

RELIABILITY ASSESSMENT OF THERMAL-ELECTRICAL MODELS FOR PHOTOVOLTAIC SYSTEMS IN MATLAB: ASSUMPTIONS VERSUS EVALUATION

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Abstract

Reliable simulation of photovoltaic (PV) panel behavior requires more than electrical accuracy. It must also reflect the thermal realities of panel operation under real-world conditions. This study investigates the reliability of a Simulink-based thermal electrical model of a Jinko JKM325P-72-V monocrystalline module by comparing simulated temperature profiles with those expected under Standard Test Conditions (STC). The model accounts for multilayer thermal mass and material-specific heat capacities. Heat generation is attributed to both unconverted irradiance and resistive losses, while thermal dissipation is governed by convective heat transfer. By tuning model parameters based on datasheet specifications and empirical coefficients, the simulation achieves close agreement with reference temperature values under standard conditions. The work highlights how common oversimplifications in PV modeling, such as assuming uniform temperature, can lead to optimistic thermal reliability assessments. The approach emphasizes the importance of verifying modeling assumptions against physical intuition and available data to support more trustworthy simulation-based design decisions for PV systems.

Keywords: PV System Reliability, Simulation Assumptions, Thermal Modeling, Model Validation, MATLAB simulation.

I. Introduction

The rapid global adoption of photovoltaic (PV) systems is driven by the urgent need for sustainable and renewable energy solutions to mitigate climate change [1,2,3]. PV technology offers a clean and scalable alternative to fossil fuels, reducing greenhouse gas emissions and supporting global energy transition goals [4,5]. However, environmental factors, particularly operating temperature, significantly influence the performance and efficiency of PV modules. Elevated cell temperatures cause a measurable decline in output power due to the negative temperature coefficient of solar cells [3,8,9]. This challenge is of increasing concern in regions experiencing high solar irradiance and rising ambient temperatures driven by global warming [5,8].

Under Standard Test Conditions (STC), defined as 1000 W/m² irradiance and a cell temperature of 25 °C, PV performance is benchmarked for rating purposes [6,7]. These conditions allow manufacturers and researchers to compare PV technologies on a standardized basis, even though actual operating environments may vary [6]. In the field, conditions often differ greatly from STC, with higher operating temperatures leading to reduced voltage and overall energy

output [3,8]. MATLAB, Simulink, and Simscape have emerged as effective platforms for modeling PV module performance under varying environmental conditions, allowing for precise simulation of temperature effects on power generation [1,5,6,10].

Thermal modeling of PV systems provides valuable insights into both electrical performance and thermal management strategies [3,4]. Models can incorporate key parameters such as irradiance and panel orientation, enabling performance prediction across diverse climatic zones [5,8]. Studies show that natural convection and active thermal regulation can mitigate efficiency losses in hot climates [4,9]. Understanding these thermal effects is critical for optimizing PV performance and ensuring long-term reliability. Moreover, the integration of PV thermal modeling into energy planning tools supports the economic viability of solar projects in various geographic contexts [4,9].

As global temperatures continue to rise, improving the thermal resilience of PV systems becomes increasingly vital [3,8]. Accurate modeling and simulation facilitate the design of effective cooling strategies, guide material selection, and inform policy decisions aimed at promoting renewable energy adoption [4,9]. The combination of performance prediction, environmental data analysis, and advanced simulation environments positions MATLAB and Simscape as essential tools in developing PV control strategies that can withstand the challenges posed by climate change [1,4,8,10].

This study focuses on creating a detailed MATLAB Simulink model of a real commercial PV module, combining manufacturer specifications with reasonable engineering assumptions. The objective is to develop a simulation framework capable of capturing both electrical and thermal aspects of operation, thereby supporting more accurate reliability analyses for PV systems under real-world conditions.

II. Methods and Simulation Setup

This study begins by exploring the functionality of the PV array block within the MATLAB environment, utilizing the Simscape Electrical library and Simulink for system-level simulation. The initial investigation shows that the electrical behavior of the solar panel is well represented, including a broad selection of preset commercial panels that allows for quick configuration. For this work, the Jinko JKM325P-72-V is chosen as a reliable and widely used solar panel model often seen in real-world installations. The physical characteristics of this model are shown in Figure 1.

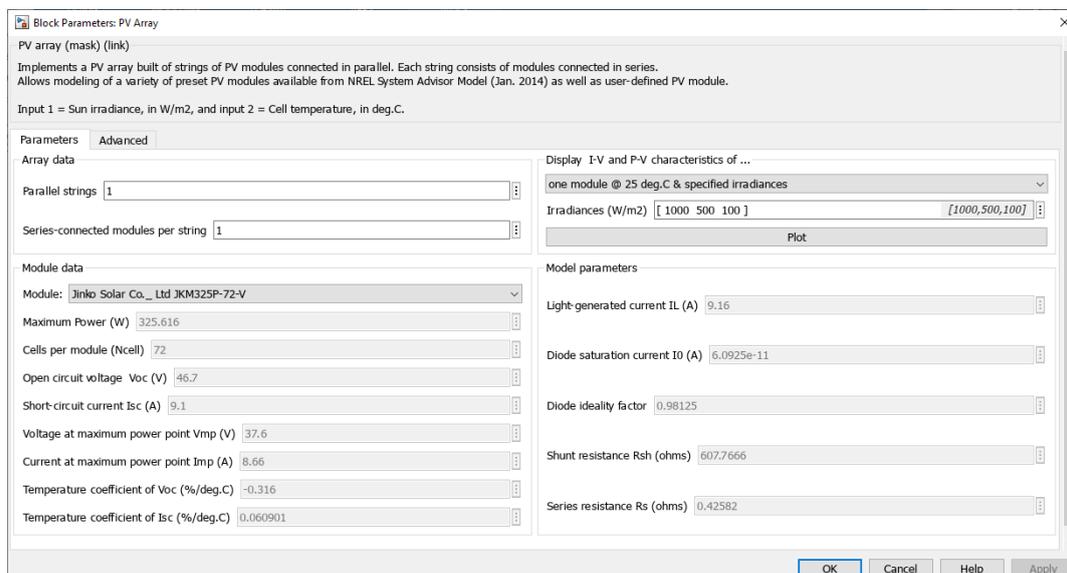


Figure 1: Preset PV array block configuration for the Jinko JKM325P-72-V module

After configuring the PV block, the simulation inputs and outputs were defined with careful consideration of standard photovoltaic testing practices. An irradiance of 1000 W/m² and a temperature of 25 °C were chosen to replicate Standard Test Conditions (STC), which provide a consistent basis for comparing both simulated and real-world module performance. These parameters allow the simulation to produce results that can be matched with the manufacturer's datasheet values. A resistive load was connected between the electrical ports of the PV array to bring the operating point close to the panel's maximum power point (MPP), ensuring that the electrical output reflects optimal energy conversion. This resistance value was calculated directly from the PV array block by dividing the maximum power voltage of 37.6 V by the maximum power current of 8.66 A.

$$R = \frac{U_{mp}}{I_{mp}} \quad (1)$$

Yielding approximately 4.34 Ω resistance. In addition to this, the output measurement port was routed through a demultiplexer, enabling voltage, current, diode current, irradiance, and temperature to be monitored as separate signals for detailed analysis as shown in Figure 2.

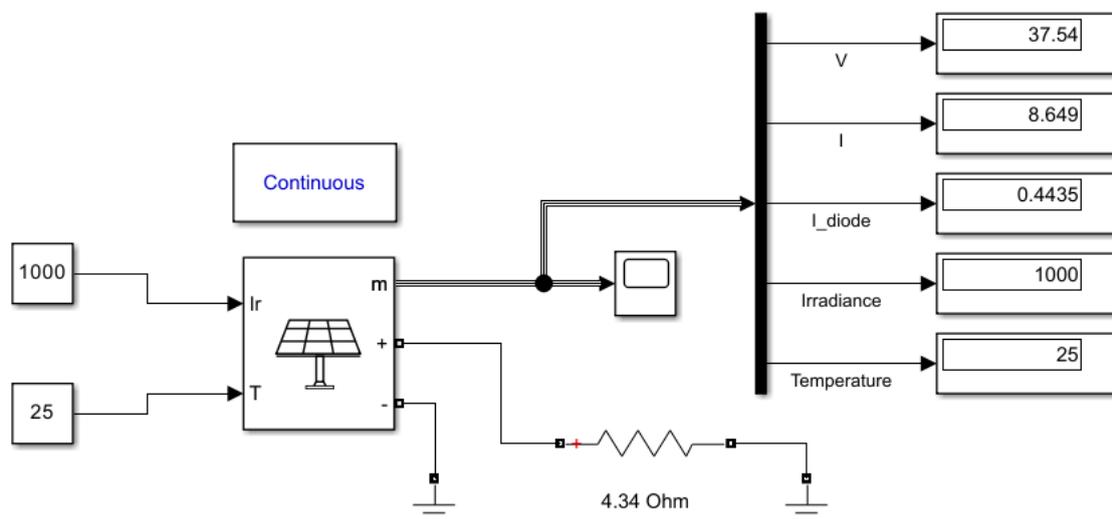


Figure 2: Simulink model of the PV array block

Running the simulation under these conditions produced an output voltage of approximately 37.54 V and a current of around 8.649 A, resulting in output power of 324.68 W, which is very close to the rated 325 W and matches the Jinko 325P-72-V manufacturer specifications. This strong agreement confirms that the PV block within MATLAB Simulink, in conjunction with the Simscape Electrical library, provides an accurate representation of the panel's electrical characteristics under STC. However, when the simulation was extended over a longer time period, it became clear that the PV array block's cell temperature output remained constant throughout the run. This observation reveals that while the PV block effectively simulates the electrical performance, it does not inherently simulate the thermal behavior of photovoltaic modules. In real-world conditions, solar panels experience significant temperature fluctuations due to both environmental heating from solar irradiance and internal heating from electrical current flow. The absence of this effect in the default PV array block highlights the need to integrate a thermal domain into the model. Such an enhancement allows for a more realistic representation of panel performance over time, capturing both electrical and thermal interactions, and enabling further studies into efficiency loss, thermal stress, and long-term reliability.

For this, we must first add a thermal mass block from the Simscape library to represent the

solar panel. However, the estimation of the thermal mass presents a challenge because manufacturers typically provide only limited data, such as glass thickness and overall weight, making it difficult to estimate the properties of individual layers that can store heat. Based on logical assumptions, the silicon layer thickness is set at 0.2 millimeters. The aluminum frame and ethylene-vinyl acetate polymer layers are then estimated so that the sum of all layer weights matches the manufacturer’s total weight specification. This approach enabled calculation of the panel’s overall heat capacity. Table 1 presents all of the estimated data about each layer.

Table 1: Layers of the Jinko JKM325P-72-V contributing to heat storage

Layer Materials	Thickness	Thermal Conductivity (k)	Density (ρ)	Specific Heat Capacity (Cp)
Glass	3.2 mm	1.4 W/(m · K)	2500 kg/m ³	750 J/(kg · K)
EVA (Combined)	1 mm	0.35 W/(m · K)	960 kg/m ³	2100 J/(kg · K)
Silicon Cell	0.2 mm	148 W/(m · K)	2330 kg/m ³	705 J/(kg · K)
Aluminum plate	1.6 mm	205 W/(m · K)	2700 kg/m ³	900 J/(kg · K)

Using the thickness and density of each material layer, it is possible to calculate the equivalent mass of the solar panel. To do this, the panel area must first be determined, which can be obtained from the manufacturer's specifications as around 1.94m². The equivalent mass m_{eq} is calculated by summing the product of density, area, and thickness for each layer.

$$m_{eq} = \sum_{i=0}^n (\rho_i \cdot A \cdot t_i) \tag{2}$$

Next, the average specific heat capacity of the panel is computed by weighting the specific heat capacity of each layer $c_{p,i}$ by its respective mass m_i , and then dividing by the total mass m_{eq} .

$$c_{p,eq} = \frac{\sum_{i=0}^n (m_i \cdot c_{p,i})}{m_{eq}} \tag{3}$$

The natural convection cooling in the model is implemented using the Convection Heat Transfer block from the Simscape Thermal library. This block requires two key input parameters, the convective heat transfer coefficient h and the convective area A . The coefficient h represents the efficiency of heat transfer through natural convection, which depends on environmental conditions such as wind speed and air properties. For this study, a reference wind speed of 1 m/s is used, leading to an assumed range for h between 5 and 10 W/(m²·K). These values align with commonly reported data for natural convection over flat surfaces and ensure the model realistically approximates heat transfer to the surrounding air. The convective area A corresponds to the total surface area of the solar panel exposed to air, where convection can occur. This includes the front and back faces as well as the edges defined by the panel thickness. The total convective area is calculated using the panel’s approximate length L of 1.956m, width W of 0.992m, and thickness T of 0.040m, with the formula below.

$$A_{convection} = 2 \cdot (L \cdot W + L \cdot T + W \cdot T) \tag{4}$$

Resulting in an overall surface area of around 4.11 m². Finally, heat generation within the solar panel must be considered from both direct solar irradiances absorbed as thermal energy and resistive heating caused by current flowing through the panel’s internal resistance. The portion of sunlight not converted to electricity increases the panel temperature, while electrical current

generates additional heat due to the panel’s series resistance. Accurately modeling this combined heat generation is crucial for predicting temperature rise and its impact on efficiency, making it an essential component of the thermal simulation.

$$Q_{gen} = G \cdot A \cdot (1 - \eta(T)) + I^2 \cdot R_s \quad (5)$$

Here, $\eta(T)$ represents the temperature-dependent efficiency of the photovoltaic panel, capturing how the panel’s ability to convert solar energy into electrical power changes with temperature variations. This efficiency is calculated using the following relation below.

$$\eta(T) = \eta_{stc} \cdot (1 + \gamma \cdot (T_{cell} - T_{ref})) \quad (6)$$

Here, η_{stc} is the efficiency at standard test conditions, γ is the temperature coefficient assumed as $-0.0041K^{-1}$, T_{cell} is the cell temperature, and T_{ref} is set as 25 °C as the reference temperature. The η_{stc} is defined as the ratio of electrical power output to incident solar power on the panel surface.

$$\eta_{stc} = \frac{P_{max}}{G_{STC} \cdot A} \quad (7)$$

Here, G_{STC} is 100 W/m², P_{max} is 325 W, and A is 1.94m². Once all parameters required for calculating the heat generation Q_{gen} are obtained, a dedicated subsystem is constructed to perform this calculation dynamically, as shown in Figure 3. The inputs to this subsystem are the panel temperature, irradiance, and electrical current, which are taken from the measurement outputs of the PV array block. The internal series resistance R_s is obtained directly from the PV array block specifications, as shown in Figure 1. The efficiency η_{stc} was calculated to be 16.75 percent, represented as 0.1675 in Simulink. By using these inputs and parameters, the subsystem computes the total heat generated within the panel at each simulation step, allowing the model to capture the influence of changing electrical and thermal conditions of the photovoltaic system.

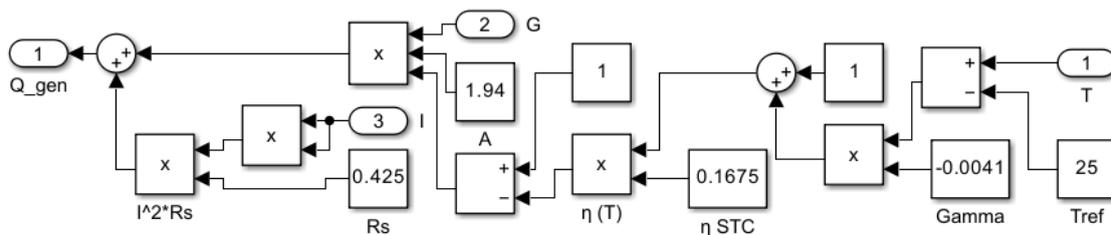


Figure 3: Subsystem model for solar panel heat generation estimation

Once the heat generation subsystem is configured, the next step is to incorporate the thermal domain into the model by assigning the required parameters. These include the convective heat transfer coefficient, convection area, total mass, and averaged specific heat capacity of the panel. For clarity and reference, all assumed values are presented in Table 2.

Table 2: Assumed parameters for integration with the thermal domain

Parameter Name	Convection Coefficient h	Overall Mass of the Panel m_{eq}	Specific Heat Capacity $C_{p,eq}$	Ambient Temperature
Value	10 W/(m ² ·K)	26.6 Kg	890 J/(kg · K)	25° Celsius

The complete simulation setup, integrating both the electrical and thermal domains, is shown

analytical estimates based on the panel's surface area and heat transfer coefficient. It is also important to confirm that the coupling between electrical and thermal behaviors produces consistent trends in voltage, current, and temperature.

Figure 5 presents the simulation results for the total heat generation rate, Q_{gen} , which stabilizes at around 1695 W. This value reflects the net thermal energy generated within the panel from solar absorption and resistive heating, after subtracting the electrical power output. The gradual rise and eventual leveling of the curve indicate that the system reaches thermal equilibrium, where internal heat generation balances heat loss to the environment.

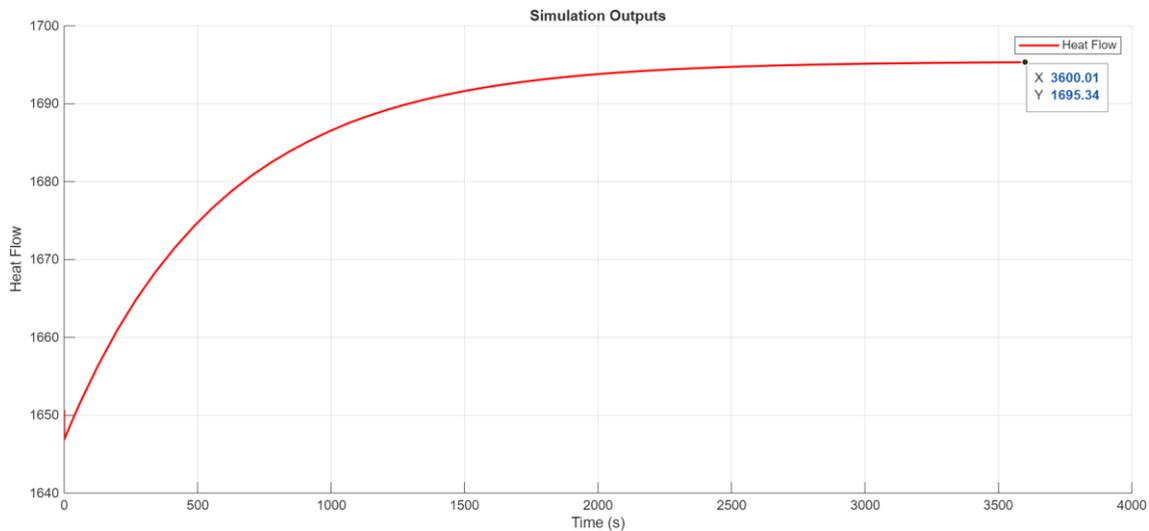


Figure 5: Simulated heat generation rate of the solar panel as a function of time

Thermal equilibrium occurs when the heat generated inside the solar panel equals the heat lost to the surroundings, resulting in a stable panel temperature. In this steady state, the total heat produced from absorbed solar radiation and resistive electrical losses is balanced by heat dissipated through convection and radiation. By calculating the combined heat generation from these sources, we can verify the simulated steady-state heat flow. The computed heat generation should closely match the heat flow observed in the simulation, confirming that the model accurately represents the thermal behavior of the photovoltaic panel.

$$Q_{gen} = Q_{sun} + Q_{res} = G \cdot A \cdot (1 - \eta) + I^2 \cdot R_s \quad (8)$$

The absorbed solar energy Q_{sun} is determined from the product of irradiance, panel surface area, and efficiency, while the resistive heating Q_{res} comes from the current squared multiplied by the series resistance. Using an irradiance G of 1000 W/m², a sun affected front surface area of 1.94 m², an efficiency of 0.1675, a steady-state current of 7.749 A, and a series resistance of 0.425 Ω, the absorbed solar energy is about 1615 W, and the resistive heating is about 25.5 W. After accounting for the portion of absorbed energy that leaves as electrical output and minor optical losses, the remaining heat within the panel is approximately 1640.5 W, which closely matches the steady-state value of 1695 W obtained in the simulation.

In addition to verifying the heat generation rate, the temperature response of the panel was also analyzed to provide a complete picture of the thermal behavior. Figure 6 shows the panel's thermal mass temperature rising from 25 °C to approximately 66.1 °C over time. This increase reflects the accumulation of heat within the panel as it approaches thermal equilibrium, balancing internal heat generation with dissipation to the environment.

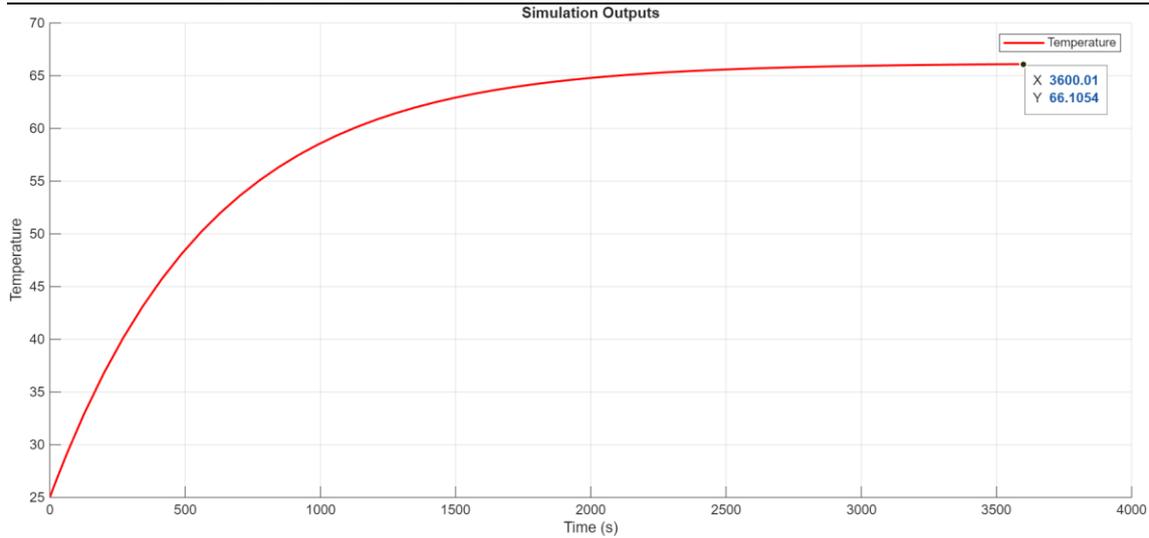


Figure 6: Simulated temperature profile of the solar panel over time

The curve shows a smooth exponential-like rise as the panel absorbs heat faster than it loses it to convection, until thermal equilibrium is reached. The final temperature represents the point where heat generation matches convective cooling. The panel temperature at steady state can be understood by equating the heat generated within the solar panel to the heat dissipated through convection. This relationship is described by Newton's law of cooling below.

$$Q_{conv} = h \cdot A_{convection} \cdot (T_{panel} - T_{amb}) \quad (9)$$

Here, Q_{conv} is the heat flowing away from the panel by convection. The coefficient h shows how well heat moves from the panel to the air around it, and $A_{convection}$ is the surface area where this happens. The heat transfer depends on the temperature difference between the panel surface T_{panel} and the surrounding air T_{amb} . In this study, we assume h to be $10 \text{ W}/(\text{m}^2\cdot\text{K})$, which corresponds to natural convection with a gentle 1 m/s breeze. The convection area is set as 4.11 m^2 based on the panel's total surface area. To figure out how much the panel's temperature rises above the ambient, we rearrange the equation like this.

$$\Delta T = \frac{Q_{gen}}{h \cdot A_{conv}} \quad (10)$$

In this form, ΔT represents the increase in panel temperature resulting from internal heat generation Q_{gen} . Using the simulated heat generation value of 1640.5 W , the calculated temperature rise is approximately $39.9 \text{ }^\circ\text{C}$, indicating how much hotter the panel surface becomes compared to the surrounding environment. Finally, adding this temperature rise to the ambient temperature provides the predicted panel temperature under steady-state conditions.

$$T_{panel} = T_{amb} + \Delta T \quad (11)$$

Given an ambient temperature of $25 \text{ }^\circ\text{C}$, the expected panel temperature is approximately $64.9 \text{ }^\circ\text{C}$. This value is in close agreement with the simulation output of $66.1 \text{ }^\circ\text{C}$, demonstrating that the thermal model accurately represents the physical heat transfer. Figure 7 presents the power output decreasing from 325 W at standard conditions to about 260.6 W at the higher temperature. The drop corresponds to the temperature-induced reduction in panel efficiency, demonstrating the thermal effect on electrical performance.

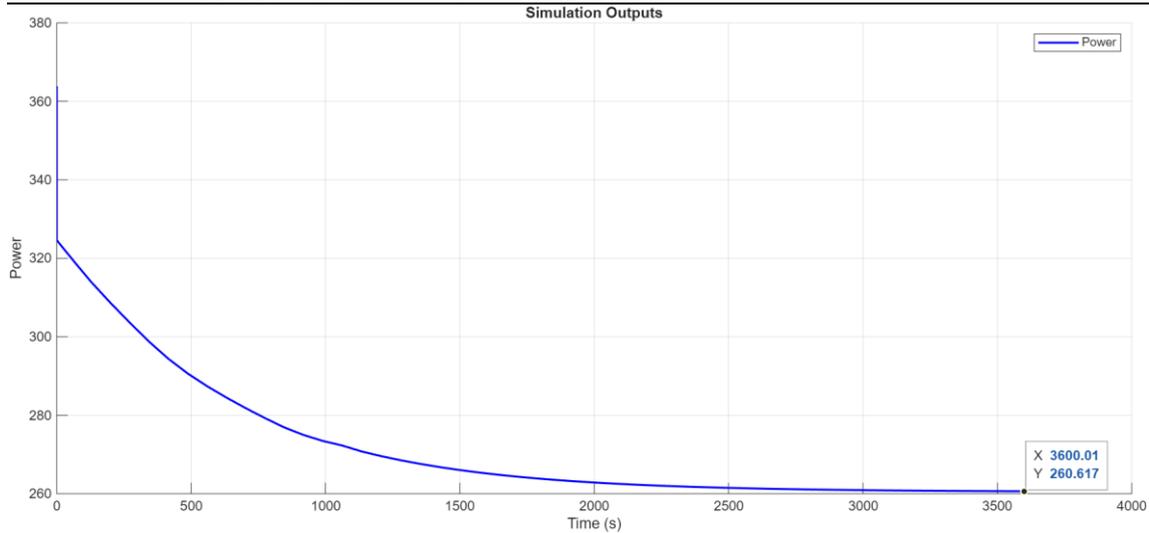


Figure 7: Simulated output power of the solar panel over time

Validation of the simulation results was performed through a two-step approach focusing on the temperature coefficient γ and the corresponding power output at elevated temperatures.

$$\gamma = \frac{\frac{P_{final}}{P_{rated}} - 1}{T_{final} - T_{ref}} \quad (12)$$

Where, P_{final} and T_{final} are the simulated power and panel temperature at steady state, and P_{rated} and T_{ref} correspond to the rated power and reference temperature. Using the simulated values of 260.6 W for P_{final} , 325 W for P_{rated} , 66.1 °C for T_{final} , and 25 °C for T_{ref} . This calculation yielded a temperature coefficient of approximately -0.00482 °C⁻¹, which closely matches the value of -0.0041 °C⁻¹ specified in the Simulink PV array block. Using the specified temperature coefficient, the expected power output at 66.1° is calculated as follows.

$$P = P_{rated} \cdot (1 + \gamma \cdot (T_{final} - T_{rated})) \quad (13)$$

Substituting the known values resulted in a power output of approximately 267.6 W, which is in close agreement with the simulated output of 260.6 W. This agreement validates the model's ability to accurately capture the performance degradation of the photovoltaic panel.

IV. Conclusion

This study developed and validated an integrated thermal-electrical simulation model of a photovoltaic panel, accurately capturing temperature-dependent power degradation. Simulation results show a steady-state heat flow of approximately 1695 W, a panel temperature of 66.1 °C, and a power output of 260.6 W with a temperature coefficient γ of -0.0041 °C⁻¹ as specified in the Simulink PV array block. Theoretical calculations yielded a heat flow of about 1640.5 W, a panel temperature near 64.9 °C, a power output of 267.6 W, and an estimated γ of -0.00482 °C⁻¹ derived from the simulation data. Minor discrepancies between simulation and calculation arise from model simplifications, such as assumptions of uniform irradiance, constant convective heat transfer, and approximate thermal mass and resistance values, rather than from fundamental methodological issues. Despite these simplifications, the close agreement of key parameters confirms the model's reliability and provides a robust foundation for simulating and analyzing photovoltaic system performance under realistic thermal conditions.

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