International Journal of Electrical Engineering and Sustainability (IJEES)
ISSN (online): 2959-9229
https://ijees.org/index.php/ijees/index
ISI 2023-2024: (0.557) Arab Impact Factor: 1.51 SJIF 2024 = 5.274
Volume 4 | Number 1 | January-June 2026 | Pages 01-14

Thermal Performance Evaluation of PV Technologies in Hot Climate Environments: A Review

Abdulhamid Salim Alajmi[1*], Zohra Ali Gebrel[2]
[1]Faculty of Science, Gharyan University, Gharyan, Libya
[2]Department of Physics, Faculty of Science, University of Sabratha, Sabratha, Libya

[*]Corresponding author: **Abdulhamidalajmi77@gmail.com**

Received: December 21, 2025 Accepted: February 10, 2025 Published: February 18, 2025

Abstract: The thermal performance of photovoltaic (PV) modules is a critical factor influencing their electrical efficiency, energy yield, and long-term reliability, particularly in hot climate regions characterized by high ambient temperatures and intense solar irradiance. This study presents a comparative thermal performance analysis of mono-crystalline, poly-crystalline, and thin-film photovoltaic modules under real operating conditions. The experimental framework included continuous monitoring of module temperature using thermocouples and infrared thermal imaging, along with simultaneous measurement of key environmental parameters such as solar irradiance, ambient temperature, wind speed, and relative humidity. The objective was to quantify thermal behavior, evaluate temperature-induced electrical performance degradation, and compare long-term thermal efficiency and energy yield across different PV technologies. The results demonstrated that module operating temperature has a significant impact on electrical performance, with increased temperature leading to reductions in open-circuit voltage, maximum power output, and overall conversion efficiency. Mono-crystalline and poly-crystalline modules exhibited higher temperature coefficients, resulting in greater performance degradation under elevated temperature conditions. In contrast, thin-film modules showed lower temperature sensitivity and improved thermal dissipation, leading to more stable electrical performance. Regression analysis confirmed a strong negative correlation between module temperature and power output for all PV technologies, with thin-film modules exhibiting the lowest thermal derating. Long-term performance evaluation revealed that thermal effects significantly influence energy yield and performance ratio in hot climate environments. Although mono-crystalline modules provided higher nominal efficiency under standard test conditions, thin-film modules maintained more stable energy production and thermal efficiency under sustained high-temperature operation. The findings indicate that thermal resilience plays a crucial role in determining real-world PV system performance and technology suitability for hot regions. Overall, this study provides a comprehensive assessment of the thermal characteristics and energy performance of different PV technologies, offering valuable insights for optimizing photovoltaic system design and technology selection in hot climate environments. The results support the adoption of thermally resilient PV technologies and improved thermal management strategies to enhance system efficiency, reliability, and long-term sustainability in high-temperature regions.

Keywords: Photovoltaic technology; Hot climate conditions; Thermal efficiency; Performance ratio.

1.Introduction

The thermal performance of photovoltaic (PV) modules is a critical determinant of their electrical efficiency, reliability, and long-term energy yield, particularly in hot climate regions characterized by high ambient temperatures, intense solar irradiance, and limited convective cooling [1,2]. Figure 1 illustrates the layered diagram of the PV/T module. Elevated operating temperatures reduce the open-circuit voltage (Voc) and maximum power output due to the negative temperature coefficient inherent to semiconductor materials. Consequently, the comparative evaluation of mono-crystalline silicon (mono-Si), poly-crystalline silicon (poly-Si), and thin-film PV technologies under high-temperature conditions is essential for optimizing technology selection in arid and semi-arid environments such as North Africa and the Middle East [3,4]. These technologies exhibit distinct thermal characteristics due to differences in bandgap structure, material composition, and module construction.

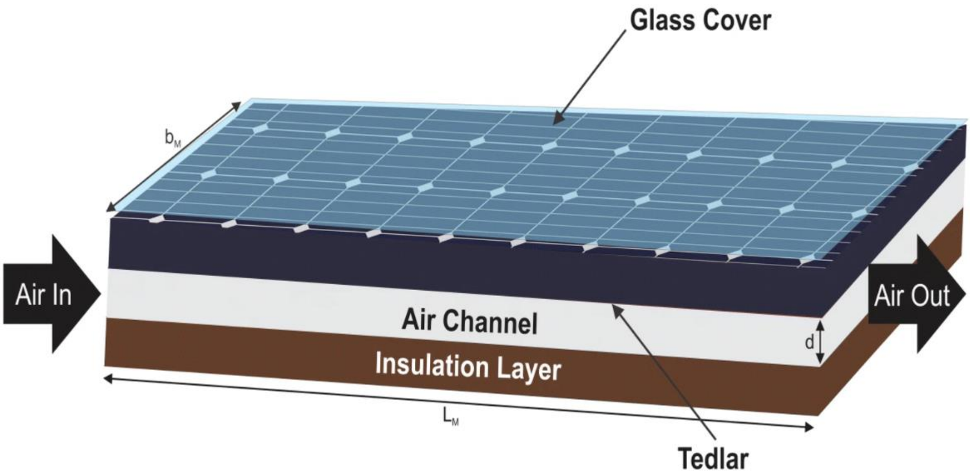

Figure 1. The layered diagram of the PV/T module [5].

Mono-crystalline silicon modules typically demonstrate the highest conversion efficiencies under standard test conditions (STC), primarily due to their uniform crystal lattice structure and reduced recombination losses. However, mono-Si modules exhibit a relatively high negative temperature coefficient, typically ranging between −0.40%/°C and −0.50%/°C for power output. As module temperature increases beyond the nominal operating cell temperature (NOCT), the electrical performance of mono-Si modules declines more significantly compared to thin-film technologies [6,7]. Furthermore, their higher packing density and lower thermal emissivity can contribute to increased heat accumulation, particularly under low wind speed conditions, resulting in elevated operating temperatures and reduced performance stability in hot climates.

Poly-crystalline silicon modules, while slightly less efficient than mono-crystalline modules under STC due to grain boundary recombination losses, exhibit similar thermal degradation behavior, with temperature coefficients typically in the range of −0.38%/°C to −0.45%/°C. The presence of grain boundaries can influence thermal conductivity and heat dissipation, although the overall thermal response remains comparable to mono-Si technology. In practical hot climate operation, poly-Si modules often experience slightly lower peak temperatures due to differences in optical absorption and surface properties, but their overall thermal performance degradation remains significant. Nevertheless, their lower manufacturing cost and relatively stable performance make them a widely adopted technology in utility-scale installations across high-temperature regions [8]. Figure 2 illustrates typical mono- and polycrystalline silicon solar cells, and a simplified cross-section of a commercial monocrystalline silicon solar cell (© 2010 Sharp).

Thin-film photovoltaic modules, including amorphous silicon (a-Si), cadmium telluride (CdTe), and copper indium gallium selenide (CIGS), exhibit superior thermal performance compared to crystalline silicon technologies due to their lower temperature coefficients, typically ranging from −0.20%/°C to −0.30%/°C. This reduced temperature sensitivity enables thin-film modules to maintain higher relative efficiency at elevated temperatures. Additionally, thin-film modules often exhibit lower operating temperatures due to their lower thermal mass, higher emissivity, and improved heat dissipation characteristics [9]. Their superior spectral response and reduced performance degradation under diffuse irradiance conditions further enhance their suitability for hot and dusty environments, where atmospheric scattering and elevated module temperatures are common.

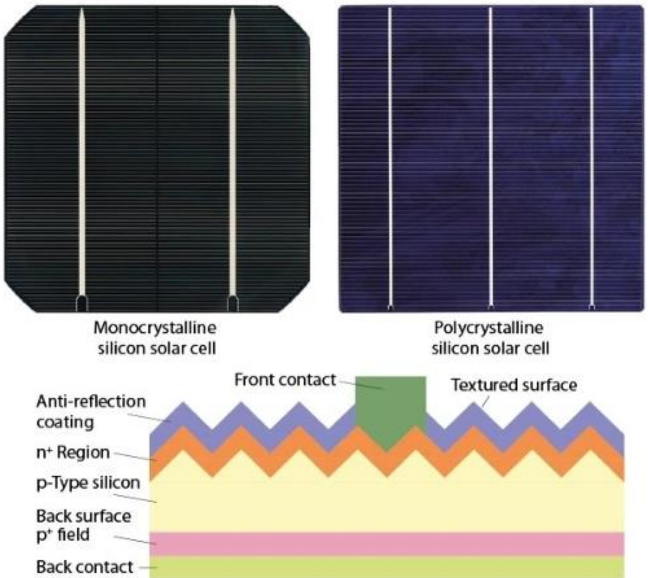

Figure 2. Typical mono- and polycrystalline silicon solar cells (above), and a simplified cross-section of a commercial monocrystalline silicon solar cell (below) (© 2010 Sharp) [10].

While mono-crystalline modules offer the highest efficiency under standard conditions, their performance is more adversely affected by high operating temperatures compared to thin-film technologies. Poly-crystalline modules exhibit similar thermal sensitivity but with slightly lower baseline efficiency. Thin-film modules demonstrate the most favorable thermal performance due to their lower temperature coefficients and improved thermal dissipation, making them particularly advantageous for deployment in hot climate regions [11,12]. In hot climate applications, thin-film technologies may provide superior real-world performance stability, while mono-and poly-crystalline technologies remain competitive due to their higher nominal efficiencies and widespread commercial availability.

A number of studies investigated the thermal performance of photovoltaic (PV) technologies functioning in hot temperature conditions, as detailed below.

In this study [13], sodium acetate trihydrate (PCM-1), palmitic acid (PCM-2), and a eutectic mixture of stearic acid and palmitic acid (PCM-3) were encapsulated in a container and integrated with monocrystalline and polycrystalline PV panels to evaluate the influence of PCMs on key performance indicators, including power output, energy efficiency, and module surface temperature. The experiments were conducted in Izmir during the summer season, representing hot-climate operating conditions. Solar irradiance levels representative of Izmir, including the standard test condition of 1000 W/m², were applied during testing. The results indicated that, at 1000 W/m² in August, the peak temperature of the monocrystalline module was reduced by 22.84% with PCM-1 and by 14.4% with the eutectic mixture compared with the reference module (without PCM). Moreover, for the polycrystalline module tested in July, the electrical power output and conversion efficiency increased by 24.97% and 24.95%, respectively.

The article results [14] revealed a clear reduction in PV module operating temperature under evaporative cooling. With natural evaporative cooling, the mean module temperature decreased by 3.98 °C, 3.74 °C, and 2.79 °C across the respective test days in July. Under forced evaporative cooling, a larger mean temperature reduction was achieved—7.07 °C, 8.44 °C, 7.65 °C, and 5.78 °C on the corresponding test days in August. This thermal mitigation translated into measurable electrical gains: PV efficiency increased by approximately 2.96%, 2.06%, and 2.05% during the natural-cooling test days, and by about 3.77%, 4.33%, 4.62%, and 5.10% during the forced-cooling test days.

This study [15] conducted a 39-day field monitoring campaign using conventional insulated and waterproof concrete roofs (CRs) as the baseline control, while Sedum-covered green roofs (GRs), photovoltaic concrete roofs (pCRs), and photovoltaic green roofs (pGRs) with three PV installation heights (0.3, 0.6, and 0.9 m) served as treated configurations. Overall, both GRs and pCRs exhibited superior thermal performance relative to CRs, with GRs showing the most pronounced improvement. Notably, the pGR configuration effectively alleviated the adverse thermal impacts associated with either Sedum vegetation or PV integration alone, leading to enhanced thermal and energy performance. Compared with CRs, pGRs reduced the exterior and interior surface temperatures by up to 17.7 °C and 0.8 °C, respectively. In addition, the pGR increased the damping factor by an average of 38.1%, reduced the time lag by an average of 46.2%, and lowered the thermal performance index by an average of 3.0%. The daily total heat gain for pGRs also decreased substantially—by 51.6%–70.9%, 1.4%–16.3%, and 13.1%–37.4% compared with CRs, GRs, and pCRs, respectively.

This study makes several important contributions to the understanding and optimization of photovoltaic (PV) performance under hot climate conditions through a comprehensive comparative analysis of mono-crystalline, poly-crystalline, and thin-film technologies. First, it provides experimental characterization of real operating temperature profiles using continuous field measurements, enabling accurate assessment of thermal accumulation and dissipation under high ambient temperature and irradiance conditions. Second, it quantitatively evaluates the impact of temperature coefficients on key electrical parameters, including open-circuit voltage, maximum power output, and conversion efficiency, establishing a clear relationship between temperature rise and performance degradation. Third, the study presents a comparative analysis of thermal efficiency and long-term energy yield, demonstrating that although crystalline silicon modules offer higher nominal efficiency, thin-film modules exhibit superior thermal stability and maintain more consistent energy production under elevated temperature conditions. Fourth, the findings identify the most thermally resilient PV technology for deployment in hot climate regions, supporting informed technology selection and system optimization. Finally, the research establishes an integrated methodological framework combining temperature monitoring, electrical performance evaluation, and energy yield analysis, providing practical guidance for improving photovoltaic system efficiency, reliability, and sustainability in high-temperature environments, particularly in arid and semi-arid regions such as North Africa and the Middle East.

2. Experimental Evaluation of Module Temperature Profiles under Hot Climate Conditions

Table 1 presents the experimental framework and measurement configuration used to evaluate and compare the thermal performance of mono-crystalline, poly-crystalline, and thin-film photovoltaic (PV) modules under hot climate conditions. Figure 3 outlines the key experimental components, including module temperature monitoring, environmental parameter measurements, instrumentation, sampling protocols, and expected output metrics. This structured experimental design ensures consistent and reliable data acquisition, enabling an accurate assessment of the thermal behavior of different PV technologies when exposed to high solar irradiance and elevated ambient temperatures typical of arid and semi-arid regions [16,17].

The experimental setup incorporates precise temperature monitoring using thermocouples and infrared thermal imaging to capture real-time module temperature variations. In addition to module temperature, critical environmental parameters such as ambient temperature, solar irradiance, wind speed, and relative humidity are measured simultaneously using calibrated meteorological instruments. These parameters play a fundamental role in determining the heat balance of PV modules, as solar irradiance drives heat generation, while ambient temperature and wind speed influence convective and radiative heat dissipation [18,19]. By synchronizing all measurements through a centralized data acquisition system, the experiment ensures high temporal resolution and accurate correlation between thermal and environmental variables.

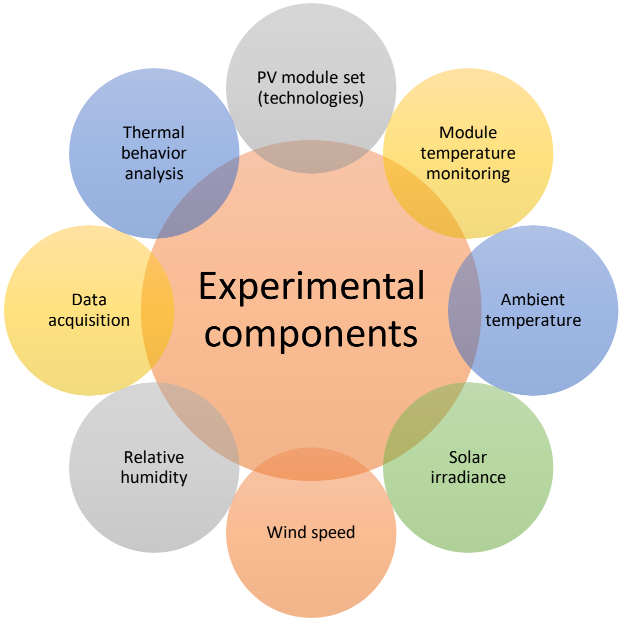

Figure 3. The key experimental components.

Furthermore, Table 1 highlights the importance of standardized mounting configurations and controlled installation conditions to eliminate external biases and ensure that observed temperature differences are primarily attributed to inherent material and structural properties of each PV technology. Uniform tilt angle, module spacing, and ventilation conditions are maintained to ensure fair comparison. The defined output metrics, including average module temperature, peak temperature, and temperature variation, provide quantitative indicators for evaluating thermal accumulation, heat dissipation efficiency, and overall thermal stability of each PV module type.

Table 1: The experimental setup and measurement framework for comparing the thermal behavior of mono-crystalline, poly-crystalline, and thin-film photovoltaic modules under hot climate conditions [20-23].

Component	Description	Instruments / Tools	Measurement Location	Sampling & Duration	Output Metrics
PV module set (technologies)	Comparative testing of mono-crystalline, poly-crystalline, and thin-film modules under identical outdoor conditions	Standard mounting racks, identical tilt and azimuth	Same test field with equal spacing	Continuous monitoring for 7–30 days	Temperature and performance comparability
Module temperature monitoring	Measure operating temperature and thermal cycling	Thermocouples (Type K), RTDs (PT100), IR thermal camera	Rear surface near center of module	1–5 min logging interval	Average, maximum, minimum module temperature
Ambient temperature	Capture environmental baseline temperature	Shielded temperature probe	1.5–2 m above ground	Synchronized with module logging	Ambient temperature trends and correlations
Solar irradiance	Measure incident solar radiation	Pyranometer or reference cell	Plane-of-array (same tilt as modules)	Synchronized with module logging	Irradiance intensity and daily energy input
Wind speed	Evaluate convective cooling effect	Anemometer	Near array height	Synchronized with module logging	Cooling effect and temperature reduction analysis

Relative humidity	Assess moisture influence on thermal behavior	Hygrometer	Weather station mast	Synchronized with module logging	Humidity impact correlation
Data acquisition	Collect and synchronize all measurements	Data logger with time synchronization	Central acquisition system	Continuous logging	Validated dataset for analysis
Thermal behavior analysis	Evaluate peak temperature and thermal response	Statistical analysis software	Post-processing stage	After data collection period	Peak temperature, temperature rise, technology comparison

The experimental configuration presented in Table 1 provides a comprehensive and systematic approach to evaluating the thermal characteristics of different photovoltaic technologies. The use of direct temperature measurements from the rear surface of each module ensures accurate representation of actual operating conditions, as backsheet temperature closely approximates cell temperature under steady-state conditions. Continuous monitoring with short sampling intervals allows for detailed analysis of thermal dynamics, including heating rates during peak irradiance and cooling behavior during low irradiance periods or increased wind activity.

The inclusion of key environmental parameters such as solar irradiance, ambient temperature, and wind speed enables a deeper understanding of the thermal mechanisms influencing PV module performance. Solar irradiance is the primary source of heat generation, and higher irradiance levels typically result in increased module temperatures. Ambient temperature directly affects the baseline thermal condition, while wind speed enhances convective heat transfer, reducing module temperature. By analyzing these parameters simultaneously, the experiment allows for quantification of the relationship between environmental stressors and module thermal response, which is essential for performance modeling and system optimization.

Moreover, the standardized mounting and installation configuration ensures that differences in thermal performance are attributed to the intrinsic properties of the PV technologies rather than external installation factors. This is particularly important when comparing crystalline silicon modules with thin-film technologies, as differences in material composition, emissivity, and thermal conductivity influence heat absorption and dissipation. Thin-film modules, for example, often exhibit lower operating temperatures due to improved thermal emissivity and reduced heat retention, while crystalline silicon modules tend to accumulate more heat under identical environmental conditions. Overall, the experimental framework summarized in Table 1 provides a robust foundation for comparative thermal performance analysis. The collected data enable identification of peak operating temperatures, evaluation of thermal stability, and assessment of the impact of environmental conditions on different PV technologies.

3. Assessment of Temperature Coefficient Impact on Electrical Performance

Table 2 presents the methodological framework for assessing the impact of temperature on the electrical performance of mono-crystalline, poly-crystalline, and thin-film photovoltaic (PV) modules. Temperature is one of the most critical environmental factors influencing PV performance, as semiconductor properties are highly sensitive to thermal variations. As operating temperature increases, photovoltaic modules experience reductions in open-circuit voltage (Voc), maximum power output (Pmax), and overall conversion efficiency (η), while short-circuit current (Isc) exhibits only minor variations. These temperature-dependent changes are quantified using temperature coefficients, which provide a standardized metric for evaluating the thermal sensitivity of different PV technologies. Understanding these coefficients is essential for predicting performance losses and optimizing PV system deployment in hot climate regions [24,26].

Table 2 outlines the procedures used to characterize temperature-dependent electrical parameters through systematic I–V curve measurements, temperature monitoring, and regression-based analysis. By establishing baseline electrical characteristics under controlled irradiance conditions, the study ensures accurate comparison across PV technologies. The measurement of temperature coefficients for power, voltage, and current enables quantification of the rate at which performance degrades with increasing temperature. In addition, efficiency analysis and power loss modeling provide insight into the overall impact of thermal stress on system performance. These analytical approaches allow for direct comparison of thermal resilience among mono-crystalline, poly-crystalline, and thin-film modules.

Furthermore, the integration of regression modeling and multivariable analysis allows for precise quantification of the relationship between module temperature and electrical output while accounting for environmental influences such as solar irradiance and wind speed. This approach ensures that the observed performance differences are attributed primarily to the intrinsic material properties and thermal characteristics of each PV technology. The resulting dataset enables identification of the most thermally stable PV technology, which is particularly important for installations in regions with sustained high ambient temperatures and intense solar exposure.

Table 2: The experimental framework used to evaluate the impact of temperature on key electrical parameters of mono-crystalline, poly-crystalline, and thin-film photovoltaic modules [27-32].

Item	What is Evaluated	Measurement / Method	Key Variables (Inputs)	Key Outputs (Electrical Metrics)	Analysis & Comparison Metric
Baseline electrical characterization	Reference electrical behavior under stable conditions	I–V curve tracing or DC logger measurement	Solar irradiance, module temperature, ambient temperature	Voc, Isc, Vmp, Imp, Pmax, efficiency	Baseline reference for comparison
Temperature coefficient of power (γP)	Sensitivity of power output to temperature	Regression of Pmax versus temperature	Module temperature, irradiance	Power temperature coefficient (%/°C)	Identify lowest power degradation
Temperature coefficient of voltage (βVoc)	Sensitivity of voltage to temperature	Regression of Voc versus temperature	Module temperature, irradiance	Voltage temperature coefficient	Voltage-driven thermal loss assessment
Temperature coefficient of current (αIsc)	Sensitivity of current to temperature	Regression of Isc versus temperature	Module temperature, irradiance	Current temperature coefficient	Technology comparison
Efficiency temperature sensitivity	Effect of temperature on conversion efficiency	Efficiency calculation and regression analysis	Power output, irradiance, module area	Efficiency variation with temperature	Efficiency stability ranking
Power loss vs temperature rise	Quantify thermal derating	Power normalization and loss calculation	Temperature difference from reference	Power loss percentage	Expected loss at high temperatures
Regression model for derating	Multivariable thermal impact analysis	Multiple regression analysis	Temperature, irradiance, wind speed, humidity	Predicted power output	Thermal resilience ranking
High-temperature resilience comparison	Performance stability at high temperatures	Compare metrics during hot conditions	Temperature above threshold	Power retention, efficiency	Final technology ranking

The experimental framework presented in Table 2 provides a comprehensive approach for evaluating the temperature sensitivity of photovoltaic module electrical performance. The baseline electrical characterization establishes reference values for key parameters such as Voc, Isc, and Pmax, which serve as essential benchmarks for evaluating temperature-induced performance degradation.

These baseline measurements ensure consistency and allow accurate comparison of thermal effects across different PV technologies. By using standardized measurement procedures, the study minimizes uncertainties and enhances the reliability of the temperature coefficient analysis.

The evaluation of temperature coefficients for power (γP), voltage (βVoc), and current (αIsc) provides direct insight into the thermal behavior of photovoltaic modules. Among these parameters, the voltage temperature coefficient is typically the most significant contributor to performance degradation, as increasing temperature reduces the semiconductor bandgap and decreases voltage output. The power temperature coefficient integrates the combined effects of voltage and current variations, providing a comprehensive indicator of thermal performance. Technologies with lower absolute values of γP exhibit greater resistance to temperature-induced performance losses and are therefore more suitable for hot climate applications.

Efficiency temperature sensitivity analysis further highlights the impact of thermal conditions on overall energy conversion efficiency. As module temperature increases, efficiency declines due to increased carrier recombination and reduced voltage output. By quantifying efficiency variation with temperature, the table enables comparison of thermal stability across different PV technologies. Thin-film modules generally demonstrate superior thermal stability due to lower temperature coefficients, while crystalline silicon modules, despite their higher nominal efficiency, tend to experience greater performance degradation under elevated temperature conditions.

The regression-based thermal derating analysis provides valuable predictive capability by quantifying the relationship between module temperature and power loss. This allows estimation of expected performance under real operating conditions, particularly during peak temperature periods when thermal losses are most significant. The final comparative assessment of high-temperature resilience enables identification of the most suitable PV technology for deployment in hot climates. Overall, the methodology summarized in Table 2 provides a robust and scientifically rigorous framework for evaluating thermal impacts on photovoltaic electrical performance, supporting optimized technology selection, improved system design, and enhanced long-term energy yield in high-temperature environments.

4. Thermal Efficiency and Energy Yield Comparison under Real Operating Conditions

The evaluation of thermal efficiency and energy yield under real operating conditions is essential for understanding the true performance of photovoltaic (PV) technologies deployed in hot climate environments. While standard test conditions (STC) provide a baseline for comparing module efficiencies, actual field performance often deviates significantly due to elevated ambient temperatures, high solar irradiance, and environmental variability [33-37]. These thermal conditions directly influence the electrical behavior of PV modules, primarily through reductions in open-circuit voltage, conversion efficiency, and maximum power output. As a result, assessing the thermal efficiency and energy yield of mono-crystalline, poly-crystalline, and thin-film PV technologies under real operating conditions is critical for determining their suitability and long-term reliability in hot climate regions [38-41].

Thermal efficiency reflects the ability of a photovoltaic module to maintain electrical performance despite increases in operating temperature, while energy yield represents the total electrical energy generated over a given period. These performance indicators are influenced by both intrinsic material properties and external environmental conditions, including module temperature, solar irradiance, wind speed, and ambient temperature. In hot climates, photovoltaic modules often operate at temperatures significantly higher than STC reference values, leading to measurable thermal losses and reduced energy generation. Therefore, evaluating temperature-corrected efficiency, performance ratio (PR), and daily and monthly energy output provides a comprehensive assessment of the thermal resilience and operational effectiveness of different PV technologies [42-44].

Furthermore, long-term performance monitoring under real environmental conditions enables identification of technology-specific thermal degradation patterns and performance stability. Thin-film technologies, for example, typically exhibit lower temperature coefficients and improved thermal stability, while crystalline silicon technologies offer higher nominal efficiency but may experience greater performance losses at elevated temperatures [45-48]. By comparing thermal efficiency and energy yield across different PV technologies, this analysis provides critical insights for optimizing photovoltaic system design, improving energy production efficiency, and supporting technology selection for deployment in regions with sustained high temperatures and strong solar resources [49-53].

A. Long-Term Monitoring of Energy Output under Real Climate Conditions

This agenda focuses on continuous monitoring of the electrical energy output of mono-crystalline, poly-crystalline, and thin-film photovoltaic modules over extended operational periods, typically ranging from several months to one year. Energy generation data should be recorded using calibrated energy meters or inverter monitoring systems. Environmental parameters such as solar irradiance, ambient temperature, and module temperature must be measured simultaneously. The objective is to quantify the actual energy yield (kWh) and evaluate the stability and consistency of energy production under varying thermal and environmental conditions representative of hot climate regions.

B. Evaluation of Temperature-Corrected Conversion Efficiency

This agenda aims to determine the temperature-corrected conversion efficiency of each photovoltaic technology by accounting for temperature-induced performance losses. Efficiency should be calculated using measured power output, incident solar irradiance, and module surface area. Temperature correction models based on experimentally derived temperature coefficients will be applied to normalize efficiency values to standard reference conditions. This analysis enables accurate comparison of intrinsic technology performance while isolating thermal effects, providing insight into the thermal resilience of different PV module types.

C. Performance Ratio (PR) Analysis under Thermal Stress Conditions

This agenda involves calculating and comparing the performance ratio (PR) of each photovoltaic technology to evaluate system-level performance independent of irradiance variations. The PR accounts for thermal losses, system inefficiencies, and environmental factors. By analyzing PR trends under high-temperature conditions, the study can quantify the extent to which thermal stress reduces system performance. This metric is particularly useful for assessing real-world system effectiveness and identifying technologies that maintain higher operational efficiency in hot climates.

D. Comparative Analysis of Daily and Monthly Energy Yield Stability

This agenda focuses on evaluating the stability and consistency of daily and monthly energy production across different photovoltaic technologies. Energy yield trends should be analyzed in relation to seasonal temperature variations and thermal loading conditions. Statistical indicators such as mean energy yield, standard deviation, and coefficient of variation will be used to assess production stability. Technologies demonstrating lower variability and higher sustained energy output under elevated temperatures will be considered more thermally stable and suitable for long-term deployment in hot environments.

E. Thermal Loss Quantification and Energy Derating Assessment

This agenda aims to quantify energy losses attributable to elevated operating temperatures by comparing measured energy output with temperature-corrected reference output. Thermal derating factors will be calculated to determine the percentage reduction in energy production caused by temperature rise. Regression analysis will be used to model the relationship between module temperature and energy yield reduction. This provides a predictive framework for estimating long-term thermal losses and evaluating the economic impact of temperature-related performance degradation.

F. *Technology Ranking Based on Long-Term Thermal Energy Performance*

This agenda focuses on integrating thermal efficiency, performance ratio, and long-term energy yield data to rank mono-crystalline, poly-crystalline, and thin-film technologies according to their thermal performance and energy production stability. Comparative performance indices will be developed to evaluate overall technology suitability for hot climate deployment. This ranking will support informed decision-making for photovoltaic system design, technology selection, and policy development aimed at maximizing energy generation and improving system reliability in high-temperature environments.

The comparative evaluation of thermal efficiency and energy yield under real operating conditions provides essential insights into the performance stability and thermal resilience of mono-crystalline, poly-crystalline, and thin-film photovoltaic technologies. The analysis demonstrates that operating temperature is a key factor influencing photovoltaic performance, with elevated temperatures leading to measurable reductions in voltage, efficiency, and overall energy generation. As a result, technologies with lower temperature coefficients exhibit improved thermal stability and reduced performance degradation under hot climate conditions.

The assessment of performance ratio, temperature-corrected efficiency, and long-term energy yield confirms that thermal effects play a significant role in determining real-world photovoltaic system performance. While mono-crystalline modules typically offer the highest nominal efficiency, their performance is more sensitive to temperature increases. Poly-crystalline modules exhibit similar thermal behavior with slightly lower baseline efficiency. In contrast, thin-film modules demonstrate superior thermal stability and reduced performance loss under elevated temperature conditions, enabling more consistent energy production in hot environments.

Overall, the findings highlight the importance of considering thermal performance in photovoltaic technology selection and system design, particularly in regions characterized by high ambient temperatures and intense solar irradiance. Long-term thermal efficiency and energy yield analysis provides a reliable basis for identifying the most suitable PV technology for hot climate deployment. By selecting thermally resilient photovoltaic technologies and optimizing system configuration, it is possible to enhance energy production, improve system reliability, and maximize the economic and environmental benefits of solar energy systems in high-temperature regions.

5. Conclusion

This study presented a comprehensive comparative thermal performance analysis of mono-crystalline, poly-crystalline, and thin-film photovoltaic modules under hot climate conditions, with a focus on experimental temperature profiling, temperature coefficient evaluation, and long-term energy yield assessment. The experimental evaluation of module temperature profiles demonstrated that photovoltaic modules operating in hot climates are subject to significant thermal stress, with module temperatures often exceeding ambient temperature by 20–35°C under peak irradiance conditions. The results confirmed that environmental parameters, particularly solar irradiance, ambient temperature, and wind speed, play a critical role in determining module operating temperature and thermal dissipation characteristics. Thin-film modules generally exhibited lower operating temperatures due to their superior thermal emissivity and lower heat retention, while crystalline silicon modules, particularly mono-crystalline technology, showed higher temperature accumulation under identical operating conditions.

The analysis of temperature coefficient impact on electrical performance revealed that temperature-induced performance degradation is primarily driven by reductions in open-circuit voltage and maximum power output. Mono-crystalline and poly-crystalline modules exhibited higher absolute temperature coefficients, resulting in more pronounced power losses as module temperature increased. In contrast, thin-film modules demonstrated lower temperature sensitivity, maintaining more stable electrical performance under elevated temperature conditions. Regression-based analysis confirmed a strong negative correlation between module temperature and power output, highlighting the importance of temperature coefficient characteristics as a key indicator of thermal resilience and suitability for hot climate applications.

Furthermore, the comparison of thermal efficiency and energy yield under real operating conditions demonstrated that temperature effects significantly influence long-term photovoltaic system performance. Although mono-crystalline modules offer higher nominal efficiency under standard test conditions, their performance advantage is partially offset by greater thermal losses in hot environments. Poly-crystalline modules showed similar trends with slightly lower baseline efficiency. Thin-film modules, despite their lower nominal efficiency, exhibited superior thermal stability, resulting in more consistent performance ratio and improved energy yield retention during high-temperature operation. This thermal stability enhances their overall energy production reliability in hot climate regions.

Overall, the findings of this study emphasize that thermal performance is a critical factor in photovoltaic technology selection and system design for hot climate environments. Thin-film photovoltaic technologies demonstrate superior thermal resilience and stable long-term performance, while mono- and poly-crystalline technologies remain competitive due to their higher nominal efficiencies and widespread commercial adoption. The integration of temperature profiling, temperature coefficient analysis, and energy yield evaluation provides a robust framework for optimizing photovoltaic deployment in high-temperature regions.

Author Contributions: Authors have contributed significantly to the development and completion of this article.
Funding: This article received no external funding.
Data Availability Statement: Not applicable.
Acknowledgments: The author would like to express their sincere gratitude to Gharyan University and University of Sabratha, Libya for their invaluable support and resources throughout the course of this research.
Conflicts of Interest: The author(s) declare no conflict of interest.

References

[1] A. S. Makhija and S. S. Bohra, "Performance and degradation analysis for different solar photovoltaic technologies under hot and humid environment: a review," *Prog. Energy*, vol. 5, no. 4, p. 042002, 2023.

[2] L. R. do Nascimento, M. Braga, R. A. Campos, H. F. Naspolini, and R. Rüther, "Performance assessment of solar photovoltaic technologies under different climatic conditions in Brazil," *Renew. Energy*, vol. 146, pp. 1070–1082, 2020.

[3] F. Tahri, A. Tahri, and T. Oozeki, "Performance evaluation of grid-connected photovoltaic systems based on two photovoltaic module technologies under tropical climate conditions," *Energy Convers. Manag.*, vol. 165, pp. 244–252, 2018.

[4] J. Luo, F. Xu, Y. Shi, C. Yu, J. Wang, and B. Yu, "The performance analysis on a multifunctional photovoltaic driven air heating, cooling and purification building roof," *Renew. Energy*, vol. 256, no. 124163, p. 124163, 2026.

[5] S. Diwania, S. Agrawal, A. S. Siddiqui, and S. Singh, "Photovoltaic–thermal (PV/T) technology: a comprehensive review on applications and its advancement," *Int. J. Energy Environ. Eng.*, vol. 11, no. 1, pp. 33–54, 2020.

[6] J. Liu, X. Li, Y. Yang, and Y. Wu, "Advancing PV temperature modeling: comparative evaluation and a novel empirical model," *Appl. Therm. Eng.*, vol. 291, no. 130228, p. 130228, 2026.

[7] M. Mehdi, N. Hmidi, and A. Alami Merrouni, "Machine learning-based approach for predicting the PV modules temperature: A multi-technological assessment including soiling impact, toward a better solar plants' operation under desert conditions," *Case Stud. Therm. Eng.*, vol. 78, no. 107640, p. 107640, 2026.

[8] M. T. Sarker, M. S. Hossen, G. Ramasamy, M. Al Qwaid, and H. A. Karim, "Techno economic and environmental evaluation of second life battery PV hybrid charging stations for sustainable e-mobility in tropical regions," *Sci. Rep.*, pp. 1–18, 2026.

[9] J. Peng, C. Luo, J. Zong, Q. Jiang, R. Peng, and H. Zhang, "Integrating experimental and theoretical approaches for seasonal performance analysis of an open solar photovoltaic/thermal pool system," *Energy (Oxf.)*, vol. 347, no. 140364, p. 140364, 2026.

[10] T. Saga, "Advances in crystalline silicon solar cell technology for industrial mass production," *NPG Asia Mater.*, vol. 2, no. 3, pp. 96–102, 2010.

[11] M. M. Ibrahim, M. A. William, A. M. Elharidi, A. A. Hanafy, and M. J. Suárez-López, "Techno-economic and environmental evaluation of building retrofit strategies toward NZEB targets in hot climatic contexts," *Sustainability*, vol. 18, no. 4, p. 1991, 2026.

[12] F. A. Moussa, I. Halidou, S. Meilinger, and B. Korgo, "Seasonal performance analysis of monocrystalline and polycrystalline photovoltaic solar panels under dust deposition in Niamey, Niger," *Energy Sci. Eng.*, no. ese3.70447, 2026.

[13] E. Sen and M. S. Celiktas, "Performance evaluation and thermal stabilization of photovoltaic panels using phase-change materials," *Energy (Oxf.)*, vol. 302, no. 131840, p. 131840, 2024.

[14] H. Altharwanee, F. Jurado, and D. Vera, "Experimental evaluation of photovoltaic performance utilizing a novel evaporative cooling method," *Sol. Energy*, vol. 299, no. 113724, p. 113724, 2025.

[15] Q. Zhan, Y. Ma, Z. Lin, S. Yin, and Y. Xiao, "Comparative experimental study on the thermal and energy performance of photovoltaic and green roofs in hot-humid climates," *Build. Environ.*, vol. 271, no. 112587, p. 112587, 2025.

[16] N. Ahmad, M. A. Zadjali, A. Husain, N. Al-Azri, and A. Al-Janabi, "Feasibility and performance analysis of a solar photovoltaic park for an industrial City," *Energy Convers. Manag.*, vol. 352, no. 121144, p. 121144, 2026.

[17] A. Altaye, P. Víg, and I. Farkas, "Hybrid PCM–nanofluid cooling for photovoltaic modules: Outdoor experimental performance evaluation," *International Journal of Thermofluids*, no. 101586, p. 101586, 2026.

[18] A. Dwivedi, V. Goel, and A. Kumar, "Experimental assessment of hybrid battery temperature regulation strategy via integration of binary nano-enhanced phase change material composite with helical fluid flow skeletons," *Renew. Energy*, no. 125226, p. 125226, 2026.

[19] J. Satpute *et al.*, "Experimental evaluation of Al2O3-water nanofluid for efficiency enhancement in a photovoltaic-thermal system under Western Indian climate," *Sci. Rep.*, vol. 16, no. 1, p. 3871, 2026.

[20] R. K. Barathraj, R. Prabakaran, P. Dhamodharan, and S. C. Kim, "Experimental evaluation of thermal performance of an indirect liquid-cooled battery module," *Appl. Therm. Eng.*, vol. 291, no. 130210, p. 130210, 2026.

[21] M. Sheikholeslami and F. A. M. A. Ali, "Experimental evaluation of vortex generators for enhancing solar photovoltaic panel performance with parabolic reflectors," *Sol. Energy Mater. Sol. Cells*, vol. 282, no. 113411, p. 113411, 2025.

[22] Y. Wen, X. Li, W. Hu, F. Yang, K. Yang, and J. Wang, "Experimental research on the temperature distribution characteristics of photovoltaic array," *Appl. Therm. Eng.*, vol. 265, no. 125507, p. 125507, 2025.

[23] Y. K. Singh, S. Dubey, P. Rajput, K. Y. Singh, and K. Pandey, "Real-time and modelled performance assessment and validation studies of PV modules operating in varied climatic zones," *Energy and Built Environment*, vol. 6, no. 4, pp. 585–595, 2025.

[24] A. Kazemian, H. Yang, and C. Xiang, "Assessing the effects of photovoltaic and solar thermal ratios on performance, cost, and emissions in combined solar configurations," *Appl. Energy*, vol. 384, no. 125438, p. 125438, 2025.

[25] I. Park, C. Kim, H. Lee, C.-L. Myung, and K. Min, "Comprehensive analysis of battery thermal management and energy consumption in an electric vehicle: Impact of driving modes and ambient temperatures," *Int. J. Automot. Technol.*, vol. 26, no. 3, pp. 621–636, 2025.

[26] J. Satpute *et al.*, "Parametric influence and efficiency assessment of water-cooled photovoltaic thermal PV/T absorber designs," *Energy (Oxf.)*, vol. 320, no. 135218, p. 135218, 2025.

[27] G. M. Tina, A. Osama, G. Mannino, A. Gagliano, A. V. Cucuzza, and F. Bizzarri, "Thermal comparison of floating bifacial and monofacial photovoltaic modules considering two laying configurations," *Appl. Energy*, vol. 389, no. 125732, p. 125732, 2025.

[28] B. Li *et al.*, "Thermal-water-electrical coupling modeling of PEMFC and its dynamic performance analysis under different operating conditions," *Appl. Energy*, vol. 398, no. 126447, p. 126447, 2025.

[29] M. Sheikholeslami and M. H. Alturaihi, "Numerical analysis of thermal management in a photovoltaic solar system with porous heat storage, parabolic reflector and self-cleaning coating," *Int. Commun. Heat Mass Transf.*, vol. 164, no. 108847, p. 108847, 2025.

[30] Z. Serat, A. G. Noori, S. A. Zamir Fatemi, and S. Popal, "Comparative performance of photovoltaic technologies and grid-connected system optimization across Afghanistan's climatic zones," *Energy Conversion and Management: X*, vol. 29, no. 101481, p. 101481, 2026.

[31] P. Sharma and R. K. Mishra, "Comprehensive study on photovoltaic cell's generation and factors affecting its performance: A Review," *Mater. Renew. Sustain. Energy*, vol. 14, no. 1, 2025.

[32] R. Feng *et al.*, "A comparative investigation on the energy flow of pure battery electric vehicle under different driving conditions," *Appl. Therm. Eng.*, vol. 269, no. 126035, p. 126035, 2025.

[33] Q. H. Chen, Y. Zhang, P. Huang, Q. Chen, Z. Yang, and Y. Jiang, "Optical, electrical, thermal, stress, and energy yield simulations enhance the performance and stability of perovskite photovoltaics," *Adv. Mater.*, vol. 38, no. 1, p. e14184, 2026.

[34] Z. Zhou, M. Zheng, B. Dong, and J. Li, "Cluster allocation strategy of multi-electrolyzers in wind-hydrogen system considering electrolyzer degradation under fluctuating operating conditions," *Renew. Energy*, vol. 242, no. 122381, p. 122381, 2025.

[35] M. Khaleel *et al.*, "Evolution of emissions: The role of clean energy in sustainable development," *Chall. Sustain.*, vol. 12, no. 2, pp. 122–135, 2024.

[36] Y. F. Nassar *et al.*, "Design of reliable standalone utility-scale pumped hydroelectric storage powered by PV/Wind hybrid renewable system," *Energy Convers. Manag.*, vol. 322, no. 119173, p. 119173, 2024.

[37] M. Khaleel and Z. Yusupov, "Advancing sustainable energy transitions: Insights on finance, policy, infrastructure, and demand-side integration," *Unconventional Resources*, vol. 9, no. 100274, p. 100274, 2026.

[38] U. Mamodiya, I. Kishor, R. Garine, P. Ganguly, and N. Naik, "Artificial intelligence based hybrid solar energy systems with smart materials and adaptive photovoltaics for sustainable power generation," *Sci. Rep.*, vol. 15, no. 1, p. 17370, 2025.

[39] Y. F. Nassar *et al.*, "Thermoelectrical analysis of a new hybrid PV-thermal flat plate solar collector," in *2023 8th International Engineering Conference on Renewable Energy & Sustainability (ieCRES)*, 2023.

[40] Y. F. Nassar *et al.*, "Carbon footprint and energy life cycle assessment of wind energy industry in Libya," *Energy Convers. Manag.*, vol. 300, no. 117846, p. 117846, 2024.

[41] M. Khaleel, E. Yaghoubi, E. Yaghoubi, and M. Z. Jahromi, "The role of mechanical energy storage systems based on artificial intelligence techniques in future sustainable energy systems," *IJEES*, pp. 01–31, 2023.

[42] A. Lekbir *et al.*, "Comprehensive investigation of rooftop photovoltaic power plants with monocrystalline polycrystalline and thin-film technologies for exergy economic and environmental assessments," *Sci. Rep.*, vol. 15, no. 1, p. 15517, 2025.

[43] F. Alasali, A. S. Saidi, N. El-Naily, O. Alsmadi, M. Khaleel, and I. Ghirani, "Assessment of the impact of a 10-MW grid-tied solar system on the Libyan grid in terms of the power-protection system stability," *Clean Energy*, vol. 7, no. 2, pp. 389–407, 2023.

[44] Y. F. Nassar *et al.*, "Sensitivity of global solar irradiance to transposition models: Assessing risks associated with model discrepancies," *e-Prime - Advances in Electrical Engineering, Electronics and Energy*, vol. 11, no. 100887, p. 100887, 2025.

[45] A. Alsharif *et al.*, "Applications of solar energy technologies in north Africa: Current practices and future prospects," *IJEES*, pp. 164–173, 2023.

[46] M. Khaleel, Z. Yusupov, N. Yasser, and H. J. El-Khozondar, "Enhancing Microgrid performance through hybrid energy storage system integration: ANFIS and GA approaches," *IJEES*, pp. 38–48, 2023.

[47] O. S. Abualoyoun and A. A. Amar, "Advancing the global integration of solar and wind power: Current status and challenges," *IJEES*, pp. 73–88, 2025.

[48] M. Khaleel, Z. Yusupov, and S. Rekik, “Exploring trends and predictions in renewable energy generation,” *Energy 360*, vol. 4, no. 100030, p. 100030, 2025.

[49] A. Ghayth, Z. Yusupov, A. Hesri, and M. Khaleel, “Performance enhancement of PV array utilizing Perturb & Observe algorithm,” *IJEES*, pp. 29–37, 2023.

[50] K. M. Omemen and M. O. Aldbbah, “Climate change: Key contributors and sustainable solutions,” *IJEES*, pp. 10–27, 2025.

[51] M. Khaleel, I. Imbayah, Y. Nassar, and H. J. El-Khozondar, “Renewable energy transition pathways and net-zero strategies,” *IJEES*, pp. 01–16, 2025.

[52] O. S. Abualoyoun and A. A. Amar, “Toward achieving net-zero in the evolution of the global energy sector,” *IJEES*, pp. 143–156, 2025.

[53] M. Dongellini, G. Martino, C. Naldi, S. Lorente, and G. L. Morini, “Experimental study on the heat transfer performance of finned-tube heat exchangers in latent thermal energy storages: Effects of PCM types and operating conditions,” *Appl. Therm. Eng.*, vol. 271, no. 126273, p. 126273, 2025.