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# IMPACT OF THERMAL DYNAMICS, SOILING, AND DEGRADATION IN PHOTOVOLTAIC ENERGY YIELD ESTIMATION: A COMPARATIVE MODELING STUDY

*Research paper*

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**Abstract:** Accurate estimation of annual energy yield is critical during the planning and design phase of photovoltaic (PV) power plants. However, basic mathematical models often rely solely on solar irradiance under Standard Test Conditions (STC), ignoring environmental dynamics such as operating temperature, wind cooling, dynamic soiling, and panel degradation. This paper presents a comparative analysis of five mathematical PV module models evaluating fixed-tilt and two-axis tracking configurations over a 16-year period (2005–2020) using meteorological data from Osijek, Croatia. Results demonstrate that neglecting thermal, soiling, and degradation impacts leads to an overestimation of energy production exceeding 12%, with each factor contributing approximately a 4% reduction in overall yield. Conversely, omitting wind cooling underestimates production by roughly 3.3%. Furthermore, modeling errors were found to be 1% higher in two-axis tracking systems, despite achieving ~40% higher overall yield than fixed-tilt systems. These findings emphasize the necessity of incorporating comprehensive environmental parameters into PV design models while highlighting the critical dependence of high-fidelity models on accurate meteorological input data.
**Key words:** Photovoltaic module modeling, Energy yield prediction, Thermal dynamics, Soiling losses

## INTRODUCTION

Photovoltaic (PV) power plants are a critical component of the global transition to renewable energy. Given the rapid expansion of solar installations, this growth is expected to persist. During the planning and design phase of a PV power plant, estimating annual electricity generation is a primary performance metric. Estimating this energy yield relies on mathematical models of PV modules. Although the solar irradiance profile is the primary input parameter governing energy yield at a given location, operating temperature also significantly affects power generation efficiency.

The influence of operating temperature on PV plant productivity is widely recognized in both experimental and theoretical literature. For instance, empirical data across two consecutive years demonstrated an approximate 5% discrepancy in annual PV generation attributable to temperature variations (Nayak & Brar, 2026). Other studies, such as Dubey et al. (2013), evaluated the inverse relationship between ambient temperature and module efficiency. Furthermore, integrated modeling of dust deposition and thermal effects showed up to a 30% reduction in energy output, depending on solar irradiance levels (Zhao et al., 2025). Alaas (2024) reviewed temperature-dependent PV system performance, emphasizing the need to evaluate efficiency as a function of thermal variation. In an investigation of environmental parameters, Bamisile et al. (2025) reported a 0.4%–0.5% decline in PV efficiency for every 1°C rise in panel temperature. Additionally, modeling temperature dependencies revealed significant variations in fundamental PV cell parameters, including the fill factor, open-circuit voltage, short-circuit current, and overall conversion efficiency (Chegaar et al., 2010).

Consequently, accounting for thermal dynamics during the design and forecasting phases of a PV power plant is essential. This paper evaluates the discrepancy in projected PV energy production during the design phase by comparing mathematical models that incorporate thermal, soiling and degradation effects against temperature-independent models.

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## MATHEMATICAL MODELING OF PV MODULE PERFORMANCE

### Baseline electrical model

In this study, the single-diode model is used to simulate photovoltaic (PV) system performance. The standard equivalent circuit model is shown in Fig. 1 and mathematically described by (1):

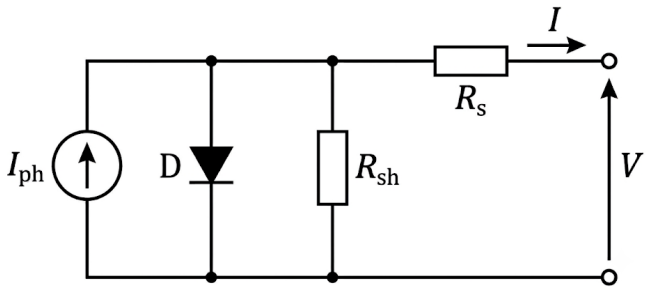


***Fig. 1.*** *An equivalent circuit of single diode PV system model*

$$\mathrm{I} = \mathrm{I_{ph}(G,T)} - \mathrm{I_0(G,T)}\left(\exp\left(\frac{\mathrm{V}+\mathrm{IR_s}}{\mathrm{nV_t(T)}}\right)-1\right) - \frac{\mathrm{V}+\mathrm{IR_s}}{\mathrm{R_{sh}}} \tag{1}$$

where are: $I$ cell output current (A), V cell output voltage (V), $I_{ph}$ photocurrent, light-generated current (A), $I_0$ diode reverse saturation current (A), $R_s$ equivalent series resistance (Ω), $R_{sh}$ equivalent shunt (parallel) resistance (Ω), $n$ diode ideality factor (typically between 1 and 2), $V_t$ thermal voltage (V), $T$ - operating module temperature (K) and, $G$ - actual solar irradiance (W/m$^2$).
Because (1) is a nonlinear, implicit equation, numerical iterative methods are required to solve it. To avoid solving (1) directly when determining the open-circuit voltage, $V_{oc}$ can be modeled as a function of irradiance and temperature via (2):

$$\mathrm{V_{oc}(G,\ T)} = \mathrm{V_{oc,n}} + \mathrm{K_I(T-T_n)}\ +\ \mathrm{nV_t(T)ln}\frac{G}{G_n} \tag{2}$$

where $V_{oc}$ is open circuit voltage (V) at irradiance $G$, $V_{oc,n}$ – open circuit voltage (V) at Standard Test Condition (STC), $K_V$ – open circuit voltage temperature coefficient (V/K) and $G_n$ – irradiance at STC.
Thermal voltage is calculated from:

$$\mathrm{V_t} = \frac{\mathrm{N_s kT}}{\mathrm{q}} \tag{3}$$

where are $N_s$ - number of series-connected cells, $k$ - Boltzmann constant (1.380649 10$^{-23}$ J/K), $q$ - elementary electron charge (1.60217663 10$^{-19}$ C)
Additional irradiance- and temperature-dependent variables are calculated according to (4) – (7):

$$\mathrm{I_{ph}} \approx I_{sc} = \left[\mathrm{I_{sc,n}} + \mathrm{K_I(T-T_n)}\right]\frac{\mathrm{G}}{\mathrm{G_n}} \tag{4}$$

where are $I_{sc}$ – short circuit current (A), $I_{sc,n}$ – short circuit current (A) at STC, $K_I$ - short-circuit current temperature coefficient (A/K), $T_n$ - nominal cell junction temperature at STC (298.15 K), $G_n$ - Nominal solar irradiance at STC (1000 W/m$^2$).
The fill factor also depend on temperature and irradiance what is modeled by:

$$\mathrm{FF} = \mathrm{FF_n} \cdot [1 + \mathrm{K_{FF}} \cdot (\mathrm{T} - \mathrm{T_n})] \cdot \left[\mathrm{k_1} + \mathrm{k_2}\left(\frac{\mathrm{G}}{\mathrm{G_n}}\right) + \mathrm{k_{3ln}}\left(\frac{\mathrm{G}}{\mathrm{G_n}}\right)\right] \quad (5)$$

where $FF_n$ is the fill factor at Standard Test Conditions (STC: 1000 W/m², 298.15 K), $K_{FF}$ is the temperature coefficient of the fill factor (%/K or 1/K), $k_1$, $k_2$, $k_3$ are fill factor coefficients.
The PV system power generation at the Maximum Power Point (MPP) is evaluated using *FF* via:

$$\mathrm{P}_{mpp}(G,T) = \mathrm{FF}(G,T) \cdot V_{oc}(G,T) \cdot I_{sc}(G,T)\backslash\mathrm{cdot}\mathrm{k_{DG}}(\mathrm{t}) \quad (6)$$

where $V_{oc}$ – open circuit voltage (V), $I_{sc}$ – short circuit current (A) and $k_{DG}(t)$ PV module generation degradation coefficient over time.
The fill factor also depends on temperature and irradiance and is modeled as:

$$\mathrm{FF} = \mathrm{FF_n} \cdot [1 + \mathrm{K_{FF}} \cdot (\mathrm{T} - \mathrm{T_n})] \cdot \left[\mathrm{k_1} + \mathrm{k_2}\left(\frac{\mathrm{G}}{\mathrm{G_n}}\right) + \mathrm{k_{3ln}}\left(\frac{\mathrm{G}}{\mathrm{G_n}}\right)\right] \quad (7)$$

where $FF_n$ is the fill factor at Standard Test Conditions (STC: 1000 W/m², 298.15 K), $K_{FF}$ is the temperature coefficient of the fill factor (%/K or 1/K), $k_1$, $k_2$, $k_3$ are fill factor coefficients.
The PV module generation degradation over time is calculated by:

$$\mathrm{k_{DG}}(\mathrm{t}) = 1 - \mathrm{c_{DG}} \cdot \frac{\mathrm{h}}{8760} \quad (8)$$

where are $c_{DG}$ – annual degradation factor and $h$ time in hours.
In this baseline formulation (2)–(8), maximum power output for a given solar irradiance profile is calculated by varying irradiance $G$ while fixing the PV cell temperature at its STC value (298.15 K) and degradation coefficient (in (6)) at value 1, irrespective of actual ambient temperature fluctuations.

**Dynamic module operating temperature model**

The baseline model presented in the previous subsection neglects the thermal impact on key PV parameters—primarily *FF*, $V_{oc}$, and $I_{sc}$—which directly govern $P_{mpp}$. To account for these effects, this subsection presents a dynamic thermal model that calculates the PV module temperature and incorporates its influence on model parameters.
A transient dynamic thermal differential equation is used to estimate the PV module temperature under varying irradiance and ambient temperature conditions:

$$C_{th}\frac{dT}{dt} = \alpha G S_m - (U_0 + U_1 v_w)(T - T_a)S_m - \eta_m \mathrm{G} S_m \quad (9)$$

where are $C_{th}$ - effective thermal capacity of the PV module (J/K), $\alpha$ - absorption coefficient of the module surface, $S_m$ – PV module area (m²), $U_0$ - constant heat loss coefficients (W/Km²), $U_1$ - wind-dependent heat loss coefficients (W/Km²), $v_w$ - instantaneous wind speed (m/s), $T_a$ - instantaneous ambient temperature (K), $\eta_m$ - electrical efficiency of the module (accounting for heat removed as electricity).
Solving (9) yields the time-dependent PV module temperature $T(t)$ under fluctuating irradiance and ambient conditions. This calculated temperature is then used to update temperature-dependent quantities—including thermal voltage, photocurrent, open-circuit voltage, fill factor, and peak power ($P_{mpp}$)—according to (2)–(8). When wind cooling is excluded from the model, $v_w$ is set to zero in (9).

### Dynamic soiling accumulation and cleaning model

The soiling effect reduces the solar irradiance reaching the PV module surface due to the gradual deposition of dust and particulate matter over time. An effective irradiance, $G_{\text{eff}}$, is calculated using a soiling reduction factor $t_{\text{soil}}$:

$$G_{\text{eff}} = \mathrm{G} \cdot \tau_{\text{soil}} \tag{10}$$

where is $\tau_{\text{soil}}$ – soiling reduction factor.
The daily degradation of the soiling reduction factor is modeled using a linear deposition relationship:

$$\tau_{\text{soil}}(t) = \tau_{\text{soil}}(0) - \mathrm{SDR} \cdot \tag{11}$$

where are $t$ – time in days, $\tau_{\text{soil}}(0)$ – soiling reduction factor after cleaning event (by manual or natural cleaning) and SDR – daily Soiling Deposition Rate.
The soiling reduction factor following a cleaning event is modeled as:

$$\tau_{\text{soil}}(0) \ = \mathrm{X} \cdot \tau_{\text{soil}}(t-1) \tag{12}$$

where $X$<1 is random number by uniform distribution $\sim \mathcal{U}(a, b)$.
Finally, the effective irradiance $G_{\text{eff}}$ replaces the raw irradiance $G$ in the PV module equations (2)–(9) to integrate soiling losses into the overall energy production model.

## SIMULATION SETUP AND RESULTS ANALYSIS

### Simulation framework and input parameters

To evaluate the influence of environmental factors on energy yield predictions, a comparative analysis was conducted using the dynamic PV models described above. Simulations were performed over a 16-year period (2005–2020) using hourly solar irradiance and meteorological data retrieved from the Photovoltaic Geographic Information System (PVGIS) for Osijek, Croatia (45.5511° N, 18.6939° E).
Ten simulation configurations were designed to isolate individual physical effects across both fixed-tilt and dual-axis tracking systems, as detailed in Table 1. The baseline system comprises a 330 Wp monocrystalline silicon PV module. Table 2 summarizes the electrical, thermal, and mechanical parameters used in the simulations.

***Table 1.*** *The compared cases of PV module models*

| Model Case | PV module model considering: | Fixed or two-axes tracking PV module |
|---|---|---|
| Model 1_f | irradiance only (STC T=25°C, $v_w$ = 0 m/s, no soiling, no degradation) | Fixed (tilt = 35°, south orientation) |
| Model 2_f | irradiance + module temperature ($v_w$ = 0 m/s, no soiling, no degradation) | |
| Model 3_f | irradiance + module temperature + wind cooling (no soiling, no degradation) | |
| Model 4_f | irradiance + module temperature + wind cooling + dynamic soiling (no degradation) | |
| Model 5_f | irradiance + module temperature + wind cooling + dynamic soiling + degradation | |
| Model 1_t | irradiance only (STC T=25°C, $v_w$ = 0 m/s, no soiling, no degradation) | Two axes tracking |

| | | |
|---|---|---|
| Model 2_t | irradiance + module temperature ($v_w$ = 0 m/s, no soiling, no degradation) | |
| Model 3_t | irradiance + module temperature + wind cooling (no soiling, no degradation) | |
| Model 4_t | irradiance + module temperature + wind cooling + dynamic soiling (no degradation) | |
| Model 5_t | irradiance + module temperature + wind cooling + dynamic soiling + degradation | |

***Table 2.*** *Input data used in simulations*

| Data | Value |
|---|---|
| Reference Temperature (STC) | 25.0 °C (298.15 K) |
| Reference Irradiance (STC) | 1000.0 W/m |
| Open-Circuit Voltage (STC) | 41.5 V |
| Short-Circuit Current (STC) | 10.2 A |
| Fill Factor (STC) | 0.785 |
| Peak Power Output (STC) | 331.15 W |
| Electrical Conversion Efficiency (STC) | 0.1698 (16.98%) |
| Number of Cells in Series | 60 |
| Diode Ideality Factor | 0.9605 |
| Module Surface Area | 1.95 m² |
| Module Thermal Capacity | 25000.0 J/K |
| Solar Absorptivity Coefficient | 0.90 |
| Static Heat Transfer Coefficient | 25.0 W/(m²·K) |
| Wind Heat Transfer Coefficient | 1.2 W/(m²·K·(m/s)) |
| Current Temperature Coefficient | +0.0045 A/K |
| Voltage Temperature Coefficient | -0.125 V/K |
| Fill Factor Temperature Coefficient | -0.0015 1/K |
| Fill Factor Coefficient 1 | 0.982 |
| Fill Factor Coefficient 2 | 0.018 |
| Fill Factor Coefficient 3 | 0.025 |
| Soiling Deposition Rate | 0.0015 / day (0.15% / day) |
| Scheduled Cleaning Days per Year | Days 90, 100, 115, 160, 200, 220, 280, 330, 350 |
| Annual degradation factor | 0.005 (0.5 %) |

For scheduled maintenance, module cleaning efficiency on specified operational days is modeled as a uniformly distributed random variable within the range [0.5, 0.8].

**Comparative performance and energy yield analysis**

Table 3 summarizes the 16-year simulation results for the five fixed-tilt PV module configurations. Excluding degradation, soiling, and temperature impacts leads to an overestimation of annual energy yield by over 12 %. Each of these three environmental factors—temperature losses, dynamic soiling, and panel degradation—accounts for approximately a 4 % reduction in overall energy production. Conversely, neglecting wind cooling overestimates thermal losses, leading to an underestimation of energy production by more than 3 % (specifically around 3.3 %) compared to models that incorporate wind speed effects.

Table 4 details the performance metrics for the two-axis tracking system models. Applying simplified mathematical models to tracking systems introduces errors over 1 % higher than those observed in fixed-tilt configurations. This indicates that comprehensive thermal and environmental modeling is even more critical when predicting energy yield for tracking PV

plants. Across all evaluated mathematical models, two-axis tracking systems produce approximately 40 % more energy than fixed-tilt systems.

***Table 3.*** *Energy production comparison for fixed PV module*

| Model Case | Total Generation (16 yrs) | Average Annual Yield | Difference vs. Baseline [%] |
|---|---|---|---|
| Model 1_f | 7520.0 kWh | 470.0 kWh/yr | 0.00 % |
| Model 2_f | 6918.4 kWh | 432.4 kWh/yr | -8.00 % |
| Model 3_f | 7160.0 kWh | 447.5 kWh/yr | -4.79 % |
| Model 4_f | 6852.0 kWh | 428.3 kWh/yr | -8.88 % |
| Model 5_f | 6584.0 kWh | 411.5 kWh/yr | -12.45 % |

***Table 4.*** *Energy production comparison for two-axis tracking PV module*

| Model Case | Total Generation (16 yrs) | Average Annual Yield | Difference vs. Baseline [%] |
|---|---|---|---|
| Model 1_t | 10678.4 kWh | 667.4 kWh/yr | 0.00 % |
| Model 2_t | 9685.8 kWh | 605.4 kWh/yr | -9.30 % |
| Model 3_t | 10024.0 kWh | 626.5 kWh/yr | -6.13 % |
| Model 4_t | 9592.8 kWh | 599.6 kWh/yr | -10.17 % |
| Model 5_t | 9217.6 kWh | 576.1 kWh/yr | -13.68 % |

***Table 5.*** *Comparison of fixed vs two-axis tracking PV module*

| Model Case | Fixed PV module Total Generation | Fixed Average Yield | Tracker PV module Total Generation | Tracker Average Yield | Tracking Yield Gain |
|---|---|---|---|---|---|
| **Model 1:** STC Temperature constant-Baseline | 7520.0 kWh | 470.0 kWh/yr | 10678.4 kWh | 667.4 kWh/yr | +42.00 % |
| **Model 2:** Thermal model without wind cooling | 6918.4 kWh | 432.4 kWh/yr | 9685.8 kWh | 605.4 kWh/yr | +40.00 % |
| **Model 3:** Thermal model with wind cooling | 7160.0 kWh | 447.5 kWh/yr | 10024.0 kWh | 626.5 kWh/yr | +40.00 % |
| **Model 4:** Thermal model with wind cooling and soiling | 6852.0 kWh | 428.3 kWh/yr | 9592.8 kWh | 599.6 kWh/yr | +40.00 % |
| **Model 5:** Thermal model with wind cooling, soiling and module degradation | 6584.0 kWh | 411.5 kWh/yr | 9217.6 kWh | 576.1 kWh/yr | +40.00 % |

Although models incorporating full environmental dynamics (Models 4 and 5) provide the most accurate forecasts, their precision relies heavily on the availability and quality of meteorological data, particularly ambient temperature, wind speed, and local soiling profiles. Figure 2 illustrates the module temperature differential between models with and without wind cooling, which directly accounts for the 3.3 % discrepancy in energy yield shown in Tables 3 and 4.
Figure 3 compares annual production between fixed-tilt and two-axis tracking systems using Model 5 across the first and final years of the 16-year simulation period.

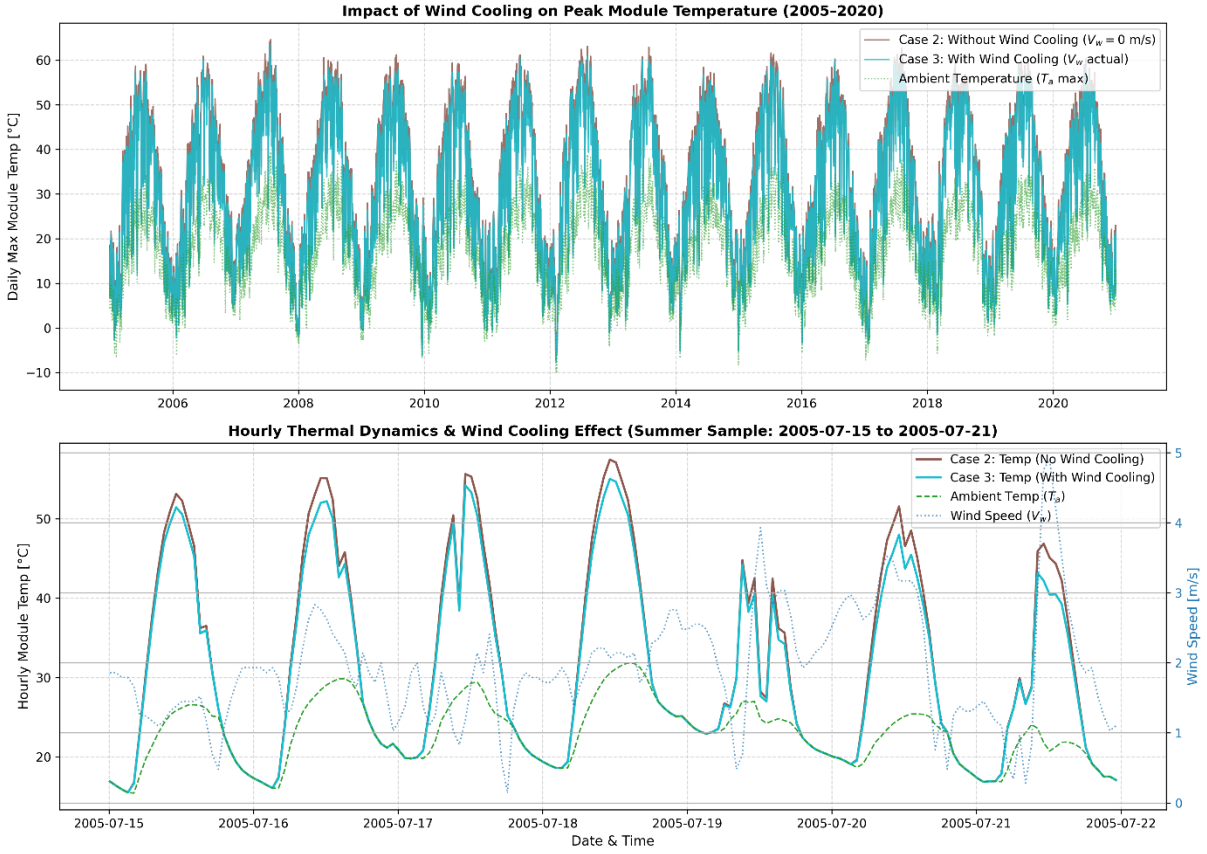


***Fig. 2.*** *PV module temperature profiles calculated according to models 2 and 3 for fixed PV module*

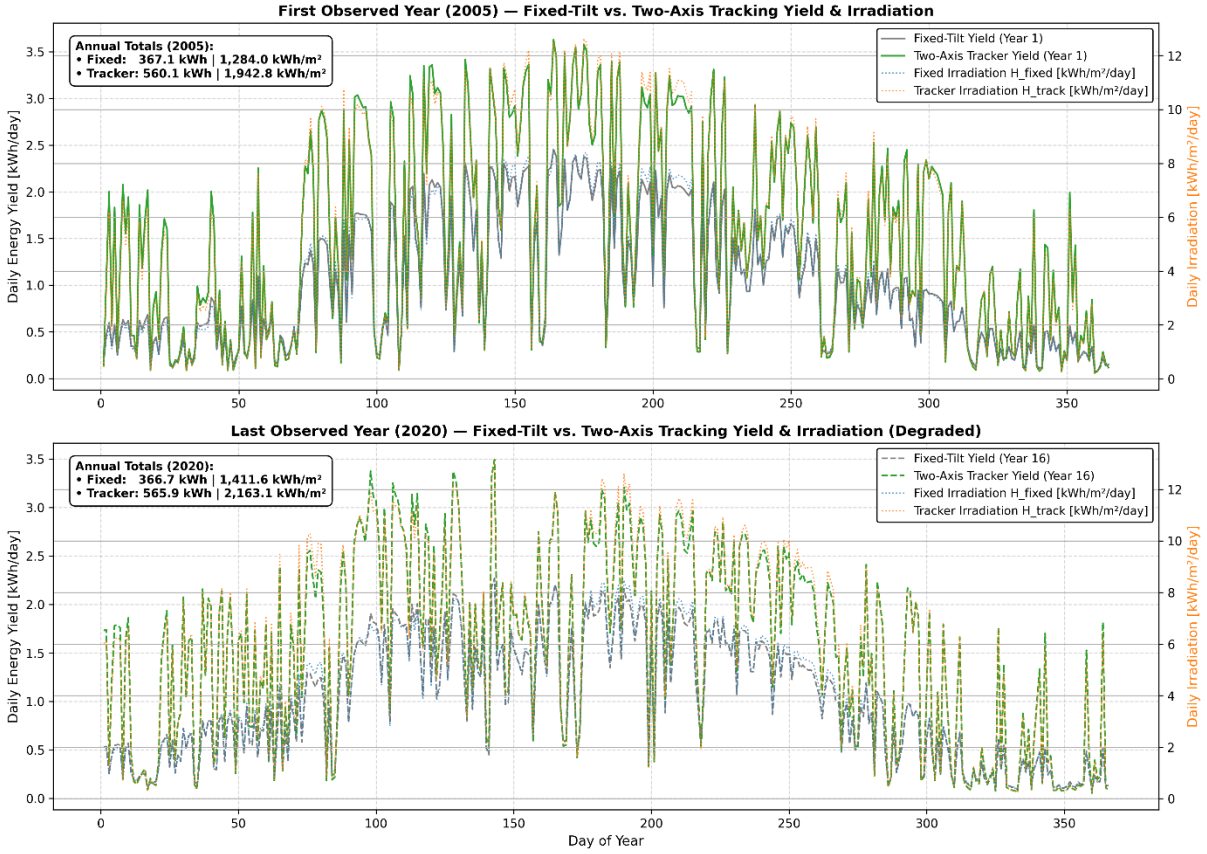


***Fig. 3.*** *Profile of soiling reduction factor including cleaning events used in the energy calculations*

Notably, this comparison reveals that interannual increases in solar irradiance can temporarily offset long-term module degradation, resulting in higher overall energy output in the final year than in the first. Finally, while scheduled cleaning events were modeled probabilistically (as detailed in Table 2) to approximate real-world maintenance, unpredictable natural cleaning cycles from rainfall introduce additional variability that remains difficult to model over multi-year horizons.

## CONCLUSION

This study evaluated the impact of incorporating thermal dynamics, wind cooling, dynamic soiling, and module degradation into mathematical models for predicting PV energy generation. Based on a 16-year simulation comparing fixed-tilt and two-axis tracking monocrystalline PV modules, several key findings emerge:

- **Yield Overestimation:** Relying strictly on STC irradiance-based models causes an overestimation of annual energy production exceeding 12%. Operating temperature, dynamic soiling, and module degradation each account for approximately 4% of energy losses.
- **Thermal Mitigation via Wind:** Incorporating wind speed mitigates predicted thermal losses, preventing an underestimation of energy production by roughly 3.3%.
- **Tracking Sensitivity:** Two-axis tracking systems generate ~40% more energy than fixed-tilt installations but exhibit ~1% higher sensitivity to mathematical modeling simplified errors, making accurate environmental modeling particularly vital for tracking plants.
- **Interannual Irradiance Effects:** Multi-year simulations reveal that interannual increases in solar irradiance can temporarily mask long-term module degradation, resulting in higher net output in later operational years despite ongoing panel aging.

Incorporating ambient temperature, wind velocity, soiling, and degradation into PV modeling significantly improves forecasting accuracy during the engineering design phase. Future research should focus on refining predictive models for stochastic natural cleaning events (e.g., rainfall) and local microclimate fluctuations.

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