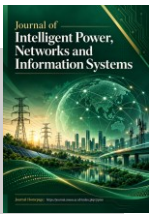
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Effect of Operating Temperature on Solar Photovoltaic Module Efficiency: A Parametric Simulation Study

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Abstract*—This paper examines the sensitivity of photovoltaic (PV) module conversion efficiency and nominal electrical output to operating temperature using a reproducible, deliberately simplified parametric model. Unlike irradiance-response studies, the incident irradiance is held at the standard reference level of 1000 W/m² while module temperature is independently varied from 25 to 65°C. A synthetic 200 W, 20%-efficient reference module is assessed using a baseline power-temperature coefficient of -0.40%/°C and alternative coefficients between -0.30 and -0.45%/°C. The baseline model predicts a reduction in maximum power from 200 W to 168 W and a reduction in conversion efficiency from 20% to 16.8% at 65°C, representing a 16% relative decline. Under the least and most temperature-sensitive coefficients, the predicted 65°C power is 176 W and 164 W, respectively. The results show why thermal coefficients strongly influence projected PV performance and why a reference-temperature rating should not be interpreted as an outdoor operating guarantee. These outcomes are mathematical scenario results, not measured panel performance or validation of a commercial product. The study supplies an auditable baseline for preliminary thermal sensitivity analysis and identifies limits of linear temperature-only modeling.

Keywords*—photovoltaic module, operating temperature, conversion efficiency, temperature coefficient, parametric simulation, thermal sensitivity.

I. INTRODUCTION

Solar photovoltaics (PV) are a major option for distributed and utility-scale power conversion, yet rated module performance is normally reported at controlled standard test conditions (STC). Actual operating temperatures often depart from the 25°C cell-temperature reference, with important consequences for generated electricity. Thermal losses are therefore relevant even when solar radiation is abundant, particularly in environments where strong sunlight coincides with high ambient temperature [1]-[3].

Temperature influences semiconductor recombination, open-circuit voltage, and the current–voltage characteristics that govern the maximum power point. For conventional silicon-based modules, a net decrease in maximum electrical power with increasing cell temperature is typical over normal operating ranges. Literature reviews document several algebraic temperature correlations of different complexity; their appropriateness depends on the specific module, installation, and intended prediction task [1], [2], [7].

Outdoor module temperature is itself a coupled heat-transfer outcome affected by irradiance, ambient temperature, convection, mounting, and wind conditions. Faiman [4] and Mattei et al. [5] investigated practical ways to estimate operating temperature, while numerical thermal approaches have also been explored [6]. Such studies should not be confused with a controlled parametric assessment in which module temperature is supplied directly as the independent input.

Recent work reviews the efficiency implications of thermal stress and possible cooling technologies [7]–[10], while experimental studies consider temperature-related PV performance under realistic settings [11]. Detailed performance models can use module-specific characteristics and weather inputs [12], and newer evaluations test alternative thermal models against field measurements [13]. These approaches offer physical richness but may be unnecessarily complex for a transparent first-order sensitivity exercise.

This study poses a narrower question: how much do predicted conversion efficiency and power change when module temperature and the assumed coefficient vary, with irradiance, collection area, and all other factors fixed? Its contribution is not a new physical law. Rather, it delivers a fully specified, replicable comparison of thermal response and parameter uncertainty, while separating arithmetic model implications from empirical evidence. This also avoids overlap with the companion irradiance-focused simulation study, which varies sunlight rather than module temperature.

II. MATERIALS AND METHODS

A. Research Design and Reference Module

A deterministic parametric simulation was implemented using Python-equivalent arithmetic. A hypothetical, monofacial crystalline-silicon-like module has STC power P_{ref} = 200 W, reference conversion efficiency η_{ref} = 20%, reference temperature T_{ref} = 25°C, and constant plane-of-array irradiance G = 1000 W/m². Accordingly, reference aperture area $A = P_{ref}/(\eta_{ref} G)$ = 1.0 m². These values describe an illustrative system, not a measured or manufacturer-certified commercial product.

A fixed-temperature experiment was intentionally modeled: T = 25, 30, 35, 40, 45, 50, 55, 60, and 65°C. For scenario comparison, four temperature coefficients were tested (−0.30%, −0.35%, −0.40%, and −0.45% per °C). The −0.40%/°C case is called the baseline, without claiming that it applies universally to PV technology [1]–[3].

TABLE I. MODEL INPUTS AND ASSUMPTIONS

Parameter	Value	Assumption
Nominal power P_{ref}	200 W	Hypothetical STC rating
Reference efficiency η_{ref}	20.0%	Fixed at 25°C
Reference irradiance G	1000 W/m²	Constant across experiments
Aperture area A	1.0 m²	Computed from reference rating
Module temperature	25–65°C (5°C step)	Independent variable
Baseline γ	−0.004/°C	Illustrative temperature coefficient
Alternative γ	−0.003, −0.0035, −0.0045/°C	Sensitivity cases

B. Equations and Indicators

Maximum power is modeled as $P(T,\gamma) = P_{ref}[1 + \gamma(T - T_{ref})]$. Conversion efficiency is defined by $\eta(T,\gamma) = P(T,\gamma)/(G\ A) \times 100\%$, yielding $\eta(T,\gamma) = \eta_{ref}[1 + \gamma(T - T_{ref})]$ under the fixed-input assumption. Relative power loss is $L(T,\gamma) = [1 - P(T,\gamma)/P_{ref}] \times 100\%$. The marginal slopes are $dP/dT = P_{ref}\,\gamma$ and $d\eta/dT = \eta_{ref}\,\gamma$. For the baseline, the modeled power decreases by 0.8 W/°C and absolute efficiency by 0.08 percentage points/°C.

The symbol γ denotes a fractional change in rated maximum power per degree Celsius; this must not be confused with percentage-point efficiency change. The model deliberately excludes wind-driven heat transfer, changing irradiance, spectral effects, thermal hysteresis, bypass diodes, aging, and possible nonlinear temperature responses. Because both P and η share the same assumed factor, their thermal trends should not be represented as independent empirical discoveries.

C. Numerical Procedure and Scope of Inference

For each coefficient, the model evaluates nine temperature points using direct substitution. Baseline tabulations and sensitivity plots are generated from the same numerical matrix, making all reported changes traceable to Equation (1). There is no stochastic fitting, measured dataset, experimental calibration, RMSE, or claimed predictive accuracy. The resulting values are mathematical scenario outputs; reported percentage changes measure differences between modeled cases only.

III. RESULTS AND DISCUSSION

A. Baseline Thermal Response

Table II indicates an exactly linear thermal penalty over the prescribed range. At 45°C, nominal maximum power becomes 184 W and conversion efficiency falls to 18.4%; at 65°C, they become 168 W and 16.8%. The 40°C rise leads to a 16% relative reduction in both indices. This does not imply that the physical efficiency falls by 16 percentage points: the absolute efficiency decrease is 3.2 percentage points. Distinguishing relative and absolute changes is essential when discussing temperature-related performance [1], [3].

TABLE II. BASELINE OUTPUT AT Γ = −0.40%/°C.

T (°C)	P_max (W)	η (%)	Relative loss (%)
25	200.0	20.00	0.0
30	196.0	19.60	2.0
35	192.0	19.20	4.0
40	188.0	18.80	6.0
45	184.0	18.40	8.0
50	180.0	18.00	10.0
55	176.0	17.60	12.0
60	172.0	17.20	14.0
65	168.0	16.80	16.0

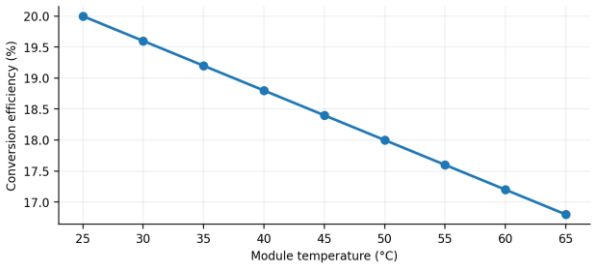


Fig. 1. Simulated baseline module conversion efficiency versus module temperature.

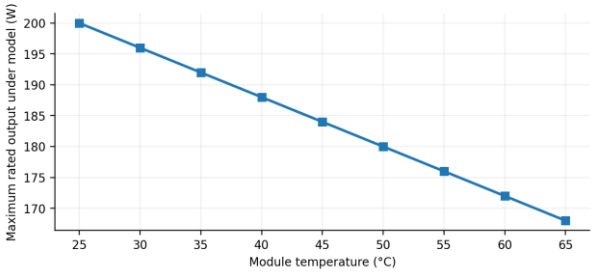


Fig. 2. Predicted maximum module power under constant 1000 W/m² irradiance.

Figures 1 and 2 visualize the same power coefficient through two different metrics. Their straight-line slopes follow directly from the selected equation, and should not be interpreted as evidence that commercial modules exhibit identical linearity across all thermal conditions. Their practical value is to establish the order of magnitude

of nominal loss when a fixed temperature coefficient is assumed.

B. Coefficient Sensitivity

TABLE III. COEFFICIENT SENSITIVITY AT SELECTED TEMPERATURES

γ (%/°C)	P at 45°C (W)	P at 65°C (W)	Loss at 65°C (%)
-0.30	188.0	176.0	12.0
-0.35	186.0	172.0	14.0
-0.40	184.0	168.0	16.0
-0.45	182.0	164.0	18.0

At 65°C, the sensitivity envelope spans 164–176 W, a 12 W difference between extreme modeled coefficients. Since all other inputs remain identical, the spread is attributable exclusively to coefficient selection. This is a model-parameter scenario range, not a probabilistic confidence interval. Module data-sheet coefficients should therefore be used whenever the calculation concerns an actual technology or candidate installation.

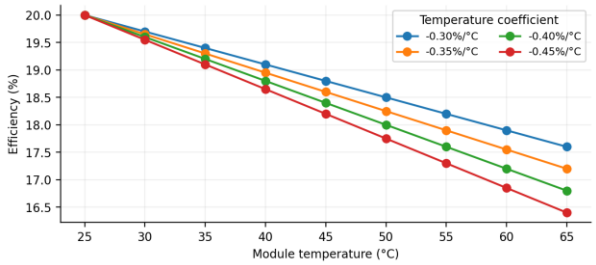


Fig. 3. Efficiency-temperature profiles for four prescribed power coefficients.

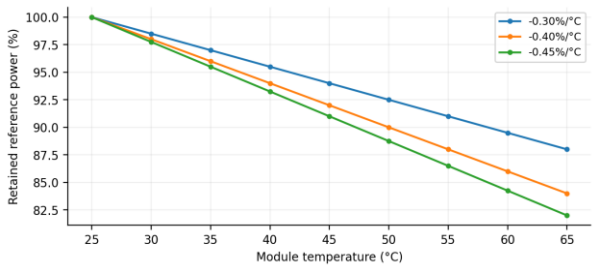


Fig. 4. Percent of retained reference power over temperature for three coefficients.

C. Temperature–Coefficient Interaction and Practical Reading

In the linear equation the loss term is proportional to $|\gamma|(T - T_{ref})$. Accordingly, the effect of coefficient uncertainty grows with the temperature difference from the reference state. At 35°C, the two extreme coefficients imply losses of 3.0% and 4.5% (a 1.5-point spread). At 65°C, their respective losses are 12% and 18% (a 6-point spread). This multiplicative pattern explains why coefficient choice becomes increasingly consequential in hotter assumed operating scenarios.

Thermal response has design implications but does not alone establish whether a specific cooling system is worthwhile. Cooling methods can raise output yet introduce material, maintenance, pumping, or installation costs; reviews survey these trade-offs [8], [10]. Likewise, irradiance and ambient temperature determine heat gain and thermal equilibrium in ways absent from the present fixed-irradiance sensitivity experiment [4]-[6]. Thus, the results should be used for preliminary screening or teaching of PV thermal sensitivity rather than independent outdoor energy-yield prediction.

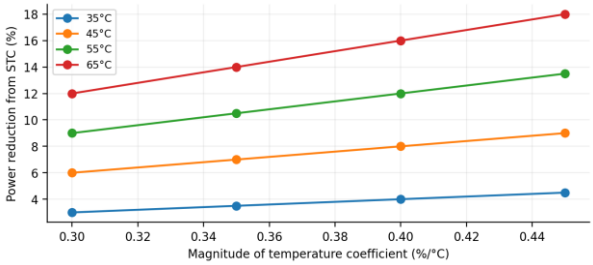


Fig. 5. Modeled relative power reduction across temperature coefficient assumptions.

D. Comparison with Literature and Research Boundaries

The modeled decline with temperature agrees qualitatively with established discussions of temperature coefficients [1]–[3] and wider evaluations of environmental PV losses [9]. However, agreement in sign is not a validation test: the cited studies investigate real systems or literature correlations, while this study does not estimate coefficients from observations. Models such as the Sandia PV performance formulation explicitly account for more electrical and environmental structure [12], and recent model validation illustrates the value of measured field data for judging thermal estimation accuracy [13].

The primary limitation is structural: with one constant power coefficient and fixed irradiance, the linear response is predetermined. The study does not quantify variations due to irradiance, wind speed, mounting, technology, or day-to-day meteorology. An experimentally grounded follow-up could specify a named module, determine its coefficient from a manufacturer sheet, obtain synchronized irradiance and module-temperature measurements, and evaluate model error on held-out observations. No such test has been undertaken here, and no empirical reliability claim is made.

E. Interpretation for Design Decisions

A practical design comparison should distinguish thermal sensitivity from thermal exposure. Two modules may have different temperature coefficients yet experience different cell temperatures under the same ambient conditions because of their encapsulation, rear ventilation, mounting clearance, and convective environment. The present model does not resolve these mechanisms. Its coefficient scenarios are useful only when the operating-temperature input is clearly defined and when the candidate modules have comparable performance ratings. In other words, a smaller magnitude temperature coefficient does not by itself prove superior annual production if other electrical and optical properties vary [2], [4], [5].

Consider a purely illustrative 45°C working point, 20°C warmer than the STC reference. The model predicts 188 W at −0.30%/°C and 182 W at −0.45%/°C; the six-watt spread represents 3% of the common reference rating. At 65°C the spread doubles to twelve watts. Neither difference

is a measured advantage, because all candidate modules in the comparison are hypothetical and share the same initial reference rating. Nonetheless, these values show why temperature-related assumptions can become material to early engineering decisions in hot operating scenarios.

The 200 W reference rating is treated as DC maximum-power capability and no conversion efficiency for an inverter is included. The simulated output must not be interpreted as AC output, daily energy production, or an experimentally observed maximum power point. The fixed irradiance also prevents us from asserting when or for how long a real module will operate at 45°C or 65°C. Converting these sensitivity results to energy requires a time-resolved temperature series coupled with plane-of-array irradiance and an electrical performance formulation that represents operating conditions adequately [12], [13].

The study deliberately retains a linear expression because it exposes assumptions and error propagation. More sophisticated physical descriptions could model open-circuit voltage, short-circuit current, resistance, diode saturation current and thermal exchange separately, at the cost of additional calibration parameters. For short conference contributions, increasing mathematical detail is justified only when it addresses a new research question or measurable discrepancy, rather than making a deterministic exercise appear experimentally comprehensive [1], [6].

IV. CONCLUSION

A transparent parametric temperature simulation was developed for a synthetic 200 W PV module at fixed 1000 W/m² irradiance. Under the baseline coefficient of −0.40%/°C, predicted power decreases from 200 W at 25°C to 168 W at 65°C, and conversion efficiency falls from 20.0% to 16.8%; this is a 16% relative loss. Across coefficients from −0.30% to −0.45%/°C, predicted 65°C power ranges from 176 to 164 W. The central contribution is an explicitly reproducible sensitivity envelope and careful distinction between relative power losses and absolute efficiency changes. The numerical outputs are not measurements and the model is not experimentally validated. Subsequent work should use module-specific coefficients and temperature observations, account for thermal coupling and nonlinear operating effects, and assess whether predicted losses reproduce measured power.

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