2.1 Panel Temperature**

During this day, a thermal comparison was carried out between the uncooled reference panel (red curve) and the panel cooled using the burlap and newspaper system (blue curve), using three temperature sensors placed at the upper part (T_1), middle part (T_2), and lower part (T_3) of the panel.

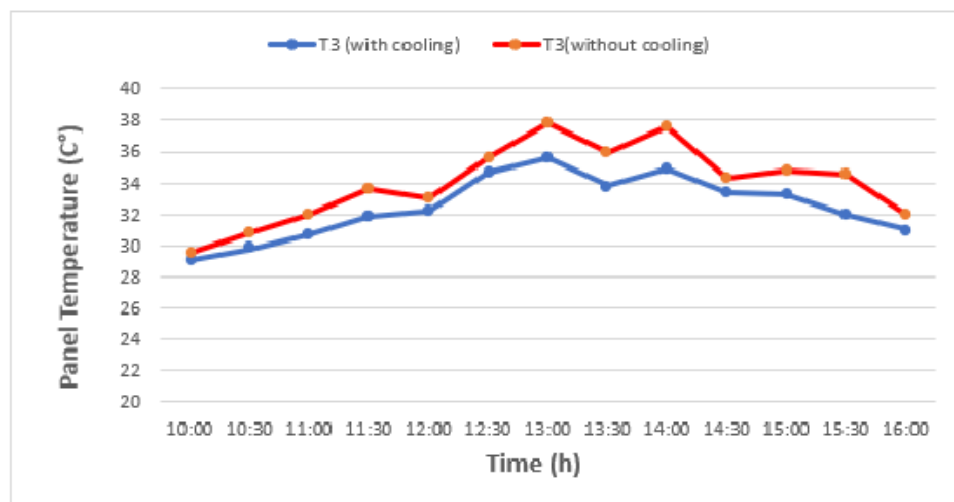
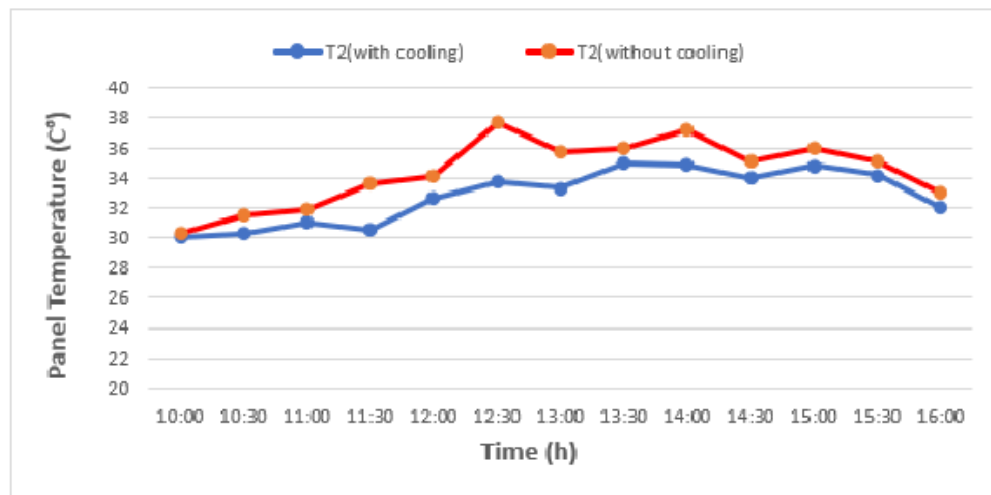
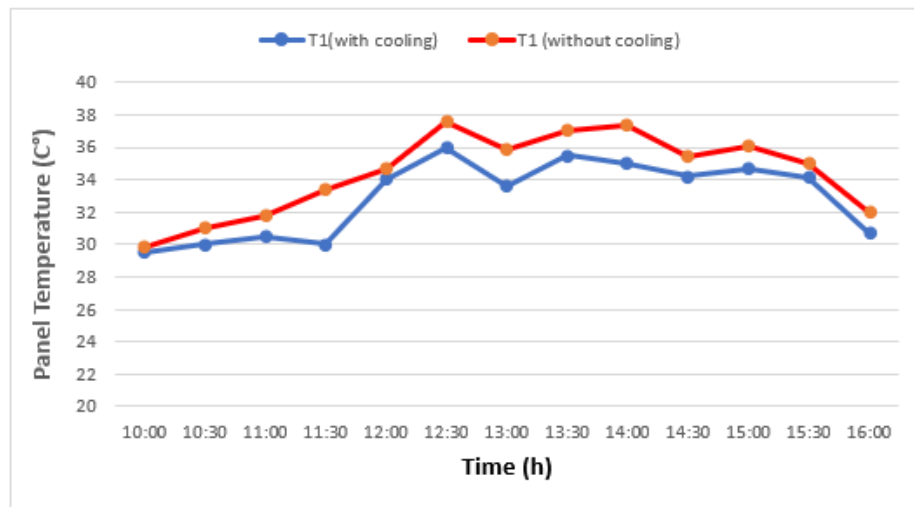


Figure III.10: Time Evolution of Photovoltaic Panel Temperature at Three Measurement Points (T_1 , T_2 , T_3)

Comment:

Comment:

The results showed that the cooled panel maintained lower temperatures than the reference panel at all measurement positions throughout the day. In the upper part (T_1), the maximum temperature difference reached about 3.6 ($^{\circ}\text{C}$), while the middle part (T_2) showed the best cooling performance with a reduction of 4 ($^{\circ}\text{C}$). The lower part (T_3) maintained a stable thermal reduction estimated at about 2.3 ($^{\circ}\text{C}$).

This performance is related to the climatic conditions of 17 May, which were characterized by moderate ambient temperatures and strong winds reaching 12.8 (m/s). These strong winds naturally contributed to cooling the reference panel through air convection. Despite this natural effect, the burlap and newspaper system achieved an additional thermal reduction because the newspaper helped retain water and reduced the rapid drying of the burlap under strong wind conditions, allowing the evaporative cooling process to continue efficiently and steadily throughout the experiment.

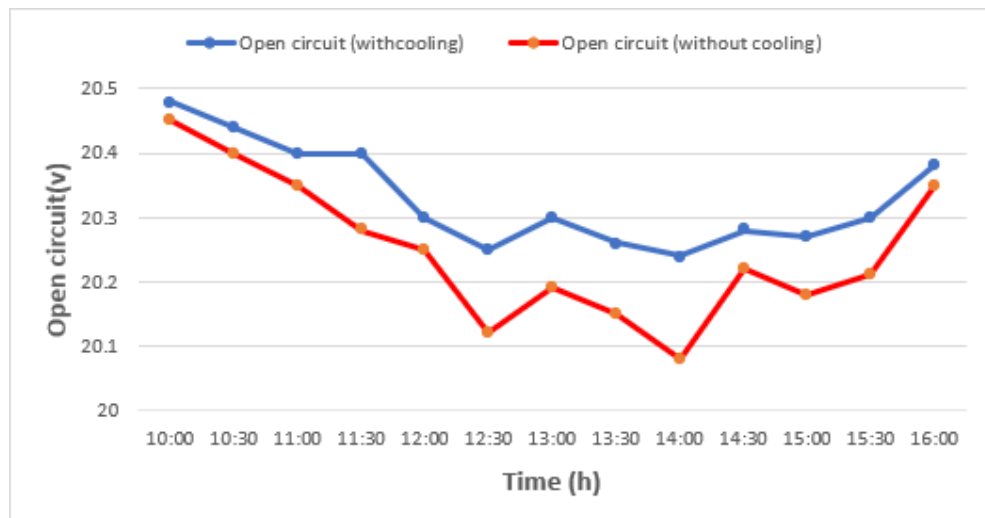
III.7.2.2 Open Circuit Voltage

Figure III.11: Time Evolution of Open Circuit Voltage (V_{oc}) of Photovoltaic Panels

Comment:

The red curve represents the uncooled reference panel, while the blue curve represents the panel equipped with the burlap and newspaper cooling system. The measurements of the open circuit voltage V_{oc} were carried out from 10:00 a.m. to 16:00 p.m.

The results showed that both curves followed a decreasing trend during the day due to the increase in photovoltaic cell temperature. The voltage of the uncooled panel decreased from 20.44 (V) in the morning to a minimum value of 20.06 (V) at 14:00, whereas the cooled panel maintained higher voltage values throughout the measurement period, recording a minimum value of 20.22 (V) at the same time.

The maximum electrical difference between the two panels was observed at 14:00, where the voltage improvement reached about 0.16 (V) in favor of the cooled panel, corresponding to the period of highest thermal stress during the day.

These results confirm the inverse relationship between panel temperature and open circuit voltage V_{oc} , since increasing temperature leads to a reduction in the electrical voltage of photovoltaic cells. The evaporative cooling system based on burlap and newspaper reduced thermal rise and helped maintain the electrical stability of the panel, allowing higher voltage values compared with the uncooled panel.

III.7.2.3 Maximum Power

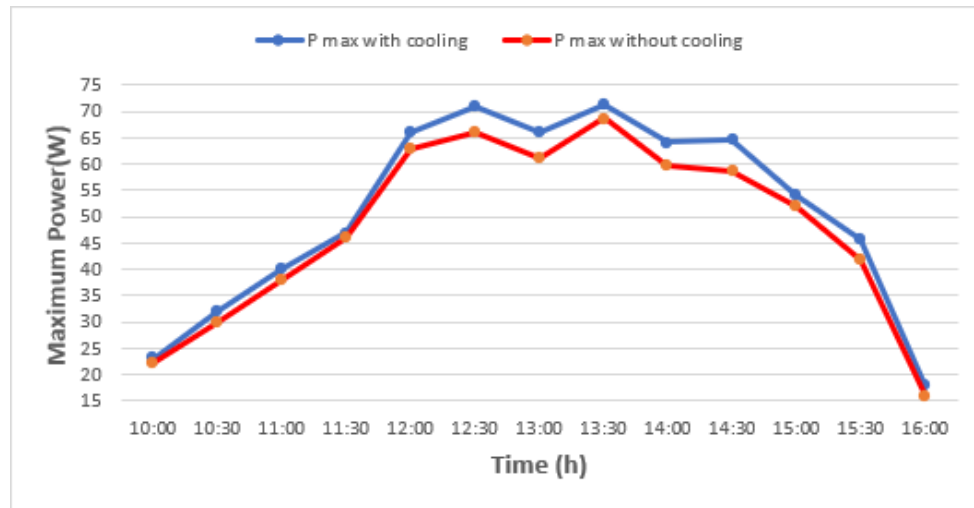


Figure III.12: Time Evolution of Maximum Power (P_{max}) of Photovoltaic Panels

Comment:

The figure presents a time-based comparison of the maximum power output P_{max} between the reference panel (without cooling) and the panel cooled using the hybrid system (burlap and newspaper) over the period from 10:00 a.m. to 16:00 p.m.

The results show that both systems followed the same general trend, characterized by an increase during the morning due to rising solar irradiance. However, the cooled panel consistently recorded higher power values compared to the reference panel.

During the peak period (12:00–14:00), the cooled panel maintained a clear advantage, reaching a maximum value of approximately 72.1 (W) at 13:30, compared to 68.7 (W) for the reference panel. The power difference between the two systems ranged from 2.5 (W) to more than 5 (W) during peak conditions.

After 14:00, the power output gradually decreased as solar irradiance declined, while the cooled panel continued to outperform the reference panel until the end of the measurements.

These results indicate that the hybrid cooling system (burlap and newspaper) improves the electrical performance of photovoltaic panels by reducing the impact of temperature rise on their electrical characteristics, which directly leads to higher and more stable $P_{\max}$ compared to the uncooled panel.

III.7.2.4 Efficiency

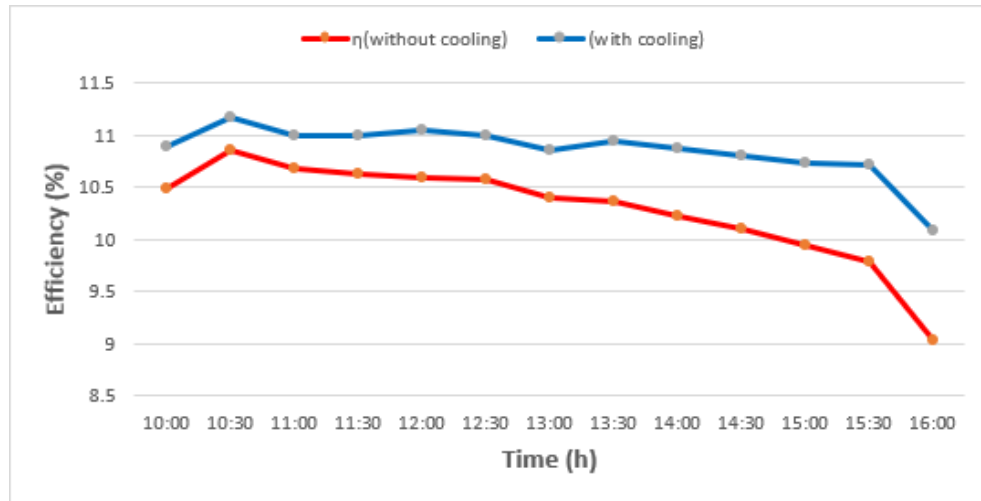


Figure III.13: Time Evolution of Electrical Efficiency (η)

Comment:

The figure presents a time-based comparison of the electrical efficiency of photovoltaic panels between the burlap-only system (red curve) and the hybrid system combining burlap and newspaper (blue curve) over the period from 10:00 a.m. to 16:00 p.m.

The results show similar behavior in the morning period, with a slight advantage for the hybrid system, followed by a clear improvement for both systems as midday approaches. The hybrid system achieved the highest efficiency value of approximately 11.53%, compared to 11.20% for the burlap-only system.

After 14:00, efficiency gradually decreased due to the reduction in solar irradiance, while the hybrid system consistently maintained higher values than the conventional system throughout the afternoon. By the end of the day, the efficiency dropped to 7.60% for the hybrid system and 7.10% for the burlap-only system.

These results confirm that the hybrid cooling system (burlap and newspaper) enhances energy conversion efficiency by improving evaporative cooling and stabilizing the operating temperature, which directly contributes to higher and more stable electrical efficiency compared to the conventional system.

III.7.3 Study of Photovoltaic Panel Temperature Variations on the Second Day (18 May)**III.7.3.1 Panel Temperature**

During this day, a thermal comparison was carried out between two cooling systems: burlap only (red curve) and burlap combined with newspaper (blue curve).

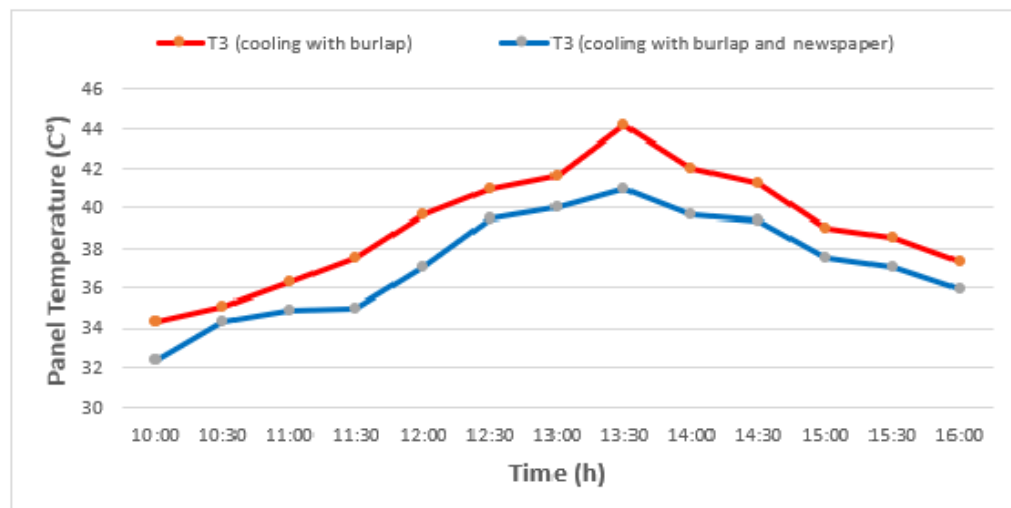
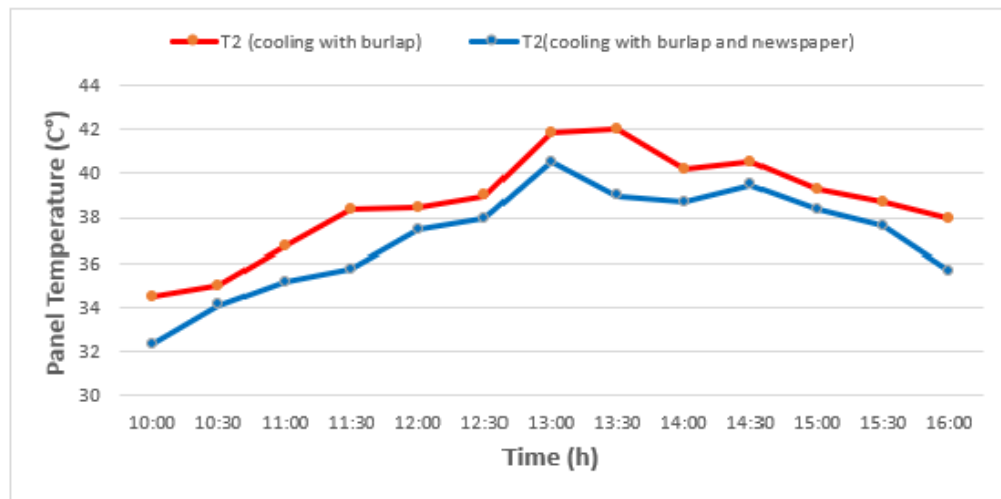
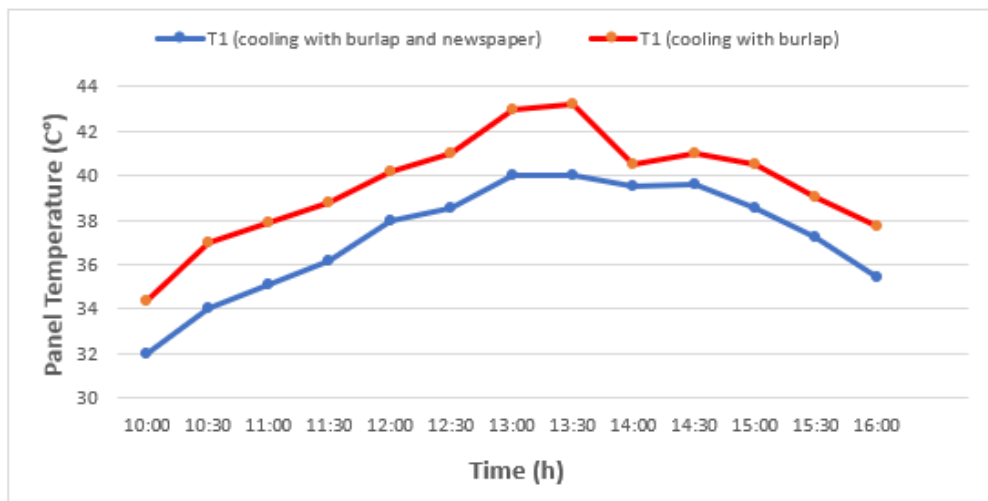


Figure III.14: Time Evolution of Photovoltaic Panel Temperature at Three Measurement Points (T_1 , T_2 , T_3)

Comment:

The results showed that the temperatures of the panel cooled with burlap and

newspaper remained lower than those of the burlap-only system at all measurement positions throughout the day. In the upper part (T_1), the maximum temperature difference reached 3.4 ($^{\circ}\text{C}$), while the middle part (T_2) recorded a difference of 2.5 ($^{\circ}\text{C}$). The lower part (T_3) showed the best cooling response, with a maximum temperature reduction of 3.7 ($^{\circ}\text{C}$) during the peak thermal period.

This improvement is related to the climatic conditions of 18 May, which were characterized by higher ambient temperatures and lower wind speeds compared with the previous day, leading to faster water evaporation. Under these conditions, the newspaper layer helped retain moisture inside the burlap and improved water distribution over the panel surface, resulting in a more stable and uniform cooling process. In contrast, the burlap-only system experienced faster drying, which caused a significant increase in temperature, especially in the lower part of the panel.

These results confirm that combining newspaper with burlap improves the efficiency and sustainability of evaporative cooling, particularly under hot and low-wind climatic conditions.

III.7.3.2 Open Circuit Voltage

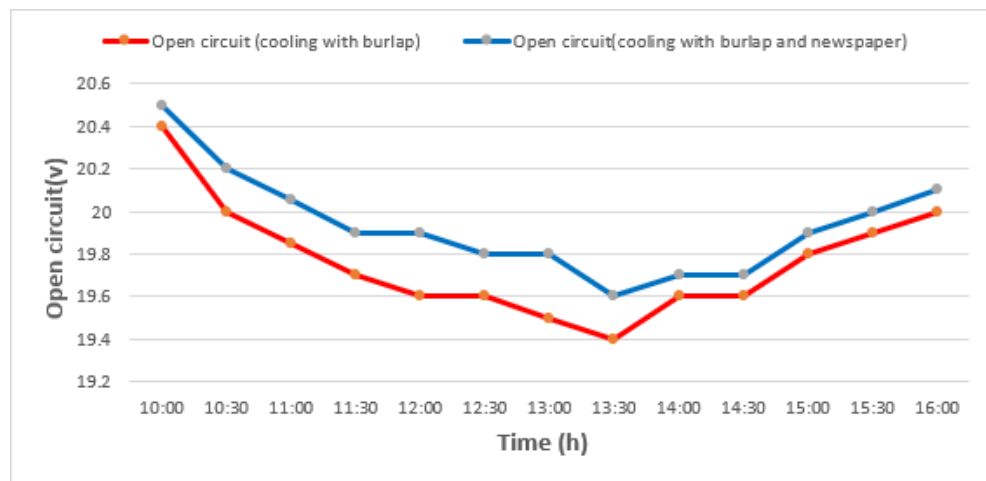


Figure III.15: Time Evolution of Open Circuit Voltage (V_{oc}) of Photovoltaic Panels

Comment:

The figure presents a comparison of the open circuit voltage V_{oc} between two evaporative cooling systems: burlap only (red curve) and the hybrid system combining burlap and newspaper (blue curve), over the period from 10:00 a.m. to 16:00 p.m.

The results show that both curves are affected by the rise in temperature during the day. The burlap-only system experienced a stronger voltage drop, reaching a minimum of

19.48 (V) at 13:30, while the hybrid system maintained higher values, with a minimum of 19.68 (V).

The maximum electrical difference was recorded at the peak thermal period (13:30), where the voltage improvement reached 0.20 (V) in favor of the hybrid system.

These results confirm that combining newspaper with burlap improves thermal performance, which positively enhances the stability of the open circuit voltage V_{oc} compared to the burlap-only system.

III.7.3.3 Maximum Power

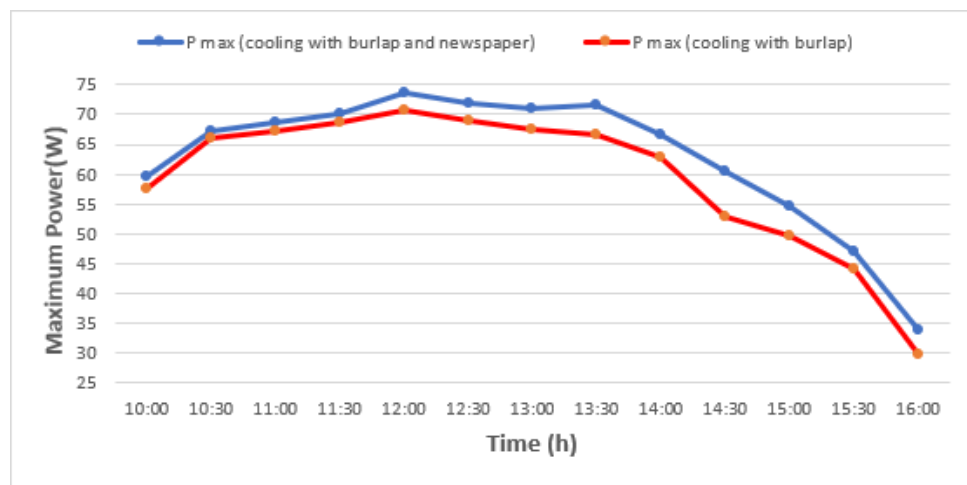


Figure III.16: Time Evolution of Maximum Power (P_{max}) of Photovoltaic Panels

Comment:

The figure presents a time-based comparison of the maximum power P_{max} between the burlap-only cooling system (red curve) and the hybrid system combining burlap and newspaper (blue curve) over the period from 10:00 a.m. to 16:00 p.m.

The results show a consistent superiority of the hybrid system throughout the day, with higher power values than the burlap-only system at all time intervals. The two systems started with close values in the morning, but the performance gap gradually increased as thermal stress intensified.

The hybrid system reached a peak power of 73.5 (W) at 12:00, compared to 70.5 (W) for the burlap-only system. The advantage persisted during the afternoon and evening, with the difference exceeding 8 (W) at 14:30.

These results confirm that adding newspaper to burlap improves evaporative cooling efficiency by enhancing moisture retention and reducing rapid evaporation, which directly leads to higher and more stable P_{max} compared to the conventional cooling system.

III.7.3.4 Efficiency

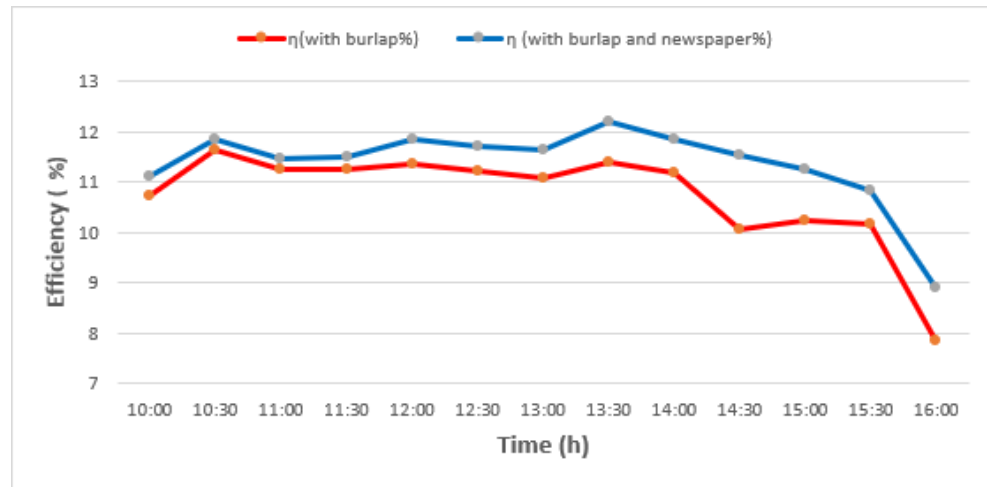


Figure III.17: Time Evolution of Electrical Efficiency (η)

Comment:

The figure presents a time-based comparison of the electrical efficiency of photovoltaic panels between the burlap-only system (red curve) and the hybrid system (burlap + newspaper) over the period from 10:00 a.m. to 16:00 p.m.

The results show a consistent superiority of the hybrid system throughout the day, with slight fluctuations in the morning followed by relatively stable performance during midday.

The hybrid system achieved its highest efficiency of approximately 12.07% at 13:30, compared to 11.29% for the burlap-only system.

After 14:00, efficiency gradually decreased due to the reduction in solar irradiance, while the hybrid system continued to outperform the conventional system until the end of the measurements, recording final values of 8.81% versus 7.62%.

These results confirm that the hybrid cooling system (burlap and newspaper) improves energy conversion efficiency by enhancing evaporative cooling and stabilizing the operating temperature, which directly leads to higher and more stable electrical efficiency compared to the conventional system.

III.7.4 Study of Photovoltaic Panel Temperature Variations on the Third Day (19 May)

III.7.4.1 Panel Temperature

During this day, a thermal comparison was carried out between the burlap-only cooling system (red curve) and the hybrid cooling system based on burlap and newspaper (blue curve).

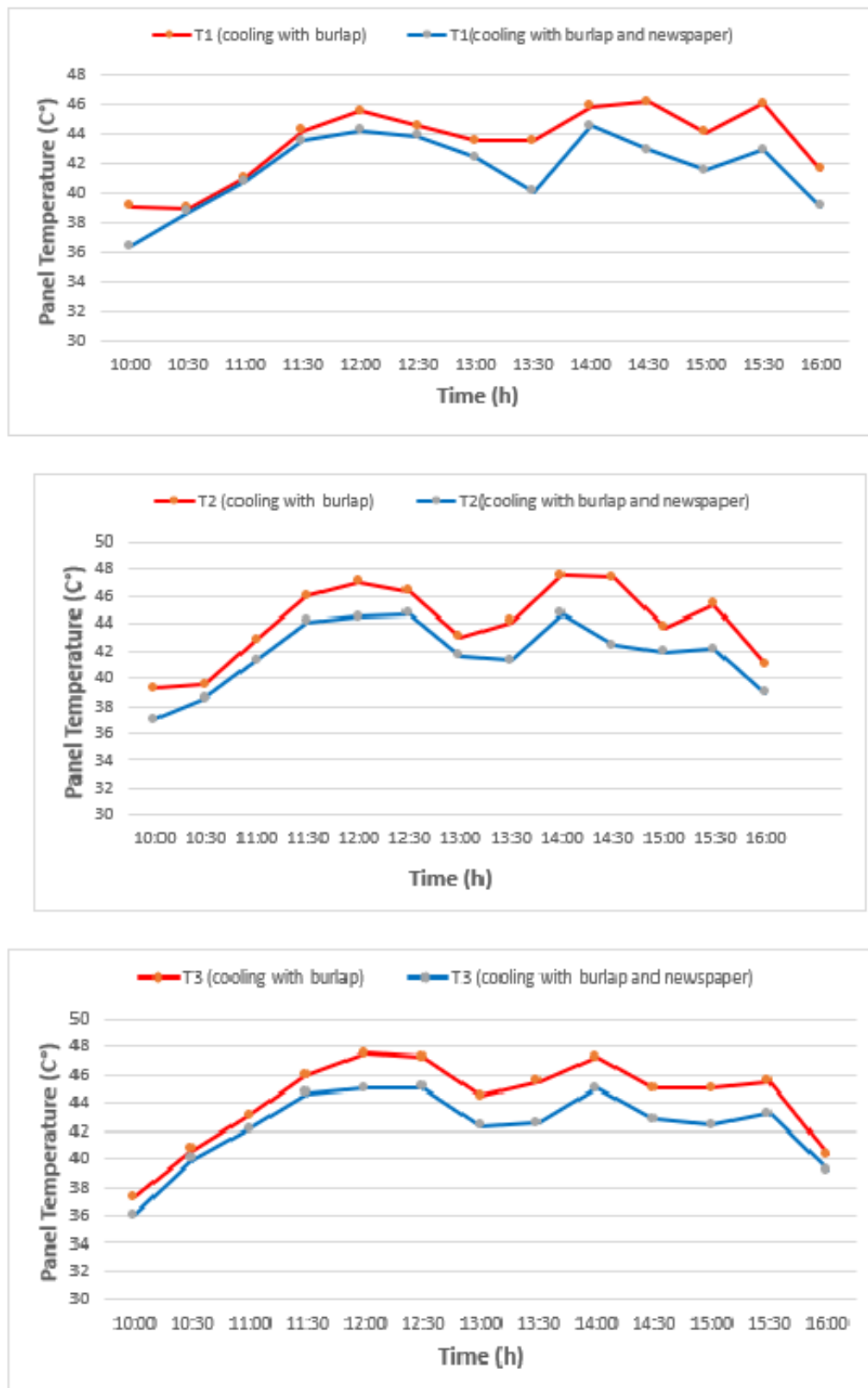


Figure III.18: Time Evolution of Photovoltaic Panel Temperature at Three Measurement Points (T_1 , T_2 , T_3)

Comment:

The results showed that the hybrid system maintained lower and more stable temperatures

than the burlap-only system at all measurement positions. In the upper part (T_1), the maximum temperature difference reached 3.3 ($^{\circ}\text{C}$), while the middle part (T_2) showed the best cooling performance with a temperature reduction of 5.3 ($^{\circ}\text{C}$). The lower part (T_3) achieved a stable thermal reduction of about 2.6 ($^{\circ}\text{C}$).

This performance is related to the severe climatic conditions of 19 May, which was the hottest day of the experimental period. The ambient temperature ranged between 28.8 ($^{\circ}\text{C}$) and 33 ($^{\circ}\text{C}$), together with low wind speeds ranging from 5.2 (m/s) to 6.9 (m/s).

These hot conditions combined with weak natural ventilation accelerated the drying of the burlap-only system, causing the panel temperature to increase and approach 48.4 ($^{\circ}\text{C}$).

In contrast, the newspaper layer helped retain water and improve moisture distribution within the burlap structure, which maintained the continuity of the evaporative cooling process and ensured more stable thermal performance even during the hottest periods of the day.

The hybrid system also showed a more uniform temperature distribution between the three measurement positions (T_1 , T_2 , and T_3) compared with the burlap-only system, reflecting a more regular cooling process and lower thermal variation across the panel surface.

These results confirm that combining newspaper with burlap improves the efficiency and sustainability of the cooling system, especially under hot and low-wind climatic conditions.

III.7.4.2 Open Circuit Voltage

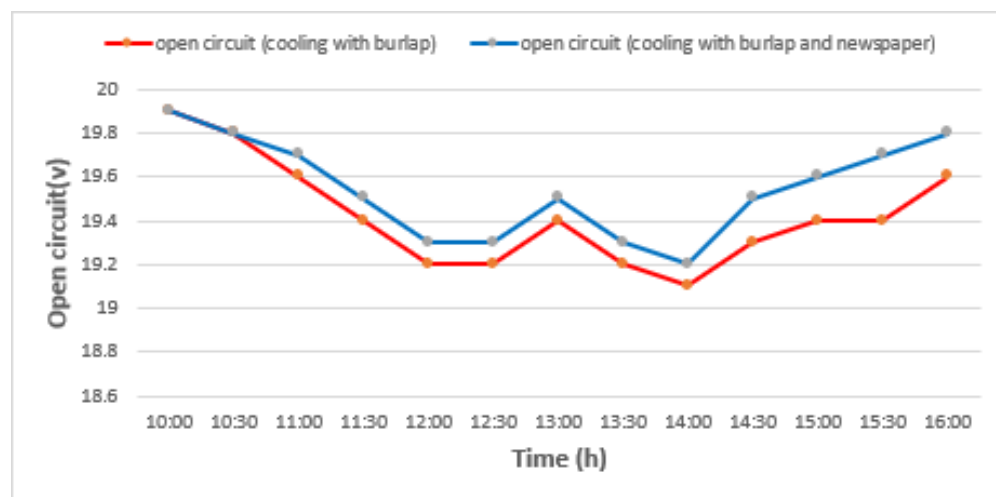


Figure III.19: Time Evolution of Open Circuit Voltage (V_{oc}) of Photovoltaic Panels

Comment:

The figure presents a time-based comparison of the open circuit voltage V_{oc} between the burlap-only cooling system (red curve) and the hybrid system combining burlap and newspaper (blue curve) over the period from 10:00 a.m. to 16:00 p.m., under high thermal stress conditions.

The results show that both systems were affected by the increase in ambient temperature during the day, with an overall decrease in voltage values compared to previous days.

The burlap-only system experienced a more pronounced drop, reaching a minimum of 19.1 (V) at 14:00, while the hybrid system maintained higher and more stable values, with a minimum of approximately 19.20 (V).

A nearly constant electrical difference of about 0.1 (V) was observed during the midday period in favor of the hybrid system, indicating stable performance under thermal stress.

These results confirm the continued effectiveness of the hybrid cooling system (burlap and newspaper) in improving the stability of the open circuit voltage V_{oc} compared to burlap alone.

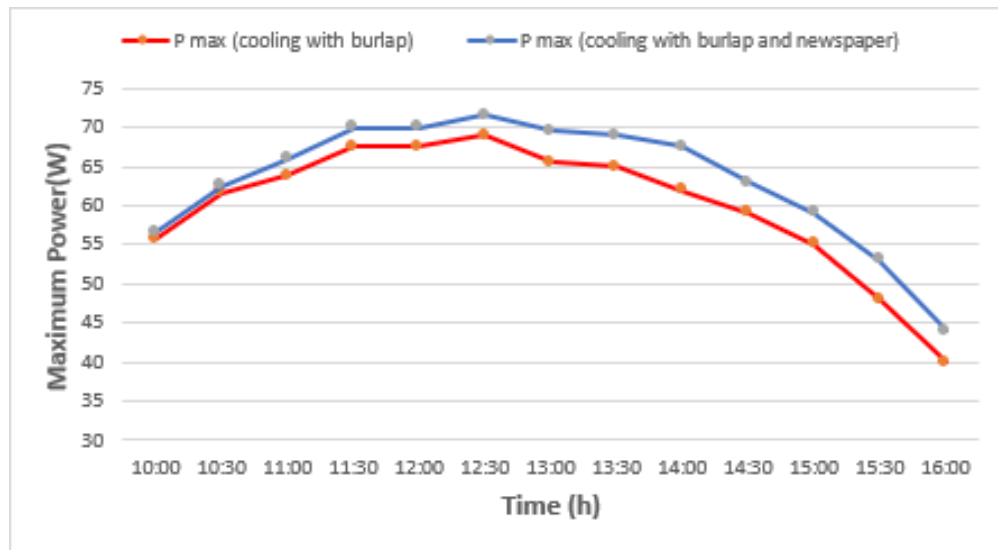
III.7.4.3 Maximum Power

Figure III.20: Time Evolution of Maximum Power (P_{max}) of Photovoltaic Panels

Comment:

The figure presents a time-based comparison of the maximum power P_{max} between the burlap-only cooling system (red curve) and the hybrid system combining burlap and newspaper (blue curve).

The results show a close agreement between both systems during the early morning period (10:00–11:00), due to sufficient initial moisture in both cooling configurations.

After this stage, the hybrid system begins to show a gradual advantage during midday operation.

During the peak period, the hybrid system maintained relatively stable performance, with a brief drop at 13:30 followed by a rapid recovery at 14:00, reaching approximately 44.5 (W).

In contrast, the burlap-only system exhibited a more continuous decline after midday.

These results indicate that the hybrid system provides more stable performance due to improved moisture retention and enhanced evaporative cooling efficiency.

III.7.4.4 Efficiency

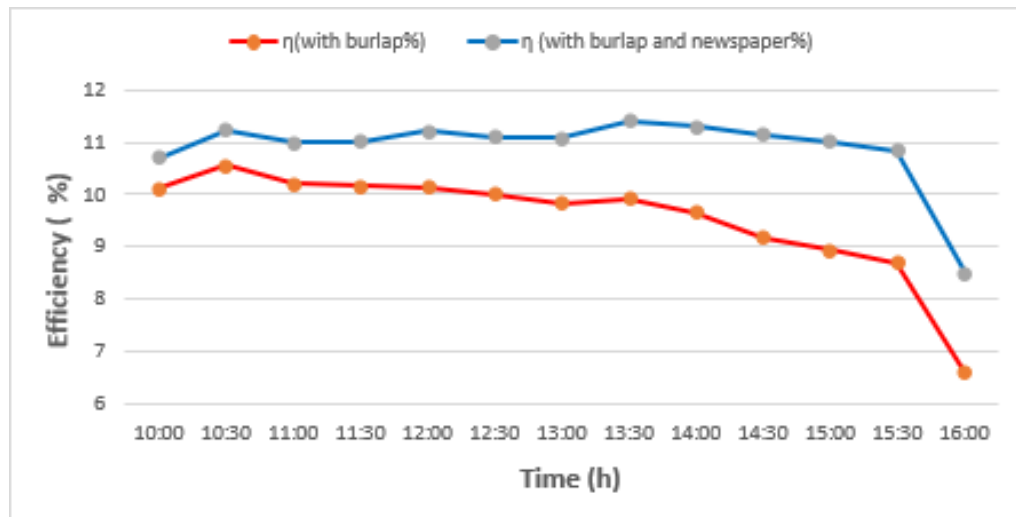


Figure III.21: Time Evolution of Electrical Efficiency (η)

Comment:

The figure presents a time-based comparison of the electrical efficiency between the burlap-only system and the hybrid system.

The results show a consistent superiority of the hybrid system throughout the day.

The hybrid system achieved a maximum efficiency of approximately 11.38% at 13:30.

After 14:00, efficiency gradually decreased in both systems due to the reduction in solar irradiance and increased thermal accumulation.

However, the hybrid system maintained higher performance until the end of the experiment, reaching 8.45% compared to 6.62% for the burlap-only system.

III.8 Summary of Research Findings

Table III.4: Summary of research findings

Days	ΔT Avg	$\Delta T_{\max}$	ΔP Avg	$\Delta P_{\max}$	ΔV Avg	$\Delta V_{\max}$
Day 1 (17 May)	3.13	4.10	2.47	5.00	0.08	0.17
Day 2 (18 May)	3.25	4.10	2.85	4.80	0.18	0.36
Day 3 (19 May)	2.15	3.50	2.10	3.90	0.14	0.21
Average	2.70	3.80	2.48	4.35	0.16	0.285

The comparative analysis presented in Table highlights the progressive evolution of the experimental tests conducted over the three study days. On the first day (17 May), the hybrid cooling system (burlap and newspaper) demonstrated effective thermal regulation compared to the uncooled reference panel, achieving an average temperature reduction of 3.13°C and a maximum reduction of 4.10°C. This thermal improvement led to an increase in electrical performance, with an average power gain of 2.47 W and a maximum gain of 5.00 W, accompanied by a voltage recovery of 0.08 V. During the second and third days (18–19 May), the comparison focused on the hybrid system versus burlap-only cooling. The hybrid configuration maintained superior thermal and electrical performance, reaching an average temperature reduction of 3.25°C and a maximum power improvement of 4.80 W. Despite variations in climatic conditions on the third day, the system preserved a stable average power gain of 2.10 W and a maximum voltage improvement of 0.21 V. Overall, the average results of days 2 and 3 confirm the technical effectiveness of integrating newspaper layers with burlap, providing stable improvements of about 2.48 W in output power and 0.16 V in open circuit voltage. These findings demonstrate that the proposed low-cost hybrid cooling system is an efficient and sustainable solution for reducing thermal losses and improving photovoltaic panel performance in hot arid climates such as Ouargla.

III.9 Economic Feasibility Study of a Low-Cost Hybrid Cooling System for Photovoltaic Panel

Table III.5: Economic Feasibility Study of a Low-Cost Hybrid Cooling System for Photovoltaic Panel

Parameter	Value	Description
Panel_Power_Watt	80	Power of each panel (W)
Gain_Per_Panel_Watt	2.47	Power gain from hybrid cooling per panel (W)
Cooling_Cost_Per_Panel_DZD	ZD 160	Cost of cooling system per panel (150 DZD burlap and 10 DZD newspaper)
Total_Power_Target_MW	1500000000	National solar power target (W)
Price_Per_kWh_DZD	8	Selling price per kWh (DZD)
Sun_Hours_Per_Day	11	Average sun hours per day (h)
Total_Power_Gain_Watt	46312500	Total power gain from hybrid cooling (W)
Energy_Gain_Per_Day_kWh	509437.5	Energy gain per day (kWh)
Daily_Revenue_DZD	4075500	Revenue from additional energy per day (DZD)
Total_Cooling_Cost_DZD	3000000000	Total cost of cooling system (DZD)
Payback_Period_Years	2.02	Payback period (years)
Annual_Revenue_DZD	1487557500	Annual revenue from additional energy (DZD)

Economic Calculation Methodology

To evaluate the economic viability of the proposed low cost hybrid cooling system (burlap combined with newspaper) on a large scale, an extrapolation was conducted based on the experimental data obtained on May 17th. The calculation is projected onto a national solar energy target of 1500 MW operating under the climatic conditions of the Ouargla region.

The mathematical equations and steps used to derive the economic indicators presented in Table III.4 are detailed below:

Panel_Power_Watt (80 W): The nominal power of a single PV panel used in the experiment.

Gain_Per_Panel_Watt (2.47 W): The net power gain per panel obtained due to cooling (the difference between the cooled and the uncooled reference panel).

Cooling_Cost_Per_Panel_DZD (160 DZD): The total fabrication cost of the cooling system per panel, which is the sum of burlap (150 DZD) and newspaper (10 DZD).

Total_Power_Target_MW (1500000000 W): The national solar power target of 1500 MW.

Price_Per_kWh_DZD (8 DZD): The national electricity tariff rate per kilowatt hour.

Sun_Hours_Per_Day (11 h): The average daily peak sun hours in the Ouargla region during the study period.

1) Total_Power_Gain_Watt

$$\text{Total power gain} = \frac{\text{total power target}}{\text{panel power}} \times \text{gain per panel}$$

$$\frac{1500000000}{80} \times 2.47 = 18750000 \times 2.47 = 46312500 \text{ w}$$

2)Energy_Gain_Per_Day_kWh

$$\text{Energy Gain Per Day} = \frac{\text{Total Power Gain (W)} \times \text{Sun Hours}}{1000}$$

$$\text{Energy Gain Per Day} = \frac{46312500 \times 11}{1000} = 509437.5 (\text{kWh/day})$$

3) Daily_Revenue_DZD

$$\text{Daily Revenue} = \text{Energy Gain Per Day} \times \text{Price Per kWh}$$

$$\text{Daily Revenue} = 509437.5 \times 8 = 4075500 \text{ DZD}$$

4) Total_Cooling_Cost_DZD

$$\text{Total Cooling Cost} = \text{Number of Panels} \times \text{Cooling Cost Per Panel}$$

$$\text{Number of Panels} = 1500000000 / 80 = 18750000 \text{ panel}$$

$$\text{Total Cooling Cost} = 18750000 \times 160 = 3000000000 \text{ DZD}$$

5) Annual_Revenue_DZD

$$\text{Annual Revenue} = \text{Daily Revenue} \times 365$$

$$\text{Annual Revenue} = 4075500 \times 365 = 1487557500 \text{ DZD}$$

6) Payback_Period_Years

$$\text{Payback Period} = \frac{\text{Total Cooling Cost}}{\text{Annual Revenue}}$$

$$\text{Payback Period} = \frac{3000000000}{1487557500} = 2.02 \text{ Years}$$

The economic indicators presented in Table demonstrate the strong feasibility of implementing the proposed hybrid evaporative cooling system (burlap combined with newspaper) in large-scale photovoltaic installations. Based on the experimental results obtained on 17 May, the system achieved an average power gain of 2.47 W per panel compared to the uncooled reference panel, while requiring a very low investment cost estimated at only 160 DZD per panel. When extrapolated to the national solar energy target of 1500 MW, the proposed cooling technique could provide an additional effective power capacity of approximately 46.31 MW. This thermal improvement contributes to reducing energy losses and enables the recovery of nearly 509,437.5 kWh of electrical energy per day. According to the national electricity tariff of 8 DZD/kWh, the recovered energy corresponds to an estimated additional daily revenue of 4,075,500 DZD and an annual financial return exceeding 1.48 billion DZD. Although the total estimated investment cost for large-scale implementation reaches approximately 3 billion DZD, the generated annual revenue significantly reduces the capital recovery period. The calculated payback period is about 2.02 years, confirming the economic profitability and rapid financial return of the proposed system. These results highlight the potential of integrating low-cost and environmentally sustainable materials as an effective cooling solution for photovoltaic systems operating under hot arid climatic conditions such as Ouargla.

III.1 Conclusion

This chapter provides a comprehensive presentation of the experimental methodology developed and implemented to evaluate the performance of the proposed photovoltaic (PV) panel cooling system. It begins with an overview of the porous materials used and their characteristics, followed by the assembly procedure and the field data acquisition protocol. These experimental procedures constitute the fundamental basis for the analysis and discussion of the obtained results presented in this chapter, with the aim of assessing the technical effectiveness and economic feasibility of the proposed cooling system.

GENERAL CONCLUSION

GENERAL CONCLUSION

This research addressed one of the principal challenges affecting photovoltaic (PV) systems operating in hot arid environments, namely the excessive rise in panel temperature and its negative impact on electrical performance. Since elevated operating temperatures reduce output voltage, power generation, and overall efficiency, the development of simple, economical, and sustainable cooling solutions remains of great importance for desert regions such as Ouargla. To overcome this limitation, a passive evaporative cooling system based on locally available and environmentally friendly materials was developed. The proposed configuration combined burlap fibers (jute) with recycled newspaper in a multilayer hybrid structure designed to enhance water retention, improve capillary transport, and prolong the evaporative cooling process without requiring any external energy consumption. The theoretical investigation confirmed the strong relationship between photovoltaic operating temperature and electrical efficiency while highlighting the advantages of passive cooling techniques over active systems in terms of simplicity, cost, and sustainability. The literature review further revealed the limited number of studies investigating hybrid porous materials capable of improving moisture retention and extending cooling duration. The experimental results demonstrated the effectiveness of the proposed hybrid cooling system under real climatic conditions. Compared with the reference uncooled panel, the system achieved an average temperature reduction of 3.13°C and a maximum reduction of 4.10°C during the first experimental day. When compared with the burlap-only configuration, the hybrid system maintained superior thermal performance, reaching an average temperature reduction of 3.25°C and a maximum reduction of 4.10°C on the second day. The thermal improvement was directly reflected in the electrical behavior of the photovoltaic panel. The proposed system produced an average power gain ranging from 2.10 W to 2.85 W, with a maximum improvement reaching 5.00 W. The overall average power increase recorded during the experimental campaign was 2.48 W, while the average open circuit voltage improvement reached 0.16 V, with a maximum increase of 0.36 V. These results confirm the positive influence of temperature reduction on photovoltaic electrical performance. Furthermore, the incorporation of recycled newspaper proved particularly beneficial due to its high porosity and moisture-retention capability. The newspaper layers improved water distribution within the cooling medium and prolonged evaporation duration, thereby enhancing the overall effectiveness of the cooling process while maintaining very low implementation costs. Despite the encouraging results obtained, certain limitations remain. The performance of the system depends on the availability of water to sustain evaporation, and the long-term durability of the porous materials under continuous outdoor exposure requires further

General Conclusion

investigation. In addition, seasonal testing under extreme summer conditions would provide a more comprehensive assessment of system performance. Future research should focus on optimizing material thickness and layer arrangement, investigating alternative recycled porous materials, integrating automated water supply regulation systems, and extending the application of the proposed cooling technique to larger photovoltaic installations and photovoltaic-thermal hybrid systems. In conclusion, this study demonstrates that a simple passive cooling strategy based on burlap and recycled newspaper can significantly improve photovoltaic thermal regulation and electrical performance. The achieved average temperature reduction of 2.70°C , average power enhancement of 2.48 W, and average voltage improvement of 0.16 V confirm the technical feasibility and practical potential of this low-cost and sustainable solution for enhancing photovoltaic performance in hot desert climates such as Ouargla.

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