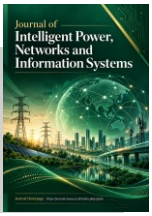
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# Performance Evaluation of Solar Photovoltaic System Under Variable Environmental Conditions: A Two-Factor Parametric Simulation

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***Abstract*—Solar photovoltaic (PV) output is shaped by irradiance and module operating temperature, yet simplified studies frequently isolate these variables. This study presents a transparent, two-factor parametric simulation of their combined influence on the maximum output of a hypothetical 200-W crystalline-silicon PV module. A 5 × 5 factorial matrix spans irradiance levels of 200–1,000 W/m² and cell temperatures of 25–65 °C. A normalized irradiance–temperature model with a −0.40%/°C temperature coefficient is used, followed by coefficient-sensitivity and interaction diagnostics. Modeled output ranges from 33.6 W to 200.0 W. At 1,000 W/m², increasing temperature by 40 °C reduces power by 32 W (16%); at 200 W/m², the same temperature shift reduces power by 6.4 W. The mixed effect on absolute power is nonzero, even though temperature-induced percentage losses are identical across irradiance levels because of the separable assumed model. Results are model-internal deductions rather than field measurements; no performance validation or location-specific yield is claimed. The study supplies a compact reproducible scenario framework and clarifies its limits for subsequent coupled thermal–electrical analysis.***

***Keywords*— photovoltaics, solar irradiance, cell temperature, parametric modeling, interaction effect, sensitivity analysis**

## I. INTRODUCTION

Photovoltaic electricity generation depends on the energy incident on the module and the fraction converted into electricity. Irradiance largely scales available photocurrent, while increasing cell temperature generally reduces voltage and maximum-power efficiency. Treating the two drivers independently can conceal operational trade-offs even when a first-order model is sufficient for a design screening exercise [1]–[4].

The electrical implications of temperature have been synthesized in classical reviews, while coupled irradiation–temperature models have been used to map PV energy performance across technologies and climates [2], [3], [5]. Module temperature itself depends on irradiance, ambient conditions, wind, construction, and heat transfer, as shown by analytical and experimental modeling studies [4], [6], [8]. These findings motivate clear separation of controlled temperature scenarios from physically coupled outdoor conditions.

The present study is intentionally narrow: it evaluates the algebraic response surface of an explicitly assumed engineering model rather than estimating the real generation of a specific site. This scope differs from a single-factor irradiance study, a temperature-only study, and an intraday energy study because it measures the joint power response and distinguishes additive absolute-power interaction from normalized efficiency change.

The research questions are (i) how the simulated module output varies over a two-factor operating grid, (ii) how the absolute and normalized temperature penalties depend on irradiance, and (iii) whether plausible changes in the assumed thermal coefficient change the relative performance pattern. The contribution is methodological transparency and an interpretable interaction diagnostic—not a new photovoltaic law or validated device model.

## II. MATERIALS AND METHODS

### A. Synthetic Factorial Design

TABLE I. ASSUMED MODEL AND SIMULATION PARAMETERS

| Parameter | Value | Interpretation |
|---|---|---|
| $P_{STC}$ | 200 W | Synthetic nominal rating |
| $G_{STC}$ | 1,000 W/m² | Reference irradiance |
| $T_{STC}$ | 25 °C | Reference cell temperature |
| $\gamma$ | −0.004 °C⁻¹ | Power coefficient |
| G levels | 200 to 1,000 W/m² | Five design points |
| Tc levels | 25 to 65 °C | Five design points |
| Module assumption | Fixed area/optics | No spectral or shading model |

Five plane-of-array irradiance levels G = {200, 400, 600, 800, 1,000} W/m² and five externally assigned cell temperatures Tc = {25, 35, 45, 55, 65} °C form 25 deterministic cases. Temperature and irradiance are varied independently to permit factorial attribution; hence the

combinations do not represent a measured climate-frequency distribution. The studied object is a hypothetical module characterized at standard test conditions (STC), not a particular manufacturer product.

### *B. Parametric Output Equation*

At each operating point, the predicted maximum power is:

$$P(G,Tc) = P_STC \times (G/G_STC) \times [1 + \gamma(Tc - T_STC)] \quad (1)$$

For the selected grid the bracket remains positive. The expression assumes proportional irradiance scaling, fixed maximum-power operation, no low-light nonlinear correction, no inverter, no degradation, and no additional electrical losses. Such simplified forms are useful for transparent sensitivity calculations but are less comprehensive than detailed device and array models [1], [9], [12].

The normalized factor:

$$f = P(G,Tc)/[P_STC(G/G_STC)] = 1 + \gamma(Tc - 25) \quad (2)$$

isolates temperature effects. The absolute temperature derivative is :

$$\partial P/\partial Tc = P_STC(G/G_STC)\gamma \quad (3)$$

The cross derivative:

$$\partial^2 P/(\partial G \partial Tc) = (P_STC/G_STC)\gamma \quad (4)$$

captures the irradiance-dependence of absolute temperature losses. This is an algebraically specified interaction, not a statistical interaction inferred from measurements.

### *C. Sensitivity and Interpretation*

A supplementary sensitivity study repeats the 1,000-W/m² temperature sweep for three imposed coefficients: −0.30, −0.40, and −0.50%/°C. All descriptive quantities are exact deterministic outputs. Confidence intervals, statistical significance, and prediction errors would be inappropriate because there are no observed targets or stochastic replications.

## III. RESULTS AND DISCUSSION

### *A. Two-Factor Power Response*

Figure 1 shows that maximum output rises monotonically with G and falls with Tc throughout the investigated domain. The grid encompasses 33.6 W at 200 W/m² and 65 °C through 200 W at 1,000 W/m² and 25 °C.

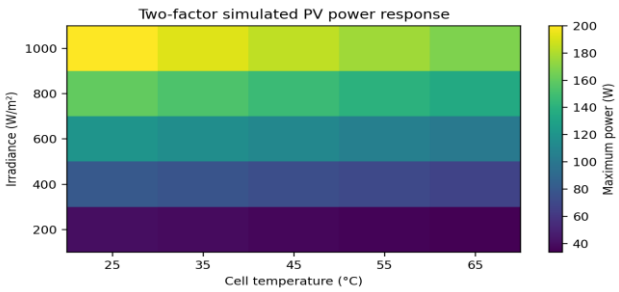



Fig. 1. Simulated maximum-power response over the 25-case irradiance–temperature grid.

The best and worst combinations are predefined by the monotone model, so they should not be interpreted as empirically discovered optimum operating points.

TABLE II. SIMULATED MAXIMUM OUTPUT POWER (W)

| G (W/m²) | 25°C | 35°C | 45°C | 55°C | 65°C |
|---|---|---|---|---|---|
| 200 | 40.0 | 38.4 | 36.8 | 35.2 | 33.6 |
| 400 | 80.0 | 76.8 | 73.6 | 70.4 | 67.2 |
| 600 | 120.0 | 115.2 | 110.4 | 105.6 | 100.8 |
| 800 | 160.0 | 153.6 | 147.2 | 140.8 | 134.4 |
| 1000 | 200.0 | 192.0 | 184.0 | 176.0 | 168.0 |

At 1,000 W/m² the temperature increment from 25 to 65 °C reduces output from 200.0 to 168.0 W. At 200 W/m², the same increment reduces output from 40.0 to 33.6 W. The 16% fractional loss is the same; however, the respective absolute penalties are 32.0 and 6.4 W. Thus the simultaneous-variable question is not exhausted by reporting a temperature coefficient alone.

### *B. Irradiance Response at Controlled Temperatures*

Each curve in Fig. 2 is linear by construction, but its slope changes with temperature. The slope is 0.200 W/(W/m²) at 25 °C and 0.168 W/(W/m²) at 65 °C for the particular 200-W nominal module.

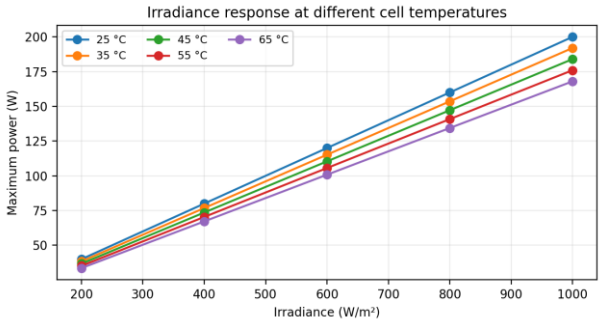



Fig. 2. Irradiance-to-power relationships at five fixed cell temperatures.

This difference is the measurable quantity in the assumed functional form. A physical module may depart from linearity due to shunt, series, optical, and low-light effects [1], [5]. Therefore the simulated near-perfect linearity must not be used as external verification of a real device.

### *C. Thermal Response and Interaction*

Figure 3 reveals larger absolute thermal penalties at higher irradiance. The modeled derivative equals −0.008 W/°C at 200 W/m² and −0.040 W/°C at 1,000 W/m². Figure 4 clarifies that, under the multiplicatively separable model, all curves collapse when temperature loss is normalized to the same-irradiance 25-°C power. Hence absolute-power interaction does not imply a changing relative thermal coefficient. Reporting both measures avoids a misleading claim that high irradiance necessarily amplifies the percentage thermal penalty. The mixed derivative equals −0.00004 W/[(W/m²)·°C]. In a two-way factorial regression with interaction, a nonzero cross-product term would be recovered exactly because the equation includes G × Tc. Such fitting would only reconstruct the input equation; significance tests or high $R^2$ would not constitute scientific validation.

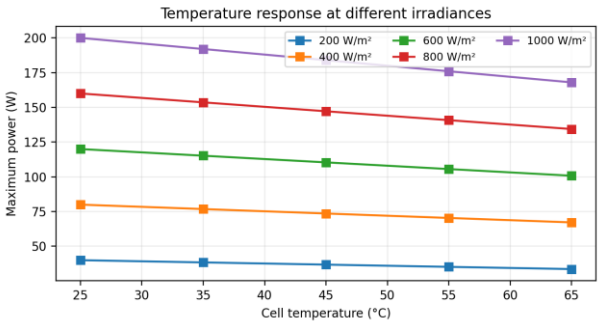



Fig. 3. Absolute temperature-related power decline for each irradiance level.

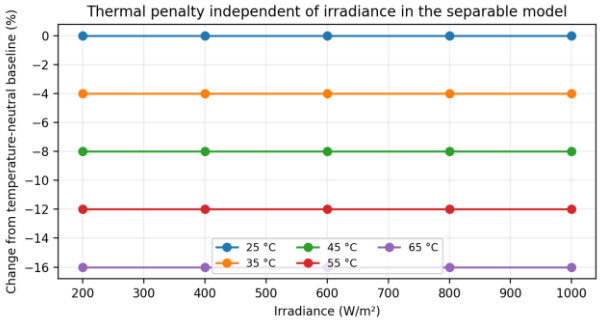



Fig. 4. Percentage temperature penalty relative to irradiance-only output.

### *D. Coefficient uncertainty and physical limits*

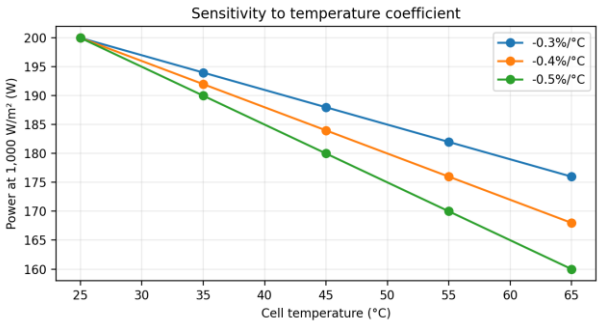



Fig. 5. Output-temperature curves for three assumed thermal coefficients at 1,000 W/m².

TABLE III. COEFFICIENT SENSITIVITY AT 1,000 W/m²

| Coefficient | Power at 65°C | 40°C loss | Relative loss |
|---|---|---|---|
| −0.30%/°C | 176.0 W | 24.0 W | 12% |
| −0.40%/°C | 168.0 W | 32.0 W | 16% |
| −0.50%/°C | 160.0 W | 40.0 W | 20% |

The coefficient sensitivity in Table III shows 160–176 W at 65 °C across the assumed technologies or uncertainty cases. The spread of 16 W is half of the baseline 32-W thermal penalty. Such model-parameter uncertainty can be more decision-relevant than increasing the number of plotted grid points. In practice, γ must be obtained from a module datasheet or fitted measurements; it should not be treated as an identified property of a physically unspecified PV module.

Crucially, outdoor temperature is not independently controlled by irradiance. Radiative heating increases with solar input, whereas airflow and mounting configuration affect thermal dissipation [4], [6], [8]. The 25-case grid therefore supports controlled comparisons but cannot estimate occurrence probabilities, realistic annual yields, or climate-dependent joint distributions. A coupled module temperature model, such as a Faiman-type relation, would be needed for meteorological scenarios.

### *E. E. Relation to prior literature and reproducibility*

Prior studies on temperature-dependent PV performance describe the importance of technology, weather and nonlinear electrical behavior [2], [3], [7]. Huld et al. [5] specifically demonstrate mapping PV performance using irradiance and temperature; the present paper is narrower and does not reproduce a geographically calibrated model. A contemporary technology comparison [11] likewise addresses broader material-level effects than the hypothetical single-coefficient exercise performed here. The present value is its small transparent design showing exactly which apparent "interaction" follows from the assumed equation.

All figures are reproducible from the two parameter vectors and one equation. A reader can recreate the full 5 × 5 matrix with a spreadsheet, and obtain absolute and normalized responses without proprietary software. To move beyond methodological illustration, researchers should compare model predictions with module-specific I–V measurements at multiple irradiances and temperatures, report residual errors, and test whether deviations are systematic [1], [10].

## IV. CONCLUSIONS

A transparent 25-case factorial simulation characterized the joint effects of irradiance and externally imposed cell temperature on the maximum power of a hypothetical 200-W PV module. Modeled output ranged from 33.6 to 200.0 W. A temperature increase from 25 to 65 °C generated a 16% loss at each irradiance in the baseline model, whereas its absolute effect increased from 6.4 to 32.0 W across the irradiance grid. The nonzero cross derivative confirms interaction in absolute power, while the common normalized loss reflects a constant temperature coefficient. Changing the coefficient between −0.30 and −0.50%/°C shifted the modeled 65-°C output from 176 to 160 W at 1,000 W/m². These results are deterministic consequences of assumed equations, not experimental discoveries or site-specific predictions. Subsequent work should introduce module-specific parameters, a physically coupled thermal model, and independent experimental validation before claiming predictive performance.

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