

Thermal Dynamics and Temperature-Related Efficiency Loss in Photovoltaic Systems under High-Temperature Conditions

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Abstract: - The operating temperature of photovoltaic (PV) modules has a direct effect on electrical performance and short-term efficiency under real outdoor conditions. During periods of strong solar irradiance, PV modules are exposed to considerable thermal stress, which increases operating temperature and can reduce power production. In this study, the thermal behavior of a photovoltaic system under high-temperature operating conditions was analyzed using a set of empirical and semi-empirical thermal models. The analysis included the classical Ross/NOCT model, a wind-corrected NOCT formulation, an irradiance-adjusted NOCT approach, and the Faiman thermal model. In addition, a semi-empirical Thermal Performance Deviation Model (TPDM) was developed to investigate the combined influence of irradiance and thermal excess on PV thermal-performance behavior. The results showed pronounced daily thermal cycling and significant temperature rise during peak irradiance periods, with modeled operating temperatures exceeding 60°C under the most thermally stressed conditions. The estimated short-term thermal efficiency loss reached 10.83%, while more than 1100 operating hours exhibited efficiency losses above 3% and 552 hours exceeded 5% thermal efficiency loss. The proposed TPDM formulation achieved the best overall statistical performance, with an R^2 value of 0.857 and an RMSE of 0.724, indicating reasonable agreement under variable outdoor operating conditions. The analysis additionally demonstrated the important role of wind-driven convective cooling in reducing thermal stress during outdoor PV operation, highlighting the importance of thermal stress analysis under high-temperature conditions.

Key-Words: - Photovoltaic systems, PV thermal modeling, operating temperature, Thermal efficiency loss, Ross model, Faiman model, NOCT model, Thermal stress analysis.

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1 Introduction

With the rapid development of PV technology and the continuous increase of global installed capacity, it is becoming increasingly important to understand the thermal behavior of PV systems under real outdoor operating conditions [1], [2], [3]. Photovoltaic modules are designed to convert solar irradiance into electricity, but only a small fraction of the absorbed solar energy is transformed into usable electrical energy, while the rest is transformed into heat in the PV material and the surrounding structure [4]. Therefore, PV modules often operate at temperatures significantly higher than the ambient temperature, especially when solar irradiance is high and convective cooling is limited [5]. The thermal response of photovoltaic systems is governed by complex heat-transfer mechanisms, including solar absorption, thermal conduction, convection, and radiative heat exchange with the surrounding environment [6], [7]. The PV operating

temperature depends on a number of interdependent factors in outdoor conditions such as irradiance intensity, ambient temperature, wind speed, mounting configuration, airflow conditions, and thermal inertia. The overall interaction of these parameters determines the transient thermal response of the PV module [8], [9]. High irradiance conditions can subject photovoltaic modules to considerable thermal loading, leading to high operating temperatures and significant daily thermal cycling. Temperature is an important factor influencing photovoltaic conversion efficiency because of the temperature dependence of electrical characteristics of semiconductor materials [4]. Increasing the cell temperature results in a reduction in the band-gap energy of semiconductor materials, which in turn results in reductions in open-circuit voltage and overall electrical efficiency [4], [10]. Consequently, elevated operating temperatures generally reduce PV power output and modify the

electrical operating characteristics of the module [4], [5], [10], [11], [12]. In practical outdoor applications, thermal effects are therefore among the most important physical factors influencing PV system performance and operational stability [6], [7], [12]. In addition to short-term efficiency reduction, prolonged exposure to elevated operating temperatures may contribute to thermal stress conditions within photovoltaic systems [13]. Repeated daily thermal cycling can generate mechanical and thermo-electrical stress due to the continuous expansion and contraction of module materials, solder joints, and encapsulation layers [14]. Although long-term degradation mechanisms depend on multiple environmental and material factors, thermal loading remains an important factor influencing the operational behavior and reliability of PV systems [15]. Direct measurement of solar-cell operating temperature under real outdoor conditions is often difficult because temperature sensors are commonly installed on the rear surface of the module, inside inverter systems, or within auxiliary monitoring equipment [8], [9], [16]. Consequently, numerous empirical and semi-empirical thermal models have been developed to estimate PV operating temperature using meteorological and operational variables such as solar irradiance, ambient temperature, and wind speed [5], [8], [9], [17]. Among the most widely used approaches are the classical Ross/NOCT model [11], wind-corrected and empirical thermal formulations [8], [17], [18], irradiance-adjusted and temperature-dependent thermal approaches [19], and the Faiman thermal model [5]. These models are widely employed in photovoltaic performance analysis and system simulation studies because they provide simplified yet physically interpretable representations of module thermal response [6], [7]. The PV thermal response under different climatic and operational conditions has been investigated in previous studies, including energy-balance thermal modeling, NOCT-based formulations, wind-driven convective cooling effects, and temperature-related efficiency variation [5], [8], [9], [10], [18], [19], [20], [21], [22]. More recent investigations have additionally examined thermal stress conditions, environmental influences, and transient outdoor operating effects on PV performance [23], [24]. Despite the large number of available thermal formulations, significant uncertainty still exists in representing transient outdoor operating conditions during periods of elevated irradiance and strong thermal loading. Simplified empirical approaches cannot always fully capture the combined influence of irradiance variability, thermal excess, and wind-

driven convective cooling under real operating conditions [25], [26]. Consequently, comparative thermal analysis and physically interpretable semi-empirical approaches remain important for evaluating PV thermal-performance behavior and temperature-related efficiency variation. In this study, the thermal dynamics of a photovoltaic system operating under high-temperature outdoor conditions were investigated using several empirical and semi-empirical thermal formulations. The analysis included the Ross/NOCT model, wind-corrected and irradiance-adjusted NOCT approaches, and the Faiman thermal model. In addition, a semi-empirical Thermal Performance Deviation Model (TPDM) was developed to investigate the combined influence of irradiance and thermal excess on PV thermal-performance behavior. Particular emphasis was placed on operating-temperature variations, thermal cycling, thermal stress conditions, and temperature-related efficiency losses under high-temperature operating conditions. The proposed methodology provides a physically interpretable and computationally efficient framework for evaluating photovoltaic thermal behavior under high-temperature outdoor operating conditions.

2 Methodology

2.1 Study Framework

This study investigates the thermal behavior and temperature-related efficiency variation of a photovoltaic (PV) system operating under outdoor high-temperature conditions. The analysis was performed using hourly climatic and operational datasets covering the period October 2024 to September 2025. The climatic variables were obtained from the European Centre for Medium-Range Weather Forecasts ERA5-Land reanalysis database [27]. The extracted parameters included: ambient air temperature, surface solar radiation, and horizontal wind components. In parallel, measured operational data from a real photovoltaic installation located in Tirana, Albania, were used for model evaluation and performance analysis. The PV system has an installed capacity of 208.82 kWp and operates under real outdoor conditions representative of Mediterranean urban environments. The climatic and operational datasets were synchronized at hourly temporal resolution prior to thermal analysis. Missing values and non-physical observations were removed during preprocessing. The overall methodological

workflow of the study is illustrated in Figure 1, including climatic and operational data collection, thermal modeling, thermal stress analysis, PV performance evaluation, and statistical validation of the investigated thermal formulations.

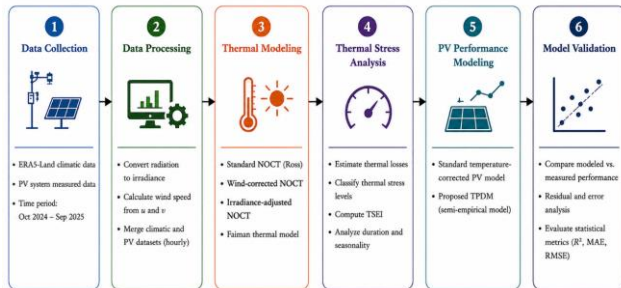


Fig. 1: Methodological workflow of the thermal and performance of the PV system
Source: created by the authors

In Table 1, the main electrical and thermal characteristics of the photovoltaic module used in the study are presented.

Table 1. Technical Specifications of the Photovoltaic Module Used in the Study

Parameter	Value
Module Model	IBEX 132MHC-EIGER
Technology	N-type Mono TOPCon
Rated Power (W)	525
Efficiency (%)	22.11
V _{mpp} (V)	39.53
I _{mpp} (A)	13.28
V _{oc} (V)	47.22
I _{sc} (A)	14.21
Temp. Coeff. P _{max} (%/°C)	-0.30
Operating Temperature	-40°C to +85°C
Dimensions (mm)	2094 × 1134 × 35
Weight (kg)	25.5

Source: Manufacturer datasheet of the IBEX 132MHC-EIGER photovoltaic module.

These parameters were used as the basis for the thermal performance analysis and temperature-related evaluation of the PV system under outdoor operating conditions.

2.2 Climatic Data Processing Study

ERA5-Land climatic variables were processed at hourly temporal resolution. Surface solar radiation values provided by ERA5-Land are expressed as accumulated hourly energy (J/m²). These values were converted into irradiance using

$$G = \frac{SSR}{3600} \quad (1)$$

where G (W/m²) represents hourly solar irradiance, SSR (J/m²) is the accumulated hourly surface solar radiation. Wind speed was calculated from the ERA5 horizontal wind vector components:

$$W = \sqrt{u^2 + v^2} \quad (2)$$

where u and v are the horizontal wind components, W (m/s) is the resulting wind speed magnitude. The processed climatic dataset was subsequently merged with the measured PV operational data to create a unified hourly thermal-performance database.

2.3 Solar Cell Temperature Modeling

To evaluate the influence of climatic conditions on PV thermal behavior, several empirical and semi-empirical solar-cell temperature formulations were investigated, including the classical Ross/NOCT model, wind-corrected and irradiance-adjusted NOCT approaches, and the Faiman thermal model [5], [8], [9], [10], [11], [17].

2.3.1 Standard NOCT / Ross Model

The first approach was based on the classical Ross/NOCT formulation, which estimates solar cell temperature as a function of ambient temperature and incident irradiance [11]:

$$T_c = T_a + \left(\frac{NOCT - 20}{800} \right) G \quad (3)$$

T_c is solar-cell temperature (°C), T_a is ambient temperature (°C), NOCT is the nominal operating cell temperature (°C), G is solar irradiance. This model assumes steady-state thermal behavior and represents one of the most commonly used simplified PV temperature estimation methods.

The Ross coefficient:

$$k = \frac{NOCT - 20}{800} \quad (4)$$

was used to quantify the irradiance-dependent thermal gain.

2.3.2 Wind-Corrected NOCT Model

Because wind significantly affects convective cooling of PV modules, a modified NOCT formulation was introduced by including a wind-dependent correction term:

$$T_c = T_a + \left(\frac{NOCT - 20}{800} \right) \cdot \frac{G}{1 + k_w W} \quad (5)$$

where: K_w is the empirical wind cooling coefficient, and W is the wind speed. This formulation allows the estimated cell temperature to decrease under stronger wind conditions, representing enhanced convective heat transfer [5], [8].

2.3.3 Irradiance-Adjusted NOCT Model

A third formulation was introduced to investigate the sensitivity of thermal behavior under elevated irradiance conditions:

$$T_c = T_a + \left(\frac{NOCT - 20}{800} \right) \cdot G \cdot \left(1 - e^{-\frac{G}{G_0}} \right) \quad (6)$$

G_0 is the irradiance scaling parameter.

This approach increases the thermal contribution of high-irradiance periods and provides a nonlinear, irradiance-dependent thermal response [19].

2.3.4 Faiman Thermal Model

To incorporate irradiance heating together with wind-driven convective cooling more explicitly, the Faiman thermal model was also implemented [5]:

$$T_c = T_a + \frac{G}{U_0 + U_1 W} \quad (7)$$

where U_0 and U_1 are empirical thermal loss coefficients. The coefficients $U_0=25$ and $U_1=6.84$ were adopted according to commonly reported literature values [5,] [9]. Compared with NOCT-based approaches, the Faiman model generally provides a more realistic representation of wind-related thermal cooling effects.

2.3.5 Theoretical Heat Transfer Framework

The operating temperature of a photovoltaic module results from the continuous interaction between absorbed solar radiation, heat storage within the module, convective and radiative heat exchange with the surrounding environment, and electrical energy conversion. Although the Ross and Faiman models represent simplified empirical formulations, they are fundamentally derived from the general energy conservation principle governing heat transfer in photovoltaic systems. To provide a rigorous mathematical basis for the proposed Thermal Performance Deviation Model (TPDM), the transient heat transfer equation is introduced as the underlying physical framework. According to the first law of thermodynamics, the local transient heat balance within a photovoltaic module can be expressed as:

$$\frac{\rho c_p \partial T}{\partial t} = \nabla \cdot (k \nabla T) + q_{abs} - q_{conv} - q_{rad} - q_{elec} \quad (8)$$

where T is the local module temperature ($^{\circ}\text{C}$), ρ is the material density (kg m^{-3}), c_p is the specific heat capacity ($\text{J kg}^{-1} \text{K}^{-1}$), and k is the thermal conductivity ($\text{W m}^{-1} \text{K}^{-1}$). The source term q_{abs} represents the absorbed solar energy, whereas q_{conv} ,

q_{rad} , and q_{elec} denote the heat losses associated with convection, long-wave thermal radiation, and electrical power generation, respectively.

The absorbed solar heat flux can be expressed as:

$$q_{abs} = \alpha G \quad (9)$$

where G is the incident solar irradiance (W m^{-2}), and α is the effective absorptivity of the photovoltaic module. Convective heat exchange between the module surface and the surrounding air follows Newton's cooling law:

$$q_{conv} = h(T_c - T_a) \quad (10)$$

where h is the convective heat transfer coefficient ($\text{W m}^{-2} \text{K}^{-1}$), T_c is the cell temperature, and T_a is the ambient air temperature. Radiative heat exchange can be expressed by the Stefan–Boltzmann equation:

$$q_{rad} = \varepsilon \sigma (T_c^4 - T_{sky}^4) \quad (11)$$

where ε is the surface emissivity and σ is the Stefan–Boltzmann constant. The electrical power extracted from the photovoltaic module represents the fraction of absorbed solar energy converted into useful electricity,

$$q_{elec} = \eta G \quad (12)$$

where η denotes the conversion efficiency.

$$q_{abs} = q_{conv} + q_{rad} + q_{elec} \quad (13)$$

which constitutes the physical basis of simplified engineering temperature models such as those proposed by Ross and Faiman. The steady-state energy balance presented in Equation (13) constitutes the physical basis of simplified engineering models used for photovoltaic thermal analysis. The Ross and Faiman models can be interpreted as reduced-order formulations obtained from the general heat-transfer balance through appropriate assumptions regarding convective and radiative heat exchange. Building upon this physical foundation, the proposed Thermal Performance Deviation Model (TPDM) does not attempt to solve the transient heat-transfer equation directly. Instead, it establishes an empirical relationship between photovoltaic specific yield, incident solar irradiation, and thermally induced efficiency degradation, thereby preserving the essential physical behavior while providing a computationally efficient model suitable for daily performance assessment. The overall theoretical framework may be summarized as follows: the general transient heat-transfer equation is simplified into a steady-state energy balance, which forms the basis of the Ross and Faiman models and ultimately supports the proposed TPDM. Unlike these classical formulations, which primarily estimate module temperature, the proposed TPDM directly relates photovoltaic specific yield to the combined

influence of solar irradiation and thermally induced performance degradation. Consequently, the TPDM should be regarded as an engineering-level empirical model physically supported by the general heat-transfer framework rather than as a replacement for the governing transient thermal equation. Overall, this formulation establishes a clear theoretical connection between fundamental heat-transfer principles and the proposed statistical model, thereby enhancing its physical interpretability and mathematical consistency.

2.4 Thermal Loss Estimation

Temperature-induced PV efficiency degradation was estimated using the manufacturer-provided temperature coefficient. Thermal losses were calculated only when cell temperature exceeded Standard Test Conditions 25°C:

$$\eta = \eta_{ref}[1 + \gamma(T_c - 25)] \quad (14)$$

where η is the operating efficiency, η_{ref} is the reference efficiency under standard test conditions, γ is the temperature coefficient, T_c is the estimated cell temperature

This formulation quantifies the percentage reduction in PV performance caused by elevated operating temperatures [14], [18]. The corresponding thermal efficiency loss was calculated as:

$$Loss_{thermal(\%)} = |\gamma(T_c - 25)| \times 100 \quad (15)$$

The analysis focuses on short-term temperature-related efficiency variation and does not represent permanent material degradation processes.

2.5 Thermal Stress Classification

To characterize operational thermal conditions, hourly solar cell temperatures were grouped into four thermal regimes: stable operation, moderate thermal stress, high thermal stress, extreme thermal stress [13], [18]. The classification thresholds were defined according to cell temperature ranges representative of increasing thermal exposure severity. This thermal regime analysis was used to quantify: the annual duration of thermal stress, seasonal variations, and extreme operating conditions.

2.6 Thermal Stress Energy Index (TSEI)

To move beyond simple temperature-based analysis, a Thermal Stress Energy Index (TSEI) was introduced. The proposed index combines thermal excess, irradiance intensity, and exposure duration. The index was defined as:

$$TSEI = \Sigma G \cdot (T_c - 25)_+ \quad (16)$$

where $(T_c - 25)_+$ represents positive thermal excess above standard operating conditions. The proposed index provides an irradiance-weighted representation of cumulative thermal exposure and identifies periods associated with the highest thermally induced operational stress.

2.7 PV Performance Modeling

A standard temperature-corrected PV performance model based on PVWatts-type formulations was first considered:

$$P = P_{ref}[1 + \gamma(T_c - 25)] \quad (17)$$

where P is PV output power, P_{ref} is reference power under standard test conditions, γ is the temperature coefficient. To further investigate the combined influence of irradiance and thermal excess, a semi-empirical Thermal Performance Deviation Model (TPDM) was proposed.

$$Y = aG - b(T_c - 25)_+ + d \quad (18)$$

Y is the specific PV yield, a, b, d are fitted empirical coefficients [14, 20]. The TPDM was designed to provide a physically interpretable representation of the combined effects of solar irradiance gain and temperature-induced performance reduction.

2.7.1 Sensitivity Analysis of the Proposed Thermal Performance Deviation Model (TPDM)

To further strengthen the mathematical interpretation of the proposed Thermal Performance Deviation Model (TPDM), a formal sensitivity analysis was performed to evaluate the influence of the model input variables on the predicted photovoltaic specific yield. Sensitivity analysis is widely employed to assess the robustness of empirical and semi-empirical models by quantifying how variations in the input parameters affect the model response. In the present study, both analytical and numerical sensitivity analyses were carried out to determine the relative contribution of solar irradiation and thermal excess to the predicted photovoltaic performance.

The proposed TPDM is expressed as

$$Y = 0.765278G - 0.007646(T_c - 25)_+ + 0.272612 \quad (19)$$

where Y denotes the photovoltaic specific yield, G represents the incident solar irradiation, and $(T_c - 25)_+$ is the thermal excess term accounting for temperatures above the Standard Test Conditions (STC).

The local analytical sensitivity of the model is obtained through the first-order partial derivatives with respect to each input variable

$$\frac{\partial Y}{\partial G} = 0.765278 \quad (20)$$

and

$$\frac{\partial Y}{\partial T_{ex}} = -0.007646 \quad (21)$$

These analytical derivatives indicate that the model response varies linearly with both explanatory variables. The positive derivative associated with solar irradiation confirms that increasing irradiance leads to higher photovoltaic energy production, whereas the negative derivative corresponding to the thermal excess reflects the reduction in conversion efficiency caused by elevated operating temperatures. Since the coefficients are constant, the analytical sensitivity remains independent of the operating point and directly represents the relative influence of each explanatory variable within the linear TPDM formulation. To facilitate comparison between variables having different physical units, normalized sensitivity coefficients were also evaluated according to:

$$S_{x_i} = \left(\frac{\partial Y}{\partial x_i} \right) \cdot \left(\frac{x_i}{Y} \right) \quad (22)$$

where x_i is the corresponding input variable.

In addition to the analytical sensitivity analysis, a numerical perturbation analysis was performed by independently varying each input parameter according to:

$$x_i^{pert} = x_i (1 + \delta) \quad (23)$$

where

$$\delta = \pm 0.05, \pm 0.10, \pm 0.15 \quad (24)$$

For each perturbation level, the corresponding relative variation in the predicted photovoltaic specific yield was calculated as:

$$\Delta Y(\%) = \left(\frac{Y_p - Y_0}{Y_0} \right) \times 100 \quad (25)$$

where Y_0 represents the baseline model prediction and Y_p denotes the predicted value obtained after perturbing the selected input variable.

The numerical perturbation analysis provides an additional assessment of model robustness by quantifying the response of the TPDM to moderate variations in the explanatory variables. This complementary analysis verifies the stability of the proposed model and allows the relative importance of solar irradiation and thermal excess to be evaluated under realistic operating conditions. Overall, the sensitivity analysis confirms that solar

irradiation is the dominant factor governing photovoltaic performance, whereas thermal excess provides a physically meaningful correction associated with temperature-induced efficiency losses. These results further enhance the robustness, mathematical transparency, and physical interpretability of the proposed TPDM.

2.8 Statistical Evaluation and Validation

The performance of the investigated models was evaluated using statistical error metrics including:

1. Coefficient of determination (R^2),

$$R^2 = 1 - \frac{\sum (y_i - \hat{y}_i)^2}{\sum (y_i - \bar{y})^2} \quad (26)$$

2. Mean absolute error (MAE),

$$MAE = \left(\frac{1}{n} \right) \sum |y_i - \hat{y}_i| \quad (27)$$

3. Root mean square error (RMSE).

$$RMSE = \sqrt{\left[\left(\frac{1}{n} \right) \sum (y_i - \hat{y}_i)^2 \right]} \quad (28)$$

Residual analysis was additionally performed to evaluate the stability of the proposed TPDM formulation under varying thermal operating conditions. The statistical metrics (R^2 , MAE, and RMSE) were calculated by comparing the modeled PV performance obtained from the investigated formulations with the measured inverter-based PV performance data. The validation therefore evaluates the capability of each formulation to reproduce the observed operational PV behavior under real outdoor conditions.

3 Results and Discussion

3.1 Thermal Behavior of the Photovoltaic System

The investigated thermal formulations showed pronounced seasonal and daily thermal variability during outdoor PV operation. Operating temperatures increased progressively from winter toward summer conditions, following the increase in solar-energy absorption and ambient thermal conditions. Figure 2 shows maximum modeled operating temperatures exceeded 60°C during summer operation, while winter conditions were characterized by substantially lower thermal loading.

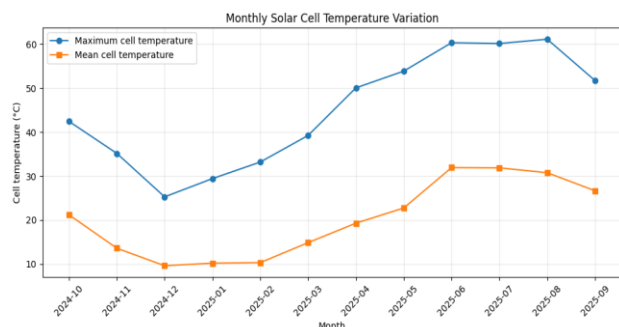


Fig. 2: Monthly variation of mean and maximum modeled PV operating temperature during the investigated period

Source: created by the authors

The highest thermal conditions were observed during the summer months (June–August), with maximum cell temperatures exceeding 60°C , while winter periods exhibited substantially lower operating temperatures. The results indicate that irradiance-driven heating represents the dominant mechanism controlling PV thermal response. Figure 3 presents the temporal evolution of the modeled PV operating temperature during the investigated period.

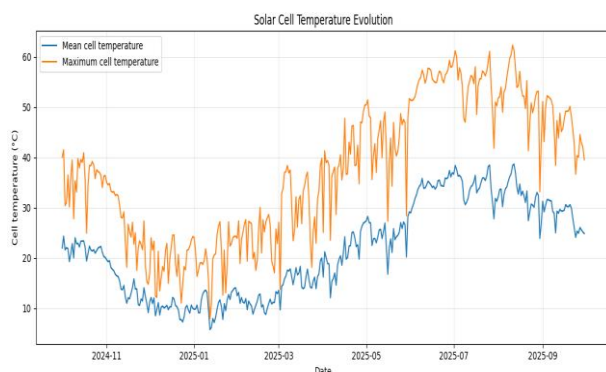


Fig. 3: Temporal evolution of mean and maximum modeled PV operating temperature during outdoor operation

Source: created by the authors

The thermal profiles show strong daily thermal cycling behavior, with rapid daytime heating followed by nighttime cooling toward thermal equilibrium conditions. Seasonal thermal accumulation becomes increasingly visible during summer operation. Figure 4 compares the Ross/NOCT and Faiman thermal formulations.

Both models reproduce the overall thermal evolution of the PV system; however, the Faiman formulation generally predicts slightly lower operating temperatures due to the explicit inclusion of wind-driven convective cooling effects. The

comparison of the investigated NOCT-based thermal formulations is shown in Figure 5.

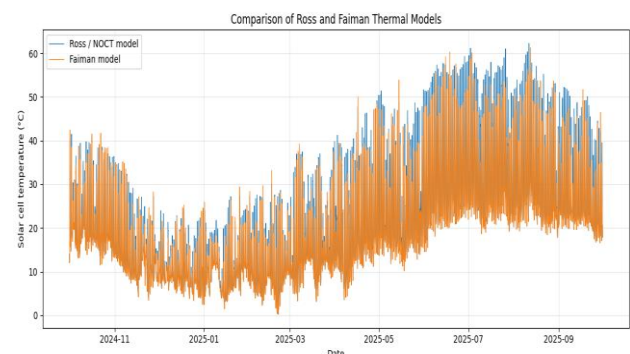


Fig. 4: Temporal comparison between the Ross/NOCT and Faiman thermal models during the investigated period

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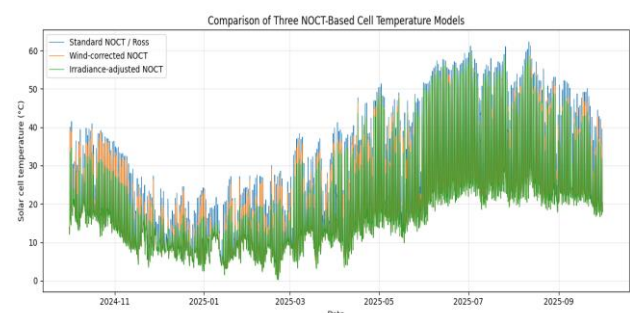


Fig. 5: Temporal comparison of the investigated NOCT-based thermal formulations during the outdoor operating period

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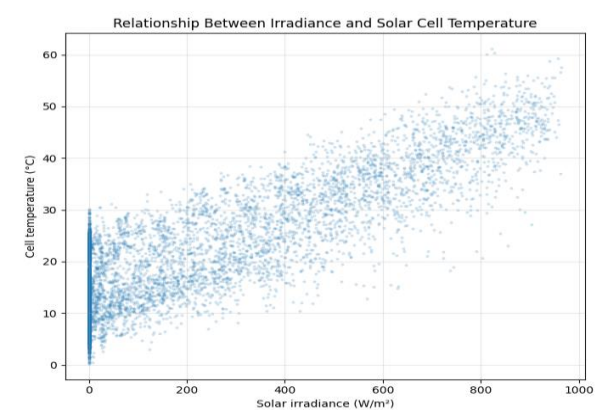


Fig. 6: Relationship between solar irradiance and modeled PV operating temperature during outdoor operation

Source: created by the authors

The standard Ross/NOCT formulation generally predicts the highest operating temperatures, while the wind-corrected and irradiance-adjusted approaches produce smoother thermal behavior under varying atmospheric conditions. Figure 6

presents the relationship between irradiance and operating temperature.

A strong positive relationship is observed between irradiance intensity and operating temperature. Elevated thermal conditions become increasingly frequent under intensified solar-energy absorption conditions. At low irradiance levels, operating temperatures remain relatively dispersed due to the stronger influence of ambient conditions and transient atmospheric variability. As irradiance increases, operating temperatures progressively rise, and thermal clustering becomes more pronounced. Under high-irradiance conditions approaching 800–1000 W/m², modeled operating temperatures frequently exceed 50°C, indicating substantial thermal loading within the PV structure. Figure 7 illustrates the influence of wind speed on PV operating temperature.

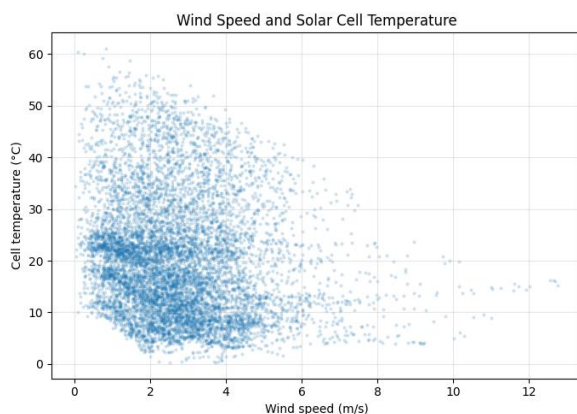


Fig. 7: Relationship between wind speed and modeled PV operating temperature during outdoor operation

Source: created by the authors

Higher wind-speed conditions generally correspond to reduced operating temperatures due to enhanced convective heat transfer from the PV surface. The results confirm the important moderating role of atmospheric cooling during outdoor operation. Although elevated wind speed reduces thermal loading, irradiance intensity remains the primary source of heat accumulation within the photovoltaic structure. Figure 8 compares the thermal operating regimes predicted by the Ross/NOCT and Faiman formulations under varying irradiance and wind-speed conditions.

Both formulations reproduce the general increase in operating temperature with increasing irradiance; however, the Faiman model exhibits slightly stronger sensitivity to wind-driven convective cooling effects. The differences become more visible during elevated thermal-loading

conditions, where atmospheric heat-transfer processes play a greater role in regulating PV operating temperature.

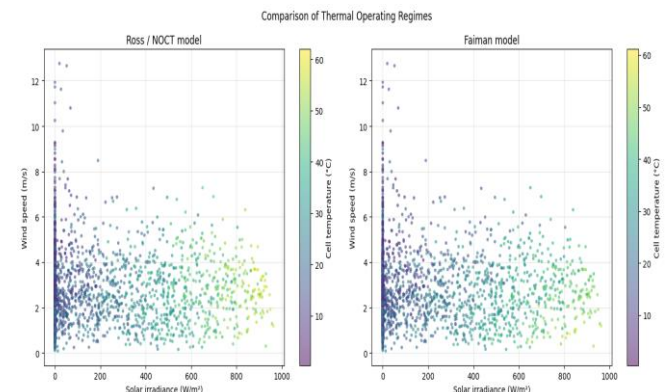


Fig. 8: Comparison between the Ross/NOCT and Faiman thermal formulations under varying irradiance and wind-speed conditions

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3.2 Comparison of Thermal Models

Figure 9 presents the thermal operating behavior of the investigated NOCT-based formulations under varying irradiance and wind-speed conditions.

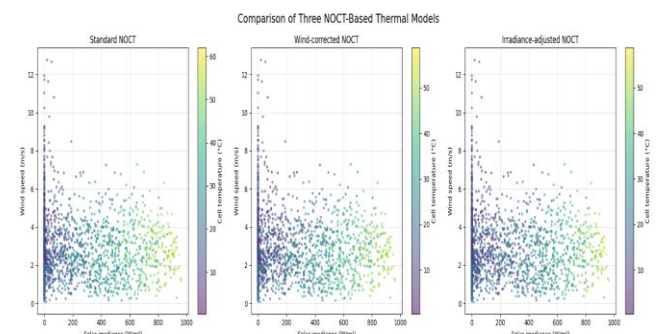


Fig. 9 Comparison of the investigated NOCT-based thermal formulations under varying irradiance and wind-speed conditions

Source: created by the authors

All formulations reproduce the general increase in operating temperature with increasing irradiance. However, the wind-corrected and irradiance-adjusted approaches exhibit slightly different thermal distributions under elevated operating-temperature conditions. The inclusion of additional thermal-response corrections moderately influences the predicted thermal operating regimes, particularly during periods associated with strong irradiance variability and changing convective cooling conditions. The statistical performance of the investigated thermal formulations is summarized in Table 2.

Table 2. Statistical performance of the investigated thermal-performance formulations

Model	R ²	MAE	RMSE
Standard NOCT / Ross	0.8549	0.5039	0.7304
Wind-corrected NOCT	0.8547	0.5049	0.7309
Irradiance-adjusted NOCT	0.8548	0.5041	0.7307
Faiman	0.8545	0.5058	0.7315
Proposed TPDM	0.8574	0.5002	0.7241

Source: created by the authors

The proposed TPDM formulation achieved the best overall statistical performance, with the highest coefficient of determination and the lowest RMSE value. The results indicate that the inclusion of the thermal-excess term improves the representation of outdoor PV thermal-performance behavior. Figure 10 presents the correlation between the Ross/NOCT and Faiman thermal formulations.

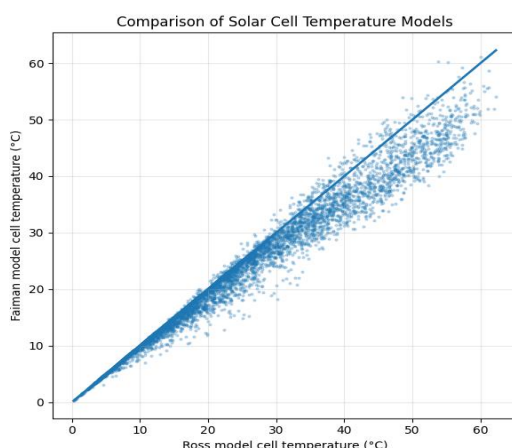


Fig. 10: Correlation between the Ross/NOCT and Faiman thermal formulations for the modeled PV operating temperature

Source: created by the authors

Figure 10 confirms the strong agreement between the two formulations, while the visible dispersion at higher temperatures reflects the increasing influence of convective cooling under thermally stressed conditions. Figure 11 compares the measured specific yield with the predicted values obtained using the standard formulation and the proposed TPDM model.

The TPDM formulation shows slightly improved agreement with the measured operating values under varying outdoor conditions. The distribution of points around the ideal agreement line indicates that the proposed formulation captures the dominant thermal-performance behavior while maintaining stable predictive behavior under elevated thermal-loading conditions. Figure 12 illustrates the difference between the Ross/NOCT

and Faiman thermal formulations under varying irradiance and wind-speed conditions.

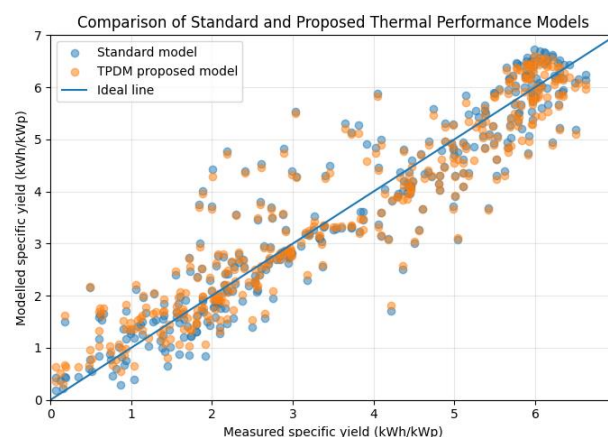


Fig. 11: Comparison between the standard thermal-performance formulation and the proposed TPDM relative to measured specific yield values

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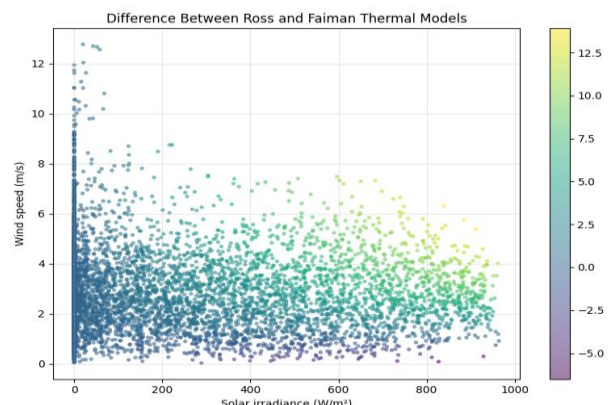


Fig. 12: Difference between the Ross/NOCT and Faiman thermal formulations under varying irradiance and wind-speed conditions

Source: created by the authors

Under these circumstances, the explicit representation of convective cooling within the Faiman model produces lower predicted operating temperatures compared with the standard Ross/NOCT approach. The differences become progressively smaller under stronger airflow conditions, where convective heat dissipation becomes more effective. The residual behavior of the proposed TPDM formulation is shown in Figure 13.

The residuals remain predominantly centered around zero, indicating stable predictive behavior across different thermal operating regimes. Limited outliers are observed during rapidly varying outdoor conditions.

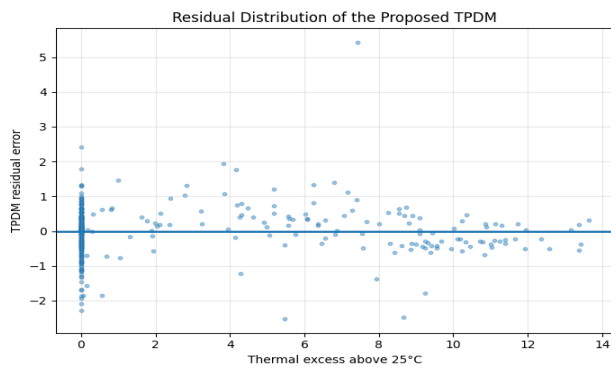


Fig. 13: Residual analysis of the proposed Thermal Performance Deviation Model (TPDM)

Source: created by the authors

3.3 Temperature-Related Efficiency Loss

The increase in operating temperature produced measurable short-term reductions in PV electrical efficiency. The maximum estimated thermal efficiency loss reached 10.83%, while the mean annual thermal efficiency loss remained 0.87%. The system experienced more than 1100 operating hours with efficiency losses above 3% and over 552 hours with losses exceeding 5%, indicating the increasing importance of thermal effects during intensified operating conditions. Figure 14 illustrates the seasonal evolution of temperature-related thermal efficiency loss, including mean thermal efficiency loss, high-loss operating hours, and thermal-loss regime distribution.



Fig. 14: Seasonal distribution of temperature-related thermal efficiency loss during the investigated operating period

Source: created by the authors

Thermal efficiency losses remained minimal during winter operation and progressively increased during spring and summer periods. The highest thermal-loss conditions occurred during June, July, and August. The monthly distribution of thermal efficiency-loss regimes is presented in Figure 15.

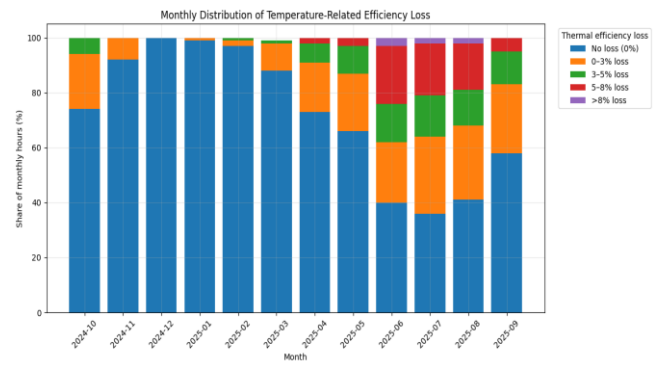


Fig. 15: Monthly distribution of temperature-related thermal efficiency loss regimes during the investigated operating period

Source: created by the authors

Moderate and high thermal-loss regimes became increasingly frequent during summer operation, reflecting stronger thermal accumulation and elevated operating temperatures. High thermal-loss regimes above 5% became increasingly significant during peak summer operation, indicating intensified short-term thermal efficiency reduction under elevated irradiance conditions

3.4 Thermal Stress Analysis

The thermal stress analysis revealed a clear seasonal transition between stable and intensified thermal operating regimes. Figure 16 presents the distribution of thermal operating regimes based on modeled PV operating temperature.

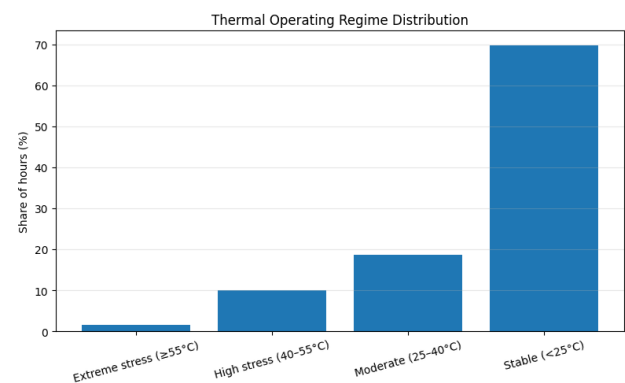


Fig. 16: Distribution of thermal operating regimes based on modeled PV operating temperature

Source: created by the authors

Stable operating conditions below 25°C dominated most of the annual operating period, while moderate and high thermal stress conditions became more frequent during summer operation. Extreme thermal stress conditions above 55°C occurred only during limited operating intervals. The monthly distribution of thermal stress regimes is shown in Figure 17.

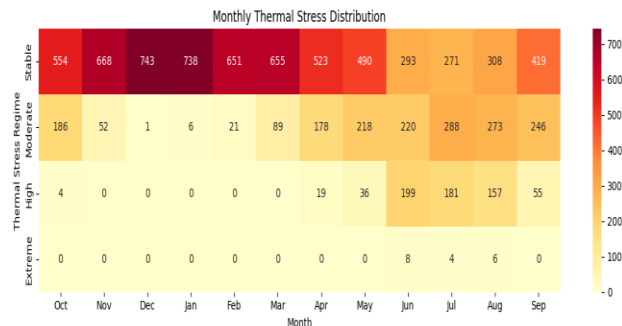


Fig. 17: Monthly distribution of thermal stress regimes during the investigated operating period
Source: created by the authors

High and extreme thermal stress conditions were concentrated primarily during June, July, and August, corresponding to periods of intensified thermal loading and reduced cooling effectiveness. Figure 18 illustrates the thermal operating regime map of the PV system.

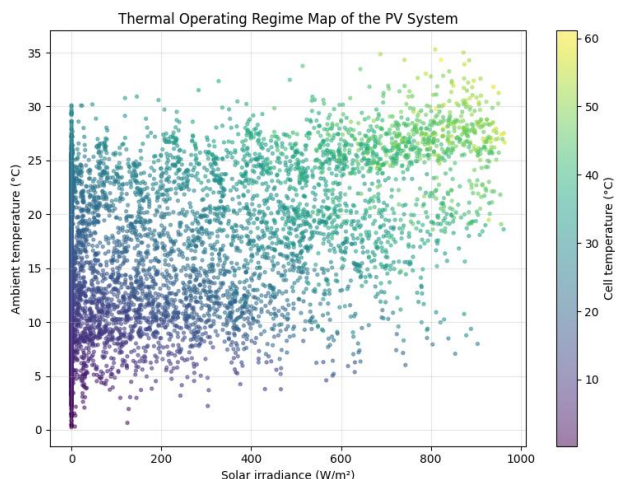


Fig. 18: Thermal operating regime map showing the relationship between solar irradiance, ambient temperature, and modeled PV operating temperature
Source: created by the authors

Elevated operating temperatures are primarily associated with simultaneous high-irradiance and high-ambient-temperature conditions, confirming the coupled influence of atmospheric and radiative thermal drivers. The results additionally indicate that irradiance intensity remains the dominant thermal driver, while ambient temperature acts as a secondary amplifying factor during high-temperature operating conditions

3.5 Operational Temperature Measurements

Figure 19 presents operational temperature measurements obtained from the inverter monitoring system during representative high-temperature operating periods.

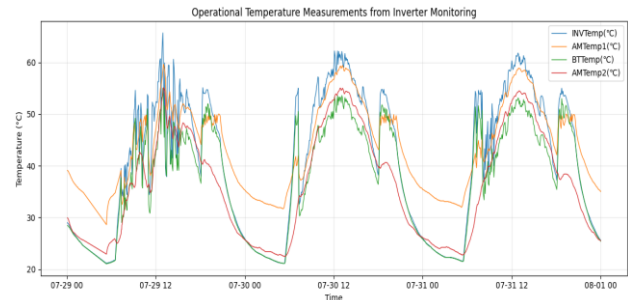


Fig. 19: Operational temperature measurements recorded by the inverter monitoring system during outdoor operation
Source: created by the authors

The measurements show pronounced daily thermal cycling behavior and operating temperatures exceeding 60°C during peak daytime conditions. Although the measurements do not directly represent solar-cell temperature, they provide important operational evidence of substantial thermal loading within the PV system during outdoor operation.

4 Conclusion

This study investigated the thermal behavior and temperature-related efficiency variation of a photovoltaic system operating under high-temperature outdoor conditions using several empirical and semi-empirical thermal formulations. The analysis included the classical Ross/NOCT approach, wind-corrected and irradiance-adjusted NOCT formulations, the Faiman thermal model, and a proposed semi-empirical Thermal Performance Deviation Model (TPDM). The results demonstrated pronounced seasonal and daily thermal variability during outdoor PV operation. Modeled operating temperatures exceeded 60°C during the most thermally stressed summer conditions, while winter operation remained characterized by substantially lower thermal loading. The analysis additionally showed a strong relationship between irradiance intensity and operating temperature, confirming that solar-energy absorption represents the dominant thermal driver of PV operating behavior. Wind-driven convective cooling was also found to play an important moderating role by reducing excessive thermal accumulation during outdoor operation. Temperature-related efficiency loss increased significantly during summer conditions, with the maximum estimated thermal efficiency loss reaching 10.83%. More than 1100 operating hours exhibited efficiency losses above 3%, while 552 operating hours exceeded 5% thermal efficiency loss. Thermal stress regime analysis further showed

that high and extreme thermal-loading conditions were concentrated primarily during June, July, and August. Among the investigated formulations, the proposed TPDM achieved the best overall statistical performance, with an R^2 value of 0.857 and an RMSE of 0.724. Although simplified empirical thermal formulations cannot fully reproduce all transient atmospheric effects under real outdoor conditions, the results indicate that the inclusion of thermal excess improves the representation of PV thermal-performance behavior.

The study additionally highlights the importance of transient heat-transfer mechanisms in determining outdoor PV operating conditions. The interaction between irradiance-driven heat accumulation and atmospheric convective cooling governs the observed thermal response and short-term efficiency variation under real operating conditions. Operational temperature measurements obtained from the inverter monitoring system further confirmed the presence of substantial thermal loading during high-temperature operation.

Overall, the presented analysis provides a physically interpretable framework for evaluating PV thermal behavior, thermal stress conditions, and temperature-related efficiency variation under real outdoor operating environments. The present analysis is based on modeled operating temperatures and operational thermal measurements rather than direct solar-cell temperature measurements. Future work may include infrared thermography or direct backside module temperature sensing in order to further improve the characterization of transient thermal behavior under real operating conditions.

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Declaration of Generative AI and AI-assisted Technologies in the Writing Process

During the preparation of this work, the author(s) utilized artificial intelligence (AI) technologies solely for the purpose of linguistic refinement and grammatical correction. Following the application of these tools, the author(s) comprehensively reviewed, verified, and edited the resulting text. The author(s) maintain full accountability and responsibility for the

accuracy, integrity, and final content of the publication.

References:

- [1] N. Kumari, S. K. Singh, S. Kumar, “A comparative study of different materials used for solar photovoltaics technology,” *Materials Today: Proceedings*, vol. 66, part 8, pp. 3522–3528, 2022. DOI: 10.1016/j.matpr.2022.06.403.
- [2] International Energy Agency Photovoltaic Power Systems Programme (IEA PVPS), “Snapshot of Global PV Markets 2024,” Report IEA-PVPS T1-42:2024, IEA PVPS, 2024. Available online: IEA PVPS – Snapshot of Global PV Markets 2024.
- [3] T. Kirchartz, G. Yan, Y. Yuan, B. K. Patel, D. Cahen, P. K. Nayak, “The state of the art in photovoltaic materials and device research,” *Nature Reviews Materials*, vol. 10, no. 5, pp. 335–354, 2025. DOI: 10.1038/s41578-025-00784-4.
- [4] E. Skoplaki, J. A. Palyvos, “On the temperature dependence of photovoltaic module electrical performance: A review of efficiency/power correlations,” *Solar Energy*, vol. 83, no. 5, pp. 614–624, 2009. DOI: 10.1016/j.solener.2008.10.008.
- [5] D. Faiman, “Assessing the outdoor operating temperature of photovoltaic modules,” *Progress in Photovoltaics: Research and Applications*, vol. 16, no. 4, pp. 307–315, 2008. DOI: 10.1002/pip.813.
- [6] T. Markvart, L. Castañer, *Practical Handbook of Photovoltaics: Fundamentals and Applications*, Elsevier, Oxford, UK, 2003. ISBN: 9781856173902.
- [7] A. Luque, S. Hegedus, *Handbook of Photovoltaic Science and Engineering*, Wiley, Chichester, UK, 2011. ISBN: 9780470721698.
- [8] D. P. N. Nguyen, K. Neyts, J. Lauwaert, “Proposed models to improve predicting the operating temperature of different photovoltaic module technologies under various climatic conditions,” *Applied Sciences*, vol. 11, no. 15, Article 7064, 2021. DOI: 10.3390/app11157064.
- [9] M. Koehl, M. Heck, S. Wiesmeier, J. Wirth, “Modeling of the nominal operating cell temperature based on outdoor weathering,” *Solar Energy Materials and Solar Cells*, vol. 95, no. 7, pp. 1638–1646, 2011. DOI: 10.1016/j.solmat.2011.01.020.

- [10] M. Mattei, G. Notton, C. Cristofari, M. Muselli, P. Poggi, "Calculation of the polycrystalline PV module temperature using a simple method of energy balance," *Renewable Energy*, vol. 31, no. 4, pp. 553–567, 2006. DOI: 10.1016/j.renene.2005.03.010.
- [11] R. G. Ross, "Flat-Plate Photovoltaic Array Design Optimization," in *Proceedings of the 14th IEEE Photovoltaic Specialists Conference*, San Diego, USA, 1980, pp. 1126–1132.
- [12] A. Djegham, T. Djedid, B. Abdelkarim, Z. Driss, "An empirical investigation of the electrical and thermal performance of a PV/T solar collector," *WSEAS Transactions on Circuits and Systems*, vol. 21, pp. 65–71, 2022. DOI: 10.37394/23201.2022.21.8.
- [13] G. Tamizhmani, Y. Ji, L. Tang, "Photovoltaic module thermal/wind performance: Long-term monitoring and model development," in *Proceedings of the World Renewable Energy Forum*, Denver, USA, 2012.
- [14] W. Durisch, B. Bitnar, J.-C. Mayor, H. Kiess, K.-H. Lam, J. Close, "Efficiency model for photovoltaic modules and demonstration of its application to energy yield estimation," *Solar Energy Materials and Solar Cells*, vol. 91, no. 1, pp. 79–84, 2007. DOI: 10.1016/j.solmat.2006.05.011.
- [15] O. A. Alimi, E. L. Meyer, O. I. Olayiwola, "Solar Photovoltaic Modules' Performance Reliability and Degradation Analysis—A Review," *Energies*, vol. 15, no. 16, Article 5964, 2022. DOI: 10.3390/en15165964.
- [16] M. Alonso García, J. Balenzategui, "Estimation of photovoltaic module yearly temperature and performance based on Nominal Operation Cell Temperature calculations," *Renewable Energy*, vol. 29, no. 12, pp. 1997–2010, 2004. <https://doi.org/10.1016/j.renene.2004.03.010>.
- [17] M. Fuentes, *A Simplified Thermal Model for Flat-Plate Photovoltaic Arrays*, Sandia National Laboratories Report SAND85-0330, Albuquerque, USA, 1987.
- [18] G. Makrides, B. Zinsser, A. Phinikarides, M. Schubert, G. E. Georgiou, "Temperature and thermal annealing effects on different photovoltaic technologies," *Renewable Energy*, vol. 43, pp. 407–417, 2012. DOI: 10.1016/j.renene.2011.11.046.
- [19] S. Dubey, J. N. Sarvaiya, B. Seshadri, "Temperature dependent photovoltaic (PV) efficiency and its effect on PV production in the world – A review," *Energy Procedia*, vol. 33, pp. 311–321, 2013. DOI: 10.1016/j.egypro.2013.05.072.
- [20] K. Sredenšek, B. Štumberger, M. Hadžiselimović, S. Seme, K. Deželak, "Experimental Validation of a Thermo-Electric Model of the Photovoltaic Module under Outdoor Conditions," *Applied Sciences*, vol. 11, no. 11, Article 5287, 2021. DOI: 10.3390/app11115287.
- [21] A. Virtuani, D. Pavanello, G. Friesen, "Overview of temperature coefficients of different thin film photovoltaic technologies," in *Proceedings of the 25th European Photovoltaic Solar Energy Conference*, Valencia, Spain, 2010.
- [22] N. Kalogirou, *Solar Energy Engineering: Processes and Systems*, Academic Press, Burlington, USA, 2009. ISBN: 9780123745019.
- [23] O. Bamisile, C. Acen, D. Cai, Q. Huang, I. Staffell, "The environmental factors affecting solar photovoltaic output," *Renewable and Sustainable Energy Reviews*, vol. 208, Article 115073, 2025. DOI: 10.1016/j.rser.2024.115073.
- [24] L. Ghabuzyan, K. Pan, A. Fatahi, J. Kuo, C. Baldus-Jeursen, "Thermal Effects on Photovoltaic Array Performance: Experimentation, Modeling, and Simulation," *Applied Sciences*, vol. 11, no. 4, Article 1460, 2021. DOI: 10.3390/app11041460.
- [25] J. Liu, X. Li, Y. Yang, Y. Wu, "Advancing PV temperature modeling: comparative evaluation and a novel empirical model," *Applied Thermal Engineering*, vol. 291, Article 130228, 2026. DOI: 10.1016/j.applthermaleng.2026.130228.
- [26] D. Afonso, O. Mesbahi, A. Bouich, M. Tlemçani, "Influence of Long-Term and Short-Term Solar Radiation and Temperature Exposure on the Material Properties and Performance of Photovoltaic Panels: A Comprehensive Review," *Energies*, vol. 18, no. 19, Article 5072, 2025. DOI: 10.3390/en18195072.
- [27] T. Huld, R. Müller, A. Gambardella, "A new solar radiation database for estimating PV performance in Europe and Africa," *Solar Energy*, vol. 86, no. 6, pp. 1803–1815, 2012. DOI: 10.1016/j.solener.2012.03.006.

Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

Driada Mitrushi developed the main idea of the study, carried out the data analysis, and prepared the manuscript. Urim Buzra contributed to data collection and analysis. Irma Bërdufi contributed to the methodology and interpretation of the results. Valbona Muda contributed to the analysis of the results and revision of the manuscript. Joan Jani contributed to data processing and preparation of the figures. All authors reviewed and approved the final version of the manuscript.

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Conflict of Interest

The authors have no conflicts of interest to declare that are relevant to the content of this article.

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