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A Data-Driven Pre-Design Framework for Annual Fixed and Monthly Optimized Building-Mounted Photovoltaic Tilt Selection Using NSRDB Irradiance Data

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Abstract

Building-mounted photovoltaic systems are frequently constrained by roof geometry, structural capacity, mounting-system limits, shading, maintenance access, and project cost. Before these project-specific constraints are applied, designers require a transparent baseline that identifies the unconstrained irradiance-maximizing tilt and quantifies the energy value of alternative adjustment strategies. This study presents the Fixed-Tilt Photovoltaic Optimization Tool (FT-PVOT), a reproducible pre-design framework that integrates National Solar Radiation Database irradiance data with explicit solar-position and plane-of-array transposition equations. The framework evaluates candidate south-facing surface tilts from 0° to 90° at 1° increments and benchmarks annual and monthly tilt behavior against PVWatts. Using 2018–2023 data for Gainesville, FL, USA, the clear-sky annual optimum was 28–29° (mean 28.8°, standard deviation 0.41°), while the all-sky annual optimum was 29–30° (mean 29.2°, standard deviation 0.41°). Both cases closely matched the 29° PVWatts annual benchmark. Annual fixed optimization produced 3276.6 kWh/m^2/year under clear-sky conditions and 2419.7 kWh/m^2/year under all-sky conditions. Monthly optimization increased these values to 3394.2 and 2492.5 kWh/m^2/year, respectively, corresponding to incremental gains of 117.6 kWh/m^2/year (3.6%) and 72.7 kWh/m^2/year (3.0%). All-sky conditions reduced annual POA irradiation by approximately 26.2% relative to clear-sky conditions but did not materially change the approximately 29° annual optimum. Monthly benchmarking against PVWatts produced mean absolute errors of 4.10° for clear-sky FT-PVOT and 4.19° for all-sky FT-PVOT, indicating that monthly prescriptions are more sensitive than annual fixed-tilt recommendations. FT-PVOT provides an auditable early-design benchmark for deciding whether more complex mounting and adjustment strategies warrant subsequent building-specific engineering evaluation.

Keywords: building-mounted photovoltaics; early design; tilt optimization; NSRDB; plane-of-array irradiance; PVWatts; monthly optimization

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Academic Editors: Chi-Ming Lai and Elena Lucchi

Received: 30 September 2026
Revised: 21 October 2026
Accepted: 26 October 2026
Published: 28 October 2026

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1. Introduction

The technically optimal inclination of a photovoltaic module is rarely the angle ultimately constructed on a building. Roof slope, orientation, parapets, adjacent structures, equipment setbacks, structural loading, wind resistance, mounting-system geometry, maintenance access, and project economics constrain the feasible configuration. Nevertheless, evaluating these constraints requires a reference condition: the unconstrained tilt angle that maximizes the incident solar resource at the site.

Fixed-tilt systems remain common because their mounting and maintenance requirements are generally simpler than those of tracking or frequently adjusted systems. For building projects, however, the practical question is not merely which angle maximizes annual irradiation, but how much irradiation is lost when a feasible roof or rack configuration departs from that optimum.

Latitude-based rules provide a useful starting point, yet they do not explicitly integrate sub-daily irradiance variability, diffuse fraction redistribution, or local atmospheric attenuation. High-resolution records from the National Solar Radiation Database (NSRDB) now permit these effects to be incorporated directly into a transparent, geometry-resolved tilt screen [1,2].

This study positions FT-PVOT as a pre-design benchmark rather than a substitute for integrated building or PV-system simulation. It isolates the irradiance value of tilt selection using standard solar geometry equations and local time-series data; roof geometry, near-field obstruction, row-to-row shading, structural capacity, mounting feasibility, electrical losses, and economics remain subsequent project-specific evaluations.

The study addresses four research questions: (1) How stable is the unconstrained annual fixed-tilt benchmark across six years of local irradiance data? (2) How much additional POA irradiation is captured when the optimization window is shortened from an annual fixed tilt to monthly optimized tilts? (3) Do actual all-sky atmospheric conditions change the recommended annual building design tilt, or do they primarily reduce the available solar resource magnitude? (4) Does external benchmarking against PVWatts support the use of FT-PVOT as a pre-design irradiance screening method rather than a final electrical output model?

The remainder of this paper is organized to move from established solar geometry theory to a reproducible irradiance-based optimization workflow. Section 2 reviews prior work on solar geometry, tilted-surface irradiance transposition, seasonal tilt optimization, and benchmarking needs. Sections 3 and 4 present the FT-PVOT mathematical framework and NSRDB-based implementation. Sections 5 and 6 describe the input data, preprocessing assumptions, and optimization procedure. Section 7 benchmarks the tilt-selection behavior against PVWatts as an external model-consistency reference. Section 8 presents the Gainesville case study, and Section 9 discusses implications, limitations, and interpretation, including the limits of applying a single-site irradiance benchmark to final building-mounted PV design. Section 10 concludes the paper, and Section 11 identifies future research directions, including expansion to a multi-city climate-adjusted tilt and irradiance ranking framework.

2. Background and Related Work

2.1. Solar Geometry and Irradiance Transposition Models

Photovoltaic tilt optimization is fundamentally governed by solar geometry and the transposition of measured irradiance components onto inclined planes. The geometric basis for solar declination, hour angle, zenith angle, and incidence angle calculations is well established in the classical solar engineering literature [2]. For fixed and adjustable PV surfaces, the central modeling requirement is the conversion of horizontal irradiance measurements into plane-of-array (POA) irradiance, which requires treatment of direct, diffuse, and ground-reflected components.

The Liu–Jordan isotropic-sky model [3] assumes diffuse sky radiance is uniform, so the diffuse POA component varies with tilt through the sky-view factor $(1 + \cos\beta)/2$. This simplifying assumption provides a transparent transposition baseline but neglects circumsolar and horizon-brightening anisotropy. More detailed models, including Klucher [4], Hay–Davies [5], and Perez [6], treat nonuniform sky radiance and may change both ab-

solute POA irradiation and the tilt angle maximizing its annual or monthly integral. No direct anisotropic model sensitivity experiment or measured POA validation is reported here. The PVWatts comparison is an external consistency benchmark, not evidence that diffuse model selection has no effect.

Recent comparisons of isotropic and anisotropic transposition models further support this modeling boundary. Tamoor et al. [7] showed that model choice can affect monthly and seasonal optimum-tilt estimates, while annual optimum-tilt values remain strongly constrained by latitude and solar geometry.

A review of 240 journal articles and models by Hafez et al. [8] summarized existing approaches and their reported accuracies. One important distinction raised in that review is that optimizing PV tilt for maximum irradiation is not identical to optimizing tilt for maximum electrical power output. Irradiance-based optimization focuses on the solar energy incident on the module surface, whereas power output optimization also depends on temperature, wind speed, ground reflectance, mounting configuration, and electrical conversion losses. For example, a flat panel near the equator may collect high irradiance at midday, but a slightly tilted, better-ventilated panel may produce more electricity if lower module temperature improves conversion efficiency.

The review also indicated that relatively few studies explicitly used day-of-year solar geometry, or the effective Earth–sun tilt relationship, as a direct input for optimal panel-tilt calculation.

Tiris and Tiris [9] derived an optimal collector slope based on latitude and day of year. Rather than relying only on a simple Earth-tilt approximation, their approach used a more complex relationship between daily and monthly irradiation to estimate the optimal tilt angle. This supports the premise that combining local latitude, seasonal solar geometry, and historical irradiance data can improve practical tilt-angle selection.

2.2. Annual and Seasonal PV Tilt Optimization Literature

A large body of research has examined annual and seasonal PV tilt optimization using empirical heuristics or deterministic POA irradiance modeling [5,10]. Many studies report that annual optimal tilt is near the local latitude, while seasonal adjustment improves yield but exhibits diminishing marginal returns as adjustment frequency increases. For instance, Despotovic and Nedic [11] compared annual, seasonal, and monthly tilt optimization and found that increasing the number of adjustments beyond seasonal intervals yields limited incremental energy gains. Similar findings have been reported for case studies in Tunisia [12], Baghdad [13,14], and Ethiopia [15], demonstrating that climate conditions affect total yield magnitude but do not necessarily justify high-frequency reorientation. Hussain et al. [16] also showed that increased panel temperature inversely affects panel performance; however, high seasonal irradiance can partially offset this efficiency loss, limiting its effect on the optimal tilt angle.

Recent work has further connected tilt-angle optimization with PV cell-temperature effects. Melhem et al. [17] found that monthly tilt adjustment can improve PV power output, but their study also illustrates why electrical output optimization requires temperature modeling beyond the incident-irradiance objective used in FT-PVOT.

Moghadam et al. [10] challenged the assumption, used by Njoku [18] and others, that solar irradiance can be treated as constant throughout the day under an isotropic approximation. Moghadam et al. reported that this assumption can introduce an error of up to 5% in optimal panel inclination. Accordingly, the present study uses actual hourly irradiance data to reduce this source of error. Empirical and data-driven models remain useful for tilt screening, but the present framework emphasizes a transparent NSRDB-based calculation that can be extended beyond a single local dataset.

Recent data-driven studies have also begun using high-resolution irradiance archives for optimum-tilt prediction. Haroun et al. [19] used six years of five-minute satellite irradiance data from 184 U.S. locations to train machine learning models for monofacial and bifacial optimum-tilt prediction. In contrast, FT-PVOT uses explicit POA integration and a brute-force tilt sweep so that the resulting recommendation remains transparent and auditable.

More recent contributions have extended these findings by analyzing multi-reorientation strategies. Prunier et al. [20] evaluated optimal PV tilt angles for short periods and multiple reorientations, confirming that while additional adjustments can increase energy capture, the marginal benefit decreases rapidly beyond a limited number of changes per year. At a broader scale, Chen et al. [21] proposed a general method for determining recommended tilt and azimuth angles worldwide, emphasizing the importance of diffuse fraction and atmospheric conditions in optimal orientation selection. Similarly, Chinchilla et al. [22] developed a worldwide annual optimum-tilt model based on hourly inclined-surface irradiance submodels. Together, these studies indicate that annual optimal tilt is strongly constrained by solar geometry, while seasonal and monthly optimization provide progressively smaller gains. In contrast, the method presented here uses historical local irradiance data to optimize the tilt angle itself. Therefore, the framework is not intended to replace detailed PV performance tools for predicting final electrical output; rather, it is designed to identify irradiance-maximizing inclination angles.

Climate-zone and large-scale data-driven studies further demonstrate the importance of scalable tilt-screening methods. Lin et al. [23] combined PVLib simulations with supervised machine learning to optimize monthly PV tilt angles across global climate zones, and Rinchi et al. [24] used 12,499 PVGIS locations to predict optimal tilt angles globally. The present study complements these data-driven approaches by testing whether a transparent NSRDB-based irradiance integration can reproduce annual fixed-tilt trends consistent with PVWatts for a site-specific case study.

A final relevant study is the work by Psomopoulos and Ioannidis [25], who compared three production assessment software programs (PVGIS, PVWatts, and RETScreen) against data from three PV test sites in Greece. The study found that these systems generally estimated production within approximately 5% of measured values. Because all three tools use historical irradiation data to estimate PV electrical output, their accuracy depends in part on the proximity and representativeness of the available irradiance data. These software tools estimate electric energy production and therefore identify tilt angles for power output, not strictly for maximum incident irradiance.

2.3. High-Resolution Irradiance Datasets and Benchmarking Needs

Despite the maturity of the tilt-optimization literature, many studies rely on monthly averages, limited-year datasets, or regression-based rules rather than direct multi-year integration of high-resolution irradiance components. The National Solar Radiation Database (NSRDB) provides hourly irradiance products at high spatial and temporal resolution, including GHI, DNI, and DHI [1]. The availability of NSRDB enables site-specific, geometry-resolved integration of irradiance at hourly resolution, supporting reproducible optimization workflows that incorporate realistic atmospheric variability.

Recent work on estimating tilted-surface radiation from horizontal measurements also reinforces the need for transparent irradiance transposition workflows. Rinchi et al. [26] developed and validated a machine learning approach for estimating monthly solar radiation on tilted surfaces from horizontal measurements across a large global dataset, underscoring the continuing importance of horizontal-to-tilted irradiance conversion in PV design.

Additionally, standardized benchmarking tools such as PVWatts [27] are widely used for PV system yield estimation and serve as useful external benchmarking references for modeling consistency. However, explicit benchmarking of tilt-optimization frameworks against PVWatts or similar reference tools remains inconsistent in the literature, with the work of Psomopoulos and Ioannidis [25] serving as a notable exception.

2.4. Contribution of the Present Study

The methodological contribution is a transparent, reproducible pre-design workflow combining hourly NSRDB irradiance components (DNI, DHI, and GHI), established solar geometry equations, an isotropic POA transposition baseline, and an exhaustive 0–90° search in 1° steps. The implemented Gainesville analyses reported in this article evaluate annual fixed and monthly optimized tilt under clear-sky and all-sky conditions; they quantify the incremental POA irradiation associated with monthly rather than annual selection. The work does not propose a new solar-position equation or demonstrate biannual/seasonal optimization outcomes. Although the optimization routine could be applied to other adjustment windows, those applications require separate calculations and data reconciliation. PVWatts provides an external model-consistency benchmark, not independent field validation.

Prior research has evaluated annual, seasonal, and monthly tilt strategies, often using rules of thumb, irradiance averages, or predictive models. This paper instead reports the Gainesville annual-fixed versus monthly-optimized comparison using time-resolved NSRDB data, while separating incident-irradiance optimization from electrical output estimation. The ability to evaluate other adjustment schedules is a potential application of the workflow and is not presented as a completed result.

Table 1 is a functional positioning comparison rather than an empirical software benchmark. It clarifies that FT-PVOT's contribution is a transparent, data-intensive pre-design reference condition: it identifies the unconstrained irradiance optimum and the marginal value of adjustment before building geometry, obstruction, shading, electrical-loss, and economic constraints are evaluated in specialized tools [27].

Table 1. Functional positioning of FT-PVOT relative to representative PV design and simulation workflows.

Capability	FT-PVOT	PVWatts	SAM/PVsyst	Building Geometry PV Tools
Primary purpose	Unconstrained irradiance benchmark	Electrical output estimate	Detailed system performance	Roof geometry and early layout
Historical local irradiance	Direct time-series integration	Resource-file dependent	Supported	Model dependent
Roof and obstacle modeling	Not included	Not included	Limited or workflow dependent	Core capability
Shading analysis	Not included	Limited	Included	Included
Electrical losses	Not included	Included	Included	Implementation dependent

3. Methodology: Solar Geometry and Plane-of-Array Irradiance Model

This section defines the solar geometry and plane-of-array irradiance equations used by FT-PVOT. The objective is to calculate, for each candidate tilt angle, the cumulative irradiance incident on a south-facing PV plane over a selected evaluation period. The formulation is intentionally transparent: it uses standard solar declination, zenith-angle, incidence-angle, and isotropic diffuse transposition relationships so that the optimization result can be reproduced and audited. The complete list of variables, symbols, and units used in the FT-PVOT model is summarized in Table 2.

Table 2. Variables and symbols used in the FT-PVOT model.

Symbol	Definition	Unit
n	Day of year, where n = 1 corresponds to 1 January	Dimensionless
t	Time step index	Dimensionless
ts	Local solar time	Hours
φ	Site latitude	Degrees
δ	Solar declination angle	Degrees
ω	Solar hour angle	Degrees
θz	Solar zenith angle	Degrees
θi	Incidence angle between the incoming solar beam and the normal to the tilted PV surface	Degrees
β	Panel tilt angle measured from the horizontal plane	Degrees
β*	Optimal panel tilt angle that maximizes cumulative plane-of-array irradiation	Degrees
GHI(t)	Global horizontal irradiance at time t	W/m^2
DNI(t)	Direct normal irradiance at time t	W/m^2
DHI(t)	Diffuse horizontal irradiance at time t	W/m^2
GT(β,t)	Total plane-of-array irradiance on a surface tilted at angle β at time t	W/m^2
Gb,T(β,t)	Direct-beam irradiance component on the tilted plane	W/m^2
Gd,T(β,t)	Sky-diffuse irradiance component on the tilted plane	W/m^2
Gr,T(β,t)	Ground-reflected irradiance component on the tilted plane	W/m^2
HT(β)	Cumulative plane-of-array irradiation for tilt angle β over the evaluation period	kWh/m^2
ρg	Ground reflectance coefficient, also called albedo	Dimensionless
Δt	Duration of each irradiance time step	Hours
N	Total number of time steps in the evaluation period	Dimensionless
cos(θi)+	Nonnegative incidence-angle correction, defined as max [0, cos(θi)]	Dimensionless

The modeling framework follows classical solar geometry and irradiance transposition methods using hourly NSRDB irradiance components to compute plane-of-array irradiance for candidate photovoltaic panel tilt angles. The method is based on standard tilted-surface radiation formulations, including the isotropic diffuse model introduced by Liu and Jordan [3] and the hourly tilted-surface radiation model comparisons presented by Reindl et al. [28].

The purpose of the method is to identify the tilt angle that maximizes incident solar irradiance on the panel plane. The model does not estimate final electrical output from a photovoltaic system. Electrical output depends on additional factors, including module efficiency, cell temperature, inverter efficiency, wiring losses, soiling, shading, degradation, and system-loss assumptions.

This distinction is central to the present study: FT-PVOT optimizes incident plane-of-array irradiance, whereas tools such as PVWatts estimate electrical energy output after applying additional PV-system performance corrections.

3.1. Solar Declination, Solar Time, and Zenith Angle

For each time step, the day of year is denoted by n, where n = 1 corresponds to 1 January. The solar declination angle, δ, is approximated as:

$$\delta = 23.45^\circ \sin[360^\circ(284 + n)/365]$$

where δ is the solar declination angle in degrees and n is the day of year.

The solar hour angle, ω, represents the angular displacement of the sun from local solar noon and is calculated as:

$$\omega = 15^{\circ}(ts - 12)$$

where ts is the local solar time in hours. Negative values of ω occur before solar noon, and positive values occur after solar noon.

The solar zenith angle, θz, is calculated as:

$$\cos(\theta z) = \sin(\varphi)\sin(\delta) + \cos(\varphi)\cos(\delta)\cos(\omega)$$

where θz is the solar zenith angle, φ is the site latitude, δ is the solar declination angle, and ω is the solar hour angle.

Only time steps with cos(θz) > 0 are considered for direct-beam irradiance. When the sun is below the horizon, the direct-beam contribution is set to zero. Figure 1 illustrates the solar angles and panel orientation used in these calculations.

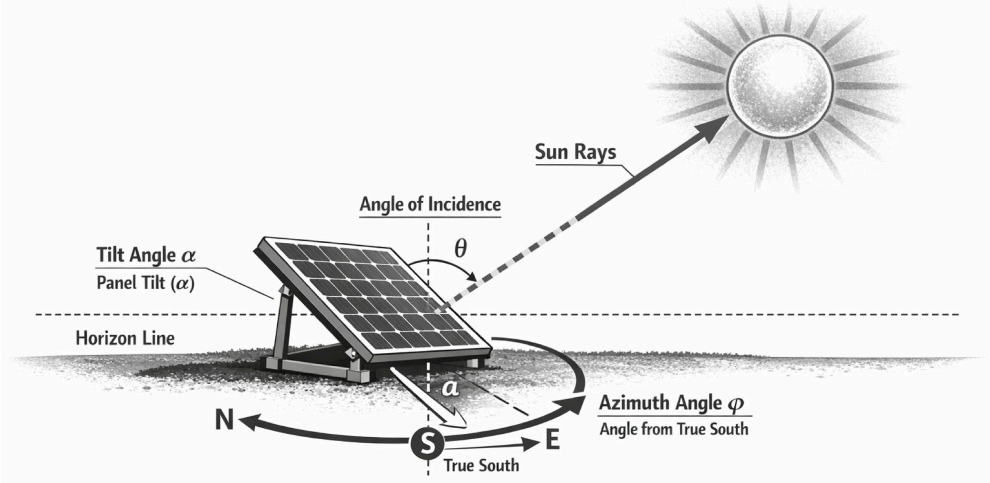


Figure 1. Solar geometry and fixed-panel orientation schematic.

3.2. Incidence Angle on a Tilted Surface

The incidence angle, θi, is the angle between the incoming direct solar beam and the normal vector perpendicular to the PV module surface. For a fixed south-facing surface in the northern hemisphere, the surface azimuth is assumed to be zero, and the cosine of the incidence angle may be written as:

$$\cos(\theta i) = \sin(\delta)\sin(\varphi - \beta) + \cos(\delta)\cos(\varphi - \beta)\cos(\omega)$$

where θi is the incidence angle on the tilted surface, φ is the latitude, β is the panel tilt angle measured from the horizontal plane, δ is the solar declination angle, and ω is the solar hour angle.

The candidate tilt angle β is evaluated over the feasible domain:

$$0^{\circ} \leq \beta \leq 90^{\circ}$$

A tilt of 0° represents a horizontal panel, while a tilt of 90° represents a vertical panel.

For numerical implementation, the direct-beam contribution is limited to nonnegative incidence values:

$$\cos(\theta i) + = \max [0, \cos(\theta i)]$$

This prevents physically unrealistic negative direct-beam irradiance when the sun is behind the panel plane.

3.3. Horizontal Irradiance Relationship

The NSRDB dataset provides global horizontal irradiance, direct normal irradiance, and diffuse horizontal irradiance. These quantities are related by:

$$GHI(t) = DNI(t)\cos(\theta z) + DHI(t)$$

where GHI(t) is the global horizontal irradiance, DNI(t) is the direct normal irradiance, DHI(t) is the diffuse horizontal irradiance, and θz is the solar zenith angle at time t.

This relationship is used as a consistency reference for the horizontal irradiance components. The optimization itself uses DNI, DHI, and GHI from NSRDB to compute the irradiance incident on each candidate tilted surface.

3.4. Plane-of-Array Irradiance Using the Isotropic Diffuse Model

For each candidate panel tilt angle, total plane-of-array irradiance is computed as the sum of direct-beam, sky-diffuse, and ground-reflected components. Using the isotropic diffuse transposition model, the total irradiance incident on a tilted surface is:

$$G_T(\beta,t) = G_{b,T}(\beta,t) + G_{d,T}(\beta,t) + G_{r,T}(\beta,t)$$

where $G_T(\beta,t)$ is the total plane-of-array irradiance on a surface tilted at angle β at time t.

The direct-beam component is:

$$G_{b,T}(\beta,t) = DNI(t)\max[0, \cos(\theta i)]$$

The sky-diffuse component is:

$$G_{d,T}(\beta,t) = DHI(t)[(1 + \cos\beta)/2]$$

The ground-reflected component is:

$$G_{r,T}(\beta,t) = \rho g GHI(t)[(1 - \cos\beta)/2]$$

Thus, the total plane-of-array irradiance is:

$$G_T(\beta,t) = DNI(t)\max[0, \cos(\theta i)] + DHI(t)[(1 + \cos\beta)/2] + \rho g GHI(t)[(1 - \cos\beta)/2]$$

where ρg is the ground reflectance coefficient, or albedo. Unless site-specific albedo data are available, a representative value such as ρg = 0.20 may be used for general ground conditions.

The isotropic formulation is a transparent baseline for this study, not a universally accurate representation of diffuse sky radiation. Its sky-diffuse contribution depends on tilt through the sky-view factor; actual diffuse irradiance is not assumed constant across panel angles. Circumsolar and horizon-brightening effects are omitted, and model choice may affect absolute POA estimates and calculated optimal tilt, especially at monthly resolution or under variable cloud cover. The present data do not isolate this transposition model uncertainty. A controlled comparison with Hay–Davies or Perez using identical NSRDB inputs remains future research.

3.5. Integrated Irradiation and Objective Function

For each candidate tilt angle, hourly plane-of-array irradiance values are integrated over the selected optimization window. The cumulative irradiation for a candidate tilt angle is calculated as:

$$HT(\beta) = \Sigma\, GT(\beta,t)\Delta t$$

where $HT(\beta)$ is the cumulative plane-of-array irradiation for tilt angle β, $GT(\beta,t)$ is the plane-of-array irradiance at time step t, Δt is the time-step duration in hours, and the summation is performed across all time steps in the evaluation period.

If irradiance is expressed in W/m^2 and Δt is expressed in hours, cumulative irradiation may be converted to kWh/m^2 as:

$$HT(\beta) = (1/1000)\, \Sigma\, GT(\beta,t)\Delta t$$

The optimal tilt angle is obtained by brute-force parametric search:

$$\beta^* = \arg\max HT(\beta), \text{ for } 0^\circ \leq \beta \leq 90^\circ$$

where β^* is the tilt angle that maximizes cumulative incident irradiation over the selected time window.

The same numerical search was applied to the annual fixed-tilt and monthly optimization windows reported in the Gainesville results. In each case, the optimum maximizes cumulative incident POA irradiation, not final AC electricity production. The objective function also permits evaluation of biannual or other seasonal windows, but such results are not reported or used to support the conclusions of this manuscript.

4. Proposed FT-PVOT Inclination Method Using NSRDB Data

The proposed FT-PVOT workflow applies the solar geometry and plane-of-array irradiance equations described in Section 3 to high-resolution NSRDB irradiance data. Rather than relying on annual or monthly average irradiance values, the method evaluates the irradiance incident on a tilted PV surface at each hourly or sub-hourly time step.

For each location and time step, NSRDB provides direct normal irradiance, diffuse horizontal irradiance, and global horizontal irradiance. These measured or modeled irradiance components already embed much of the local atmospheric variability, including cloud cover, aerosol effects, water vapor, and seasonal irradiance variation. The role of the FT-PVOT model is therefore not to recreate atmospheric conditions independently, but to transpose the available horizontal and direct normal irradiance components onto candidate tilted surfaces.

The computational workflow proceeds as follows. First, the solar declination, hour angle, zenith angle, and tilted-surface incidence angle are calculated for each time step. Second, plane-of-array irradiance is computed for each candidate tilt angle using the direct-beam, sky-diffuse, and ground-reflected irradiance components. Third, the resulting plane-of-array irradiance values are integrated over the selected evaluation window. Finally, the candidate tilt angle with the highest cumulative irradiation is selected as the optimum tilt for that period.

Because the model uses hourly or sub-hourly irradiance data, no separate weighting factor is required to emphasize midday solar conditions. Higher irradiance periods, such as late morning and early afternoon, naturally contribute more strongly to the cumulative irradiation total through the time-series integration.

The implemented method searches candidate tilt angles from 0° to 90° in 1° increments. The reported Gainesville results use annual fixed-tilt and independently optimized monthly

windows, under both clear-sky and all-sky NSRDB inputs. Other adjustment schedules could be examined with the same algorithm but were not part of the reconciled comparisons presented here.

The resulting workflow is therefore best understood as a first-stage tilt-screening method. It does not replace full PV production simulators, but it provides a defensible irradiance-maximizing angle that can be used as an input to PVWatts, SAM, PVsyst, or future storage and economic analyses.

Use of Generative AI: OpenAI's ChatGPT 6.0 was used as a supporting research and editorial tool during the development and documentation of the FT-PVOT framework. Its assistance included reviewing technical explanations, examining the consistency of computational workflow descriptions, organizing manuscript content, and refining the presentation of analytical findings. The underlying solar geometry equations, NSRDB datasets, optimization procedures, numerical results, and scientific interpretations were subject to author review and validation. ChatGPT was not treated as an independent source of scientific evidence or as a substitute for established computational methods.

5. Data Sources and Preprocessing

Hourly irradiance and meteorological data were obtained from the National Solar Radiation Database (NSRDB) provided by NREL. The dataset includes global horizontal irradiance (GHI), direct normal irradiance (DNI), and diffuse horizontal irradiance (DHI), along with supporting meteorological variables [1].

The mathematical model was evaluated using both clear-sky and all-sky irradiance series. The NSRDB clear-sky variables represent modeled clear-atmosphere conditions, whereas the standard irradiance series are referred to here as all-sky data because they represent actual atmospheric conditions across clear, partly cloudy, and cloudy periods. 'All-sky' therefore does not mean that every time step was cloudy. The clear-sky series was used to verify geometric behavior under idealized conditions, and the all-sky series was used to evaluate sensitivity to realistic atmospheric attenuation.

In the FT-PVOT framework, cloudiness was expected to reduce annual irradiance totals without materially changing the annual optimum fixed tilt angle. This expectation was tested directly by comparing clear-sky and all-sky simulations. Because the annual optimum angle is controlled primarily by latitude, solar declination, and the annual distribution of incidence geometry, the simulations were expected to produce similar annual optimum-tilt values, even when the total irradiance magnitude changed.

The NSRDB data were selected for the Gainesville, FL, USA, study location so that the irradiance inputs correspond as closely as possible to the modeled site. Gainesville also represents a hot, humid, partly cloudy environment in a university setting, making it a useful case study for later comparison with measured PV performance data from the University of Florida region.

The present analysis is restricted to Gainesville, FL, USA (29.65° N), and to physically feasible surface tilts from 0° to 90°. In seasonal calculations at low latitudes, a negative signed optimum should not be converted automatically to a positive tilt by taking its absolute value, because the sign may indicate that the irradiance-maximizing surface faces the opposite azimuth. Such cases require either an azimuth reversal or application of a project-specific constraint, such as a horizontal minimum tilt. Low-latitude and cross-equatorial treatment is therefore outside the scope of this study and should be evaluated explicitly before broader geographic application.

PVWatts is an online calculator that estimates the electrical energy output of a PV system using user-defined system size, module type, array geometry, inverter behavior, and standard loss assumptions [27]. For each user-specified tilt and azimuth, PVWatts converts

the solar resource data into hourly plane-of-array irradiance and then applies additional performance corrections, including incidence-angle effects, module temperature response, DC power conversion, system losses, and inverter efficiency. Because these calculations extend beyond incident irradiance, PVWatts was used in this study only as an external benchmark for tilt-angle trends rather than as the primary optimization model.

Through repeated simulations across candidate tilt angles, PVWatts can be used to infer best-performing tilt configurations. However, PVWatts reports electrical energy output, not incident irradiance on the module surface. Therefore, in this study, PVWatts was used only as an external consistency benchmark for best-performing tilt trends; PVWatts energy estimates were not treated as the primary study outcome.

This data structure allows FT-PVOT to evaluate the geometric effect of tilt while preserving the observed or modeled atmospheric variability already embedded in the NSRDB irradiance components. As a result, high-irradiance periods naturally receive greater weight during integration, and no separate midday weighting factor is required.

6. Optimization Framework

The FT-PVOT optimization procedure evaluates candidate tilt angles using a brute-force search over the feasible domain. For each candidate tilt, plane-of-array irradiance is computed for all time steps and integrated to obtain cumulative irradiance. The tilt corresponding to the maximum cumulative irradiance is selected as optimal.

Tilt optimization was performed using a brute-force parametric search over $\beta \in [0°, 90°]$ at 1° increments. The reconciled Gainesville dataset directly supports annual fixed and monthly optimized cases under clear-sky and all-sky conditions. Biannual or other seasonal schedules are possible extensions only; their outcomes are not estimated or asserted in this study.

Because the model uses hourly time steps, no additional value-weighting system was required to account for the higher irradiance typically observed between approximately 10:00 a.m. and 2:00 p.m. The FT-PVOT workflow captures this temporal variability directly through the irradiance time series.

For each reported optimization window, the same brute-force procedure was applied so that differences reflect the time window over which irradiance is accumulated rather than differences in optimization method. This makes the annual-versus-monthly comparison directly interpretable.

7. External Benchmarking Against PVWatts

External benchmarking was performed by comparing selected FT-PVOT tilt results against PVWatts reference outputs. PVWatts was selected because it is a widely used NREL-based photovoltaic performance calculator and provides an external reference for evaluating whether the proposed tilt-selection workflow produces reasonable and reproducible results.

Prior validation studies have examined the ability of PVWatts to estimate PV electrical production. For example, Psomopoulos and Ioannidis [25] compared measured production from three PV systems in Greece with outputs from PVGIS, PVWatts, and RETScreen. PVWatts showed reasonable annual agreement with measured PV output, although the authors noted that limited availability of local irradiance data likely contributed to the deviation. This prior work supports the use of PVWatts as a design-relevant benchmark, particularly when the comparison is framed as model-consistency benchmarking rather than direct proof of absolute electrical output accuracy.

Accordingly, PVWatts was used in this study as an external consistency benchmark for tilt-angle trends. Agreement between the FT-PVOT irradiance-based optimum and the

PVWatts energy-based optimum supports confidence in the solar geometry formulation, irradiance integration procedure, and brute-force tilt sweep. Differences between the two methods, especially at monthly resolution, are interpreted as expected second-order effects rather than as model failure.

Simulation runs were performed in PVWatts and compared with the FT-PVOT results. Figure 2 summarizes the basic logic flow used to accumulate the comparison results.

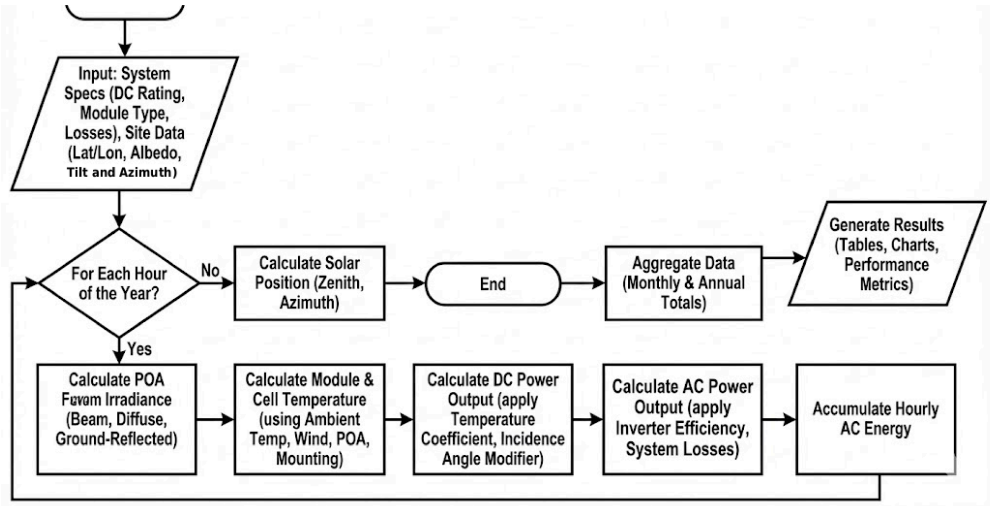


Figure 2. PVWatts benchmarking workflow used as the external consistency reference for FT-PVOT tilt-angle trends.

The first benchmark comparison evaluated annual fixed-tilt optimization. The optimum annual tilt was calculated using FT-PVOT with clear-sky data, and then compared with the tilt producing the highest annual output in PVWatts. Figure 3 shows that the two methods produce annual optimum tilt angles differing by no more than 1°.

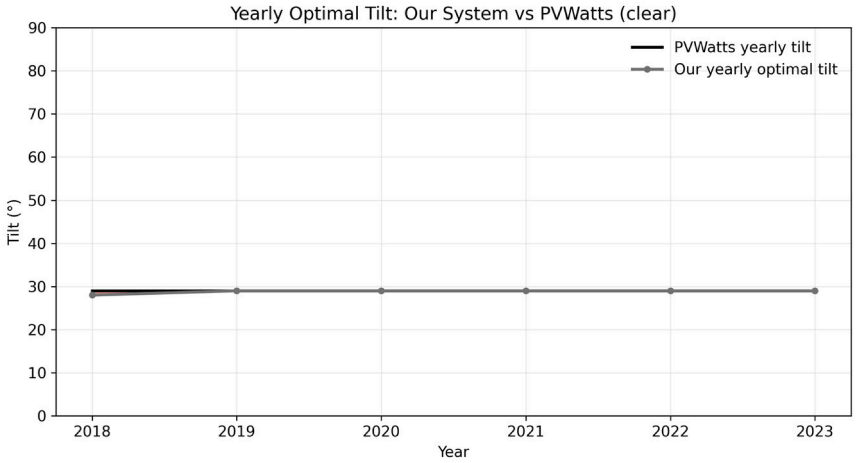


Figure 3. Annual optimum fixed tilt from FT-PVOT and PVWatts, 2018–2023. The two methods agree within 1° for every year.

The annual fixed-tilt comparison showed strong agreement. Both methods identified an annual optimum within approximately one degree of each other. This result is important because annual fixed-tilt selection is the primary use case for the proposed framework. It indicates that the simplified irradiance integration method captures the dominant geometric relationship between latitude, solar declination, and fixed-panel inclination.

This comparison also provides a practical check on the simplified diffuse-treatment assumption used in FT-PVOT. FT-PVOT uses the Liu–Jordan isotropic diffuse model to

preserve transparency and reproducibility, whereas PVWatts applies a more complete NREL PV performance workflow that carries the calculation beyond incident irradiance into additional performance corrections. Therefore, agreement between the two methods should not be interpreted as independent field validation. Rather, it indicates that the simplified FT-PVOT irradiance formulation produces annual fixed-tilt recommendations consistent with a widely used external benchmark. The larger monthly differences reported below are consistent with the expected sensitivity of shorter optimization windows to diffuse fraction behavior, transient weather, and electrical performance assumptions.

The simulation was then repeated using the all-sky dataset in FT-PVOT. Figure 4 likewise shows that the annual optimum tilt remains within 1° of the PVWatts benchmark.

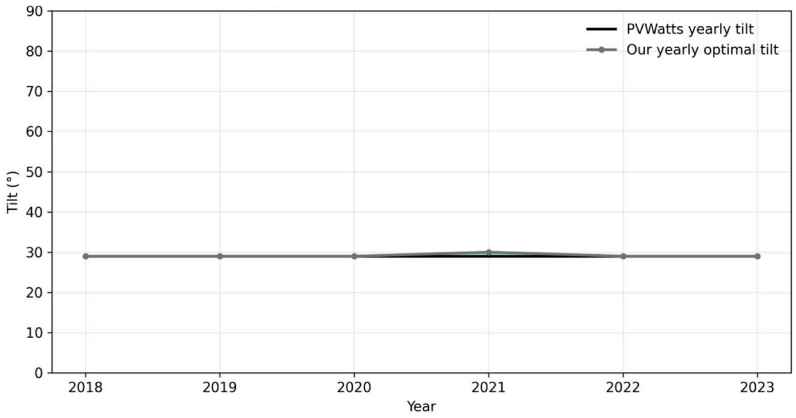


Figure 4. All-sky annual fixed-tilt benchmark comparison for FT-PVOT versus PVWatts, 2018–2023. The annual optimum remains within 1° of the PVWatts benchmark.

Table 3 summarizes the annual benchmark comparisons, showing that the optimum tilt remains stable across the six study years despite changes in irradiation magnitude.

Table 3. Annual fixed-tilt benchmark comparison against PVWatts, clear-sky, and all-sky datasets.

Mode	Year	FT-PVOT (°)	PVWatts (°)	Difference (°)
Clear sky	2018	28	29	1
Clear sky	2019	29	29	0
Clear sky	2020	29	29	0
Clear sky	2021	29	29	0
Clear sky	2022	29	29	0
Clear sky	2023	29	29	0
All-sky	2018	29	29	0
All-sky	2019	29	29	0
All-sky	2020	29	29	0
All-sky	2021	30	29	1
All-sky	2022	29	29	0
All-sky	2023	29	29	0

The all-sky comparison confirmed that the optimal annual tilt remains stable even when total irradiance magnitude changes. All-sky conditions reduced the calculated irradiance total, but they did not materially alter the annual fixed-tilt optimum. This supports the interpretation that annual fixed-tilt selection is governed primarily by solar

geometry, while atmospheric conditions mainly affect the magnitude of energy incident on the module plane.

The benchmark comparison was then extended to monthly tilt optimization. For clarity, the clear-sky and all-sky monthly FT-PVOT results are presented together in a single grouped bar-chart comparison. Figure 5 compares three monthly tilt prescriptions: the PVWatts monthly average, the FT-PVOT six-year monthly average using clear-sky data, and the FT-PVOT six-year monthly average using all-sky data. This format makes the monthly differences among methods easier to evaluate while avoiding redundant figures.

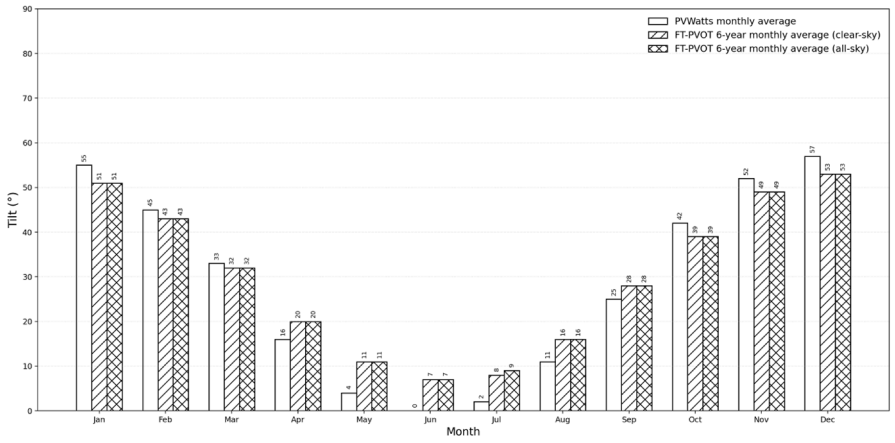


Figure 5. Consolidated monthly optimum tilt comparison among the PVWatts monthly average, FT-PVOT clear-sky six-year monthly average, and FT-PVOT all-sky six-year monthly average.

The consolidated comparison confirms the benchmarking behavior observed throughout the study. The clear-sky and all-sky FT-PVOT monthly averages follow nearly identical seasonal tilt patterns, indicating that either NSRDB sky condition dataset can be used by the proposed workflow to identify physically reasonable tilt-angle trends. Agreement with PVWatts remains strongest at the annual fixed-tilt scale, while the grouped monthly bars show that differences become more visible when the optimization window is shortened. This pattern is consistent with greater sensitivity at monthly resolution to transient weather, diffuse fraction variability, and the electrical performance corrections included in PVWatts.

Table 4 summarizes the quantitative benchmarking and sensitivity metrics. Relative to PVWatts, the monthly clear-sky comparison produced an MAE of 4.10°, a bias of +1.32°, and an RMSE of 4.52°. The all-sky comparison produced a similar MAE of 4.19°, bias of +1.25°, and RMSE of 4.61°. The six-year mean annual optimum differs by only 0.33° between clear-sky and all-sky FT-PVOT runs, while the all-sky annual POA irradiation shown in Table 4 is 26.15% lower than the clear-sky value. These results support annual fixed-tilt screening and cautious interpretation of monthly optima while showing that monthly prescriptions are more sensitive to weather variability and PV-system performance assumptions.

The benchmark results support the use of FT-PVOT for annual fixed-tilt selection and comparison with monthly optimized tilt. Agreement with PVWatts at the annual fixed-tilt scale indicates that FT-PVOT captures the dominant geometry of the problem. Larger differences at monthly resolution are expected because PVWatts estimates electrical energy after applying additional performance corrections, whereas FT-PVOT optimizes incident irradiance only.

Table 4. Summary metrics for benchmarking and sensitivity comparisons.

Metric	Reported Value
Annual optimum tilt difference	0.17°
Monthly MAE, clear-sky FT-PVOT vs. PVWatts	4.10°
Monthly MAE, all-sky FT-PVOT vs. PVWatts	4.19°
Monthly bias, clear-sky FT-PVOT vs. PVWatts	+1.32°
Monthly bias, all-sky FT-PVOT vs. PVWatts	+1.25°
Monthly RMSE, clear-sky FT-PVOT vs. PVWatts	4.52°
Monthly RMSE, all-sky FT-PVOT vs. PVWatts	4.61°
Clear-sky vs. all-sky annual optimum tilt shift	0.33°
All-sky reduction relative to clear-sky irradiation	26.15%

8. Results: Case Study of Gainesville, Florida

Gainesville, FL, USA (29.65° N) was selected as the primary case study location because it combines a moderate subtropical latitude with a humid, partly cloudy solar resource environment. This makes it a useful test case for evaluating whether high-resolution irradiance data materially alter annual fixed-tilt and monthly optimization results relative to common latitude-based rules. The FT-PVOT model was applied to NSRDB irradiance data using the solar geometry and plane-of-array transposition framework described in Sections 3 and 4. Candidate tilt angles from 0° to 90° were evaluated at 1° increments, and the angle producing the highest cumulative plane-of-array irradiation was selected for each optimization window.

The results are organized around the four research questions. They evaluate the stability of the annual fixed-tilt benchmark, quantify the incremental irradiation captured by monthly optimization relative to annual fixed optimization, test whether all-sky conditions alter the recommended tilt or primarily reduce irradiance magnitude, and interpret the scale at which external PVWatts benchmarking supports FT-PVOT as a pre-design screening tool.

8.1. Gainesville Case Study Parameters

Table 5 summarizes the baseline modeling assumptions used for the Gainesville case study. The optimization target is cumulative plane-of-array irradiation rather than final AC electrical output. The results therefore represent irradiance-maximizing tilt recommendations, not complete PV production forecasts. This boundary is intentional: FT-PVOT is designed to isolate the geometric and irradiance effects of tilt selection, whereas tools such as PVWatts also incorporate module temperature, inverter efficiency, incidence-angle modifiers, and system-loss assumptions.

Table 5. Gainesville case study parameters and modeling assumptions.

Parameter	Value
Location	Gainesville, FL, USA
Latitude	29.65° N
Dataset period	2018–2023
Data source	NSRDB
Irradiance inputs	GHI, DNI, DHI

Table 5. *Cont.*

Parameter	Value
Tilt search range	0° to 90°
Tilt increment	1°
Primary optimization target	Cumulative POA irradiation
Electrical output modeling	Not included in FT-PVOT result

8.2. Annual Fixed-Tilt Optimization

The annual fixed-tilt analysis shows that the Gainesville optimum is highly stable across the 2018–2023 dataset. The FT-PVOT annual optimum ranged from 28° to 29°, with a mean of approximately 28.8° and a standard deviation of approximately 0.41°. PVWatts produced an optimum of 29° for the same annual fixed-tilt comparison, yielding an average difference of approximately 0.17°. This narrow range indicates that normal interannual variation in irradiance magnitude has little design-relevant effect on the annual fixed optimum tilt angle. Figure 6 illustrates the consistent annual optimum tilt across the six years analyzed.

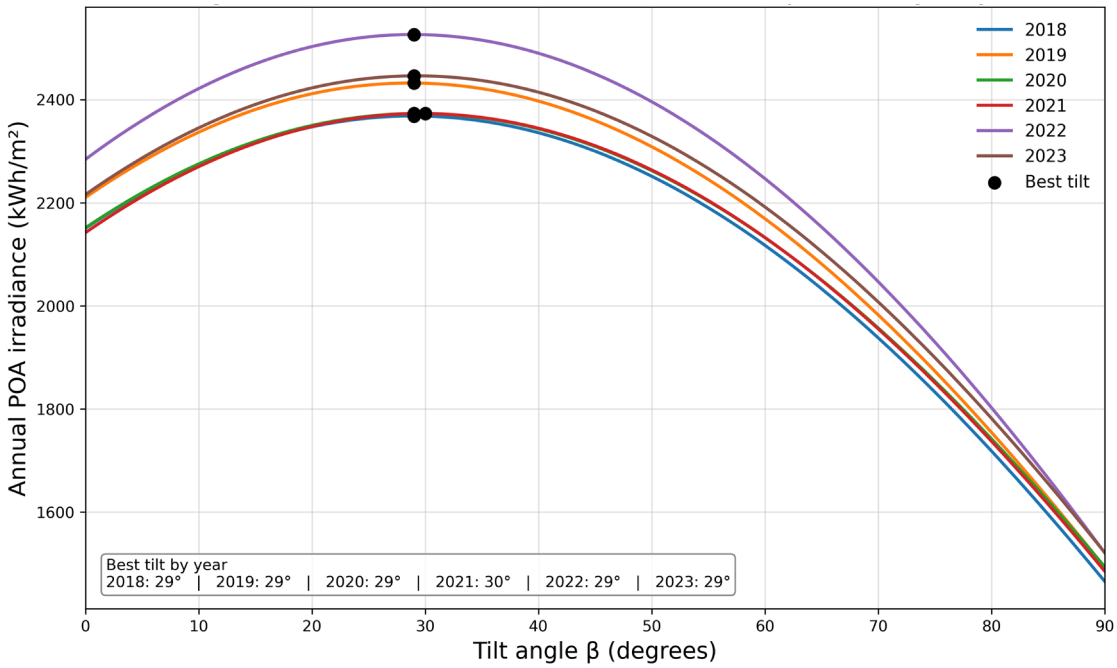


Figure 6. POA irradiation versus fixed tilt angle for Gainesville, 2018–2023. Annual maxima cluster at 28–29°, demonstrating interannual stability.

This result supports the first major finding of the case study: for fixed annual systems, the optimum tilt is controlled primarily by latitude and annual solar geometry. Although the total annual irradiance changes from year to year, the best fixed inclination remains essentially unchanged. For implementation-relevant PV design, this means that a single annual fixed-tilt recommendation near local latitude is robust for Gainesville under normal year-to-year irradiance variability. Table 6 provides the corresponding annual tilt values, which range from 28° to 29°.

Table 6. Annual fixed-tilt stability for Gainesville, 2018–2023.

Mode	Year	FT-PVOT Optimum Tilt (Degrees)	PVWatts Optimum Tilt (Degrees)	Difference (Degrees)
Clear sky	2018	28	29	1
Clear sky	2019	29	29	0
Clear sky	2020	29	29	0
Clear sky	2021	29	29	0
Clear sky	2022	29	29	0
Clear sky	2023	29	29	0
Summary	2018–2023	Mean = 28.8; SD ≈ 0.41	29	Mean Difference ≈ 0.17

8.3. Comparison of Tilt Strategies

The corrected Gainesville dataset supports direct comparison of annual fixed optimization and monthly optimization under clear-sky and all-sky conditions. These two cases isolate the added irradiance captured by shortening the optimization window from one year to one month while keeping the same location, tilt search range, and irradiance input structure. Figure 7 illustrates the modest additional irradiation obtained through monthly rather than annual fixed-tilt optimization.

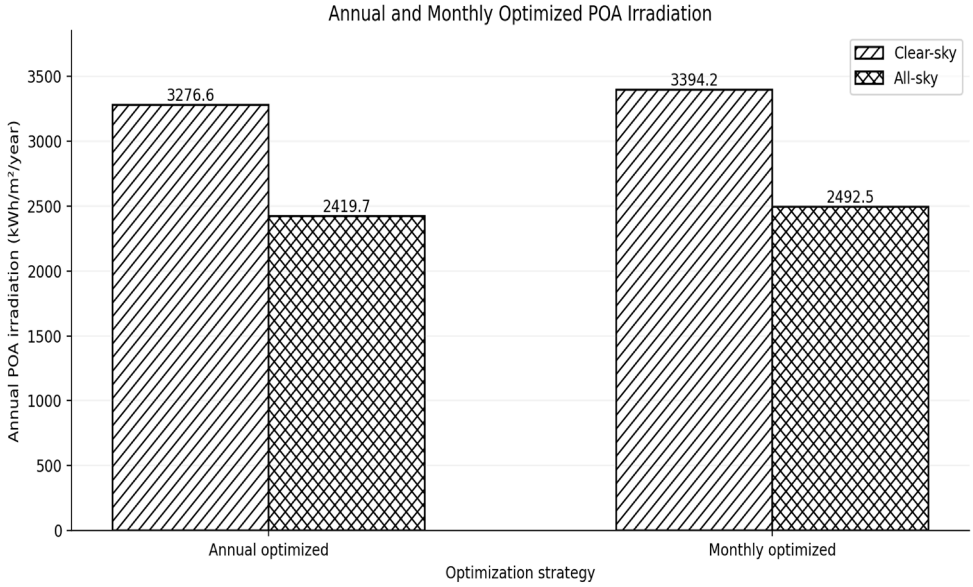


Figure 7. Corrected annual and monthly optimized POA irradiation for Gainesville under clear-sky and all-sky conditions. Monthly optimization provides a modest increase over annual fixed optimization in both datasets.

Monthly optimization increased clear-sky annual POA from 3276.6 to 3394.2 kWh/m^2/year, an increase of 117.6 kWh/m^2/year (3.6%) beyond annual fixed optimization. Under all-sky conditions, monthly optimization increased annual POA from 2419.7 to 2492.5 kWh/m^2/year, an increase of 72.7 kWh/m^2/year (3.0%). This pattern supports the narrower conclusion that high-frequency tilt adjustment is mathematically beneficial, but that its incremental gain over annual fixed optimization is modest compared with the added operational complexity.

For practical design, the corrected data indicate that monthly optimization provides a measurable but modest gain beyond annual fixed optimization. This gain may justify further project-specific evaluation where adjustable systems are feasible, but the present study does not calculate mounting cost, structural feasibility, shading, lifecycle value,

or final roof-layout performance. Table 7 quantifies the modest irradiation gains; their economic value depends on project-specific mounting and operating conditions.

Table 7. Corrected annual and monthly optimized POA irradiation values from the reconciled Gainesville dataset.

Optimization Case	Annual POA Irradiation (kWh/m^2/Year)	Increment Relative to Annual Fixed Optimization
Annual optimized, clear-sky	3276.6	Baseline
Monthly optimized, clear-sky	3394.2	+117.6 kWh/m^2/year (+3.6%)
Annual optimized, all-sky	2419.7	Baseline
Monthly optimized, all-sky	2492.5	+72.7 kWh/m^2/year (+3.0%)

These corrected results translate into a simple screening implication: annual fixed tilt angle near 29° is a stable reference condition, monthly optimization adds approximately 3.0–3.6% relative to annual fixed optimization under the supplied Gainesville datasets, and all-sky conditions mainly reduce POA magnitude rather than shift the annual optimum. The result does not determine final roof layout; roof geometry, row spacing, shading, structural capacity, mounting feasibility, and cost remain project-specific follow-on evaluations.

8.4. Clear-Sky and All-Sky Sensitivity

The clear-sky/all-sky comparison tested whether atmospheric attenuation changes the annual optimum fixed tilt angle or primarily reduces the magnitude of available irradiance. The results support the second interpretation. Both clear-sky and all-sky simulations produced an annual optimum tilt of approximately 29°, while the all-sky annual POA irradiation was approximately 26.2% lower than the clear-sky value. Figure 8 illustrates that both sky-condition datasets yield an annual optimum tilt near 29°, despite the difference in irradiation magnitude.

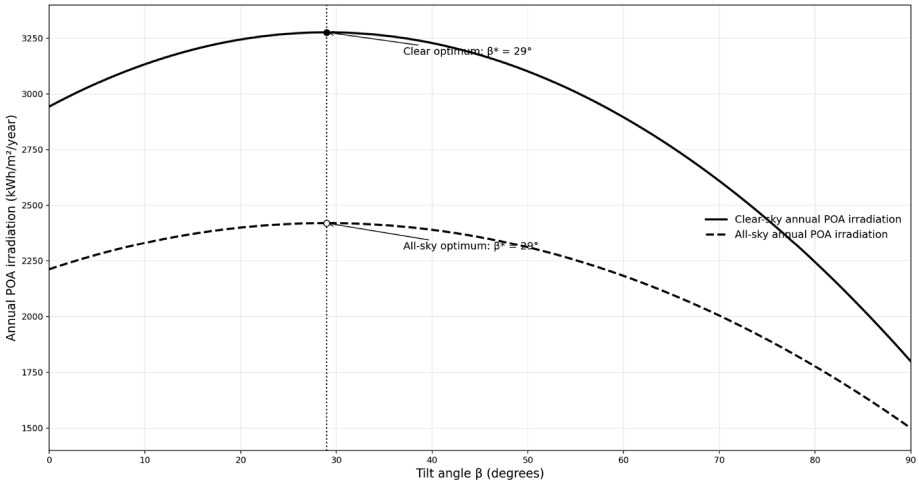


Figure 8. Clear-sky and all-sky annual POA irradiation versus tilt angle for Gainesville. Both curves peak near 29°, while all-sky irradiation is approximately 26.2% lower than clear-sky irradiation.

This finding clarifies the role of atmospheric attenuation in the FT-PVOT model. All-sky conditions reduce the amount of solar energy available, but they do not materially change the annual fixed optimum tilt angle. The annual optimum remains governed primarily by latitude, solar declination, and the yearly distribution of solar incidence geometry. Using the values in Table 8, all-sky annual POA irradiation is 26.2% lower than the clear-sky value, while both cases retain an optimum near 29°. Additional ±10%

perturbation testing of DNI and DHI changed the annual optimum tilt by less than 1°, further supporting the stability of the fixed-tilt recommendation.

Table 8. Clear-sky and all-sky sensitivity for Gainesville.

Dataset	Annual Optimum Tilt	Annual POA Irradiation	Reduction Relative to Clear Sky
Clear sky	29°	3276.6 kWh/m^2/year	Baseline
All-sky	29°	2419.7 kWh/m^2/year	26.2%

The Gainesville results answer the research questions within the limits of the corrected Gainesville dataset. First, the annual fixed optimum tilt remained highly stable across 2018–2023 and aligned closely with local latitude. Second, monthly optimization increased annual POA relative to annual fixed optimization, but the gain was modest: approximately 3.6% in the clear-sky dataset and 3.0% in the all-sky dataset. Third, all-sky conditions substantially reduced annual POA irradiation but did not materially shift the annual fixed optimum tilt. Together, these findings support FT-PVOT as a transparent early-stage screening framework for annual fixed-tilt selection and monthly comparison.

9. Discussion

The Gainesville case study shows that high-resolution irradiance integration strengthens, rather than overturns, the practical value of an annual fixed-tilt benchmark near local latitude. The corrected data show that the annual optimum remains clustered around 29° under both clear-sky and all-sky conditions. Monthly optimization increases annual POA, but the incremental gain over annual fixed optimization is modest relative to the additional operational complexity.

The consolidated monthly benchmark chart and the revised statistical summary further clarify the scale at which FT-PVOT is most reliable. Annual fixed-tilt selection is very stable, with an average difference of approximately 0.17° relative to PVWatts. Monthly comparisons remain reasonably close, with clear-sky and all-sky MAE values of 4.10° and 4.19°, respectively, but the larger monthly error metrics show that shorter optimization periods are more sensitive to weather variability and PV-system performance assumptions.

Agreement of the annual FT-PVOT tilt estimate with the PVWatts benchmark provides a useful external consistency check, but it is not a controlled sensitivity test of the isotropic diffuse model. PVWatts and FT-PVOT differ in additional modeling assumptions and optimization objectives, so their agreement cannot isolate the effect of circumsolar or horizon-brightening radiation on the optimum tilt. The reported monthly MAE and RMSE identify differences between workflows but cannot establish that those differences arise from weather or diffuse treatment alone. Accordingly, the findings support annual fixed-tilt screening for Gainesville, while anisotropic transposition testing and measured POA comparison remain open validation tasks.

For building-mounted PV systems, the unconstrained irradiance optimum should not be interpreted as the final constructed roof layout. On flat commercial roofs, higher tilt angles may increase inter-row shading or require wider row spacing, reducing ground coverage ratio and total installed capacity on a fixed roof footprint. Roof access paths, parapets, mechanical equipment, wind loading, ballast or attachment requirements, and structural capacity may also constrain feasible tilt. Recent work on tilted surfaces and parallel PV rows reinforces that direct and anisotropic diffuse shading can affect irradiance estimates when row geometry is introduced [29]. This confirms why FT-PVOT should be interpreted as an unconstrained irradiance benchmark rather than a complete roof-layout or row-spacing model.

The clear-sky and all-sky results strengthen this interpretation. Atmospheric attenuation reduced the total POA irradiation available to the system, but it did not materially alter the annual fixed-tilt recommendation. This distinction is important: atmospheric conditions affect the amount of solar energy available, while annual fixed-tilt geometry is governed primarily by latitude, declination, and the yearly distribution of solar incidence angles.

Because the analysis is limited to Gainesville, the numerical findings should be interpreted as case-study results rather than national design rules. Gainesville provides a useful humid subtropical test case, but arid, high-altitude, northern, coastal, and cloudier regions may show different seasonal irradiance distributions and different marginal benefits from adjustment. The planned multi-city extension will test whether the Gainesville conclusions generalize across approximately 54 U.S. cities and will identify where latitude-based tilt remains sufficient and where climate-sensitive adjustment provides measurable value.

The framework intentionally optimizes incident POA irradiation rather than final AC electrical output. Accordingly, module temperature, inverter clipping and efficiency, soiling, shading, wiring losses, degradation, mounting height, and other system losses are outside the present optimization objective and should be evaluated in subsequent project-specific analyses.

Future work should connect the irradiance-maximizing tilt angles identified here to economic and system design outcomes. For example, the incremental gain from monthly optimization relative to annual fixed optimization should be compared with mounting structure cost, roof access constraints, maintenance requirements, and expected system lifetime. This step is especially relevant for residential and community-scale PV deployment, where modest design changes may improve performance without adding complex tracking hardware.

This modeling boundary is deliberate. FT-PVOT identifies the geometric irradiance optimum; subsequent tools can then evaluate whether that optimum is electrically, structurally, and economically preferable for a specific PV system.

10. Conclusions

This study developed and evaluated FT-PVOT as a transparent, NSRDB-based pre-design framework for annual fixed-tilt selection and monthly tilt optimization in Gainesville, FL, USA. The approach combines established solar geometry equations, isotropic plane-of-array transposition, and an exhaustive 0–90° tilt search. The reported results compare the annual fixed and monthly optimized windows; seasonal or biannual strategies are potential future applications, not outcomes established by the present analysis. The method isolates incident irradiation and does not predict final electrical production.

For Gainesville, FL, USA, the annual fixed optimum tilt was highly stable across the 2018–2023 NSRDB dataset. FT-PVOT identified a clear-sky annual optimum range of 28–29° with a mean of approximately 28.8° and a standard deviation of approximately 0.41°. The all-sky annual optimum ranged from 29–30°, with a mean of approximately 29.2° and a standard deviation of approximately 0.41°. PVWatts produced an annual fixed optimum of approximately 29°, yielding a mean annual difference of about 0.17°. This close benchmark agreement supports the interpretation that annual fixed-tilt selection is governed primarily by latitude and annual solar geometry rather than by normal year-to-year variation in irradiance magnitude.

The corrected optimization comparison provides the main design insight available from the supplied Gainesville data files. Annual fixed optimization produced 3276.6 kWh/m^2/year under clear-sky conditions and 2419.7 kWh/m^2/year under all-sky conditions. Monthly optimization increased these values to 3394.2 and 2492.5 kWh/m^2/year, respectively. The incremental gain from monthly adjustment over annual fixed optimization was therefore

117.6 kWh/m^2/year (3.6%) under clear-sky conditions and 72.7 kWh/m^2/year (3.0%) under all-sky conditions. This confirms that monthly adjustment is mathematically beneficial, but the additional gain is modest relative to the simpler annual fixed-tilt benchmark.

The clear-sky and all-sky comparison further clarifies the role of atmospheric attenuation. All-sky conditions reduced annual POA irradiation by approximately 26.2% relative to the clear-sky case, but both datasets produced an annual fixed optimum of approximately 29°. Additional DNI and DHI perturbation testing changed the annual optimum tilt by less than 1°. These results indicate that atmospheric attenuation strongly affects the magnitude of available solar energy but does not materially shift the annual fixed-tilt recommendation for the Gainesville case study.

The findings reinforce a necessary distinction between irradiance optimization and electrical output prediction. FT-PVOT optimizes incident plane-of-array irradiation only. Final PV electricity production depends on module efficiency, cell temperature, inverter behavior, soiling, shading, wiring losses, degradation, mounting height, and other site-specific assumptions. Therefore, the framework is best used as an early-stage screening tool that produces a reproducible tilt recommendation for subsequent evaluation in PVWatts, SAM, PVsyst, or project-specific techno-economic models.

Overall, the study converts a common rule of thumb into a quantified, auditable, location-specific design result. For Gainesville, the annual fixed tilt remains close to local latitude; monthly optimization provides a modest additional gain over annual fixed optimization; and all-sky conditions reduce irradiance magnitude without materially changing the annual fixed optimum. Because FT-PVOT relies on public irradiance data, explicit equations, and a simple 0–90° brute-force tilt sweep, the workflow can be replicated by students, researchers, and practitioners for other locations and future comparative studies.

11. Future Research

Future research should extend FT-PVOT from a single-site Gainesville case study to a multi-city national evaluation. The companion research direction is a climate-adjusted irradiance and fixed-tilt assessment across approximately 54 U.S. cities. That study would test whether the Gainesville findings generalize across arid, humid, coastal, high-altitude, northern, and subtropical environments, and would identify where latitude-based tilt remains sufficient and where climate-sensitive adjustments provide measurable value.

The second-stage framework should combine annual optimum fixed tilt, total POA irradiation, seasonal adjustment benefit, and climate modifiers such as cloudiness, humidity, aerosol/dust loading, temperature, and altitude. The purpose would not be only to compute an optimal tilt angle for each city, but to produce a ranked PV suitability and irradiance-performance comparison. Such a framework would address the gap identified in the literature review: existing studies provide strong methods for irradiance mapping, tilted-surface modeling, and climate effect analysis, but they do not appear to provide an integrated U.S. city-level ranking that combines fixed-tilt optimization with climate modifiers.

Additional technical extensions should compare the isotropic diffuse model used in the present study with anisotropic transposition models such as Hay–Davies, Klucher, Reindl, or Perez formulations. This comparison would determine whether more detailed diffuse-radiance treatment changes annual fixed tilt, seasonal tilt, or only the absolute POA magnitude. A multi-model comparison would be especially useful in humid and partly cloudy regions where diffuse fraction is higher.

A further research path is to connect irradiance-maximizing tilt recommendations to electrical output, storage, and economic outcomes. FT-PVOT can provide the geometric input angle, while PVWatts, SAM, PVsyst, or project-specific models can evaluate mod-

ule temperature, inverter losses, system cost, storage sizing, and payback. This would allow future studies to distinguish the mathematically optimal irradiance angle from the economically optimal PV system design.

Finally, future work should produce an open dataset and reproducible code repository so that students, researchers, designers, and planners can replicate the workflow for additional locations. A public implementation would strengthen the educational value of the method and support broader use in residential, community-scale, and early-stage utility PV planning.

Author Contributions: Conceptualization, M.J.C.; methodology, M.J.C.; software, G.S.; validation, G.S.; formal analysis, M.J.C.; investigation, M.J.C.; resources, M.J.C.; data curation, G.S.; writing—original draft preparation, M.J.C.; writing—review and editing, M.J.C. and R.S.S.; visualization, M.J.C. and G.S.; supervision, R.S.S.; project administration, M.J.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The NSRDB input data used in this study are publicly available from the National Renewable Energy Laboratory (NREL). The processed Gainesville datasets, FT-PVOT code, and figure-generation scripts used to reproduce the reported results are available from the corresponding author upon reasonable request.

Acknowledgments: During the preparation of this manuscript, the authors used OpenAI's ChatGPT for assistance with manuscript organization, technical explanations, computational workflow review, and editorial refinement. All AI-assisted material was critically reviewed and revised by the authors, who retain full responsibility for the methodology, data analysis, interpretation of results, and final published content.

Conflicts of Interest: The authors declare no conflicts of interest.

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