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Research Article

Analysis of Solar Panel Surface Thermal Distribution Using Thermal Imaging

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ABSTRACT

This study investigates the temperature distribution across solar cells on the surface of a solar panel, specifically focusing on the effect of anti-reflective coating homogeneity. The research aims to analyze how temperature variations affect power output and performance ratio under high solar radiation and ambient temperature conditions in Baghdad, Iraq. Using a photovoltaic (PV) analyzer and a thermal imaging camera, the study measures the electrical characteristics and thermal distribution of an 80 Wp monocrystalline solar panel. The results reveal a significant decrease in performance ratio as solar cell temperatures rise, with values such as 88.7% at 35.5 W, 85.2% at 40.88 W, and 78.8% at 44.56 W. These findings underscore the importance of maintaining uniform anti-reflective coatings and effective heat dissipation to enhance solar panel efficiency. The study provides valuable insights for optimizing solar panel performance in high-temperature environments and suggests directions for future research on improving thermal management in photovoltaic systems.

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1. INTRODUCTION

The study was conducted in Baghdad, Iraq (latitude: 33.3152° N, longitude: 44.3661° E), a region characterized by high solar irradiance and ambient temperatures. The average solar radiation in Baghdad ranges from 5.5 to 6.5 kWh/m²/day, with ambient temperatures often exceeding 40°C during the summer months. These conditions make Baghdad an ideal location for studying the thermal distribution and performance of solar panels under extreme solar radiation and temperature conditions. Light plays an essential role in sustaining life, as it nourishes plants and animals according to their respective needs. In the context of solar energy, light serves as a vital source for photovoltaic (PV) systems. When light strikes the surface of an object, it is reflected based on the nature of the surface, with varying intensities depending on material properties (Dash et al., 2015). In photovoltaic, however, reflection becomes problematic when light is reflected off the silicon wafer, reducing the amount of incident light available for the photovoltaic effect. Typically, more than 35% of light is reflected from the polished silicon surface (Lim et al., 2013). To improve solar cell performance, effective light management strategies are essential, including the use of anti-reflective coatings and methods to optimize light capture (Fernandez et al., 2021).

1.1 Problem Statement and Objectives

The efficiency of solar panels is greatly influenced by temperature variations across the surface of the solar cells. Non-uniform anti-reflective coatings can cause uneven absorption of solar radiation, leading to localized heating and a reduction in overall performance. This study aims to investigate the thermal distribution across solar cells in a monocrystalline solar panel, with a particular focus on how the homogeneity of the anti-reflective coating affects temperature variations and power output. Additionally, the study assesses the impact of ambient temperature and solar radiation on the performance ratio of the solar panel under real-world conditions in Baghdad, Iraq.

1.2 Literature Review

Recent studies have highlighted the significance of thermal management and anti-reflective coatings in enhancing solar panel performance. An uncertainty analysis of photovoltaic power measurements using solar simulators was conducted, highlighting the effect of temperature on power output (Virtuani et al., 2013). A novel solar PV module model was developed for accurate power prediction under real outdoor conditions, emphasizing the significance of thermal distribution analysis (Kumar et al., 2023). Additionally, maximum power point tracking techniques for optimizing solar photovoltaic power generation were reviewed (Mohanty et al., 2024), while the performance of various solar photovoltaic technologies under comparable outdoor conditions was assessed (Skoplaki et al., 2013). These studies underscore the critical role of temperature control and anti-reflective coatings in optimizing solar panel efficiency. Furthermore, recent advancements in solar panel technology have focused on improving power prediction and performance under diverse environmental conditions. A model accounting for temperature fluctuations and solar radiation variability was

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proposed, enabling improved prediction of solar PV module performance in real-world conditions (Kumar et al., 2023). A comprehensive review of maximum power point tracking (MPPT) techniques was presented, emphasizing their effectiveness in enhancing power generation efficiency under partial shading and temperature variations (Mohanty et al., 2024). The performance of various photovoltaic technologies was compared, highlighting the importance of effective thermal management in high-temperature environments (Skoplaki et al., 2013). Collectively, these studies emphasize the need for advanced thermal management strategies and precise performance prediction models to optimize solar panel efficiency under real-world conditions.

1.3 Role of Anti-Reflective Coatings

Anti-reflective coatings are essential for reducing the reflection of incident light and enhancing the absorption of solar radiation (Shannmugam et al., 2020, Paudyl et al., 2021). The homogeneity of these coatings is particularly important for ensuring uniform temperature distribution across the surface of the solar panel. Non-uniform coatings can cause localized heating, which negatively affects the panel's overall efficiency. Recent advancements in anti-reflective coating technologies, including nanostructured coatings and multi-layer designs, have shown promise in enhancing light absorption and thermal management (Panagea et al., 2014, Minenoto et al., 2007). However, the effect of coating homogeneity on temperature distribution and the performance ratio under real-world conditions continues to be an active area of research (Skolpaki et al., 2008, Hussein et al., 2018).

Approximately 83% of photovoltaic panels are produced for terrestrial applications and typically consist of three layers—a glass cover, the solar cells, and a back sheet—often made from crystalline silicon or alternative materials (Mahdi et al., 2025,Obaid et al., 2024). Cell and module temperatures strongly influence PV system behavior by altering both efficiency and energy output (Hussein et al., 2020). These temperatures depend on the encapsulation materials' heat-dissipation and light-absorption properties, as well as the module's operating conditions (Mohammed et al., 2020, Zhang et al., 2020). Additionally, a panel's electrical performance is shaped by its optical characteristics, which are determined by layer composition, front-glass quality, and the effectiveness of cell coatings (Wang et al., 2022, Garcia et al., 2021). Coating homogeneity further affects temperature distribution across the module: outdoor photo-degradation, the glass cover, and the dark cell surfaces intensify the "greenhouse effect," transferring heat to the airflow around the collector (Rouholamini et al., 2016, Dierauf et al., 2013). Finally, atmospheric factors—such as solar irradiance, ambient temperature, wind speed, and specific installation conditions—directly impact overall panel performance (Ekren et al., 2018, Shanmugam et al., 2020).

2. EXPERIMENTAL

To investigate the temperature distribution across the solar cells in the solar panel and the effect of ambient temperature on the panel's output, an experiment was conducted using a silicon monocrystalline solar panel (Sharp Solar Module-NE-80EZEA). The solar panel was installed at a 30° tilt angle, which is optimal for maximizing solar radiation absorption in Baghdad, Iraq (latitude: 33.3152° N), as shown in Figure 1. The series connection of solar cells used in the panel is illustrated in Figure 2, the electrical characteristics of the solar panel were measured using a photovoltaic system analyzer as shown in Figure 3, which allowed for the measurement of both the solar radiation incident on the panel and the ambient temperature. A remote thermometer was used to measure the temperature of the solar cells within the solar panels, and these measurements were compared with those obtained using an infrared thermal imaging camera (Fluke Type TIS10 9HZ, 80 x 60 resolution, temperature range -20°C to 250°C, 9Hz frame rate, IP54 rating), as shown in Figure 4. The thermal imaging camera allowed for the detection of temperature differences across the solar cells of the photovoltaic module and visualized these variations in a thermal image, providing a clear representation of the temperature distribution on the panel. The technical specifications and measurement uncertainties of the equipment used in this study are summarized in Table 1

Figure 1. The solar panel on the optimal tilt angle

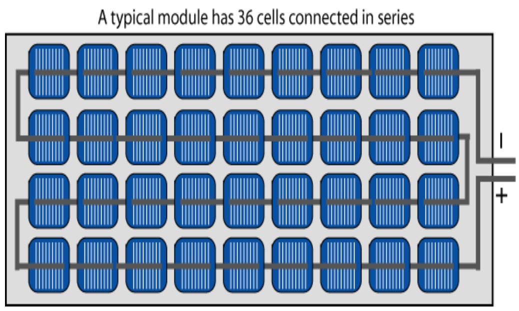

Figure 2. The series connection solar cells in solar panel

Figure 3. PV analyzer

Figure 4. Thermal imaging camera

Table 1. Technical Specifications and Measurement Uncertainties of Equipment Used in the Study

Equipment	Model	Measurement Range	Accuracy	Uncertainty
PV Analyzer	PV A-600	0-1000 W/m²	±2%	±1.5%
Thermal Imaging Camera	Fluke TIS10 9Hz	-20°C to 250°C	±2°C	±1.5°C

3. RESULTS AND DISCUSSION

3.1 Morning Measurements (9:00 AM)

- **Solar Radiation and Temperature Distribution:**
  - At 9:00 AM, the solar radiation was 627 W/m², and the ambient temperature was 36°C, as shown in Figure 5.
  - The temperature of the solar cells ranged between 43°C and 48.6°C, with the highest temperature observed in cell R2C6 (48.2°C) and the lowest in cell R1C1 (43°C).
  - The temperature difference of 5.2°C is attributed to variations in the anti-reflective coating, which affect the absorption of solar radiation.

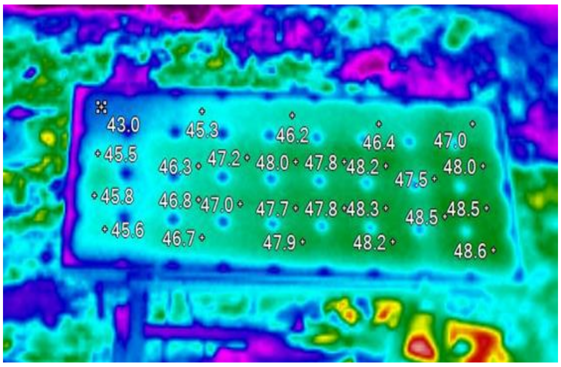

Figure 5. The measuring of solar cell's temperatures by thermal imaging camera at 9 A.m.

- **Electrical Output and Performance Ratio:**
  - The solar panel produced 35.5 W power, with a performance ratio of 88.7%, the relation between power and solar radiation is shown in Figure 6.
  - The lower performance ratio is due to the initial heating of the solar cells and the relatively low solar radiation at this time, The corresponding performance ratio at 9:00 AM is illustrated in Figure 7.

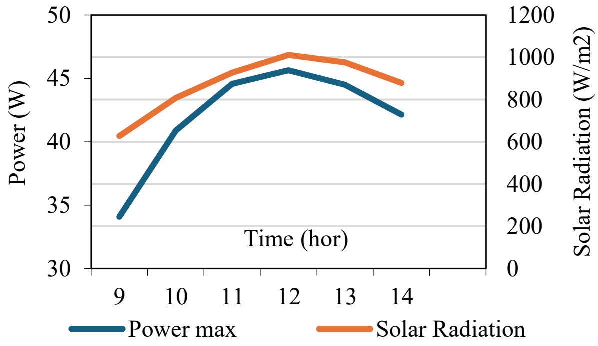

Figure 6. The solar panel's electrical power Synchronized with solar radiation.

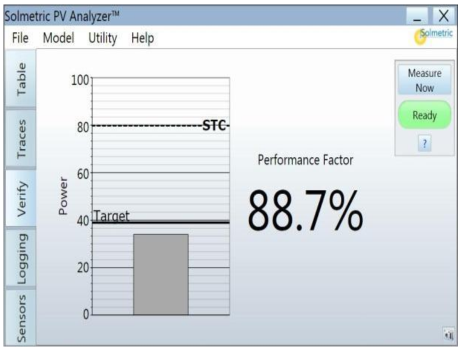

Figure 7. The solar panel's performance ratio at 9 A.m

3.2 Mid-Morning Measurements (10:00 AM)

- **Solar Radiation and Temperature Distribution:**
  - At 10:00 AM, the solar radiation increased to 807 W/m² and the ambient temperature rose to 37°C.
  - The temperature of the solar cells ranged between 52.7°C and 59.5°C, with a maximum difference of 7.3°C.
  - The increase in temperature is due to prolonged exposure to solar radiation and reduced heat dissipation caused by higher ambient temperatures, the thermal image at 10:00 AM is shown in Figure 8.
- **Electrical Output and Performance Ratio:**
  - The solar panel produced 40.88 W power, with a performance ratio of 85.2%.
  - The decrease in performance ratio is attributed to the higher temperatures and increased solar radiation, the performance ratio of the solar panel at 10:00 AM is presented in Figure 9.

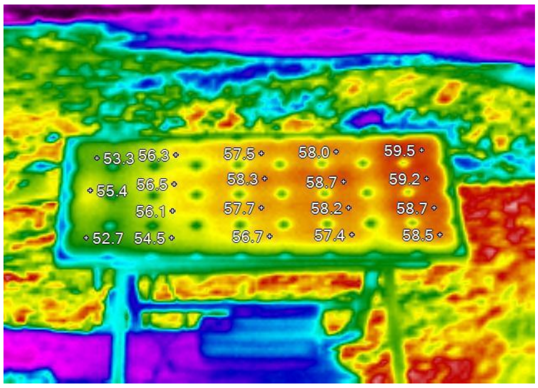

Figure 8. Measuring of solar cell's temperatures by a thermal imaging camera at 10 A.m.

3.3 Midday Measurements (11:00 AM to 12:00 PM)

- **Solar Radiation and Temperature Distribution:**
  - At 11:00 AM, the solar radiation reached 927 W/m² and the ambient temperature was 39.5°C.
  - The temperature of the solar cells ranged between 54.6°C and 64.4°C, with a maximum difference of 9.8°C. The thermal image of the solar cells at 11:00 AM is shown in Figure 10, the performance ratio of the solar panel at 11:00 AM is shown in Figure 11.
  - At 12:00 PM, the solar radiation peaked at 1011 W/m² and the ambient temperature was 41.9°C.
  - The temperature of the solar cells ranged between 51.5°C and 67.8°C, with a maximum difference of 16.3°C. The thermal image of the solar cells at

12:00 PM is illustrated in Figure 12, the electrical characteristics of the solar panel at 12:00 PM are illustrated in Figure 13.

- **Electrical Output and Performance Ratio:**
  - At 11:00 AM, the solar panel produced 44.56 W power, with a performance ratio of 80.3%.
  - At 12:00 PM, the performance ratio decreased to 78.8% despite the higher power output (44.56 W).
  - The significant drop in performance ratio results from the combined effect of high solar radiation and ambient temperature, which increased the temperature of the solar cells and reduced their efficiency, the electrical characteristics of the solar panel at midday are illustrated in Figure 14 and the performance ratio of the solar panel at 12:00 PM is presented in Figure 15

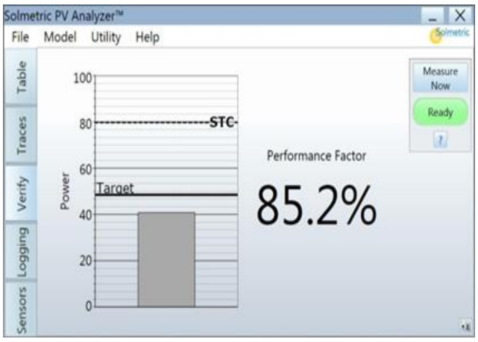

Figure 9. The solar panel's performance ratio at 10 A.m.

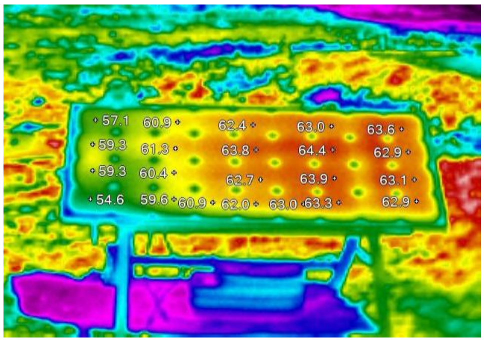

Figure 10. The solar cell's temperature measurements by thermal imaging camera at 11 A.m.

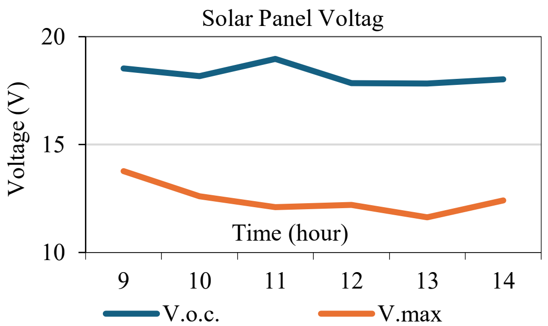

Figure 11. The solar panel's performance ratio at 11:00 AM.

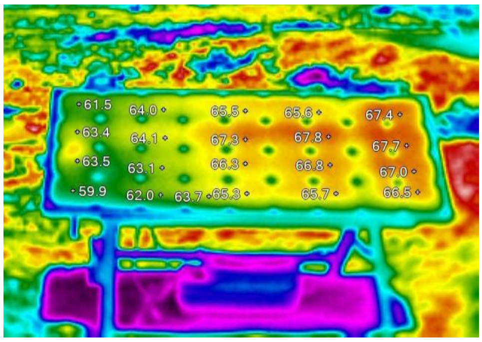

Figure 12. The measuring of solar cell 's temperatures by thermal imaging camera at 12 A.m.

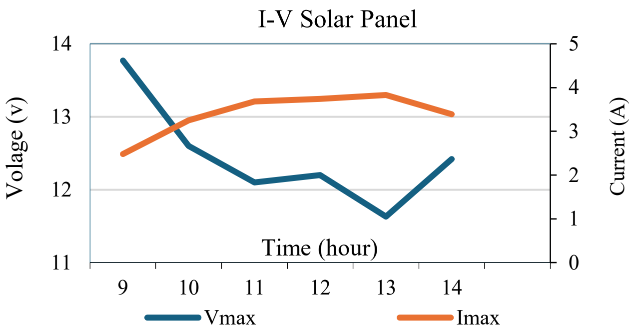

Figure 13. The solar panel's electrical characteristics at 12:00 PM.

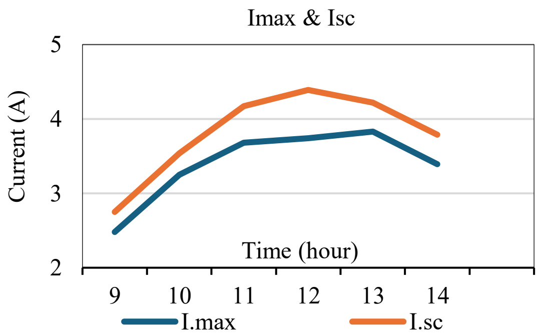

Figure 14. The solar panel's electrical characteristics.

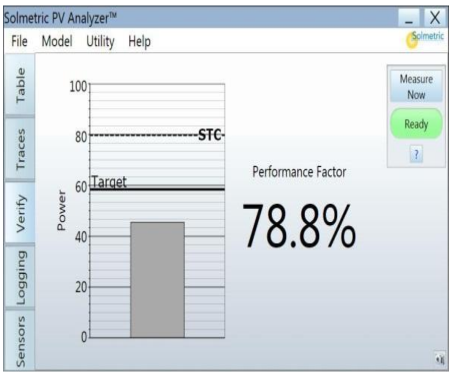

Figure 15. The solar panel's performance ratio at 12 A.m.

3.4 Afternoon Measurements (1:00 PM to 2:00 PM)

- **Solar Radiation and Temperature Distribution:**
  - At 1:00 PM, the solar radiation decreased to 975 W/m² and the ambient temperature was 41.6°C.
  - The temperature of the solar cells ranged between 61.6°C and 66.1°C, with a maximum difference of 4.5°C, The thermal image of the solar cells at 1:00 PM is shown in Figure 16.
  - At 2:00 PM, the solar radiation further decreased to 879 W/m² and the ambient temperature remained at 41.6°C.
  - The temperature of the solar cells ranged between 56.2°C and 60.5°C, with a maximum difference of 4.3°C, the thermal image of the solar cells at 2:00 PM is presented in Figure 17.
- **Electrical Output and Performance Ratio:**
  - At 1:00 PM, the solar panel produced 45.13 W of power, with a performance ratio of 80%, the performance ratio of the solar panel at 1:00 PM is illustrated in Figure 18.
  - At 2:00 PM, the performance ratio increased to 82.9%, as the solar radiation decreased and the temperature of the solar cells began to stabilize, the performance ratio of the solar panel at 2:00 PM is shown in Figure 19.

3.5 Key Trends and Relationships

- **Temperature and Performance Ratio:**
  - The performance ratio of the solar panel decreases as the temperature of the solar cells increases. This is consistent with previous studies, which have shown that higher temperatures reduce the efficiency of solar cells. The relationship between solar cell temperature and performance ratio is illustrated in Figure 20.
- **Solar Radiation and Power Output:**
  - The power output of the solar panel increases with higher solar radiation, but the performance ratio decreases due to the associated increase in temperature. The relationship between solar cell temperature and output power is shown in Figure 21.
- **Anti-Reflective Coating and Temperature Distribution:**
- The non-uniform anti-reflective coating leads to temperature across the solar panel surface. Cells with less effective coatings absorb more solar radiation, leading to higher temperatures and reduced efficiency. The relationship between solar radiation and performance ratio is presented in Figure 22. A summary of the measurements recorded at different times of the day is presented in Table 2.

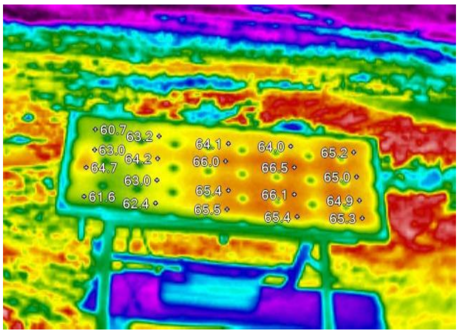

Figure 16. The measuring of solar cell's temperatures by thermal imaging camera at 1 P.m.

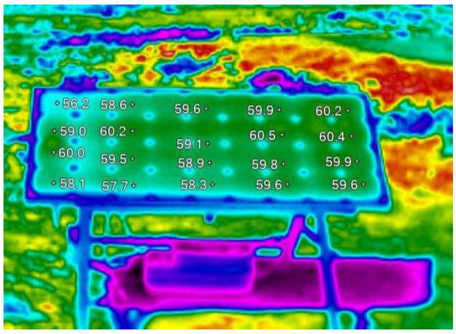

Figure 17. The measuring solar cell's temperatures by thermal imaging camera at 2 P.m.

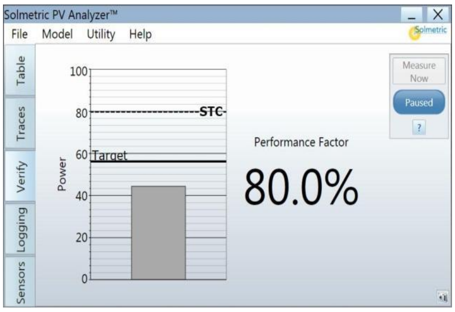

Figure 18. The solar panel's performance ratio at 1 P.m.

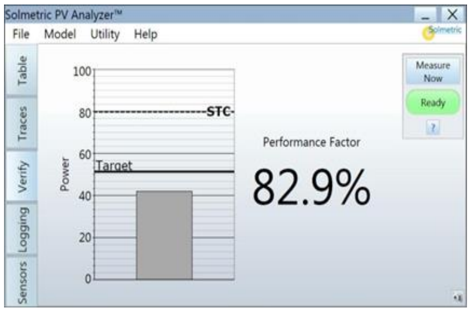

Figure 19. The solar panel's performance ratio at 2 P.m.

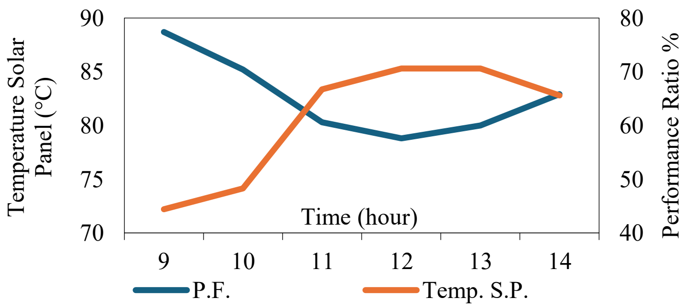

Figure 20. The relationship between temperature and the solar panel's performance ratio

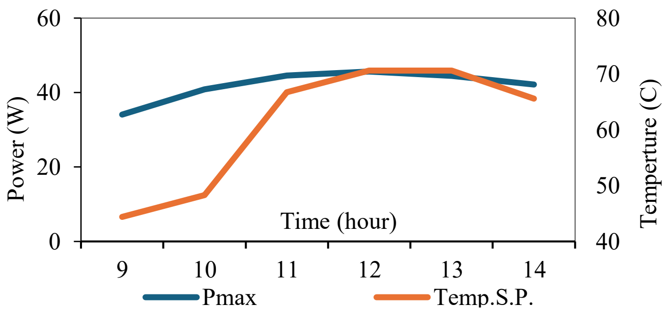

Figure 21. The relationship between temperature and the solar panel's output power

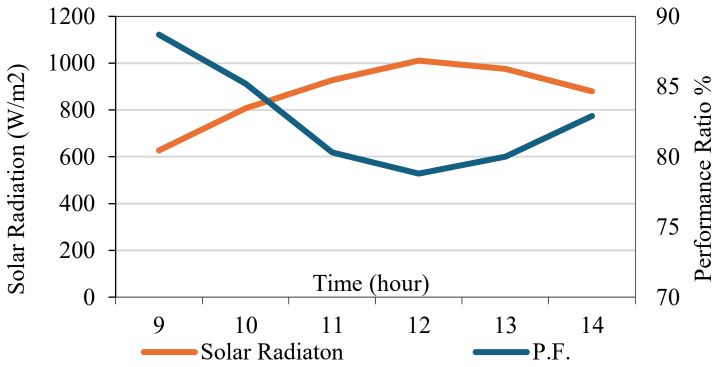

Figure 22. The relationship between solar radiation and the solar panel's performance ratio

Table 2. Summary of Measurements at Different Times

Time	Solar Radiation (W/m²)	Ambient Temp (°C)	Solar Cell Temp Range (°C)	Power Output (W)	Performance Ratio (%)
9:00 AM	627	36	43 - 48.6	35.5	88.7
10:00 AM	807	37	52.7 - 59.5	40.88	85.2
11:00 AM	927	39.5	54.6 - 64.4	44.56	80.3
12:00 PM	1011	41.9	51.5 - 67.8	44.56	78.8
1:00 PM	975	41.6	61.6 - 66.1	45.13	80.0
2:00 PM	879	41.6	56.2 - 60.5	42.11	82.9

4. CONCLUSIONS

This study investigated the thermal distribution across solar cells on the surface of a solar panel, focusing on the impact of anti-reflective coating homogeneity, temperature variations, and their effect on the performance ratio. The key findings and conclusions are summarized as follows:

- **Temperature Distribution and Anti-Reflective Coatings:**
  - The temperature distribution across the solar panel surface was found to be non-uniform, with variations of up to 16.3°C between cells.
  - These temperature differences are primarily attributed to variations in the anti-reflective coating, which affect the absorption of solar radiation.
  - Cells with less effective coatings absorbed more solar radiation, leading to higher temperatures and reduced efficiency.
- **Impact of Temperature on Performance:**
  - The performance ratio of the solar panel decreased significantly as the temperature of the solar cells increased. For example:
    - At 9:00 AM, the performance ratio was 88.7% in the temperature range of 43°C to 48.6°C.
    - At 12:00 PM, the performance ratio dropped to 78.8% in the temperature range of 51.5°C to 67.8°C.
  - This confirms that higher temperatures negatively impact the efficiency of solar cells, consistent with previous studies.
- **Solar Radiation and Power Output:**
  - The power output of the solar panel increased with higher solar radiation, but the performance ratio decreased due to the associated rise in temperature.
  - For instance, at 12:00 PM, the solar radiation peaked at 1011 W/m², and the power output reached 44.56 W, but the performance ratio dropped to 78.8%.
- **Ambient Temperature and Heat Dissipation:**
  - High ambient temperatures (up to 41.9°C) reduced the heat dissipation from the solar panel, leading to increased solar cell temperatures and further reductions in efficiency.
  - The study highlights the importance of effective thermal management in high-temperature environments like Baghdad, Iraq.
- **Key Recommendations for Future Research:**
  - **Advanced Anti-Reflective Coatings:** Future studies should focus on developing and testing advanced anti-reflective coatings with improved thermal properties to ensure uniform temperature distribution.
  - **Cooling Techniques:** Innovative cooling techniques, such as passive or active cooling systems, should be explored to enhance heat dissipation and improve solar panel efficiency.
  - **Long-Term Field Studies:** Long-term field studies are needed to assess the durability and performance of solar panels under varying climatic conditions, particularly in high-temperature regions.
  - **Integration of Smart Monitoring Systems:** The integration of smart monitoring systems, such as IoT-based sensors, could provide real-time data on temperature distribution and performance, enabling better optimization of solar panel systems.

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