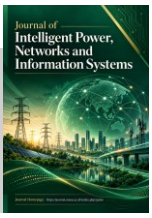
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Performance Analysis of Solar Photovoltaic Modules Under Different Tilt Angles: A Simulation-Based Study

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Abstract*— Fixed photovoltaic (PV) tilt influences the distribution of direct, diffuse, and ground-reflected radiation on the module surface. This paper develops a reproducible, deliberately simplified simulation to compare north-facing fixed tilts from 0° to 30° at a tropical reference latitude of 7.2575° S. Twelve synthetic monthly global-horizontal irradiation values, rather than measured meteorological records, drive a solar-position and isotropic-sky transposition model. A 1-kWp PV system with constant performance ratio (0.78) is used to compare monthly and annual electricity proxies. The model identifies an annual optimum within the examined angle range, quantifies the relatively flat response near that optimum, and shows that monthly preferences can differ from annual preferences. Outcomes are conditional on synthetic input profiles, the assumed beam–diffuse split, and omission of thermal and shading effects. This work is intended as a transparent numerical demonstration of the role of geometric tilt, not a site-validated recommendation for a physical installation.

Keywords*— photovoltaic, tilt angle, solar geometry, isotropic diffuse radiation, sensitivity analysis, simulation

I. INTRODUCTION

Solar photovoltaic deployment requires decisions concerning module position as well as electrical ratings. The tilt of a fixed array changes the direct-beam incidence angle, the fraction of diffuse sky visible to the module, and the amount of ground-reflected irradiance intercepted. An orientation chosen without reference to solar geometry may sacrifice energy even when the module and inverter are otherwise appropriate. The resulting tradeoff is particularly subtle at low latitudes, where solar declination crosses both sides of the local zenith over the year [1], [5], [7].

Published studies have examined annual, seasonal, monthly, and dynamically updated tilt rules. Tamoor et al. [1] compared radiative transposition assumptions; Prunier et al. [2] studied repeated adjustments; Awasthi et al. [3] proposed location-dependent correlations. Data-driven and algorithmic approaches have also been proposed [4], [8], whereas equatorial rooftop applications raise distinct practical questions [7]. These studies do not imply a universal optimum: estimated values depend on latitude, atmospheric inputs, transposition model, azimuth, and optimization objective.

For a compact educational simulation, a valuable question is how much annual energy changes when tilt is varied within the modest range likely to be feasible on tropical roofs. This is distinct from analyzing solar resource availability, the current–voltage characteristic of a PV module, or temperature-induced efficiency loss. The contribution here is not the invention of a new irradiance model; instead, the paper documents a fully specified scenario, identifies the annual optimum within it, and measures the tolerance of estimated generation to nonoptimal tilt.

The research questions are: (i) which tested fixed north-facing tilt maximizes modeled annual output, (ii) how do seasonal patterns modify the preferred tilt, and (iii) how large is the energy penalty for deviations from the optimum? Results are explicitly interpreted as modeled responses under chosen hypothetical inputs rather than observations in Surabaya.

II. MATERIALS AND METHODS

A. Scenario Definition and Synthetic Inputs

A southern-hemisphere tropical coordinate (7.2575° S, 112.7521° E) is used only to set solar geometry. The system faces geographic north (toward the equator) at zero azimuth offset. Monthly synthetic global horizontal irradiation (GHI) values are adopted from a preceding hypothetical exercise. They do not represent NASA POWER, PVGIS, or ground-station records. For a nonleap year, the monthly values sum to 1942.67 kWh/m². Tilt is evaluated at integer increments from 0° through 30°. The fixed diffuse fraction is 0.35 and ground albedo is 0.20; they are selected assumptions, not estimated atmospheric parameters.

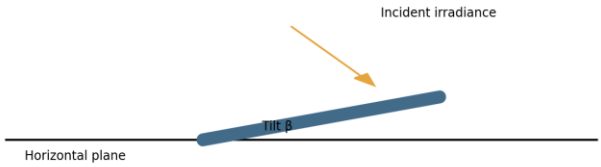


Fig. 1. Geometry of the fixed-tilt scenario (schematic, not to scale).

TABLE I. SYNTHETIC SIMULATION INPUTS

Input / parameter	Assumed setting
Reference latitude	7.2575° S
Reference longitude	112.7521° E
Tilt / azimuth	0–30°; north-facing
Monthly GHI	12 synthetic values
Diffuse/GHI fraction	0.35 constant
Ground albedo	0.20
PV nameplate	1 kWp
Performance ratio	0.78 constant

B. Solar Geometry and Transportation

For representative day n in each month, declination is approximated by $\delta = 23.45° \sin[360°(284+n)/365]$, and hour angle by $\omega = 15°(t-12)$. With latitude φ, horizontal solar incidence is $\cos\theta z = \sin\varphi \sin\delta + \cos\varphi \cos\delta \cos\omega$. The north-facing slope is represented by an effective incidence latitude $\varphi+\beta$, giving $\cos\theta i = \sin(\varphi+\beta) \sin\delta + \cos(\varphi+\beta) \cos\delta \cos\omega$. Negative incidence cosines are clipped to zero, ensuring no beam contribution when the sun is behind the plane.

Representative hourly GHI weights are proportional to $\max(0,\cos\theta z)^{1.15}$ from 05:00 to 19:00 solar time and normalized so their integral equals the input monthly mean daily GHI. The tilted-to-horizontal direct-beam factor is $Rb=\max(0,\cos\theta i)/\max(\cos\theta z,\varepsilon)$, with $\varepsilon=10^{-8}$. The isotropic transposition is $H\beta=Hb\ Rb+Hd(1+\cos\beta)/2+\rho Hg(1-\cos\beta)/2$. In the numerical implementation the same hourly weighting is assigned to the beam component; the diffuse and ground terms are applied to monthly integrated GHI. This deliberately simplified approach cannot represent measured cloud variability or anisotropic sky brightness.

C. Electricity Proxy and Response Metrics

The modeled energy for a month is $E\beta,m = H\beta,m \times (1\ kWp / 1\ kW/m^2) \times PR$; the chosen normalized capacity makes the numerical value $H\beta,m \times 0.78$ kWh per kWp. Annual energy is the sum over twelve months. The optimum is the argmax of annual energy among all 31 tested integer tilts. Relative improvement is $\Delta\beta=100(E\beta/E0-1)\%$. Monthly best angles are likewise selected from the grid. The model assumes perfect electrical availability, no mutual shading, constant PR, and no tilt-dependent soiling or temperature response.

D. Reproducibility and interpretation

Every result is a deterministic output of the supplied monthly irradiations, month-representative solar days, 0.1-h integration step, and stated assumptions. Therefore, confidence intervals, hypothesis tests, and model–measurement error statistics would be inappropriate. The analysis instead emphasizes the geometry-driven response, the difference between monthly and annual objectives, and the uncertainty that would arise if radiation partition or albedo assumptions were modified.

III. RESULT AND DISCUSSION

A. Annual tilt-response curve

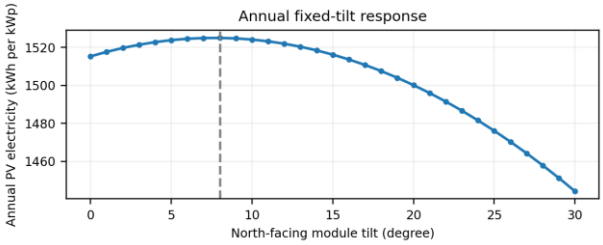


Fig. 2. Modeled annual fixed-tilt electricity at 1 kWp (synthetic scenario).

The annual horizontal baseline equals 1515.28 kWh/kWp. The largest modeled output is 1524.99 kWh/kWp at 8°, corresponding to a gain of 0.64% relative to the 0° reference. This maximum is conditional on the tested north-facing range and the chosen synthetic radiation profile. The result should not be interpreted as a field-validated optimal installation angle. The annual curve is relatively broad near its peak, suggesting that small mounting deviations may be more defensible than complicated adjustment mechanisms for this scenario.

TABLE II. ANNUAL ELECTRICITY BY TILT

Tilt	Annual (kWh/kWp)	vs. 0° (%)
0°	1515.3	+0.00
5°	1523.8	+0.56
10°	1524.1	+0.58
15°	1516.2	+0.06
20°	1500.2	-1.00
25°	1476.1	-2.59
30°	1444.3	-4.69

Table II makes the scale of the gain explicit. Because all outputs are calculated using the same constant PR, the ratio of two scenarios equals the ratio of their plane-of-array irradiations. In other words, the output changes here do not establish a new electrical efficiency phenomenon. The technical implication is geometric: incidence differences can improve or reduce the radiation available to the module even when the module conversion model is held unchanged.

B. Seasonal reversal and monthly objectives

Figure 3 compares four representative tilts and shows that monthly rankings can reverse. A fixed arrangement designed for the whole year is necessarily a compromise among changing seasonal incidence patterns. These variations are linked to the annual progression of solar declination, which moves the noon sun between northern and southern skies at low latitude. The use of a single representative day per month smooths fluctuations within individual months and consequently understates the range expected in cloudy real-world weather.

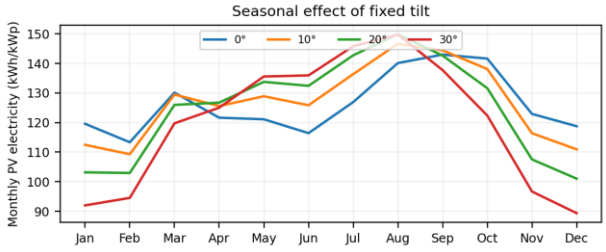


Fig. 3. Monthly estimated energy for four fixed tilt angles.

Figure 4 extends this comparison to every simulated tilt and month. The heat map should be read horizontally to identify the monthly favorable tilt region and vertically to compare monthly output at a fixed mounting angle. This makes the conflict between seasonal and annual optimization visually clear. The implied dynamic-tilt opportunity is not an economic conclusion: mechanical cost, structural loading, maintenance, and shading can outweigh small modeled energy gains. Findings in studies considering periodic adjustment likewise depend on local atmospheric and logistical assumptions [2], [4], [9].

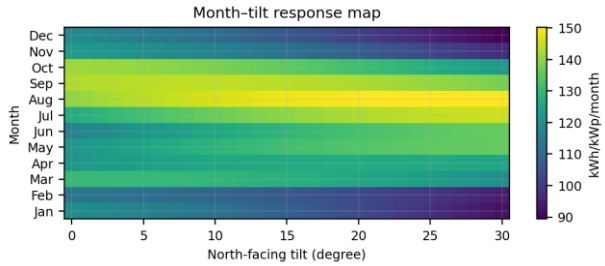


Fig. 4. Heat map of monthly production versus fixed tilt (synthetic).

C. *Sensitivity and practical tolerance*

A useful design question is the loss relative to the optimum, not only which exact tilt achieves the largest number. Fig. 5 expresses the outputs as percentages relative to the horizontal configuration; these benefits reflect the current transposition assumptions. Near the maximum, the curve is weakly varying. This indicates an interval of approximately comparable energy outcomes and supports reporting both an optimal angle and a tolerance region. Whether a flat roof or pitched-roof mounting is superior in practice cannot be resolved without engineering and economic constraints, as noted in relevant equatorial literature [7].

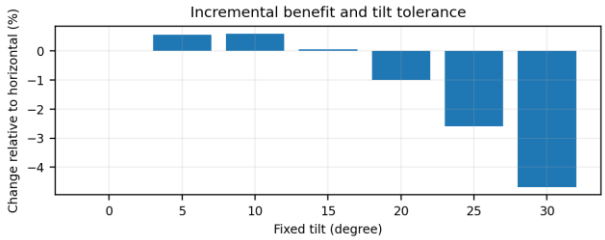


Fig. 5. Change in estimated annual electricity compared with 0° tilt.

TABLE III. MONTH-SPECIFIC OPTIMA (kWh/kWp)

Month	Best tilt	Energy at best
Jan	0°	119.6
Feb	0°	113.3
Mar	3°	130.2
Apr	19°	126.7
May	30°	135.5
Jun	30°	135.9
Jul	30°	145.8
Aug	25°	150.2
Sep	9°	144.4
Oct	0°	141.6
Nov	0°	122.9
Dec	0°	118.7

D. *Model uncertainty, study boundaries, and context*

The largest limitation is the absence of measured radiation components. GHI alone does not uniquely determine the direct normal and diffuse horizontal irradiance, both of which influence the tilted-plane result. A fixed 35% diffuse share is convenient for a controlled thought experiment but is not suitable as an unqualified representation of tropical cloud fields. Likewise, the isotropic assumption treats diffuse brightness as uniform across the sky; the relative advantages of slopes may change under alternative anisotropic formulations [1]. The ground albedo assumption also influences steeper surfaces more strongly.

A second limitation concerns the electricity approximation. A constant 0.78 PR conceals temperature, inverter behavior, mismatch, clipping, soiling, degradation, and seasonal losses. The simulation cannot isolate the joint influence of operating temperature and irradiance and intentionally leaves these mechanisms to separate research questions. More sophisticated numerical or experimental studies have shown the importance of orientation and ambient conditions [5], [10], [10]; the current work does not attempt to replicate their calibration or measurement procedures.

Third, synthetic month-level GHI values cannot support assertions about particular years, statistically significant trends, local microclimates, or the exact optimum for Surabaya rooftops. Numerical reproducibility is not empirical validation. A useful follow-up would replace the hypothetical monthly GHI with independently sourced site-specific hourly GHI/DNI/DHI series, compare at least two diffuse transposition models, and quantify how robust the ranking of tilt angles remains. Such extensions would constitute stronger evidence for a site-specific installation recommendation.

Finally, the incremental gain from tilt adjustment should be interpreted relative to the costs and constraints of implementation. Near-equatorial roofs often favor practical mounting angles for drainage, wind resistance, maintenance, and available area. A numerically highest yield by itself is insufficient to establish the preferred engineering design, and optimized ground-level irradiance is not automatically

optimized whole-system electricity or economic performance [3], [7], [9].

E. Interpretation of the annual optimum

The optimum obtained from a discretized grid must not be assigned more precision than the simulation warrants. A nominal optimum at an integer tilt means only that the evaluated energy was largest among the angles in the grid; it does not justify a specific engineering mounting tolerance at the tenth-of-a-degree scale. More importantly, the modeled improvement relative to the horizontal case is small in this low-latitude example. Even a substantial relative uncertainty in the tilt benefit can therefore translate into a modest absolute energy difference. A well-presented engineering analysis should report both the maximizing configuration and the magnitude of the advantage. Reporting only the maximizing angle conceals whether the result matters operationally.

The result also depends on the reference configuration. Here the baseline is a horizontal surface, which avoids arbitrary azimuth selection at zero tilt. In existing rooftop installations, the relevant counterfactual may instead be a pitched roof with a preselected slope and a mechanically constrained orientation. The incremental cost of mounting hardware and the reduction in usable panel density could therefore exceed a modeled benefit estimated per installed kWp. This study compares energy per nameplate capacity and does not compare energy per square meter of roof. These are separate decision criteria and may favor different arrangements.

A second issue is the distinction between monthly and annual optimization. A month-specific angle is selected after examining a single representative solar day and the assumed monthly GHI weight. It is an optimum within a hypothetical transposition scheme, not a recommendation to adjust real panels twelve times per year. If the schedule of adjustments were itself optimized, the switching costs and practicality would have to enter the optimization objective. That richer problem has been considered in the published reorientation literature [2], while the current study intentionally isolates the fixed-angle case.

F. Sensitivity to structural assumptions

Several inputs are held constant to make the tilt effect identifiable. Consider first diffuse fraction. Direct irradiance is geometrically directional, and changing tilt can increase or decrease its incidence factor sharply. Isotropic diffuse irradiance depends on the sky-view factor $(1+\cos\beta)/2$ and varies more gradually over the small tilt range investigated here. Accordingly, the optimum and the size of the yield advantage could change if the assumed diffuse fraction were increased or decreased. This is a structural sensitivity, not random measurement noise; reporting a statistical confidence interval without an underlying data-generating sampling model would not resolve it.

A comparable argument applies to albedo. The ground-reflected term increases with the factor $(1-\cos\beta)/2$, so the advantage from albedo is zero for a horizontal collector under the present equation and grows with tilt. If the reflecting environment were a bright roof rather than a darker urban surface, the optimum could shift. Local shading is likewise excluded. A panel placed at a geometrically favorable tilt but affected by nearby buildings, vegetation, or other panel rows can produce less electricity than a flatter, unshaded array. Radiation transposition must not be confused with a shading-free real-world performance prediction.

The synthetic GHI input warrants particular caution. The monthly values create the relative weight attached to each period in the annual objective. A change in which months receive the largest irradiation changes how much the angle favorable to those months contributes to the year total. Annual GHI alone is therefore not sufficient to reproduce the tilted-plane optimum when months have distinct solar incidence. Unlike the first article in the series, which treats solar-resource magnitude and its temporal structure, this study takes those assumed values only as boundary conditions for a tilt experiment. It makes no new claim about local resource reliability, climatic trends, or measured irradiation in Indonesia.

G. Comparison with related studies

Prior studies have reported different preferred tilts because their climates, radiation distributions, and analysis objectives are different. Equatorial rooftop work [7] directly emphasizes low latitude and built-environment geometry. The geographical multi-location comparisons of Tamoor et al. [1] show why sky-radiation formulation matters, and Kecili et al. [5] make the distinction between horizontal surfaces and latitude-dependent tilt choices. These publications provide theoretical context, not a numeric external validation of the present synthetic results. A meaningful quantitative comparison would require consistent definitions of azimuth, plane-of-array irradiation, electrical losses, temporal coverage, and roof area constraints.

The value of the present demonstration is methodological transparency: every assumed input is explicitly stated, the feasible angle set is finite, and the output metric is energy per rated kWp. A reviewer can modify the monthly inputs or diffuse partition and reproduce a new ranking without hidden software defaults. Its value is correspondingly limited: because the model omits site measurements and uses simplifying assumptions, it is more appropriate as an exploratory model demonstration than as a final design optimization for deployment.

IV. CONCLUSION

This simulation-only study assessed the effect of fixed north-facing photovoltaic tilt from 0° to 30° at a hypothetical tropical reference site. With synthetic monthly irradiation, isotropic diffuse transposition, and constant 78% performance ratio, the modeled annual production ranged around a horizontal baseline of 1515.3 kWh/kWp and reached 1525.0 kWh/kWp at 8°. Month-level preferred tilts differed, indicating that a year-round fixed optimum is a seasonal compromise. More importantly, the annual response remained comparatively insensitive to modest deviations around its peak, a feature relevant to practical mounting tolerance.

The principal contribution is a transparent and reproducible numerical comparison, not a new physical solar model or a measured performance benchmark. Synthetic inputs, uniform diffuse share, isotropic sky, and constant losses constrain external validity. Before physical deployment or stronger geographic claims, the model must be tested against traceable hourly meteorological measurements and realistic PV loss mechanisms.

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