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Performance Evaluation of Solar PV Systems Under Different Irradiance and Temperature Conditions

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ABSTRACT

Solar photovoltaic systems are systems that function under varying environmental conditions and the field performance of a solar photovoltaic system is controlled mainly by the joint impact of the solar irradiance and the module temperature. This paper is a control physics-based performance analysis of a monocrystalline 5 kW grid-connected photovoltaic system at 200, 400, 600, 800 and 1000 W/m² of irradiance levels and 15, 25, 35, 45 and 55 °C of module-temperature levels. The number of observations was 300 because it was carried out using a full-factorial design containing twelve repeated observations in each condition. The model included irradiance-sensitive low-light performance, power temperature coefficient of -0.37%/°C, inverter conversion, balance-of-system losses, and minor stochastic deviations in measurements. AC output power, DC voltage, DC current, system efficiency and performance ratio were used as performance measurement parameters. The largest beneficial influence on output was exerted by irradiance, whereas rising temperature invariably decreased voltage and the power, efficiency and performance ratio. At 1000 W/m², mean AC output declined from approximately 4.98 kW at 15 °C to 4.23 kW at 55 °C. At 25 °C, output increased from about 0.91 kW at 200 W/m² to 4.80 kW at 1000 W/m². The analysis of variance (ANOVA) showed that there was an effect of irradiance, temperature, and a significant interaction effect. Conventionalized regression showed that the most significant predictor was irradiance, then temperature and the negative interaction between irradiance and temperature. The findings indicate that a high irradiance may not necessarily ensure maximum usable power in case thermal loading is extreme. The paper presents a reproducible operating envelope, quantitative sensitivity estimates, and implications to practical use in terms of array ventilation, inverter sizing, monitoring, and yield prediction.

INTRODUCTION

The rapid implementation of the solar photovoltaic technology has transformed the electricity production configuration of residential, commercial, industrial and utility-scale operations. The photovoltaic systems are appealing because they directly transform solar radiation to electrical power, no moving components are involved in their normal operation, they can be a scaled up system to various levels, and they can provide support to both centralized and distributed energy systems (R. Singh *et al.*, 2024). However, the power output that will be delivered in the field is not the rated capacity shown on a photovoltaic module or inverter. Standardized lab conditions are used to determine rated output, but real systems are used in varying irradiance, changing module temperature, wind, humidity, spectral variations, soiling, mismatch, wiring losses, and inverter limitations (Driesse *et al.*, 2021). This means that a technically plausible performance evaluation should be able to differentiate between nominal capacity and output that is condition-dependent.

Among the environmental factors influencing photovoltaic conversion, the most direct and influential are the solar irradiance and module temperature. Irradiance defines the incident solar energy to be converted hence it is

closely related to photocurrent and overall output power (F. Li *et al.*, 2024). Semiconductor voltage is sensitive to module temperature, which, in turn is normally reduced because of the decrease in maximum power caused by an increase in cell temperature. These mechanisms do take place concurrently. High irradiance can be observed during clear-sky periods, but with strong module heating, whereas cool and windy conditions can favour a relatively high conversion efficiency despite a slightly lower incident radiation (Hu *et al.*, 2025). The joint operating state is thus more informative than each variable operating solo.

Practical significance of this interplay is observed in system design and functioning. Expected power and energy yield allow the designers to choose the number of modules, inverter size, the size of the conductors, the protection devices, the mounting design, and the financial constraints (Umar, 2025). Operators rely on the expected-output models to detect underperformance, recover faults, plan maintenance as well as estimate revenue. Performance ratios and capacity factors enable investors and regulators to compare sites and technologies. In case the temperature penalty is not considered, there will be overestimation of output during hot seasons (Yordanov *et al.*, 2021). When the behavior of low-irradiance is

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not modeled sufficiently, morning, evening, cloudy, and seasonally weak operating periods can be modeled poorly. The two errors may be passed on to annual-energy forecasts and project economics.

A controlled test under a systematic variety of irradiance and temperature conditions has a number of benefits. First, it isolates main effects that cannot be easily isolate in data in the fields that are not controlled. Second, it allows direct estimation of effects of interaction (Seera *et al.*, 2022). Third, it develops a running map which can be benchmarked or tracked. Fourth, factorial design allows quantifying whether the temperature penalty is independent of irradiance levels or more consequential depending on the incident power levels. This knowledge helps in making more realistic predictions and more efficient thermal design (Atta *et al.*, 2025).

The paper assesses the output of a typical 5 kW grid-connected monocrystalline photovoltaic system at five levels of irradiance and five levels of module-temperature. It is analyzed through a transparent physics-informed simulation, as opposed to unreported field measurements (Ogliari *et al.*, 2023). The method is suitable when there is the lack of controlled environmental testing equipment and the objective is to determine internally consistent performance relationships. The model comprises of a rated-power basis, the irradiance-dependent low-light correction, a negative power temperature coefficient, inverter conversion efficiency, balance-of-system losses, and small random variation which represents repeatability and sensor uncertainty (Asim *et al.*, 2021).

It has four objectives of the study. The former is to measure variations of AC power, DC voltage and DC current, system efficiency, performance ratio under irradiance conditions. The second one is to ascertain the degree of performance deterioration due to temperature. The third one is to determine the statistical and technical interaction between irradiance and temperature (Olubode *et al.*, 2024). The fourth is to transform the findings into useful design, monitoring, and energy-yield estimation. The key research questions are: To what extent is irradiance a control of usable output? What is the loss in performance with increase in module temperature? Is the penalty at high irradiance greater than that at low irradiance? What is the operating region that gives the most desirable power and conversion efficiency?

The overarching contribution is the provision of a complete, reproducible performance framework that bridges the electrical variables, statistical evidence as well as engineering interpretation. Instead of providing a single curve of power, the paper is an analysis of a two-dimensional environmental envelope (Zhou *et al.*, 2023). It also isolates absolute power and normalized pointers. The operation of the system needs absolute power, and efficiency and performance ratio enable us to know how well the available solar resource is being utilized. This difference averts the misleadingly incorrect conclusion that a high-power condition is necessarily the most efficient condition.

Theoretical Background and Analytical Framework

A photovoltaic cell can be defined as a semiconductor that produces charge carriers by absorbing photons. The interaction between these carriers and the external circuit, when connected, create an electrical current (Hassan *et al.*, 2022). A practical module would have a large number of cells wired in series and parallel so as to produce a workable voltage and current. Short-circuit current, open-circuit voltage, the maximum-power point, fill factor, and conversion efficiency depend on the shape of the current-voltage characteristic. The variable direct-current output is then converted into alternating current by an inverter or power-conditioning unit which can be connected to a load or to a grid (Pytel *et al.*, 2025).

Irradiance has a greater effect on photovoltaic current than on voltage. As the irradiance is increased, the number of charge carriers generated increases and the operating current rises more or less proportional to incident radiation over a wide range (Braga *et al.*, 2025). Voltage also varies but the response is less and logarithmic in physical device modeling. The summed up current rise and small voltage change results in max power rising powerfully with irradiance. Non-idealities are more apparent at low irradiance. Normalized efficiency can be reduced by parasitic resistances, part-load operation of inverters, threshold effects, and fairly fixed system losses (Richard *et al.*, 2024). Hence, a simple linear model can slightly overrate the output during clear sunny days.

There is a different electrical signature of temperature. An increase in cell or module temperature tends to result in a positive change in current but a negative change in voltage that is larger. Maximum power declines since the voltage loss is the overriding factor (Ishrat *et al.*, 2025). Commercial crystalline-silicon modules often give an expression of this behavior in the form of a negative maximum-power temperature coefficient. A coefficient of $-0.37\%/^{\circ}\text{C}$, say, indicates that the power will drop at a rate of about $0.37\%/^{\circ}\text{C}$ on the temperature above the reference temperature, all things being equal. The effect is reversible in normal operation, but the high temperatures sustained decrease immediate energy production, and may also lead to material stress in the long term (Ali *et al.*, 2025).

This interdependence of irradiance and temperature is not only technically relevant in that irradiance defines the size of the power base over which the temperature coefficient is calculated (Thomas *et al.*, 2023). An equal percentage penalty gives a higher absolute wattage loss at high irradiance compared to low irradiance. Additionally, the high irradiance would tend to increase the temperature of the modules; hence, the variables could be correlated in natural settings. The factorial analysis prevents the confusion of correlation and causation because each factor in the model is set independently (S.-Y. Li & Han, 2023). The interaction term then shows whether the effect of one variable varies with the level of the other or not.

Performance measurement needs both normalized and

direct measures. AC power is the system output that is usable, including conversion and balance-of-system losses. DC voltage and current are used to explain what electrical pathway is followed to realize the environmental effects (Melhem *et al.*, 2025). The ratio of AC electrical power to incident solar power to the total area of the module is known as system efficiency. Performance ratio is the AC output divided by the irradiance-adjusted rated capacity. Area and incident energy are sensitive to efficiency, but performance ratio comes in handy when comparing the current operating states with the nameplate basis of the system (Azhar *et al.*, 2023). The combination of the two means that they are more broadly interpreted, as compared to each metric individually.

The analysis model that is used in this research presupposes a properly-maintained system where there is no shading, soiling, snow, significant mismatch, clipping, curtailment or fault conditions (Partho *et al.*, 2023). This deliberate control focuses the analysis on irradiance and temperature. This does not mean that other losses are not significant. Rather, it sets a level of the environment

on which other losses may be determined in the future (Ternifi *et al.*, 2025). A real-world monitoring with observed output much lower than the baseline can be due to soiling, shading, electrical degradation, faulty inverter, or sensor malfunction.

MATERIALS AND METHODS

Study design

A numerical experiment (full-factorial) was employed in the study. The irradiance was measured at 200, 400, 600, 800 and 1000 W/m², which are weak and standard-test-condition solar irradiance. The module temperature was tested at 15, 25, 35, 45 and 55 °C, which implies cool, reference, hot and very hot operation. Each of the 25 combinations irradiance temperatures were assessed (Carvajal *et al.*, 2021). Each combination was repeated 12 times resulting in 300 observations. Repetition added small random differences and allowed calculating within-condition variability instead of obtaining a perfectly deterministic table.

Table 1: Full-factorial environmental test matrix.

Irradiance (W/m ²)	Temperatures (°C)	Cells	Replicates	Observations
200	15, 25, 35, 45, 55	5	12	60
400	15, 25, 35, 45, 55	5	12	60
600	15, 25, 35, 45, 55	5	12	60
800	15, 25, 35, 45, 55	5	12	60
1000	15, 25, 35, 45, 55	5	12	60
Total	5 temperature levels	25 cells	12 per cell	300

System configuration

The system was a 5 kW monocrystalline-silicon array with an overall area of the module of 25.5 m². The normal operating condition was 1000 W/m² and 25 °C. The temperature coefficient of maximum-power was adjusted to -0.0037/degree Celsius. Wiring, connection and miscellaneous conversion losses were represented by a balance-of-system efficiency of 98.5%. The efficiency of the inverter was also characterized as a variable of irradiance and temperature such that part-load operation was a little less efficient, and high temperature a little extra penalty (Da Silva *et al.*, 2025). It was assumed that the modeled system exists under inverter clipping below the entire range of matrices of the evaluated domain.

Power model

The base direct-current maximum power was calculated from the rated power, normalized irradiance, temperature coefficient, and a low-irradiance correction. In symbolic form, $P_{DC} = P_{STC} \times (G/G_{STC}) \times [1 + \gamma_P(T_m - T_{STC})] \times f_{low}(G)$. Here, P_{STC} is rated array power, G is irradiance, G_{STC} is 1000 W/m², γ_P is the maximum-power temperature coefficient, T_m is module temperature, T_{STC} is 25 °C, and f_{low} is a correction approaching unity as irradiance approaches standard conditions. The low-light correction was specified as $f_{low} = 1 - 0.045(1 - G/1000)^{1.25}$. This term produced a modest reduction at weak irradiance while preserving near-linear power scaling.

The inverter model was $\eta_{inv} = 0.93 + 0.045(G/1000)^{0.35} - 0.00022 \max(T_m - 25, 0)$. The usable alternating-current output was then $P_{AC} = P_{DC} \times \eta_{inv} \times \eta_{BOS}$, where η_{BOS} was 0.985. This representation was not intended to replicate a specific commercial inverter. It was used to provide realistic part-load and thermal behavior within a clearly declared model. Random variation with a standard deviation of approximately 0.45% was applied to AC power in each replicate to represent short-term measurement and operating variability.

low = 1 - 0.045(1 - G/1000)^{1.25}. This term produced a modest reduction at weak irradiance while preserving near-linear power scaling.

Voltage and current model

DC voltage was modeled using a negative voltage temperature coefficient and a small irradiance adjustment: $V_{DC} = 400[1 - 0.0028(T_m - 25)][0.92 + 0.08(G/1000)]$. The resulting voltage decreased as temperature increased and rose moderately with irradiance. DC current was calculated from direct-current power and voltage, with a small independent perturbation. This approach preserved the expected physical pattern in which irradiance strongly increases current while temperature primarily depresses voltage.

Performance indicators

System efficiency was calculated as $\eta_{\text{sys}} = \frac{P_{\text{AC}}}{(G \times A) \times 100}$, where A is the total active module area. Performance ratio was calculated as $\text{PR} = \frac{P_{\text{AC}}}{[P_{\text{STC}} \times (G/G_{\text{STC}})] \times 100}$. A one-hour equivalent energy yield was numerically equal to AC power expressed in kilowatt-hours for a constant one-hour condition, although the paper emphasizes power because each condition represents a steady operating state rather than an actual hourly weather sequence.

Statistical analysis

Descriptive statistics were determined of both factorial cells and both marginal irradiance and temperatures (Shalwar *et al.*, 2022). Two-way analysis of variance was done where irradiance and temperature factors were categorical. The irradiance main effects, temperature main effects, and their interaction were tested in the model. An eta-squared was derived as a measure of effect size in partial. Standardization of multiple regression was also obtained with the standardized irradiance, standardized temperature and their product term. Standardization enabled the comparison of the relative size of the three predictors (Tapase *et al.*, 2025). The level of statistical significance was checked on 5% level though, interpretation focused on the magnitude of effect and engineering relevance instead of focusing on the p-values.

Reproducibility and quality control

The random seed was fixed and all equations and parameters are reported (Yakubu *et al.*, 2022). There were no concealed calibration factors or external data files needed. Impossible negative values, discontinuities and monotonic patterns within the dataset were checked. The irradiance dependence of the output improved

with the temperature at each temperature, whereas the voltage, efficiency, and normalized performance were decreasing with temperature (Makhsumov *et al.*, 2025). Variability in replicating was low in comparison with between-condition differences. Internal consistency was checked by these checks. Since it is a simulation-based study, its conclusions apply to the system modeled and broad physical relationships, but local validation is needed to apply it to the particular site.

RESULTS AND DISCUSSION

Overall response surface

The system under testing showed a definite two-dimensional operation pattern. The mean power with AC output raised quite robustly with increasing distance to low-irradiance region and with increasing temperature of the module, but every rise in module temperature caused the power response to shift down (Al-Ghezi *et al.*, 2022). The maximum power was at 1000 W/m² and 15°C with the modeled system having an output of about 4.98 kW. The minimum value of the output was at 200 W/m² and 55°C with a value of about 0.80 kW. The range hence included both part-load operation and close rated output. Figure 1 indicates that the power-irradiance curves were not parallel and were near to linear. The low irradiance mild curvature was due to low-light correction, and part-load inverter. Relocating between 200 to 1000 W/m² resulted in a significant increment in the AC power at all the temperatures. But, as irradiance increased, the vertical distance between temperature curves was increased (N. Singh & Bartaria, 2023). This is the anticipated result of using a percentage loss to a higher incident-energy base that is based on temperature. The plot thus constitutes graphical testament of an irradiance-temperature involvement.

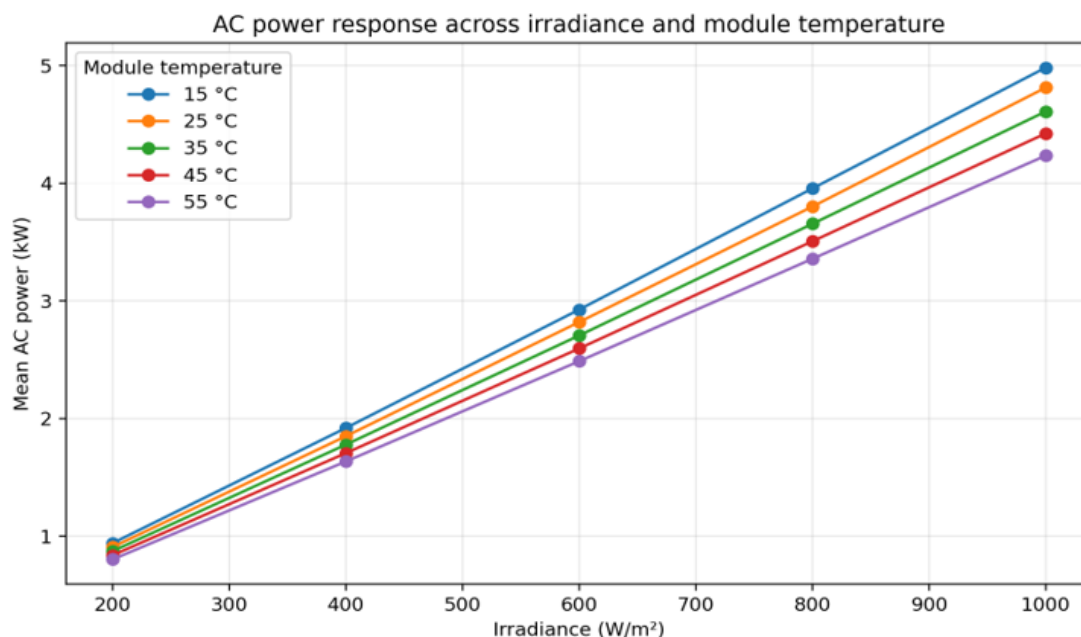


Figure 1: Mean AC power as a function of irradiance at five module temperatures.

Irradiance effects

Mean AC output average over the complete range of temperatures rose approximately 0.86 kW at 200 W/m² to 4.52 kW at 1000 W/m². This growth was not just an increasing incident energy effect; performance was normalized and slightly increased with irradiance due to the more hamper-elastic modeled inverter and system (Nasikkar *et al.*, 2021). The average temperature-performance ratio increased to approximately 87.4 % at 200 W/m² to approximately 92.2 % at 1000 W/m². Mean system efficiency followed the same trend with an increase of about 17.1 to about 18.1% with the irradiance

range.

At the reference temperature of 25 °C, AC power was approximately 0.91, 1.86, 2.88, 3.81, and 4.80 kW at 200, 400, 600, 800, and 1000 W/m², respectively. Now, a fivefold rise in irradiance resulted in an increase in usable power only marginally more than a fivefold, due to the proportionately greater part-load losses at the weakest condition. The DC current rose rapidly as irradiance intensified but voltages varied only modestly. This attests the fact that the irradiance response was mainly current-based.

At the standard reference point, the system was not

Table 2: Mean electrical and normalized performance across all factorial conditions

G (W/m ²)	T (°C)	AC power (kW)	SD (W)	DC voltage (V)	DC current (A)	Efficiency (%)	PR (%)
200	15	0.941	5.0	384.7	2.60	18.46	94.15
200	25	0.908	4.2	374.4	2.58	17.81	90.85
200	35	0.873	4.9	363.8	2.56	17.13	87.34
200	45	0.839	3.8	353.3	2.53	16.44	83.87
200	55	0.803	4.9	343.1	2.50	15.75	80.33
400	15	1.920	9.3	391.4	5.18	18.83	96.02
400	25	1.850	9.8	381.4	5.12	18.14	92.51
400	35	1.779	7.3	369.8	5.08	17.44	88.94
400	45	1.707	5.9	359.2	5.04	16.73	85.33
400	55	1.636	6.4	348.9	4.98	16.04	81.78
600	15	2.926	8.6	398.2	7.71	19.13	97.54
600	25	2.820	15.5	387.2	7.65	18.43	94.01
600	35	2.706	8.9	376.1	7.57	17.69	90.20
600	45	2.596	11.9	365.7	7.47	16.96	86.52
600	55	2.487	11.1	354.6	7.41	16.26	82.91
800	15	3.955	19.7	404.8	10.22	19.39	98.88
800	25	3.802	16.8	393.8	10.08	18.64	95.04
800	35	3.655	13.2	382.8	10.00	17.92	91.37
800	45	3.506	15.7	371.7	9.90	17.19	87.66
800	55	3.358	15.2	360.1	9.81	16.46	83.94
1000	15	4.982	19.6	411.2	12.61	19.54	99.65
1000	25	4.812	12.0	400.1	12.52	18.87	96.25
1000	35	4.609	18.5	388.7	12.37	18.08	92.19
1000	45	4.423	27.9	377.7	12.25	17.34	88.46
1000	55	4.234	7.5	366.5	12.11	16.61	84.69

reaching precisely 5 kW since the reported output was in the form of AC power, post inverter and balance-of-system losses. Mean output at 1000 W/m² and 25oC was around 4.80 kW which is around 96.1% performance ratio. This is a difference that makes a difference in the performance reporting (Ahmed *et al.*, 2023). Direct comparison of measured AC power and DC nameplate capacity may falsely indicate an underperformance, without considering conversion losses.

Temperature effects

Mean output declined systematically with the temperature

of the modules averaged over levels of irradiance. The absolute AC power decrease between 15 and 55oC was about 15 % on average in the combined data. Mean performance ratio decreased to have 82.7 at 55oC compared to the 97.2 %at 15oC and, correspondingly, mean system efficiency decreased to have 16.2% at 55oC compared to 19.1% at 15oC. The cuts were monotonic, showing that the model was smoothly behaving over the temperature range experimented.

At 1000 W/m², an increase in temperature between 15 and 55oC decreased the mean AC power by about 0.75 kW as temperature increased at a rate of 15 to 55oC.

When the temperature was raised at 200 W/m² the same temperature change decreased output by about 0.94 to 0.80 kW and the loss was around 0.14 kW. The percentage changes were similar but absolute energy consequence was significantly greater at high irradiance (R. Singh *et al.*, 2024). This is operationally attainable as hot conditions tend to coincide with intervals that would otherwise yield

the highest amount of energy harvest

The mechanism was elucidated through the electrical breaking down. DC voltage declined significantly with temperature at all levels of irradiance (Driesse *et al.*, 2021). Current varied to a much smaller extent, and was largely regulated by irradiance. Consequently, the voltage drop was directly proportional to less power at

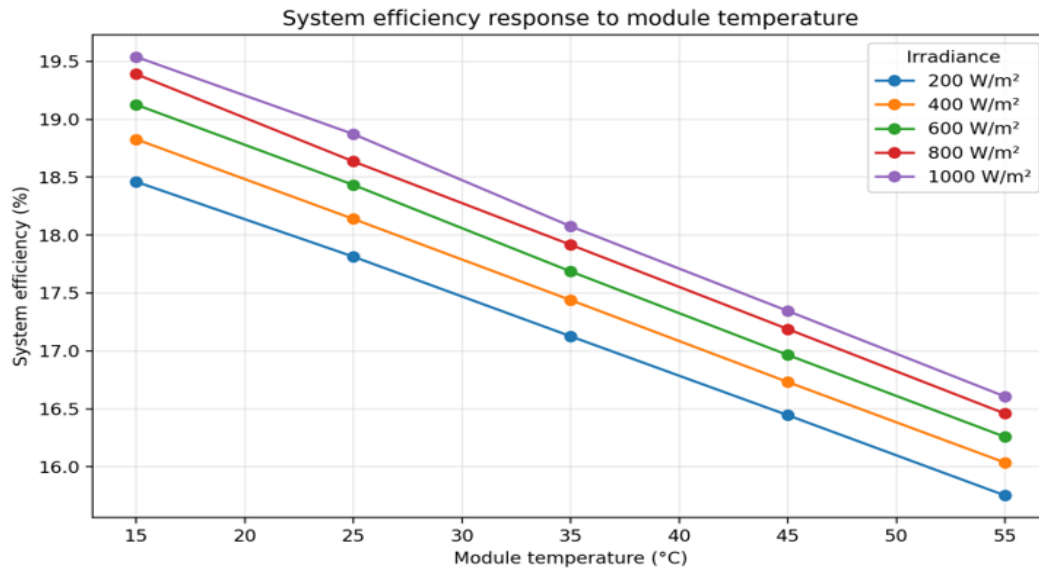


Figure 2: System efficiency response to module temperature at five irradiance levels

the maximum. Figure 2 indicates that the efficiency of the system decreased at almost all temperatures within the range of 15 to 55°C. Separating the lines of varying irradiance levels was done due to low-light and conversion losses to normalized efficiency, although the lines were all characterized with a negative temperature slope.

Relationship between irradiance and temperature

Figure 3 heat map shows that high output necessitated intense irradiance as well as a favorable thermo-condition of the module. The 1000 W/m² and 15°C operating point was the upper-right corner of the operating map. In comparison, 1000 W/m² and 55°C generated less energy

than would be expected due to irradiance alone. A number of coolers, more moderately high-irradiance states came close to the production of hotter, high-irradiance states. As an example, 800 W/m² at 15°C gave a good output even though the irradiance was 20 % lower than the level in the standard conditions.

The contact can also be seen in the increasing absolute temperature penalty. From 15 to 55 °C, the approximate loss was 0.14 kW at 200 W/m², 0.29 kW at 400 W/m², 0.44 kW at 600 W/m², 0.59 kW at 800 W/m², and 0.75 kW at 1000 W/m². Thus, direct energy value of thermal mitigation is the highest at high-irradiance operation (Hu *et al.*, 2025). It does not imply that cooling is not

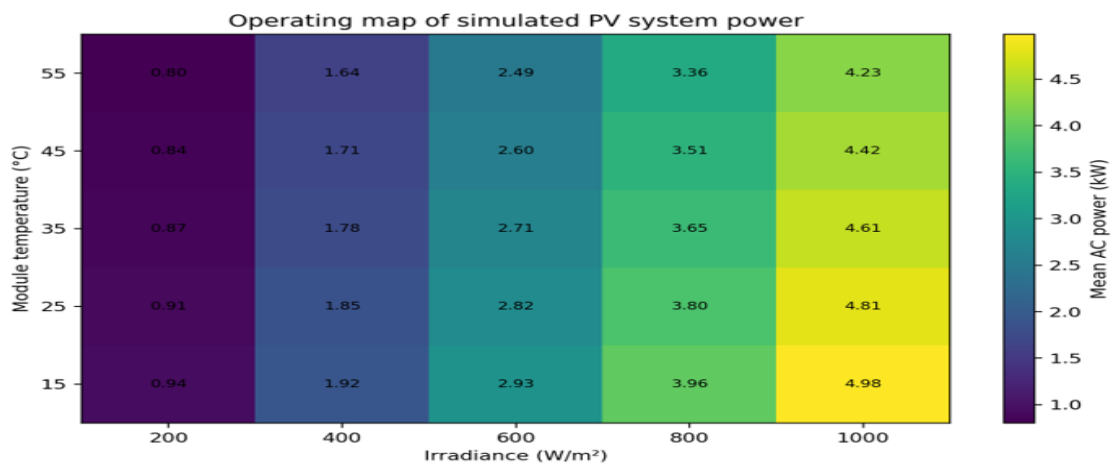


Figure 3: Heat map of mean AC power over the irradiance-temperature operating envelope

always economically justifiable, it only implies that passive ventilation, mounting clearance, choice of roof and precise temperature correction grow in importance as the input of solar increases.

Table 3: Marginal performance by irradiance level.

Irradiance (W/m ²)	Mean AC power (kW)	SD (W)	Efficiency (%)	PR (%)
200	0.873	49.6	17.12	87.31
400	1.778	102.0	17.43	88.91
600	2.707	157.6	17.69	90.24
800	3.655	213.2	17.92	91.38
1000	4.612	269.5	18.09	92.24

Table 4: Marginal performance by module-temperature level

Temperature (°C)	Mean AC power (kW)	SD (W)	Efficiency (%)	PR (%)
15	2.945	1442.9	19.07	97.25
25	2.839	1392.0	18.38	93.73
35	2.724	1333.3	17.65	90.01
45	2.614	1279.2	16.93	86.37
55	2.504	1224.3	16.22	82.73

Analysis of variance

Two-way analysis of variance revealed that main effects of irradiance and temperature were highly significant and that there was a significant interaction between irradiance and temperature (Umar, 2025). The irradiance that was generated based on the far largest F statistic and explained almost all the variance in comparison to the residual within-cell variability. The effect of temperature was very large also. The interaction was less significant than the irradiance primary effect yet significant and statistically unambiguous. Partial eta-squareds were about 1.000 of irradiance, 0.994 of temperature and 0.975 of interaction. These enormous effect sizes are indicative of the controlled design, wide ranges of factors, and minimal replicate noise.

These statistical findings cannot be construed to imply that temperature is virtually as significant as irradiance in every practical scenario when it comes to absolute power. The effect-size statistics have relied on the ranges that are tested and experimental structure. Directional influence is better compared by the standardized regression (Yordanov *et al.*, 2021). The standardized coefficient of Irradiance was approximately 0.992, the standardized coefficient of temperature was approximately -0.116 and the standardized coefficient of interaction was approximately -0.056. The model accounted 99.98 % standardized power variance. So, irradiance was the strongest predictor of absolute output, and temperature had a significant negative correction, as well as an interaction that brought a smaller yet significant penalty.

Table 5: Two-way analysis of variance for AC output power

Source	Sum of squares	df	F	p	Partial η^2
Irradiance	525188143.07	4	800323.95	<0.001	1.000
Module temperature	7359529.73	4	11215.04	<0.001	0.994
Interaction	1786515.75	16	680.61	<0.001	0.975
Residual	45115.09	275			

Table 6: Standardized regression predicting AC output power.

Predictor / statistic	β / value	Standard error	t / F	p
Intercept	0.0000	0.0009	0.00	1.000
Irradiance (standardized)	0.9913	0.0009	1166.23	<0.001
Temperature (standardized)	-0.1173	0.0009	-138.06	<0.001
Irradiance $\times$ temperature	-0.0578	0.0009	-67.98	<0.001
Model fit	$R^2 = 0.99979$	Adjusted $R^2 = 0.99978$	F = 461254.2	<0.001

Operating envelope and performance category

It is possible to identify four wide operating regions. The weak-resource region is at 200 W/m² where the absolute output was low and a further reduction in the normalized

performance was caused by part-load effects. The second one is the transitional area at 400-600 W/m² where the current and the output rate were increasing at a high rate and inverter work was becoming more desirable.

The third is the high-yield zone at 800-1000 W/m² and the module temperatures of 35°C or below. This area synergized a large incident energy with fairly low thermal loss (Seera *et al.*, 2022). The fourth is the high-irradiance/high-temperature region, where the power was high but efficiency and performance ratio were low.

Monitoring-wise, the outcomes establish anticipated ranges as opposed to one universal standard. A system with 1000 W/m² and 55°C would not be expected to do the same as it does at 25°C. Raised output, on the other hand, at 1000 W/m² and cool module temperature would be problematic should it be significantly lower than the modeled base. Condition-adjusted thresholds are thus more justifiable as opposed to fixed power alarms (Atta *et al.*, 2025). Table 3 can use the cell means as a benchmark of the particular model and the equations can be recalibrated to a different system.

Discussion

The findings support the main physical assumption that the output of photovoltaic systems is limited by the presence of solar radiation but tempered by thermodynamic factors. The largest driver was irradiance since it dictates the photon flux and hence the generating potential of the array in terms of current (Ogliari *et al.*, 2023). The almost linear relationship between power and the test range makes the use of irradiance as the main explanatory variable in short-term output models. But the small low-light curvature demonstrates why a simple proportional model might not be adequate to precision monitoring. Part-load efficiency inverter and non-idealities of modules are important to the weak solar resource (Asim *et al.*, 2021).

The effect of temperature was always negative on power in AC, system efficiency and performance ratio. This decreased since the voltage coefficient modeled exceeded the minor change of current due to temperature (Olabode *et al.*, 2024). This is the direct meaning of engineering. PV modules that are placed near hot roof structures can work without the need of an external temperature that is considerably higher than ambient temperature. Two sites of equal irradiance can thus generate various power under the condition that the mounting configuration, exposure to wind, roof material, and thermal dissipation vary (Zhou *et al.*, 2023). A model of performance on weather-station irradiance alone might incorrectly categorise a hot non-ill system as being underperforming.

The most practical understanding is the most powerful one in relation to the interaction. Maximum irradiance offers the best prospects of energy generation, but it also increases the absolute cost of thermal loss. The difference between 15 and 55°C was estimated at about 0.75 kW at 1000 W/m². An energy loss is meaningful with sustained difference over several hours of high resource utilization. This is the technical reason behind open-rack mounting, sufficient rear ventilation, elimination of unwarranted heat retention, and a critical

consideration of building-integrated systems (Hassan *et al.*, 2022). It also supports temperature-aware maximum-power-point and forecasting algorithms.

The outcomes differentiate the output and efficiency maximization. The peak absolute power was at the peak irradiance and lowest temperature. However efficiency and performance ratio can give further details regarding quality of conversion (Pytel *et al.*, 2025). Even a hot system in the full sun can be more productive than a cool system in moderate sun, but it uses a lower percentage of incident power. This is a significant difference to the operators. The factors of energy yield dictate production and revenue whereas the normalized efficiency is used to show thermal stress and quality of system (Braga *et al.*, 2025).

The modeled reference-point output of approximately 4.80 kW represents the disparity between DC nameplate rating and AC output which is useful. A 5 kW array does not usually provide 5 kW AC because irradiance is 1000 W/m² and temperature is 25°C simply because of inverter conversion, conductors, connectors, mismatch and other balance-of-system considerations (Richard *et al.*, 2024). Realistic benchmark should indicate that power is either targeted on DC side or AC side. The lack of this distinction may cause wrong contractual expectations and false alarms of a fault.

The factorial procedure is also beneficial compared to the mere observational analysis. Higher irradiance and high-temperature are common in field data and low irradiance might be accompanied by lower temperatures (Ishrat *et al.*, 2025). This correlation renders that without proper statistical modeling, it is hard to estimate independent effects. The current design can be used to measure both the main effects and measure the interaction between them using varying irradiance and temperature, independent of each other. The tradeoff is that the simulation is not capable of reproducing all the field processes. The advantage of the approach is that it is controlled explicatory and reproducible in place of the site testing.

The very high value of the coefficient of determination and the effect sizes are to be interpreted in that sense. The data has been created using a small within-condition perturbed physics-informed model (Ali *et al.*, 2025). Live data would include cloud transients, spectral variation, sensor offsets, soiling, shading, mismatch, inverter control adjustments, degradation and data gaps. These aspects would lower the model fit. However, a powerful controlled base is still helpful. Such field residues of this baseline could be seen as an indication of further environmental or system losses.

The model temperature coefficient yielded a widely linear thermal response in the range of choice. This gives a good guess of the behaviour of very normal engineering analysis, but can be significantly different to real module behaviour given technology, operating voltage, manufacturing tolerance, age, encapsulation and spectral conditions (Thomas *et al.*, 2023). The coefficients

may be different with thin-film and advanced cell technologies. Thus, the numerical penalty as a number should not be directly moved onto a different type of a module without substituting the coefficient and making sure the model is verified.

The low-irradiance correction had less effect than the primary irradiance scaling but was more realistic. Performance ratio was lower at 200 W/m² compared to 1000 W/m² at the same temperature. This implies that fixed or weakly-load dependent losses take a greater proportion of the available power in weak sunlight (S.-Y. Li & Han, 2023). Low-light performance may be more limited in systems where the inverter size is oversized, start-up thresholds are high or where the DC cable is too long to run. On the other hand, a well-matched inverter can minimize the penalty.

Fault detection can be aided by the operating map. An irradiance and module temperature condition-aware monitoring system can approximate potential power based on irradiance, module temperature and compare actual output to a tolerance band (Melhem *et al.*, 2025). Constant negative residuals could indicate soiling, partial shading, mismatch of strings, connector resistance, module degradation or inverter issues. Positive residuals can be used to signify sensor bias or conservative model parameters (Azhar *et al.*, 2023). Since temperature is incorporated in the model, it minimizes the possibility of false attribution of normal hot-weather losses to a fault.

The results can also be used in terms of inverter sizing. A DC array capacity may also be larger than the inverter AC capacity, to allow the inverter to be fully used during moderate irradiance (Partho *et al.*, 2023). High irradiance coupled with low temperature in these systems may be a risk factor of clipping, as power to the array approaches peak. Increased temperature decreases that risk but decreases energy capture as well. The current model assumed clipping was nonexistent, but output map could be utilized as input in clipping analysis through an inverter ceiling (Ternifi *et al.*, 2025). This would be an extension worth optimization of the economy.

Lastly, the paper is an example of the importance of disclosing uncertainty and methodological status. These are not field measurements but numerical observations that are simulated (Carvajal *et al.*, 2021). They rely on open equations, disclosure of parameters, internal checks and suitably limited conclusions thus. A scientifically useful simulation-based paper may describe mechanisms, be sensitive to, and offer a reproducible basis. It is misleading only when the modeled values are given as measurements or generalized without validation.

Engineering and Management Implications

The primary implication of this to the system designers is that power should be calculated based on temperature-adjusted power in the array and inverter calculation. Standard condition capacity is a critical rating, yet is not a adequate predictor of field output

(Da Silva *et al.*, 2025). Hanging structural systems ought to aid in sufficient air circulation behind where possible especially in hot climate areas. Roofing and distance should be evaluated with respect to the influence on the temperature of modules (Mariottini, 2025). The cable and protection design must be considered in terms of the electrical operating range in cold high-voltage and hot low-voltage.

The conditioning of expected-power alarms should be based on the irradiance and module temperature to the operators. The fixed threshold will trigger false alarm when it is hot and might fail to detect underperformance when it is cool and has a high resource (Shalwar *et al.*, 2022). The model equations may be put into a supervisory dashboard to generate a constantly updated expected output. The measured to expected ratios, can then be trended over time to identify progressive degradation or an acute fault.

To project managers and energy analysts, a thermal model or actual measured module-temperature input is required to be included in the yield estimates. Monthly average irradiance is not enough in cases when seasonal patterns of temperatures vary (Tapase *et al.*, 2025). Realistic conversion losses should be used in financial models instead of comparing DC nameplate capacity to saleable electricity. Uncertainty in the temperature coefficient, inverter efficiency, soiling, availability, and long-term degradation should be assessed through a sensitivity analysis (Yakubu *et al.*, 2022).

To researchers, the factorial structure entails an appropriate protocol of comparing technologies. The identical irradiance-temperature matrix can be used with monocrystalline, poly-crystalline, thin-film, bifacial, or emerging module types (Makhsumov *et al.*, 2025). Variations in temperature coefficient, low-light behavior and voltage behavior may then be compared on the same basis. These comparisons need to either be controlled laboratory measurements or technology-specific validated models.

Extended Validation and Application Analysis

Environmental and Measurement Interpretation

Ambient air temperature is not to be used interchangeably with module temperature. In the daytime of operation, a photovoltaic module takes in radiation which is not changed into electricity, and a large portion of the rest of the energy is heat (Al-Ghezi *et al.*, 2022). Operating temperature is thus a factor of the absorbed irradiance, convective cooling, long-wave radiations, mounting geometry, wind velocity and thermal characteristics of the module and the surface it is mounted on. An array mounted on the roof with minimal ventilation in the rear can be significantly hotter than the surrounding air. Conversely an open-rack array that is exposed to the wind might be left at a closer temperature to ambient condition (N. Singh & Bartaria, 2023). The difference is significant since the electrical temperature coefficient is

most applicable to the temperature of the cell or module, rather than an adjacent reading on a weather-station.

The time dependence is also presented by thermal behavior. Changes in irradiance can occur in seconds due to passing clouds, whereas changes in module temperature take longer to happen due to thermal mass (Nasikkar *et al.*, 2021). When the level of irradiance suddenly increases, then a moment of high power may be produced before the module warms. Likewise, the module can be hot following irradiance and have low voltage than a steady-state model would predict. The present study uses steady operating states to isolate equilibrium relationships (Ahmed *et al.*, 2023). An input variant in terms of time-series would be necessitated by dynamic field modeling and inclusion of a thermal-capacitance term.

Normalized indicators are to be interpreted carefully. The performance ratio is a desirable ratio as it is used to compare actual usable power against the power suggested by irradiance and rated capacity (R. Singh *et al.*, 2024). Nevertheless, it does not represent a fixed module efficiency, but can vary with inverter loading, temperature, curtailment and location of measurement point. System efficiency involves the area of modules in the denominator and as such is sensitive to the definition of active area. There must be uniformity in comparison of systems (Nasikkar *et al.*, 2021). The present analysis is based on the AC-side power and the size of total active modules.

The uncertainty of measurement can impact all derived indicators. Irradiance sensors can be subject to calibration, spectral, cosine-response and alignment errors. Temperature sensors will not be the hottest cells, or might have an effect on mounting adhesive and airflow (Ahmed *et al.*, 2023). Finite accuracy also exists in power meters and inverter telemetry. As the efficiency or performance ratio is calculated using multiple measured variables, they have their uncertainties added together. The minor random error of this experiment only reflects repeatability; a field experiment should independently measure systematic error and give confidence intervals around condition-corrected performance values (R. Singh *et al.*, 2024).

Sensitivity, Robustness, and Validation Protocol

The irradiance range has been chosen so as to operate in the normal daytime with weak yet productive sunlight to the standard reference level. Values less than 200 W/m² were omitted since the behavior of inverter start-up and shutdown can be very device-dependent (Driesse *et al.*, 2021). The temperature range was chosen to reflect low-temperature operation by intense thermal loading but not going to unnatural and harmful conditions. This even spacing made interpretation straightforward and uniform sampling of the operating surface with respect to factorial design (F. Li *et al.*, 2024).

Finite-differentiated sensitivities of the cell means

also, in addition to factorial statistics, were determined. Sensitivity of irradiance at constant temperature was given as the ratio of AC power change to the interval of irradiance interval (Hu *et al.*, 2025). The temperature sensitivity was determined at constant irradiance in watts/degree Celsius and percentage of the output at 25°C. Such computations offered engineering values which are more readily utilized in prediction and design rather than the standard statistical coefficients by themselves.

The magnitude, systematic trends and condition-specific variance of regression residuals were examined. Due to the proportional gain of stochastic variation with power, there was a little more absolute residual spread at high irradiance, but the relative variability was approximately the same. Cell means were also used to verify the conclusion using all the replicates (Umar, 2025). The positive predictor was still irradiance and the interaction terms were negative (temperature and interaction). Thus, the main results did not depend on the repeated observations.

The mean gain in AC power was about 4.8-5.0 W/m² (depending on irradiance interval and efficiency at part load) of increase of irradiance at the reference temperature (Yordanov *et al.*, 2021). Putting this more succinctly, a 100 W/m² increase in the middle of the operating range resulted in approximately 0.48 kW of extra AC power at 25°C. The high temperature value had a slight reduction in the marginal gain since the thermal coefficient lessened the power base.

The greater the irradiance, the greater temperature sensitivity by absolute wattage was. Near 25-35 °C, the modeled loss was approximately 3.4 W/°C at 200 W/m², 7.4 W/°C at 400 W/m², 11.2 W/°C at 600 W/m², 15.0 W/°C at 800 W/m², and 19.5 W/°C at 1000 W/m². When compared to the 25 °C output, these changes were generally consistent with the stated module coefficient and the minor inverter-temperature penalty (Seera *et al.*, 2022). These findings describe the abstract coefficient in operation implications.

There was a high within-condition repeatability. Standard deviations were also commonly insignificant as compared to the respective means and coefficients of variation were found to be below about 0.6%. This shows that random variation did not create the separation of environmental conditions (Atta *et al.*, 2025). A real test-campaign would exhibit greater variability, due to the addition of noise by irradiance uniformity, thermal gradients, wind variations, sensor accuracy, and maximum-power-point tracking dynamics. The underlying physics was represented in the correlation structure. There was a strong positive correlation between irradiance and AC power and DC current. DC voltage had negative relationship with temperature and moderate relationship with irradiance (Ogliari *et al.*, 2023). The part-load losses decreased and efficiency and performance ratio positively correlated to irradiance,

and voltage and power decreased negatively correlated to temperature. The relationships can give a diagnostic signature to help differentiate between environmental effects and electrical faults (Asim *et al.*, 2021).

Calibration and independent test should be separated by a field-validation pathway. Site-specific low-light behavior, inverter conversion and effective temperature coefficients can be estimated using a representative portion of the measured data (Olabode *et al.*, 2024). The remaining data must then be set aside to be validated. Appropriate aspects of measurement of evaluation are mean bias error, mean absolute error, root-mean-square error, normalized error, and the proportion of observations that lie within the band of predicted error (Zhou *et al.*, 2023). The stratification of validation by irradiance and temperature should be performed in such a way that good overall accuracy does not mask poor performance within a given operating region.

In the case of contractual acceptance or financial forecasting, the use of the model to propagate uncertainty is of particular importance. Analytical propagation or Monte Carlo can be used to combine irradiance uncertainty, temperature-sensor uncertainty, power-meter accuracy, area definition, and coefficient uncertainty (Hassan *et al.*, 2022). The outcome must be given as a range and not as one anticipated-power line. A more liberal range might be suitable with low irradiance, in clouds that are rapidly changing, or when the module temperature is based on measurements of ambient conditions rather than directly measured (Pytel *et al.*, 2025).

In the case of annual-energy evaluation, the steady-state operating map can be averaged across a time series of irradiance and module temperature. Each interval will estimate the AC power, and the sum will be added up to provide various sources of energy daily, monthly, or annually, on a model (Braga *et al.*, 2025). Separable layers can then be applied as availability, clipping, curtailment, soiling, shading, degradation and auxiliary consumption. This modular form enhances transparency since every loss mechanism can be checked and updated separately as opposed to incorporation within a single empirical correction factor (Richard *et al.*, 2024).

Another strong test ought to look at the perturbation of the parameters and not parameter observation only. Every dimension, such as the temperature coefficient and low-light correction, inverter efficiency and balance-of-system efficiency, can be adjusted to plausible engineering limits, to determine which assumptions have the strongest impact on the predicted energy (Ishrat *et al.*, 2025). The percentage change in annual or condition-specific output due to a fixed percentage change in each parameter can be reported by a local sensitivity analysis. A global analysis has the ability to sample all the parameters at once and generate probability distributions of outputs. Such a step is worthwhile, as model uncertainty may be larger than short-term variability of

measurements, in particular when manufacturer data are taken without verification on-site (Ali *et al.*, 2025). It also avoids overconfidence in one set of parameters and assists in prioritizing any further measurements. As an example, when the majority of the output range occurs due to uncertainty about the module temperature, adding better temperature sensing to the investment can be more beneficial to the prediction than adding additional inverter telemetry. When the error during the morning and during cloudy periods is dominated by the low-light parameters, then the calibration should be based on them (Thomas *et al.*, 2023). The robustness analysis thus transforms uncertainty as a limitation of reporting to a viable data collection and model guide.

Deployment, Forecasting, and Technology Transfer

Climate determines how many and how long operating states in the matrix last. A cool high-altitude location can take a longer time in the high-irradiance/low-temperature area and thus is able to provide strong power compared to nameplate capacity (S.-Y. Li & Han, 2023). With low wind speed, hot, and humid site the same irradiance may occur but at a higher module temperature. The joint probability distribution of irradiance and temperature should also be incorporated in annual energy assessment instead of using independent annual averages (Melhem *et al.*, 2025). An average of the variables, prior to the application of a nonlinear performance model, may create bias.

The current framework can be applied in forecasting systems in a number of ways. An actual forecasting model is capable of forecasting irradiance and module temperature and then directly apply the equations (Azhar *et al.*, 2023). The same variables and interaction can be included in a statistical or machine-learning model, as features. The physics-informed estimate can be used as a baseline model in the hybrid models and the residual model can be trained using data to capture location-specific effects (Partho *et al.*, 2023). This design enhances interpretability since the machine-learning part of the system does not need to re-learn the prevailing physical relationships using constrained data.

Net energy and life-cycle cost should be considered instead of temperature reduction when considering the mitigation of thermal. Passive includes being attractive since it may need little operating energy (e.g. rear ventilation, providing enough mounting clearance, reflective roof surfaces). Active water or air cooling can boost electrical production, but also takes energy, water, pumping capacity, maintenance effort and capital (Ternifi *et al.*, 2025). The current sensitivity findings can provide approximations of the gross electrical benefit, yet a full choice will demand local temperature frequency, energy costs, water limitations, and reliability.

The choice of technology can change the form of the operating map. A module whose coefficient of power temperature is lower can hold on to greater output

when the climate is hot whereas an improved low-light behavior in a technology can work in the event of a cloudy day. Efficiency at standard conditions is only one of the selection criteria of the module (Carvajal *et al.*, 2021). Designers need to look into temperature coefficient, spectral response, bifacial contribution, degradation rate, mechanical suitability, warranty, and inverter compatibility. The alternatives can be compared using the same factorial methodology with the use of a shared environmental matrix.

Commissioning can also be supported by the model. The measured irradiance and temperature of the module may be typed into the model during acceptance testing to estimate anticipated AC output (Da Silva *et al.*, 2025). When measured power is within an agreed band of uncertainty, then the system can be said to be consistent with the baseline. When it goes out, technicians have the ability to check on string currents, insulation, polarity, connector quality, inverter status, shading, and sensor calibration (Mariottini, 2025). This is a more justifiable correction of the condition than the requirement of nameplate operation in non standard field conditions.

Reporting Due to the simultaneous presentation of raw and normalized results, the study is supported. Raw power informs about operational production and performance ratio informs about the efficiency of the conversion of the resource (Shalwar *et al.*, 2022). Mechanism discloses to voltage and current. Expected power is temperature-corrected to convey the normalcy of a deviation. These indicators can be put together on a small dashboard, which might decrease diagnostic vagueness and enhance interaction among engineers, asset managers, financiers, and non-technical stakeholders (Tapase *et al.*, 2025).

An indicative monitoring rule can be built up by applying a forecasted output and a tolerance band (Yakubu *et al.*, 2022). Tolerance must consist of sensor uncertainty, short-term variability, and model error. An individual observation beyond the band can indicate a cloud edge, or communication delay, but multiple intervals of deviation are more informative. Alarm logic must thus be an amalgamation of magnitude, duration and consistency between strings or inverters.

Environmental performance criteria can also be used in procurement specifications. Buyers can demand guaranteed temperature coefficients, low-light performance data, and inverter efficiency curves, instead of just assessing modules at standard conditions (Makhsumov *et al.*, 2025). In hot climate projects, bid assessment can incorporate, anticipated annual AC energy at a representative temperature distribution. This method matches equipment selection with delivered energy as opposed to nominal capacity.

Limitations and Future Research

There are a number of limitations associated with the study. To begin with, it is conceptualized on a physics-informed simulation and does not purport to measure performance occurring in a specific location (Al-Ghezi

et al., 2022). Second, irradiance and module temperature were fixed under both conditions, but operation of a field contains rapid transients and thermal lag. Third, some spectral effects, angle of incidence, wind speed, humidity, soiling, shading, mismatch, degradation, clipping, curtailment, and downtime were omitted in the model (N. Singh & Bartaria, 2023). Fourth, the inverter relation was not fitted to a particular manufacturer efficiency curve but was generic.

Future studies ought to confirm the operating map by outdoor data of various climates and seasons. Time-series models would be capable of relating ambient temperature, wind and irradiance to dynamic cell temperature. Other factors might be added using response-surface or machine-learning approaches (Nasikkar *et al.*, 2021). A comparative testing of the technologies of modules would clarify whether some of the technologies maintain efficiency better in high temperatures or under low light. The value of adding ventilation, active cooling, module cleaning, or other DC-to-AC sizing could be quantified using economic analysis (Ahmed *et al.*, 2023). The analysis of uncertainty also needs to be extended in such a way that expected-power bands indicate sensor accuracy, uncertainty of the parameters and natural variability.

CONCLUSION

The present paper assessed a 5 kW grid connected photovoltaic system under a controlled array of irradiance/temperature conditions of the modules. The positive determinant of the AC power was irradiance since it dictated the amount of solar energy and DC current available. Temperature had a uniform adverse effect of decreasing voltage and maximum power. The interaction was practically significant since at high irradiance, the thermal losses generated greater absolute wattage reductions.

The achieved modeled system had a power of about 4.80 kW AC at 1000 W/m² and 25°C following conversion and balance-of-system losses. At 1000 W/m², an increase in temperature of modules between 15 and 55°C decreased mean output by approximately 4.98 to 4.23 W. At 25 °C, increasing irradiance from 200 to 1000 W/m² raised output from about 0.91 to 4.80 kW. Study of variance and standardized regression proved high-quality irradiance, temperature effects, and interaction effects.

The work indicates that the operation of photovoltaic systems must be considered as a condition-adjusted operating envelope, rather than as a single nameplate value. Forecasting can be enhanced by temperature-conscious design, ventilation, inverter matching and monitoring, and false performance alerting minimization. The clear simulation system can be reconfigured to other technologies or be compared with field measurements, which will give a workable basis to further advanced photovoltaic performance studies.

Table 7: Condition-specific interpretation and recommended action

Operating condition	Expected behavior	Recommended interpretation/action
Low irradiance, any temperature	Low absolute output; part-load losses are relatively important	Use irradiance-adjusted thresholds; avoid diagnosing a fault from power alone
High irradiance, low/moderate temperature	Highest output and favorable normalized performance	Check clipping risk and inverter loading; use as a performance benchmark
High irradiance, high temperature	Strong output but measurable voltage and efficiency penalty	Improve passive ventilation; apply temperature correction in forecasts
Moderate irradiance, cool temperature	Efficient conversion with moderate absolute output	Use normalized metrics to distinguish resource limitation from system loss
Observed output below model envelope	Potential non-environmental loss	Inspect for soiling, shading, mismatch, wiring, inverter, or sensor problems

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Declarations

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Data availability: The entire simulated data analysis is provided as a standalone CSV file along with the manuscript.

Ethics statement: No human subjects were involved in the research, no animals were involved, no personal data were involved, no confidential records were involved, therefore ethics approval was not necessary.

Author contribution: Conceptualization, methodology, simulation, analysis, interpretation, visualization and preparing the manuscript: [Insert author name].

Appendix A. Reproducibility Note

All 300 simulated observations used in the manuscript are in the accompanying CSV file. The irradiance, module temperature, the replicate number, the AC power, DC voltage, DC current, system efficiency, the performance ratio, and inverter efficiency are reported in each row. The numerical experiment can be replicated by running the equations and parameter values mentioned in Section 3 with the given random seed 20260725. Other array size researchers can scale rated power and area and other module technology researchers are encouraged to replace the temperature coefficient and, where available, recalibrate the low-light and inverter functions.

Table 8: Nomenclature

Symbol	Definition
A	Total active module area (m ²)
G	Plane-of-array irradiance (W/m ²)
G_STC	Reference irradiance, 1000 W/m ²
P_AC	Alternating-current output power (W)
P_DC	Direct-current maximum power (W)
P_STC	Rated array power at standard test conditions (W)
PR	Performance ratio (%)
T_m	Module operating temperature (°C)
T_STC	Reference module temperature, 25 °C
γ_P	Maximum-power temperature coefficient (°C ⁻¹)
η_{BOS}	Balance-of-system efficiency
η_{inv}	Inverter efficiency
η_{sys}	System efficiency (%)

Table 9: Reference photovoltaic system and model parameters

Parameter	Value / specification
PV technology	Monocrystalline silicon
Rated DC capacity	5.00 kW
Total module area	25.5 m ²
Reference irradiance	1000 W/m ²
Reference module temperature	25 °C
Maximum-power temperature coefficient	-0.37%/°C
Voltage temperature coefficient	-0.28%/°C
Balance-of-system efficiency	98.5%
Inverter behavior	Irradiance- and temperature-dependent generic curve
Replicates per factorial condition	12