Vol. 24, No. 3(2025) IE25590
Revista Mexicana de Ingeniería Química

Using a composite coating ($Cu/(TiO_2) + (SiO_2)/Al_2O_2$)to increase the efficiency of photovoltaic panels

Usando un recubrimiento compuesto($Cu/(TiO_2) + (SiO_2) / Al_2O_2$)para aumentar la eficiencia de los paneles fotovoltaicos

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Sent date: May 11, 2025; Accepted: August 31, 2025

Abstract
This research analyzes the effect of applying a heat-reflective coating to a 270W polycrystalline panel. Solar panels suffer reduced efficiency due to high temperatures, negatively impacting their performance, especially in high solar irradiance conditions. This is a fundamental step toward promoting solar energy as an economical source. The research aims to evaluate the effect of a heat-reflective coating technique (using a multilayer system (copper, a titanium dioxide/silicon dioxide middle layer, and an aluminum oxide protective layer), on improving panel efficiency by increasing energy production. The researchers followed an exploratory, experimental approach, comparing the performance of a standard panel to a coated panel by estimating irradiance, temperature, and power generation under varying climatic conditions. The results showed increased photovoltaic efficiency, approaching the panel's maximum power with an increase of 8% to 9%. The study highlights the practical potential of this technology in improving the efficiency of solar systems and expanding their application in environments with high temperatures and radiation, supporting the long-term development of clean energy solutions. It is an effective method for improving panel efficiency, paving the way for advanced solar energy technologies.
Keywords: Solar energy, Heat-reflective coating , Polycrystalline panel, Photovoltaic efficiency , Multilayer design.

Resumen
Esta investigación analiza el efecto de aplicar un revestimiento termorreflectante a un panel policristalino de 270W. Los paneles solares sufren una eficiencia reducida debido a las altas temperaturas, lo que afecta negativamente a su rendimiento, especialmente en condiciones de alta irradiación solar. Este es un paso fundamental para promover la energía solar como fuente económica. La investigación tiene como objetivo evaluar el efecto de una técnica de recubrimiento reflectante del calor (utilizando un sistema multicapa (cobre, una capa intermedia de dióxido de titanio/dióxido de silicio y una capa protectora de óxido de aluminio), en la mejora de la eficiencia del panel al aumentar la producción de energía. Los investigadores siguieron un enfoque exploratorio y experimental, comparando el rendimiento de un panel estándar con un panel recubierto estimando la irradiancia, la temperatura y la generación de energía en condiciones climáticas variables. Los resultados mostraron una mayor eficiencia fotovoltaica, acercándose a la potencia máxima del panel con un aumento del 8% al 9%. El estudio destaca el potencial práctico de esta tecnología para mejorar la eficiencia de los sistemas solares y expandir su aplicación en entornos con altas temperaturas y radiación, apoyando el desarrollo a largo plazo de soluciones de energía limpia. Es un método eficaz para mejorar la eficiencia de los paneles, allanando el camino para tecnologías avanzadas de energía solar.
Palabras clave: Energía solar, Revestimiento termorreflectante, Panel policristalino, Eficiencia fotovoltaica, Diseño multicapa.

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https://doi.org/10.24275/rmiq/IE25590
ISSN:1665-2738, *issn-e*: 2395-8472

1 Introduction

Solar energy is becoming one of the most prominent environmentally friendly renewable sources (Maka & Alabid, 2022). It provides practical solutions to address the world's environmental and economic challenges. Solar panels play a key role in converting solar energy into electrical energy (El Hammoumi *et al*., 2022). With the advancement of technology and the growing interest in renewable energy sources, it has become necessary to understand the impact of the nature of these materials on the performance of solar panels, especially under different natural conditions such as high temperatures. This challenge affects the efficiency of solar panels in hot regions (Agyekum *et al*. 2021). High temperatures decrease the efficiency of these panels due to the negative impact of heat on their photovoltaic efficiency (Li *et al*. 2023). Solar panels must be made of materials that allow the free movement of electrons to convert light into electricity (Dambhare et al,2021). When light falls on the solar panel, the material absorbs some of it. This excites the electrons, which in turn move, triggering chemical reactions that generate electricity. However, if the material becomes too hot, the electrons stop functioning properly, and the energy production system collapses (Vaillon *et al*.,2018). Cell efficiency declines almost linearly with temperatures above 25°C (~0.3%/°C for silicon and ~0.5%/°C for cadmium telluride) (McCandless *et al*., 2011), (Sachenko *et al*., 2019). Consequently, standard test conditions are set at 25°C, the cell temperature, and the module's open-circuit voltage (the cell voltage when no current is drawn from the module) (Mavromatakis et al, 2014). However, solar panel temperatures on sloping residential roofs can significantly exceed standard test conditions. Solar photovoltaic modules lose their efficiency due to unwanted heating. Part of the solar spectrum is absorbed, causing them to heat up (Santhosh et al,2016) . Standard single-junction crystalline silicon panels reach operating temperatures between 45°C and 62°C. This thermal effect degrades output and can lead to cell cracking as large temperature gradients develop within the device. There are models and experimental correlations linking increased temperature to efficiency loss. Several past studies have addressed the effect of temperature on the efficiency of photovoltaic cells (Sun *et al*.,20222),(Murtadha *et al*.,2022),(Jathar et al,2023).Given the threat of global warming, scientists are proposing chemically treating solar panels to increase their efficiency, allowing them to avoid overheating and efficiency loss (Xu *et al*.,2022) . One option is to use copper, abundant in the Earth, to manufacture the solar cells in the panels. Copper absorbs sunlight better than the more expensive and widely used silicon. Unfortunately, the Earth is also rich in heat, which weakens copper's ability to absorb sunlight. By adding a thin, inexpensive, heat-reflecting layer to solar cells, sunlight is absorbed, and heat is reflected (Wette *et al*.,2019). As a result, the panel can generate more electricity from the absorbed sunlight. Copper is one of the few materials that best meets the theoretical limits for light absorption. A drawback of copper is that it is not cheap compared to the price of materials like silicon, which is commonly used in solar panels (Dias *et al*.,2022). Although it does not absorb sunlight as efficiently as copper, it is cheap. Reducing the use of cheaper materials in commercial panels means producing less electricity for the same amount of sunlight. On the other hand, this would mean using more hazardous chemicals to manufacture silicon solar panels. In this context, using heat-reflective coatings is a promising innovation that contributes to reducing the surface temperature of solar panels, enhancing their performance, and extending their lifespan (Sarkın *et al*.,2020). Heat-reflective coatings are advanced materials used to reduce heat absorption by reflecting a large portion of the sun's radiation, especially infrared radiation, which is the primary support for surface heating (Shanmugam *et al*.,2020). This coating has optical properties allow it to reflect harmful radiation while allowing visible light to pass through to the solar cells. It does not negatively affect the amount of light needed for energy generation (El-Khozondar *et al*.,2021). In hot regions such as Algeria, solar radiation is high year-round, ranging from 800 W/m^2 to 1200W/m^2. Significant increases in electrical output can be achieved (Nia *et al*.,2013). Furthermore, using smart coatings improves performance and reduces the need for dynamic cooling systems, saving operating costs and making systems more maintainable and naturally attractive (Kausar,2018). Smart coatings are more practical and wise than other technical solutions, such as water-cooling systems or dynamic-mechanical technologies. Heat-reflective coatings are an innovative solution to address solar panel efficiency challenges in hot climates (Adak *et al*.,2022). Some studies have shown that heat-reflective coatings improve solar panel efficiency by reflecting infrared radiation and sunlight, reducing heat absorption. This has improved solar panel efficiency, as high temperatures negatively impact energy generation (Law *et al*.,2023),(Adak *et al*.,2020),(Ji *et al*.,2022). In a study conducted by Yu *et al*.., aspects of coating design, process control, and scientific characterization (regarding microstructure and spectral properties) were addressed (Yu *et al*.,2020). In another study, novel copper ferrite and polyaniline (PANI) nanocomposites were studied using state-of-the-art chemical and experimental methods to use in solar collector applications. The results showed a strong solar absorption of 95% within the apparent range and a 1% reduction in thermal emissivity, giving them an ultrahigh solar selectivity of up to 96.28%

(Mostafa et al,2024). Various types of coatings are applied in this field, such as ceramic coatings deposited by vacuum evaporation or spraying. The absorption of solar radiation in ceramic coatings originates from the metallic component, typically nickel and chromium. At the same time, an insulating material such as alumina controls the reflectance of infrared radiation (Winnicki *et al*.,2021). Black chrome absorbers are typically deposited on a stainless steel substrate and generally have an absorptivity of 95% or more and a low thermal emissivity of between 5% and 12%. Paint coatings, also known as organic or composite coatings, are widely used commercially. Various companies are developing various paint coating technologies (Nazari *et al*.,2020). The technology developed specifically for solar collectors involves complex equipment and processes that can apply a nanocomposite coating of heat-resistant metal oxide nanoparticles embedded in an electrochemically bonded polymeric material (Khan *et al*.,2023). Not all of these technologies have been sufficiently proven for large-scale solar collector projects. This new technology can manufacture highly selective Cr-Ni-Steel sheets with a solar absorption of 95.57 ± 1.20% and a low thermal emittance of 4.94 ± 0.91%.

This study used a three-layer experimental copper, titanium dioxide, and aluminum oxide coating. These coatings were deposited using a magnetic sputtering technique. This produced thin, homogeneous layers that ensured high stability on the target surface, significantly increasing the panel's efficiency. The results demonstrated that this coordinated formulation could lower the panel temperature, representing a breakthrough in improving panel production efficiency and extending its operational life. It embodies a futuristic vision in materials construction and mechanical innovations. It contributes to the sustainability of energy projects and electronic systems by improving thermal performance and reducing reliance on traditional cooling methods.

2 Materials and tests

Solar panels are an efficient form of renewable energy, using sunlight as a natural energy source to produce electricity (Deshmukh *et al*.,2023). Due to the increasing use of solar panels, research, and development of their efficiency through nano-coating is constantly being conducted. The global acceptance and commercialization of solar panels have expanded the market size and encouraged the rapid growth of the panel industry. Solar panels are primarily made of glass or plastic, 0.3 to 0.5 mm thick, and are reinforced or coated with an anti-reflective (AR) coating. This coating is known as UV-visible cutting technology (Belançon *et al*.,2023).

Heat-reflective coatings are typically arranged in layers consisting of three main components (Mara *et al*.,2023):

2.1 *Reflective metal layer*

This is the basic fabric and typically uses metals such as aluminum (Al), copper (Cu), and silver (Ag). These metals have high reflectivity in the infrared range. They reflect this thermal radiation and reduce heat transfer to the inner layers or the surface used for photo conversion.In this research, a 120-nm-thick copper metal is used.

2.2 *Intermediate layer*

This insulating fabric with a high refractive index creates an impedance effect that improves the system's reflectivity in the infrared range without affecting the transmittance of visible light. In this work, we add titanium dioxide (TiO_2) and silicon dioxide (SiO_2) with a thickness of 90 nm.

2.3 *Protective outer layer*

The materials used in this layer are thin polymeric or ceramic materials or even some oxides. Within this layer, aluminum oxide (Al_2O_2) is used with a thickness of 90 nanometers.Figure 1 shows a cross-section of the coating used.

Magnetic sputter coating is an advanced technique for depositing thin layers of materials on various surfaces. It relies on a technique known as physical vapor deposition (PVD), where a magnetic field generates plasma in a vacuum chamber. The plasma ionizes the target material, causing it to disperse or vaporize and be deposited on the substrate (Pošković *et al*., 2021).

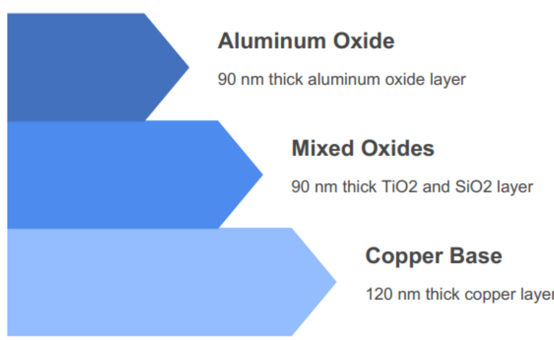

Figure 1 . Structure of the paint components.

Table 1. Polycrystalline solar panel characteristics.

Electrical Data		Thermal Characteristics	
Power	270W	Nominal Operating Cell Temperature (NOCT)	45°C±2°C
Maximum Power Voltage-Vmp(V)	30.7V	Temperature Coefficient of Voc	-0.32%/°C
Maximum power current-Imp(A)	8.79A	Temperature Coefficient of Isc	0.05%°C
Open Circuit Voltage-Voc(V)	37.9V	Temperature Coefficient of Pmax	-0.39%/°C
Short Circuit Current-Isc(A)	9.76A	Operational Temperature	-40~+85°C

2.4 *Polycrystalline solar panel*

The thermal and electrical characteristics of this panel are shown in Table 1.

Summary of the solar panel's electrical and thermal characteristics:

Electrical characteristics:

- The maximum control power (Pmax) is 270 W, the highest output of the panel.
- The maximum control voltage (Vmp) is 30.7 volts, designed for optimal performance.
- The maximum control current (Pixie) is 8.79 amps when operating at full power.
- The maximum open-circuit voltage (Voc) is 37.9 volts, the maximum voltage when no charge is present.
- The short-circuit current (Isc) is 9.76 amps when the circuit is fully connected.

Thermal characteristics:

Apparent operating temperature (NOCT): 45°C ± 2°C, representing the panel's temperature under normal conditions.

Thermal voltage coefficient (Voc): indicating a decrease in voltage with increasing temperature. Efficiency decreases by 0.32% at a temperature of 25°C.

The thermal voltage coefficient (Isc) is 0.05%/°C, indicating a decrease in current with temperature. The Pmax temperature coefficient is -0.39%/°C, demonstrating a decrease in control as the temperature increases. The operating temperature range is between -40 and +85°C, demonstrating the board's ability to withstand harsh conditions. Performance Testing: Efficiency is negatively affected by temperature. The board is designed for medium-performance systems that can withstand harsh operating conditions.

2.5 *Mathematical equations used*

2.5.1 *Calculating the electrical power output of a solar panel (P)*

$$P = V \times I \tag{1}$$

P: Electrical power output (Watts).V: Electrical voltage (Volts). I: Electrical current (Amperes).

$$P_{actual} = P_{stc} \times \left(\frac{G}{1000}\right) \times [1 - \gamma \times (T - 25)] \tag{2}$$

$\mathbf{P_{actual}}$: Actual power produced by the solar panel (watts).$\mathbf{P_{stc}}$: Rated power under standard test conditions (STC), typically at 1000 W/m^2 irradiance and 25°C.**G**: Solar irradiance incident on the solar panel (W/m^2). γ: Temperature effect coefficient on power, a constant that determines the change in performance per degree of temperature increase (usually a negative value).**T**: Actual solar panel temperature (°C).**25**: Standard temperature under standard test conditions (°C).

This equation is important because it takes into account the true impact of natural conditions on the solar panel, which makes a difference in design optimization and performance prediction in many situations (Pervez *et al.*,2023).

2.5.2 *The effect of temperature on efficiency*

Efficiency is affected by temperature according to the following equation:

$$\eta = \eta_{STC} \times (1 - \beta \times (T - T_{STC}) \tag{3}$$

Where:

$\eta_{\mathbf{STC}}$: Efficiency at Standard Test Conditions. β: Temperature effect coefficient on efficiency (%/°C).$\boldsymbol{T}$: Solar panel operating temperature (°C).$\boldsymbol{T}_{\mathbf{STC}}$: Standard temperature (typically 25°C).

2.5.3 *Calculating the current and voltage generated by the panel*

The resulting current depends on solar radiation:

$$I = I_{sc} \times \frac{G}{G_{stc}} \tag{4}$$

The output voltage is affected by temperature:

$$V = V_{oc} \times (1 - \gamma \times (T - T_{STC}) \tag{5}$$

Where:

$\mathbf{I_{SC}}$: Maximum current at standard conditions.$\mathbf{G_{stc}}$: Irradiance at standard conditions.$\mathbf{V_{OC}}$: Open-circuit voltage at standard conditions. γ: Temperature coefficient on voltage (%/°C).

2.6 Tests

To comprehensively evaluate the performance and effectiveness of the heat-reflective coated panel, we conducted tests that included thermal aspects.

2.6.1 Surface temperature measurement

Thermal sensors are used to monitor the temperature of the coated panel compared to the uncoated panel. Figure 2(a) shows the apparatus used to measure air temperature using an HTC-1 thermo-hygrometer conforming to ASTM E1251 standard (Immanuel & Panigrahi,2015). Figure 2(b) shows the irradiance value measured using a Fluke 572-2 infrared thermometer conforming to ASTM E220 (Dillingh *et al*.,2021). The researchers conducted the measurement on March 17, 2025. The measurement period lasted 8 hours, from 11:00 a.m. to 6:00 p.m. This study aimed to investigate the effect of exposure time on the efficiency of the coated solar panel. A Fluke FLK-IRR1-SOL solar radiometer was used to measure the solar radiation. The device was connected to a precision sensor conforming to ASTM E892 (Gueymard *et al*.,2002). Figure 3 illustrates the device used for the measurement. The temperature was measured on the sun-exposed side and the unexposed back side. The measurement results for both panels are shown in Figure 4.

The HT M70 is used to measure various electrical variables, such as DC and AC voltage, frequency, resistance, and solar radiation, making it suitable for electrical engineers and professionals in the fields of solar energy and electrical systems.

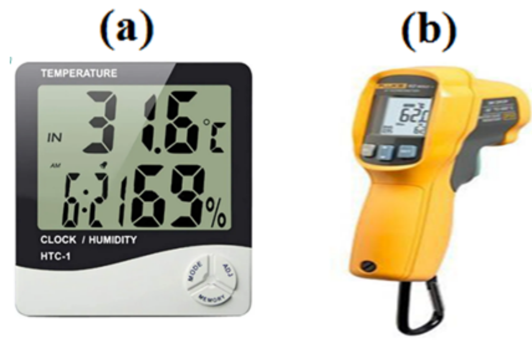

Figure 2.(a) digital thermometer, (b) infrared thermometer.

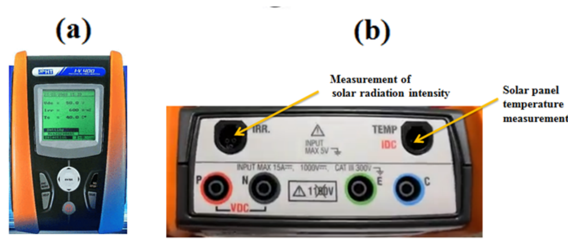

Figure 3. Solar panel-connected solar radiation meter.

Figure 4(a) shows the temperature difference between the coated panel's ambient and front and back surfaces. Figure 4(b) shows the temperature difference between the uncoated panel's ambient and front and back surfaces. Figure 5 represents the change in solar radiation value during the experiment. The initial analysis shows that the amount of solar radiation is low at the beginning of the day and then increases with the increase in temperature until it reaches its peak at 14:00 PM. Then it decreases.

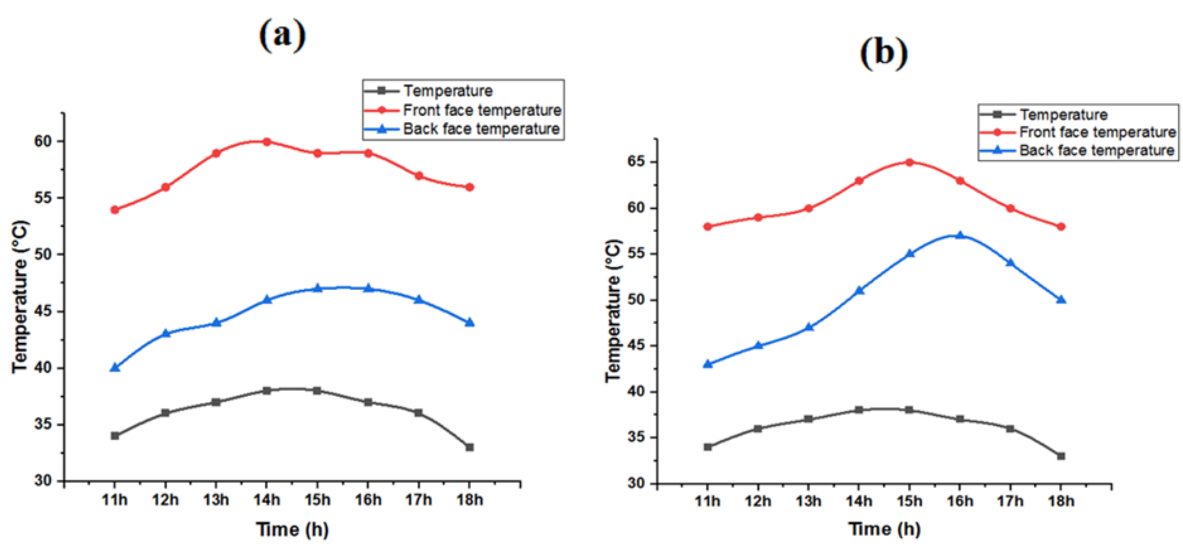

Figure 4. (a) Coated solar panel, (b) Uncoated solar panel.

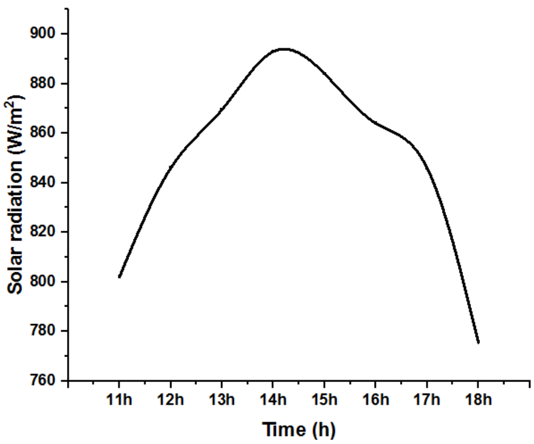

Figure 5. Change in solar radiation value during the experiment.

Meters play a pivotal role in evaluating the performance of photovoltaic cells. These devices help determine solar radiation levels and quantify solar energy changes, enabling researchers to evaluate cell performance under various conditions. Measuring cell temperature also enables us to monitor the effects of thermal energy on efficiency, as high temperatures lead to lower voltage and conversion yield. Measuring current and voltage also contributes to analyzing the electrical performance curve, enabling us to determine optimal operating points. These devices provide accurate data that can be used to analyze energy loss due to shade, dust, or weather changes, contributing to the development of plans and improved maintenance.

Analyzing the two figures,(Figure 4(a),4(b)) the effect of the coating can be seen by comparing the temperatures recorded for the coated panel with those of the uncoated panel. A closer examination follows:

2.6.2 Coated panel

The difference between the ambient and front surface temperatures ranged from 20 to 27 degrees, while the temperature between the front and back surfaces ranged from 11 to 15 degrees.

2.6.3 Uncoated panel

The difference between the ambient and front surface temperatures ranged from 6 to 17 degrees, while the temperature between the front and back surfaces ranged from 6 to 14 degrees.

For example, at 2:00 PM, the coated panel recorded a front temperature of 59°C, compared to 65°C .for the uncoated panel, representing a discrepancy of 6 degrees Celsius. At most hours, the difference between the two panels is approximately 1 to 6 degrees on the front side, with the uncoated panel tending to record higher temperatures as solar radiation increases. However, the difference on the back surface ranges from 2 to 10 degrees. From this, the coating reduces heat exchange from the front to the back surface, as the coating maintains lower temperatures than the uncoated panel. This is consistent with previous research examining the effect of coatings on reducing heat transfer (Mozumder *et al*.,2019),(Sharma & Chandra,2025),(Atkinson *et al*.,2015).

Reflective coatings play a vital role through their high reflectivity toward the sun, reducing the total radiation the panel absorbs the panel absorbs (Alshammari *et al*.,2024). When a large amount of incident radiation is reflected, the thermal mass on the front surface decreases, thus reducing the total heat exchanged to the back surface through thermal conduction(Alshammari *et al*.,2024). This effect is most pronounced during peak heat hours (such as 3:00 PM - 4:00 PM) when solar radiation is high, leading to greater temperature differences.

2.6.4 Thermal productivity

Using coatings on solar panels, or even in building materials, contributes to lower surface temperatures, significantly impacting operational efficiency and component life (Fang *et al*.,2024). Lower temperatures reduce thermal stress, which can lead to fabric damage over time. Reference data show that reflective coatings positively reduce the temperatures of solar panels' front and back surfaces compared to uncoated panels. The higher the solar radiation level, the greater the differences between panels, confirming that reflecting more radiation reduces heat absorption and transfer within the panel. This effect makes smart coatings a preferred option for improving thermal performance and preventing overheating, which can affect the efficiency of panels and materials used in engineering and energy applications (Balal *et al*.,2024). We are conducting further experiments to understand the effects of temperature, radiation, and panel productivity.

Tests will be conducted on March 19, 20, and 21, 2025. A study was conducted at the Materials Research Facility at the University of Ghardaia, southern Algeria, to test the performance of two polycrystalline solar panels. The first panel was unmodified, while the second panel was coated with a 390-nanometer layer of this coating within the concentrated spectral range and left to dry for 72 hours. Figure 6 shows the temperature changes in the external medium. Both panels were exposed to direct sunlight. Solar radiation and temperature were recorded at the test site from 9 a.m. to 6 p.m. throughout the three days. The power of both panels was also measured during the study. Figures 7 and 8 illustrate the power changes for both panels. Table 2 represents the change in solar radiation value during the experimental days.

Table 2. Change in solar radiation value during the experimental days.

Time (h)	March 19, 2025	March 20, 2025	March 21, 2025
	Solar radiation (W/m^2)		
9h	723,85	653,8	677,15
10h	747,2	677,15	700,5
11h	793,9	723,85	770,55
12h	863,95	770,55	840,6
13h	910,65	793,9	887,3
14h	957,35	863,95	980,7
15h	934	910,65	957,35
16h	910,65	863,95	934
17h	887,3	840,6	863,95
18h	840,6	817,25	793,9

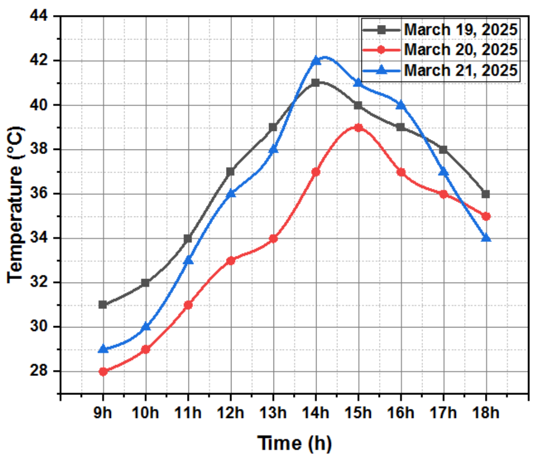

Figure 6. Temperature changes in the external environment.

Table 2 represents the variation in solar radiation throughout the experiment. It is noted that radiation increases throughout the day from 11 AM to 2 PM, reaching its highest levels between 1 PM and 2 PM. Radiation steadily declines from 2 PM to 6 PM, with values declining completely with sunset.

Examining the daily peak radiation, we find that the peak occurs between 1 PM and 3 PM when the temperature is at its highest. For example, on March 21, the radiation reaches 980.7 W/m^2 at 2 PM, the highest recorded estimate.

Some variations can be observed between days, with radiation being higher on March 21 than on the 19th and 20th. This is related to climatic conditions and the sun's altitude. Despite the slight variations, the prevailing solar radiation curve follows the same behavior: it rises in the morning, peaks in the evening, and gradually decreases until evening. This information can be used to evaluate the performance of solar systems during these periods. For example, the best time to take measurements is between 12:00 and 3:00 PM, when the radiation concentration is at its highest.

Figure 6 represents the change in air temperature during the experiments. Temperatures typically start low in the early morning and rise steadily due to increased solar radiation from 12 noon to 3 PM: Solar radiation peaks, accompanied by the highest temperatures of the day. The post-peak period is from 3 PM to 6 PM when temperatures slowly decline as solar radiation decreases. From 6 PM to nightfall: Temperatures drop primarily due to the loss of radiant heat from the ground and the lack of a consistent heating source such as daylight.

On March 19, temperatures ranged between 31°C and 41°C, while on March 20, temperatures ranged between 28°C and 39°C. On March 21, temperatures ranged between 29°C and 42°C, making this the hottest day of the experiments.

2.7 The effect of solar radiation and temperature on the power decrease of a polycrystalline panel (270W)

2.7.1 Solar radiation

Radiation is the primary energy source, with the amount of power generated increasing with increasing radiance (for example, on the 21st, at 2:00 p.m., the radiance was 980 W/m^2, with a power of 256.48 W). When the radiance value decreases (for example, on the 20th, at 9:00 a.m., the power was 653.8W/m^2, with a power of 183.77W), A decrease in energy production is observed due to a decrease in solar radiation value. These results are consistent with previous studies that examined the effect of solar radiation on the ability to control panel power (Kurpaska *et al*., 2018),(Chikate *et al*., 2015).

2.7.2 Temperature

Temperature negatively affects the efficiency of solar panels. According to the criteria specified in Table 1, the efficiency decreases by approximately 0.32% for each degree Celsius above 25°C. This is typically observed on the 21st, at 2:00 p.m., with a temperature of 42°C (17 degrees larger). The decrease in productivity was between 5.1% and 8.5%, and the power loss was between 13.77W and 22.95W.We can conclude that high temperature affects the efficiency of the solar panel.This is consistent with previous research in this field (Abdel-Aziz *et al.*, 2025),(Libra *et al.*, 2021).

2.7.3 Comparison of energy yield with maximum power (270 W)

During periods of high irradiance (980.7W/m^2) and high temperatures (42°C), the efficiency reaches 95% of the maximum power (256.48/270) W. During periods of low irradiance (653.8W/m^2) and moderate temperatures (28°C), energy yield drops to 68% (183.77W/270 W), underscoring the dominance of radiation and temperature in controlling energy production (Hasan *et al.*,2022),(Mohammad & Mahjabeen, 2025). Solar radiation is a determining factor in the total energy output, while high temperatures cause a slight decrease in yield (3-9% depending on conditions). To improve yield, optimizing the placement of panels to absorb maximum radiation and providing the necessary ventilation to reduce the heat impact is recommended.

3 Discussion and analysis

Figures 7 and 8 show the changes in the energy yield of the two solar panels(normal and coated)over the three test days.

Figure 7 shows the changes in the energy yield of the uncoated polycrystalline solar panel. On March 19, 2025, the temperature changed from 31°C to 41°C, and the solar irradiance ranged between 724 W/m^2 and 957 W/m^2. The panel's energy yield decreased between 6.5% and 29%, with the power output starting at 191.47 W and reaching a maximum of 252 W.

During the morning, the efficiency decreases (191.47W at 9:00 a.m.) due to the decreasing sun angle and solar irradiance.

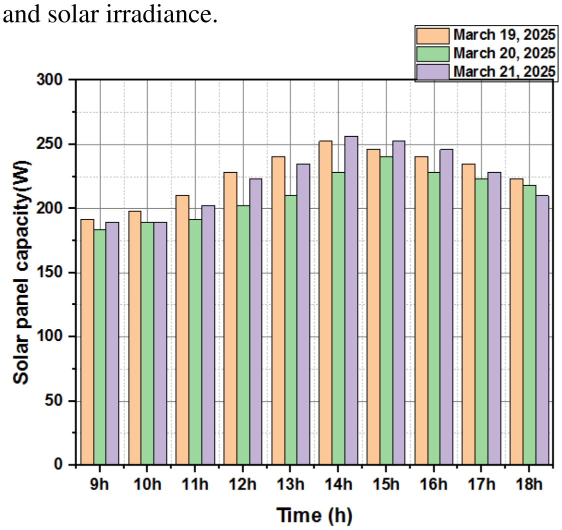

Figure 7. Change in the energy production value of the coated solar panel.

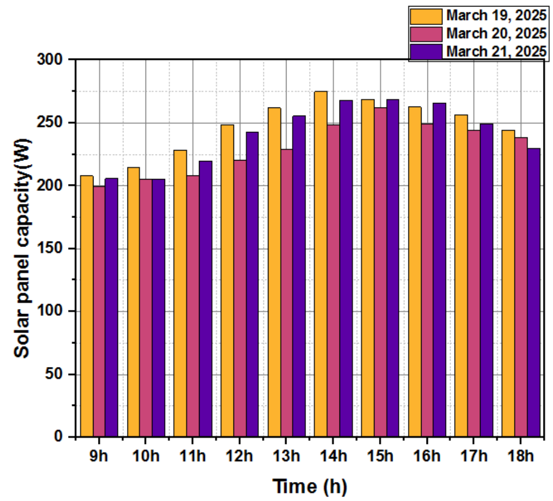

Figure 8. Change in energy production value of uncoated solar panel.

As the day progresses, the output gradually increases, reaching its peak at noon12:00 p.m. (252W at 2 p.m.), when the sun is high in the sky, and the irradiance is at its highest. After that, performance gradually declines (246W at 3:00 p.m. and 223.28W at 6:00 p.m.) due to the decreasing sun angle and the effect of shadows.

On March 20, 2025, the temperature changed from 28°C to 39°C, and solar radiation ranged between 653W/m^2 and 911W/m^2. The decrease in panel power ranged between 11% and 32%, with power output starting at 183W and reaching a peak of 241W.

The same pattern was observed: the lowest panel power output was at 9:00 a.m. (183W), peaking at 3:00 p.m. (241W) and then declining at 6:00 p.m. (218W).

On March 21, 2025, the temperature changed from 29°C to 42°C, and solar radiation ranged between 677W/m^2 and 980W/m^2. The decrease in panel power ranged between 5% and 30%, with power output ranging from 189 watts to a peak of 256 watts.

Figure 8 represents the change in power output of a coated polycrystalline solar panel.

On March 19, 2025, the temperature changed from 31°C to 41°C, and the solar radiation ranged between 724W/m^2 and 957 W/m^2. The decrease in panel power ranged between 0.6% and 23%, with power output starting at 207W and reaching a peak of 268 W.

On March 20, 2025, the temperature changed from 28°C to 39°C, and the solar radiation ranged between 653 W and 911 W/m^2. The panel power decreased between 2.9% and 26%, with power output starting at 199W and reaching a peak of 262W.

On March 21, 2025, the temperature changed from 29°C to 42°C, and the solar radiation ranged between 677 W/m^2 and 980 W/m^2. The panel power decreased between 0.7% and 24%, with power output starting at 206W and reaching a peak of 268W.

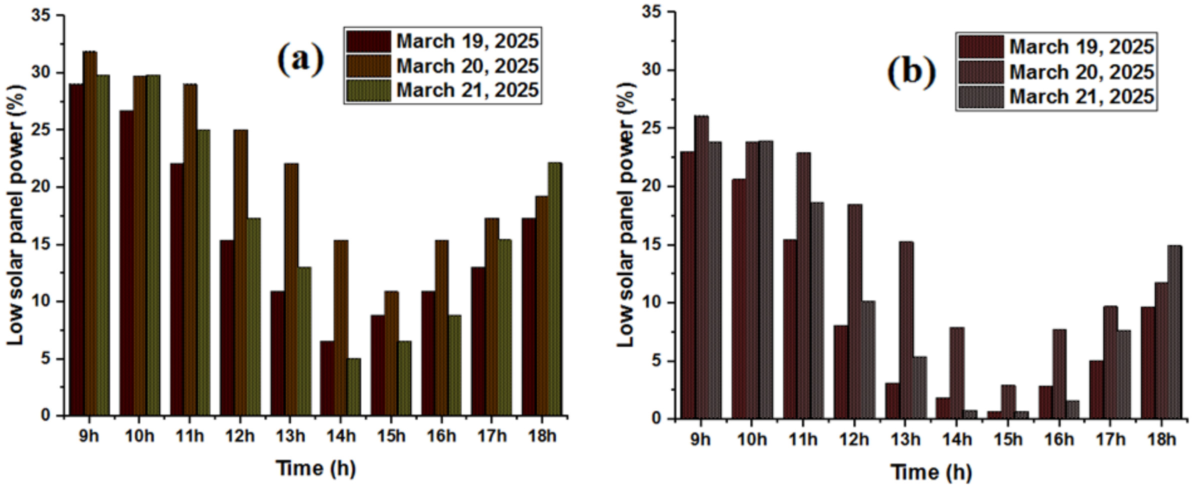

Figure 9. Energy loss in solar panels.

3.1 *Energy loss in solar panels*

Analyzing Figure 9(a), which shows the power loss on the uncoated panel during the test days, it is noted that the power loss rate is greatest during the early morning hours. For example, at 9:00 a.m., a 29% decrease is observed on March 19, 31% on March 20, and 29.8% on March 21. This is typically explained by the lower solar radiation at sunrise. Over time, the power loss decreases with increased power generation until the peak hours between 2 p.m. and 3:00 p.m. Then, a rise in power loss is observed until sunset. On March 19, power generation on the uncoated panel started at 71% at 9:00 a.m., then increased to 93.5% at 2:00 p.m. The power loss increased from 6.5% to 29%, then decreased to 82.3%, a decrease of 17.7%. On March 20, the power loss increased from 6.5% to 29%, then decreased to 82.3%, a decrease of 17.7%. The productivity drop ranged from 32% to 11% between 9:00 a.m. and 2:00 p.m., then increased from 11% to 17.3%. On March 21, the same situation recurred, with the solar panel's efficiency ranging from 70% to 95%, with an average power loss of 5% to 30%. A change in productivity was observed after 2:00 p.m. Analyzing Figure 9(b), which represents the power loss within the reflective-coated panel during the test days, it is noted that the power loss rate is higher during the morning hours due to the lower solar radiation. In the experiment on March 19, power generation within the coated panel started at 77% at 9:00 a.m. and then increased to 99.4% at 2:00 p.m. The power loss ranged from 0.6% to 23%. In the experiment on March 20, the power loss ranged between 2.8% and 26% between 9:00 a.m. and 2:00 p.m., then increased from 7.7% to 11%. In the experiment on March 21, the same pattern was observed, with solar panel efficiency ranging between 76% and 99.4%, with power loss ranging from 0.6% to 24%. A change in efficiency was observed after 2:00 PM.

Coated panels have lower output loss than uncoated panels. At all times, the efficiency loss (%) for coated panels is lower than for uncoated panels. For example, on March 19, at 12:00 p.m., the uncoated panel lost 15.40%, while the coated panel lost only 8.04%. At 3:00 p.m., the uncoated panel lost 8.81%, while the coated panel lost only 0.60%.

The highest efficiency loss values are recorded in the early afternoon (9:00 a.m. to 2:00 p.m.) for both types, but the difference between them is clear. In the morning (9:00 a.m. to 11:00 a.m.), the uncoated panel loses approximately 22–29%, while the coated panel loses 15–23%. The values for both types decrease during the evening (1 p.m. to 6 p.m.), but the coated panel maintains its superiority. From this, it can be concluded that smart coatings reduce sunlight reflection from the panel surface, increasing solar energy retention and improving efficiency (Thongsuwan *et al*.,2022),(Alhodaib *et al*.,2024).

Furthermore, the materials used in the coatings help retain heat more effectively, reducing energy loss and providing additional protection against moisture or corrosion, maintaining panel performance over time (Oni *et al*., 2024), Smart coatings transfer heat evenly across the panel surface, reducing heat concentrations that lead to efficiency loss (Elnozahy *et al*., 2024).

3.2 *The relationship between temperature, irradiance, and solar energy generation*

3.2.1 *Effect of solar irradiance*

It is observed that the higher the sun's brightness, the more energy is produced, and this is reflected in increased solar energy generation up to the peak. For example, March 21st saw the highest irradiance (980 W/m^2), which was expected to increase energy generation. However, high temperatures (up to 42°C) negatively impacted conversion efficiency, keeping solar energy generation at 268 watts.

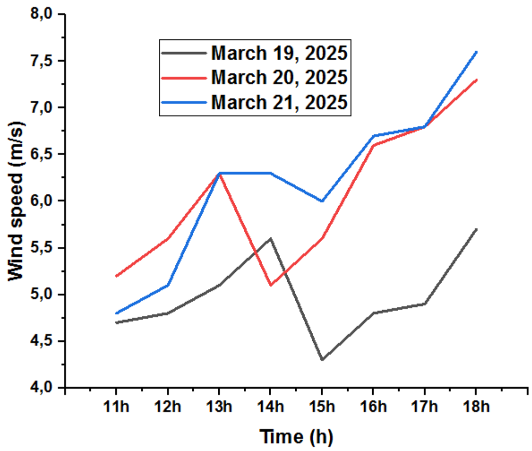

Figure 10. Wind speed change during testing.

3.2.2 *Variation in solar energy generation*

Compared to the uncoated panel, the coated panel produced approximately 15W-22 W more energy, or 5% to 7.4%, despite the variation in irradiance and temperature over the three days. The effects of temperature and irradiance were observed to be different on each day; increased irradiance pushed production to the higher end, while high temperatures negatively impacted efficiency. The coated panel achieved record output (268 W on March 19 and 21, with a slight decrease on the 20th).

Figure 10 represents the variation in wind speed during the three-day experiment.

It is noted that wind speed did not significantly affect the output of the two panels, as the speed generally ranged between 4 m/s and 8 m/s.The nature of the hot region explains this.

3.2.3 *Variation of decrease rates*

The lowest decrease rate (0.6%- 0.7%) reflects ideal conditions in terms of radiation point and energy use without significant thermal impact, while the highest rate (23%- 26%) shows periods when increasing temperature or other factors (such as partial shade or changes in surface point) could significantly decrease energy conversion output.

3.2.4 *Notes on overall performance*

Despite the variability of daily conditions, the ability of the coated panel to achieve maximum output remains constant.

- Increased irradiance leads to increased output. - On March 21 at 2:00 p.m., the solar irradiance was 980.7 W/m^2, resulting in a power output of 268W (99.2% of maximum power) for the coated panel.

This is typically 9% higher than for the uncoated panel. - Compared to the uncoated panel, an improvement in efficiency (from 95% to 99%) was observed, which may reflect improvements in operating conditions or panel quality. Decreased irradiance reduces power output: On March 20 at 9:00 a.m., the solar irradiance was 653.8 W/m^2, resulting in a power output of 199.39 W (73.8% of maximum power).

3.2.5 *Effect of temperature on efficiency*

The panel efficiency decrease ranged between 5.1% and 8.5%, with an estimated power loss ranging from 13.77W to 22.95W. For the coated panel, at 2:00 p.m. on March 21, output increased from 256.48Wto 268.02 W(an increase of 4.5%). It is noted that solar radiation remains the most important factor in output, as its increase is closely related to the increase in generated power. This is generally consistent with previous studies that examined the effect of solar radiation on solar panel efficiency (Akhlaghi *et al*., 2025);(Darjay *et al*.,2025). High temperatures cause a decrease in output, but this effect is limited for both panels (3%-9%, depending on the conditions). It is noted that the coated panel provides greater power output than the uncoated panel at different times of the day.

3.3 *Explanation of the effect of heat-reflective coating*

3.3.1 *Reducing panel temperature rise*

It is well known that solar panels are negatively affected by high temperatures. High temperatures lead to a decrease in voltage and conversion efficiency due to the negative temperature coefficient. Heat-reflective coatings reflect a portion of the thermal radiation (especially in the infrared range) and trap it for some time, reducing the heating of the panel surface. As a result, the coated panel maintains a relatively low operating temperature, minimizing the impact of heat loss on photovoltaic performance.

3.3.2 *Stability of performance over time*

Over a day, and with changes in irradiance, temperature, and wind speed, the coated panel provides consistent performance, showing a positive difference from the conventional panel most of the time. This indicates that the coating technology is beneficial at high temperatures and operates in low irradiance conditions, maintaining consistent system efficiency.

3.4 *Natural factors and their combined effect*

3.4.1 *Solar radiation*

As solar irradiance increases, power output increases; however, a coated panel benefits from the radiation while reducing the effect of rising temperatures, resulting in increased power generation.

3.4.2 Temperature

A conventional panel is subjected to greater thermal stress, decreasing efficiency. Instead, the coating reduces this effect by reducing heat absorption. This can be demonstrated in relative variations; as the temperature difference increases, the energy output remains approximately constant, demonstrating the effective portion of the coating.

4 The importance of coating materials

Coating additives significantly improve solar panel efficiency by reducing the effect of temperature rise, bringing the panel closer to achieving its maximum potential under harsh operating conditions. Our experimental results indicate that the relative variation in efficiency typically ranges between 8% and 9% over most periods, demonstrating the coating's effectiveness in maintaining consistent and extended performance under high irradiance, high temperatures, and moderate wind speeds.

5 Future development

Future research in this area includes examining the temperature coefficient and its effect on the coating. Temperature variations on the panel surface (rather than the ambient temperature) can be measured to obtain more accurate information about the coating's effect. Conversely, testing coating efficiency with different solar panel models can reveal options that may increase system performance under certain climatic conditions. The thickness and nature of coatings can also be varied because they reflect thermal radiation, reducing heat penetration into the inner layers or surface that converts light into energy. This significantly reduces the temperature of the photovoltaic cells, maintaining their efficiency, as high temperatures often lead to decreased performance. Coating thickness is important in determining the efficiency of a solar panel. The thickness in experiments is the value chosen to achieve a homogeneous band with high infrared reflection efficiency. The thinner coating may not form a consistent layer; therefore, it is believed that a thicker coating can lead to increased radiation diffusion. The type of coatings can also be varied because each layer has a specific role in radiation diffusion. Metal reflects infrared radiation while insulating layers form useful barriers that improve the reflection of unwanted spectra while maintaining light transmittance. Therefore, precisely varying the thickness and composition of these layers directly affects the efficiency of the solar panel.

6 Conclusions

This study investigated the effect of applying a heat-reflective coating to two 270W polycrystalline panels and observed improvements in the performance of the coated PV panels. Comparing the plain and coated panels, the study showed that the application of the coating reduced heat absorption, thus lowering operating temperatures. This improved the PV energy conversion efficiency, increasing by approximately 8% to 9%. With an increase in power output of 16W to 22W, this research demonstrates that the multilayer design (120nm-thick copper as an infrared smart layer, in addition to middle and outer layers of titanium dioxide/silicon dioxide and aluminum), improves the stability and performance of PV systems under changing climatic conditions. The research also highlights the importance of controlling thermal and radiative factors to balance low temperatures and essential visible light transmittance in electrical exchange. Based on the experimental results, the heat-reflective coating technology can be considered an effective tool for improving the efficiency of solar panels, opening up prospects for its application in environments with high temperatures and strong solar radiation. Furthermore, this technology serves as a foundation for creating a modern advancement to improve reliance on solar-based energy as a sustainable and successful solution to future energy challenges.

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