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Hourly Geometry-Based Estimation of Global Horizontal Irradiance Using One-Year Ground-Based Pyranometer Data in Kamphaeng Phet, Thailand

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ABSTRACT

Accurate characterization of hourly global horizontal irradiance (GHI) is critical to solar energy resource assessment and modeling. In the tropics, atmospheric conditions and seasonal monsoon dynamics strongly influence the surface solar radiation. This study aimed to characterize hourly GHI and evaluate a geometry-based linear regression framework using one year (January–December 2025) of ground-based pyranometer measurements in Kamphaeng Phet Province, Thailand. The continuous annual data set allows an overall investigation of diurnal and seasonal changes of solar irradiance under tropical monsoon conditions. A geometry-based linear regression model was developed for estimating hourly GHI using solar position parameters, where the cosine of the solar zenith angle is the primary geometric control on surface irradiance. The recorded data show a clear bell-shaped diurnal pattern with a maximum irradiance near local solar noon. Seasonal analysis shows the pre-monsoon period has the highest irradiance levels, while the wet monsoon season is characterized by reduced and more variable irradiance due to increased cloud cover and atmospheric moisture. The geometry-based model reproduced the dominant diurnal variability of GHI with low systematic bias, although larger deviations occurred during periods of strong atmospheric variability. The one-year ground-based dataset and geometry-based framework provide a useful baseline reference for solar radiation assessment, satellite validation, and future irradiance modeling under tropical monsoon conditions.

1. Introduction

Solar radiation is a major factor in the Earth-atmosphere energy balance and is of fundamental importance in climate regulation, atmospheric dynamics and the hydrological cycle. Solar radiation is also an important resource for renewable energy applications in natural systems. Its importance is increasing with the increase in global energy demand and the transition of the world towards low-carbon energy systems. Solar energy is now the most popular renewable energy source because it is abundant, sustainable and costs less to implement. Hence, accurate estimation and characterization of surface solar radiation are important for solar resource assessment, photovoltaic (PV) performance evaluation and optimization of solar energy systems [1–3].

The global horizontal irradiance (GHI) is one of the radiative components and is a fundamental variable in solar energy research, as this is the total incoming shortwave radiation at a horizontal surface, including both direct and diffuse components. Hourly GHI observations are particularly useful for characterizing the diurnal irradiance variability and for enhancing the modeling of solar energy production, grid integration studies and system reliability assessment [4–6]. A variety of techniques have been used to estimate solar irradiance, including empirical relationships, physical radiative transfer models, satellite-based retrieval methods and more recently machine learning approaches. Empirical models commonly relate irradiance to solar geometry, sunshine duration, or meteorological variables and provide computationally efficient estimation approaches. Physical models are used to simulate the interaction between radiation and atmospheric constituents (e.g., clouds, aerosols and gases) and satellite-based techniques merge remote sensing measurements with atmospheric models to generate spatially continuous irradiance products [7–10]. It has been shown that the application of sophisticated irradiance models is associated with large uncertainties in the case of highly variable atmospheric conditions, thus emphasizing the importance of reliable ground-based observations and model validation [1-3].

The most reliable reference for the assessment of solar radiation is still based on ground measurements with pyranometers, which provide direct observations at high temporal resolution [4, 5]. These measurements allow detailed investigation of diurnal and seasonal irradiance variability and improve understanding of atmospheric effects such as cloud formation, aerosol loading, and water vapor variability. However, the development and validation of representative models for irradiance estimation is hampered by the lack of long-term, high-resolution ground-based datasets in many tropical regions.

Physically interpretable baseline approaches for solar radiation estimation have been extensively used in the form of regression-based and geometry-based formulations [4, 6]. These methods are computationally efficient and provide insight into the dominant

geometric controls of irradiance variability. However, the model performance changes significantly with the local climatic conditions, emphasizing the need for site-specific analysis and regional model evaluation [8, 9]. The behaviour of solar radiation is further complicated in tropical monsoon regions by seasonal variations in cloud cover, atmospheric humidity, and aerosol loading, which strongly influence atmospheric transmissivity and surface irradiance [10–14]. Previous studies in Thailand have investigated diffuse–global relationships and empirical irradiance estimation under tropical conditions [8–9], and more advanced machine learning and hybrid approaches are increasingly being adopted to improve the predictive performance [15–20]. While such techniques can reach higher predictive accuracy, they generally require larger datasets, multiple atmospheric predictors, and more complex computational procedures [15–20].

Recent studies have also pointed out the importance of the uncertainty of solar radiation measurements such as the instrumental limitations, calibration drift, environmental effects and quality control procedures [1, 3]. These uncertainties can be transferred to the irradiance estimation models and affect their predictive accuracy, especially at hourly temporal scales. Thus, physically interpretable baseline models continue to be useful for understanding dominant irradiance behaviour and providing transparent reference frameworks for evaluating more advanced estimation methods. The variation of cloud cover, atmospheric moisture and aerosol concentration results in large seasonal variation of solar radiation in tropical monsoon regions [10–14]. The wet monsoon season is typically characterized by lower irradiance and greater variability, while the dry and pre-monsoon seasons are typically characterized by clearer conditions and higher irradiance. However, quantification of these seasonal patterns requires continuous high-resolution ground-based observations, which are sparse over much of Southeast Asia. Thus, there is still a need for site-specific studies for better understanding of variability of solar radiation in the tropical atmospheric conditions.

Accordingly, the present study does not aim to replace advanced irradiance prediction models but rather to establish a physically interpretable geometry-based baseline framework using one year (January–December 2025) of high-resolution ground-based observations collected in Kamphaeng Phet Province, Thailand. The specific contribution of this study lies not in proposing a new solar-geometry equation, but in quantifying the performance, seasonal stability, and atmospheric limitations of a transparent geometry-only baseline using continuous ground measurements under tropical monsoon conditions. The objectives are to: (1) characterize diurnal and seasonal variability of hourly GHI under tropical monsoon conditions; (2) evaluate the performance of a geometry-based estimation framework; and (3) provide a reference dataset and baseline irradiance behavior for future solar resource assessment, satellite validation, and data-driven modeling studies in tropical regions. Unlike prediction-oriented studies, the present work emphasizes physical interpretation of irradiance variability and development of a transparent geometry-based reference framework for future comparison with more sophisticated empirical and machine learning approaches.

2. Data and Methods

2.1 Study Area and Dataset

Hourly Global Horizontal Irradiance (GHI) data used in this study were obtained from a ground-based pyranometer measurement station located in Kamphaeng Phet Province, Thailand. The study site is situated in a tropical monsoon climate region characterized by distinct seasonal variations associated with the dry season (November–February), the pre-monsoon or transition season (March–May), and the wet monsoon season (June–October). These seasonal transitions are primarily driven by large-scale atmospheric circulation patterns and significantly influence cloud formation, atmospheric humidity, and aerosol loading, all of which affect surface solar radiation. Seasonal monsoon circulation strongly influences precipitation patterns, cloud cover, and atmospheric humidity throughout the year. Wet monsoon conditions are generally associated with increased cloudiness and reduced surface irradiance, whereas dry and pre-monsoon periods typically exhibit clearer conditions and higher solar radiation levels. These climatological characteristics are important for interpreting seasonal variability in GHI observed at the study site.

The dataset covers a continuous one-year period from January to December 2025, enabling a comprehensive analysis of the full annual cycle of solar radiation. Continuous measurements over a full annual cycle are essential for capturing both diurnal and seasonal variability in solar irradiance, particularly in tropical regions where atmospheric conditions can change rapidly. The one-year dataset captures representative variations associated with different atmospheric conditions occurring throughout the annual cycle, including clear-sky and cloudy monsoon periods. The analyzed dataset includes mixed sky conditions occurring throughout the annual cycle, including clear-sky, partly cloudy, and overcast periods associated with tropical monsoon variability. Consequently, the proposed geometry-based formulation represents an all-sky baseline relationship derived from averaged irradiance behavior under varying atmospheric regimes. No explicit cloud classification scheme (e.g., clear-sky, partly cloudy, or overcast categories) was applied in the present analysis. Instead, all daytime observations after quality control filtering were retained to establish a representative all-sky baseline relationship under naturally varying tropical atmospheric conditions.

The pyranometer measurements with high temporal resolution were first obtained at short time intervals and then averaged to hourly values. The hourly data are consistent with the temporal resolution commonly adopted in solar resource assessment, photovoltaic system modeling, and irradiance estimation studies [1, 4]. Averaging over an hour also reduces the effects of short-term variability and measurement noise, leading to a more consistent dataset for statistical analysis and regression modeling.

Ground-based pyranometer observations remain the most reliable reference source for solar radiation studies because they provide direct irradiance measurements with high temporal resolution. These measurements are commonly used as reference datasets for evaluating empirical models and satellite-derived solar radiation products [1, 5]. In this study, the ground-based dataset serves as the primary reference for analyzing solar radiation characteristics and for developing a geometry-based estimation model. Solar position parameters were computed using standard astronomical and solar geometry relationships following established solar engineering formulations [21].

Solar radiation measurements were obtained using an SMP10-V pyranometer (ISO 9060 Secondary Standard/Class A) installed in a horizontal configuration at the measurement site, as shown in Fig. 1. The instrument (Serial Number 242042; Calibration Certificate Number 031525242042) was calibrated on 03 July 2024 prior to deployment. The measurement system operated continuously throughout the observation period using an HIOKI LR8431-20 Memory HiLogger.

Table 1. Monthly summary statistics of the 3,958 hourly daytime global horizontal irradiance (GHI) observations used in the final analysis in Kamphaeng Phet, Thailand.

Month	N (hours)	Mean (W m^{-2})	Max (W m^{-2})	Min (W m^{-2})	Std (W m^{-2})	CV (%)
Jan	329	463.96	829.59	36.67	257.66	55.53
Feb	264	465.01	923.78	13.49	284.45	61.17
Mar	341	499.91	944.5	17.19	287.81	57.57
Apr	330	506.72	1025.26	1.27	309.29	61.04
May	340	472.65	1058.14	2.16	295.58	62.54
Jun	330	442.45	1017.83	9.08	255.43	57.73
Jul	341	375.18	1016.34	0.42	243.97	65.03
Aug	341	478.97	1044.72	5.4	286.92	59.9
Sep	330	424.54	1110.76	1.02	278.56	65.61
Oct	341	416.68	1004.41	0.2	271.81	65.23
Nov	330	365.72	895.5	2.84	247.23	67.6
Dec	341	402.58	824.4	7.97	252.57	62.74
Annual	3958	442.45	1110.76	0.2	276.42	62.47

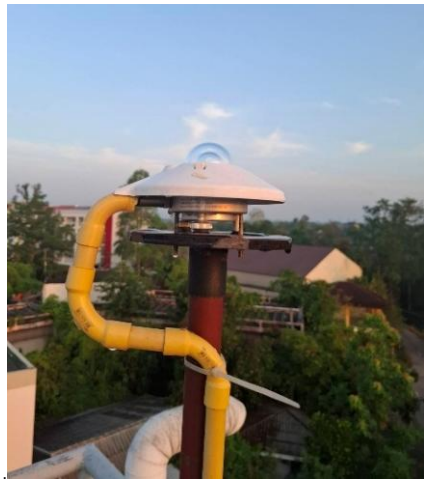

Fig. 1 SMP10-V pyranometer installed in a horizontal configuration at the ground-based solar radiation measurement site in Kamphaeng Phet Province, Thailand.

High-temporal-resolution irradiance observations were initially recorded at 5-second intervals and subsequently processed into hourly averaged values for analysis. Instrument installation, maintenance, and operational procedures followed manufacturer recommendations to ensure measurement reliability, consistency, and long-term data quality during the entire observation period.

Table 1 summarizes the monthly descriptive statistics of the hourly daytime GHI observations included in the final analytical dataset. A total of 3,958 hourly observations were available for statistical analysis and geometry-based model development. The annual statistics were calculated directly from all 3,958 hourly observations rather than from the arithmetic mean of the monthly summary statistics. For subsequent analysis, each hourly record consisted of the measured GHI, corresponding timestamp, calculated solar zenith angle (θ_Z), $cos\ \theta_Z$, extraterrestrial horizontal irradiance, and seasonal classification used in the geometry-based and seasonal analyses.

2.2 Data Quality Control

Prior to analysis, quality control procedures were applied to ensure the physical consistency of the measured irradiance data [3, 13]. The original voltage measurements recorded at 5-s intervals were first converted to GHI using the pyranometer calibration relationship.

Negative GHI values were removed at the 5-s measurement level before temporal aggregation. The remaining valid 5-s observations were subsequently aggregated into hourly averages.

For the hourly dataset, nighttime observations were excluded using the solar-geometry criterion so that only daytime observations were retained for analysis. Hourly GHI values were also checked against the adopted physical range of 0–1,400 W m^{-2}. No hourly observations were negative or exceeded 1,400 W m^{-2} during the study period; therefore, no hourly records were removed on the basis of these physical-limit criteria. After data screening and temporal aggregation, 3,958 daytime hourly observations remained for statistical analysis and geometry-based model development.

No additional statistical outlier rejection, such as IQR-based, z-score-based, or distributional trimming, was applied to the hourly dataset. This approach retained physically plausible irradiance fluctuations associated with rapidly changing cloud and atmospheric conditions, which constitute an important component of the all-sky variability examined in this study.

High-frequency measurements were aggregated into hourly averages, which improved dataset stability for regression-based analysis by reducing short-term fluctuations linked to transient clouds and atmospheric turbulence. Hourly averaging is in line with standard procedure in empirical irradiance modeling studies and solar resource assessment. Hourly aggregation reduces high-frequency fluctuations associated with transient cloud passages and measurement noise while retaining the broader diurnal and seasonal irradiance variability required for the geometry-based analysis. No additional statistical outlier filtering was applied after hourly aggregation.

2.3 Solar Geometry Calculations

For each hourly timestamp, standard astronomical relationships describing the apparent motion of the sun relative to the Earth were used to calculate solar position parameters. Solar geometry is the foundation of the understanding of the diurnal variation of solar irradiance and is widely used in solar radiation modeling and solar resource assessment [13, 14]. The solar zenith angle (θ_Z) was calculated using standard solar geometry relationships following the formulations described by Duffie and Beckman (2013) [21]:

$$\cos\theta_Z = \sin\phi\,\sin\delta + \cos\phi\,\cos\delta\,\cos\omega \quad (1)$$

Where $\phi$is the latitude of the study location (degrees), δ is the solar declination angle (degrees), ω is the hour angle (degrees). Solar declination represents the angular position of the sun relative to the equatorial plane and varies throughout the year as a function of the day of year (DOY). The hour angle represents the angular displacement of the sun from local solar noon and determines the diurnal change in solar elevation.

These relationships provide a direct and physically meaningful link between solar position and the amount of solar radiation received at the surface. The cosine of the solar zenith angle is particularly important because it represents the projection of solar radiation onto a horizontal surface and therefore governs the primary diurnal pattern of GHI [13]. The extraterrestrial solar irradiance on a horizontal surface (I_0) was calculated following standard solar engineering formulations [21]:

$$I_0 = I_{sc}\left(1 + 0.033\cos\left(\frac{360\ n}{365}\right)\right)\cos\theta_Z \quad (2)$$

where I_{sc} is the solar constant $\left(1367\ Wm^{-2}\right)$ and n is the day of year (DOY, dimensionless), and θ_Z is the solar zenith angle (degrees). Extraterrestrial irradiance represents the maximum incoming solar radiation at the top of the atmosphere and provides an upper physical reference for surface irradiance. This parameter is commonly used as a solar-geometry-dependent physical reference for irradiance calculation, plausibility assessment, and solar radiation analysis [13, 21]. In the present study, extraterrestrial irradiance was used as a solar-geometry reference for interpreting the physical range and temporal behavior of surface irradiance. The hourly QC procedure itself applied the predefined GHI range of 0–1,400 W m⁻² described in Section 2.2.

2.4 Geometry-Based Estimation Model

A geometry-based estimation framework was designed to probe the relationship between solar geometry and surface irradiance. The underlying assumption of this approach is that the first-order diurnal variation of GHI is primarily governed by solar position, particularly the projection of incoming solar radiation onto a horizontal surface through $\cos\theta_Z$, whereas atmospheric processes introduce variability around this geometric baseline [13, 21]. Consequently, the proposed model is not intended to fully represent all atmospheric processes affecting irradiance, but rather to isolate the deterministic geometric component of solar radiation variability. Such geometry-based linear regression formulations have been widely adopted as physically interpretable baseline models for irradiance estimation because they provide computationally efficient representations of the dominant geometric control on solar radiation variability [4, 6].

The relationship between measured hourly GHI and solar geometry was expressed using a linear regression model:

$$GHI_{est} = a\cos\theta_Z + b \quad (3)$$

where GHI_{est} represents the estimated global horizontal irradiance (Wm^{-2}), $a$and b are regression coefficients expressed in Wm^{-2}. The coefficient a represents the scaling factor associated with the geometric component of irradiance, while b accounts for systematic offsets related to atmospheric effects and measurement conditions. The regression coefficients a and b were estimated using the complete annual daytime dataset, and the fitted Eq. (3) was then used to calculate hourly estimated irradiance (GHI_{est}) for model performance evaluation and comparison with the corresponding observed hourly GHI values.

This formulation provides a simple and physically interpretable representation of the diurnal structure of solar radiation. Geometry-based and regression-based models have been widely used in solar radiation studies as baseline approaches for irradiance estimation [4,6]. Unlike more complex models that require multiple input variables, the geometry-based approach relies only on solar position parameters, making it computationally efficient and easy to implement.

The regression model was developed using the complete one-year daytime dataset after quality control filtering. This approach was adopted because the primary objective of the study was to establish a representative annual geometry-based baseline describing the relationship between solar geometry and hourly GHI under varying seasonal atmospheric conditions. Unlike forecasting-oriented studies that require independent training and testing datasets, the present work focuses on physical characterization and first-order interpretation of irradiance variability rather than predictive optimization.

2.5 Model Performance Evaluation

The performance of the geometry-based estimation model was evaluated through statistical indicators commonly used in solar radiation studies. These measures quantify systematic bias and overall estimation accuracy and allow comparison with previously reported results [4, 16]. The Mean Bias Error (MBE), Root Mean Square Error (RMSE), and Mean Absolute Error (MAE) were calculated following commonly adopted model evaluation formulations [4, 16, 22]:

$$MBE = \frac{1}{N}\sum(GHI_{est} - GHI_{meas}) \quad (4)$$

$$RMSE = \sqrt{\frac{1}{N}\sum(GHI_{est} - GHI_{meas})^2} \quad (5)$$

$$MAE = \frac{1}{N}\sum|GHI_{est} - GHI_{meas}| \quad (6)$$

where GHI_{est} and GHI_{meas} represent the estimated and measured global horizontal irradiance (Wm^{-2}), respectively, N is the number of observations (dimensionless). The error metrics MBE, RMSE, and MAE are expressed in $W\,m^{-2}$.

In order to normalize the error metrics and facilitate comparison across datasets and climatic conditions, relative error indicators, such as relative RMSE (rRMSE) and relative MAE (rMAE), were also computed. Scale-independent measurements of model performance are provided by these normalized metrics, which are dimensionless and expressed as percentages (%) [4, 16]. Model performance statistics were first calculated for the complete annual dataset to assess the overall relationship between GHI and solar geometry. The dataset was then divided into dry, pre-monsoon, and wet monsoon seasons for seasonal analysis. This seasonal evaluation provides additional insight into the stability of the geometry-based formulation under different atmospheric conditions, including variations in cloud cover and atmospheric transmissivity.

2.6 Uncertainty Considerations

Uncertainty in this study arises from three primary sources: measurement uncertainty, data processing uncertainty, and model structural uncertainty. These sources of uncertainty may influence both the measured irradiance values and the performance of the geometry-

based estimation model [1, 3]. Measurement uncertainty is associated with the pyranometer response, calibration condition, sensor leveling, and environmental influences such as temporary shading, sensor contamination, or atmospheric instability. Although ground-based pyranometer observations are widely regarded as the most reliable reference measurements for solar radiation studies, small uncertainties may still occur under rapidly changing atmospheric conditions [1, 3, 13]. Data processing uncertainty may arise from the screening of high-frequency observations and their subsequent aggregation into hourly averages. The use of hourly averaging reduces short-term fluctuations and measurement noise; however, it may also smooth rapid irradiance variations caused by transient cloud events. Consequently, data screening and temporal aggregation may introduce additional processing uncertainty [1, 13].

Model structural uncertainty arises from the assumption that solar geometry is the dominant mechanism controlling the diurnal variability of GHI. As the geometry-based formulation does not explicitly include atmospheric variables such as cloud cover, humidity, aerosols and atmospheric water vapour, it cannot fully represent short-term atmospheric variability. This limitation is more pronounced during wet monsoon conditions, when cloud dynamics strongly affect atmospheric transmissivity and irradiance variability [6,15–20]. Despite these uncertainties, the current geometry-based framework provides a physically interpretable baseline representation of the behavior of hourly irradiance and remains useful in studying the dominant influence of solar geometry on surface solar radiation.

3. Results

3.1 Annual Diurnal Characteristics of GHI

The mean diurnal variation of measured hourly Global Horizontal Irradiance (GHI), averaged over the full observation period from January to December 2025, is shown in Fig. 2. The diurnal cycle displays a distinct bell-shaped distribution, which is typical of the behavior of solar radiation during the day under mixed sky conditions. GHI values rise quickly after sunrise (around 07:00 local time), peak between 12:00 and 13:00 local solar noon, and then progressively decline until sunset (approximately 17:00). The predominant impact of solar geometry on surface irradiance is reflected in the observed diurnal profile. The atmospheric path length shortens as the solar elevation angle rises in the morning, increasing irradiance and decreasing attenuation at the surface. On the other hand, GHI gradually decreases in the afternoon due to increased atmospheric path length and attenuation brought on by the decreasing solar elevation.

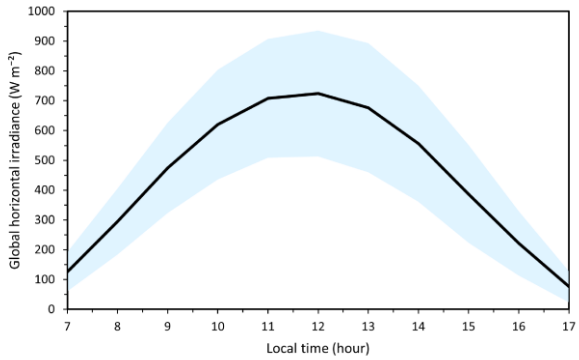

Fig. 2 Mean diurnal distribution of measured hourly global horizontal irradiance (GHI) averaged over the entire year (January–December 2025) at Kamphaeng Phet, Thailand. Values are shown for local time 07:00–17:00; shaded bands represent ±1 standard deviation.

Numerous studies of solar radiation have documented this symmetric pattern around solar noon, which is in line with theoretical predictions based on solar geometry [10–12].

The standard deviation band in Fig. 2 indicates the variability of GHI throughout the day. Variability is relatively low during early morning and late afternoon, when irradiance values are generally small, whereas the highest variability occurs around midday when GHI reaches its peak. The greater variability is due to transient meteorological phenomena, particularly cloud formation and movement, which are more pronounced under conditions of high solar radiation. Even for the same solar geometry, the rapid changes in cloud cover, aerosol concentration and atmospheric moisture could result in large variations in GHI. The mean diurnal curve is smooth, suggesting that the one-year dataset is temporally sufficient to capture representative hourly GHI behavior at the study site.

3.2 Seasonal Variation in Model Performance

Fig. 3 illustrates the seasonal variation in the normalized error metrics of the geometry-based GHI estimation model for three distinct seasons: the dry season (November–February), the pre-monsoon or transition season (March–May), and the wet monsoon season (June–October). These seasonal groupings represent the typical climatic conditions associated with Thailand's tropical monsoon climate. Model performance is compared using relative RMSE (rRMSE) and relative MAE (rMAE).

The pre-monsoon period exhibited the lowest normalized errors, with an rRMSE of 34.74% and an rMAE of 27.13%. The dry season showed slightly higher errors, with an rRMSE of 36.92% and an rMAE of 30.57%. In contrast, the wet monsoon season exhibited the highest normalized errors, with an rRMSE of 43.77% and an rMAE of 33.85%.

The lower normalized errors during the pre-monsoon period are consistent with comparatively clearer atmospheric conditions, whereas the higher normalized errors during the wet monsoon season reflect the greater influence of cloud cover, atmospheric humidity, and short-term atmospheric variability. The dry season shows intermediate model performance between the pre-monsoon and wet monsoon periods. These seasonal differences indicate that the accuracy of the geometry-based model is influenced by atmospheric conditions, particularly during the wet monsoon season.

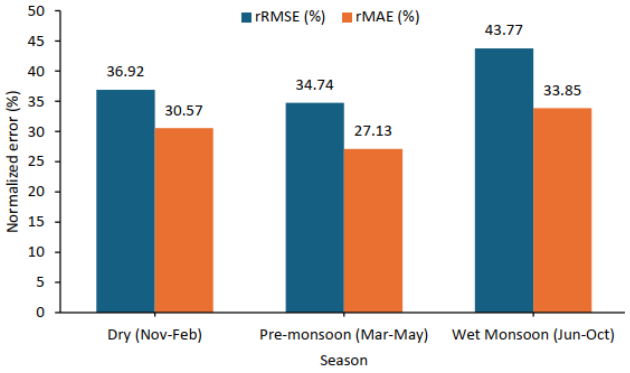

Fig. 3 Seasonal comparison of normalized error metrics for the geometry-based GHI estimation model. Relative RMSE (rRMSE) and relative MAE (rMAE) are shown for the dry (Nov–Feb), pre-monsoon (Mar–May), and wet monsoon (Jun–Oct) seasons using hourly daytime observations from January to December 2025.

Table 2 Annual performance of the geometry-based linear regression model for hourly GHI (Jan–Dec 2025).

Model	Equation	a (W m^{-2})	b (W m^{-2})	N (hours)	MBE (W m^{-2})	RMSE (W m^{-2})	MAE (W m^{-2})	rRMSE (%)	rMAE (%)	R^2
Geometry-based linear regression	$GHI_{est} = a\cos\theta_Z + b$	844.71	-94.61	3958	0.00	173.59	136.9	39.23	30.94	0.61

3.3 Geometry-Based Estimation and Model Performance

The relationship between measured hourly GHI and solar geometry is examined in Fig. 4, which plots GHI as a function of the cosine of the solar zenith angle ($cos\ \theta_Z$). A generally linear relationship is observed, indicating that solar geometry provides a physically meaningful first-order approximation of the diurnal variability of irradiance.

The linear regression model applied in this study captures the overall trend between GHI and $cos\ \theta_Z$, demonstrating that the cosine of the solar zenith angle is an effective predictor of hourly irradiance. The coefficient of determination (R^2 = 0.61) indicates that a moderate portion of the variability in GHI can be explained by solar geometry alone, with the corresponding regression coefficients and annual performance statistics summarized in Table 2. This result confirms the dominant role of solar position in controlling the diurnal structure of irradiance, consistent with established theoretical relationships in solar geometry and previous irradiance studies [13, 21].

Despite the overall linear trend, some scatter is observed in the data points, particularly at higher values of cos(θz) corresponding to midday conditions. This dispersion reflects atmospheric processes, including cloud variability and changes in atmospheric transmissivity, which cannot be fully represented by solar geometry alone. The increased scatter at high solar elevation indicates that rapid atmospheric fluctuations can significantly alter surface irradiance even under similar solar geometric conditions.

The apparent vertical columns in Fig. 4 occur because similar solar zenith angle values may correspond to substantially different irradiance levels under varying atmospheric conditions, particularly during rapidly changing cloud cover. Additional filtering targeting specific atmospheric conditions was not applied because the objective of the present study was to establish an all-sky geometry-based baseline relationship representative of mixed tropical atmospheric conditions. This effect is particularly evident under tropical monsoon conditions, where rapid changes in cloud cover and atmospheric moisture can alter irradiance independently of solar geometry.

The performance of the geometry-based regression model is summarized in Table 2 for the entire annual dataset. The annual model performance indicates moderate explanatory capability but limited predictive accuracy. The RMSE of 173.59 W m^{-2} and rRMSE of 39.23% demonstrate substantial point-to-point deviations between the geometry-based estimates and measured hourly GHI. These errors are primarily associated with atmospheric variability that is not explicitly represented by the geometry-only formulation. Previous hourly irradiance studies have similarly reported reduced predictive accuracy under highly variable atmospheric conditions, particularly when cloud variability is not explicitly represented [15–20].

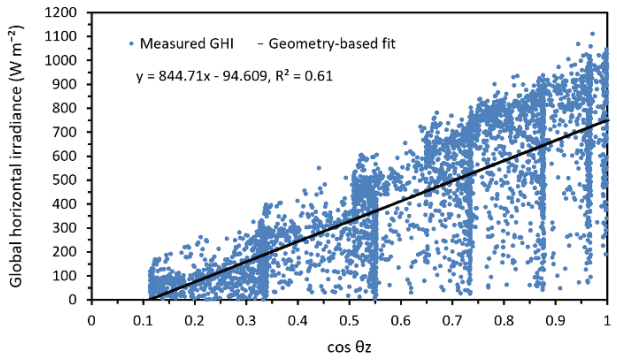

Fig. 4 Relationship between measured hourly global horizontal irradiance (GHI) and the cosine of the solar zenith angle ($cos\ \theta_Z$). The fitted regression line illustrates the geometry-based baseline model developed for hourly GHI estimation using one-year ground-based observations.

Table 3 Regression statistics of the geometry-based linear model for the complete annual dataset.

Parameter	Value
Slope coefficient (a)	844.71
Intercept (b)	-94.61
R^2	0.6055
Adjusted R^2	0.6054
t-statistic for slope	77.93
p-value	< 0.001
95% Confidence Interval of slope	823.46 – 865.96

Regression analysis and additional statistics summarized in Table 3 demonstrated statistically significant geometric dependence between hourly GHI and $cos\ \theta_Z$. The regression coefficient associated with $cos\ \theta_Z$ remained significant ($p < 0.001$), confirming a meaningful relationship between solar geometry and hourly GHI.

The adjusted R^2 remained comparable to the ordinary R^2, indicating that the explanatory capability of the model was not artificially influenced by model complexity. In addition, the 95% confidence interval for the regression slope coefficient remained entirely positive, supporting the stability of the observed geometric dependence.

To further evaluate the robustness of the model under different atmospheric conditions, seasonal performance statistics are presented in Table 4. The results show that the model performs best during the pre-monsoon season, where clearer atmospheric conditions allow solar geometry to dominate the irradiance signal. In contrast, higher error values are observed during the wet monsoon season, reflecting increased atmospheric variability and the greater influence of cloud processes.

The seasonal variation in model performance demonstrates that while the geometry-based approach is effective in capturing the general behavior of GHI, its accuracy is influenced by atmospheric conditions.

Table 4 Seasonal performance of the annual geometry-based model for hourly GHI.

Season	N (hours)	Mean GHI (W m^{-2})	MBE (W m^{-2})	RMSE (W m^{-2})	MAE (W m^{-2})	rRMSE (%)	rMAE (%)	R^2
Dry (Nov-Feb)	1264	421.97	-69.71	155.79	129	36.92	30.57	0.65
Pre-monsoon (Mar-May)	1011	492.97	-5.91	171.27	133.77	34.74	27.13	0.67
Wet (Monsoon) (Jun-Oct)	1683	427.49	55.9	187.12	144.72	43.77	33.85	0.52

The relatively consistent seasonal behavior indicates that the model provides a physically interpretable baseline representation of irradiance variability, although predictive accuracy remains limited under highly variable atmospheric conditions. The scattering of data points is especially apparent at high solar elevations, where fast cloud formation and short-term atmospheric changes can have a large influence on surface irradiance even at comparable solar geometric conditions. These effects are particularly important under tropical monsoon conditions, where variations of cloud cover, atmospheric moisture and aerosol loading strongly influence the atmospheric transmissivity and the amount of solar radiation reaching the surface.

Overall, the results confirm that solar geometry is the primary factor governing the diurnal variation of GHI, while atmospheric processes introduce secondary variability that affects model performance. The geometry-based regression model developed in this study captures the dominant structure of hourly irradiance and provides a useful reference for further analysis and model development. In addition, the consistency of the regression coefficients obtained from the annual dataset indicates that the geometry-based model provides a consistent first-order representation of irradiance behavior over time. This stability is particularly important for establishing a reference framework for subsequent studies, including model comparison, satellite-based product validation, and the development of hybrid or data-driven approaches. The ability of the model to capture the dominant diurnal pattern with minimal systematic bias further supports its suitability as a baseline model for solar radiation analysis in tropical environments.

4. Discussion

The annual and seasonal results collectively demonstrate a clear separation between the deterministic influence of solar geometry and atmosphere-driven irradiance variability. The dominant diurnal structure is physically associated with changes in solar zenith angle, atmospheric path length, and projection of incoming radiation onto a horizontal surface [3, 13, 21]. Deviations from this geometric structure therefore provide useful information on the modulation of surface irradiance by atmospheric processes.

Despite this dominant geometric control, the spread of observed GHI values around the mean diurnal curve—particularly during midday—indicates the presence of significant atmospheric modulation. Variability in cloud cover, atmospheric water vapor, and aerosol loading influences both the magnitude and temporal stability of solar radiation reaching the surface. Even under conditions of high solar elevation, transient cloud formation can induce rapid fluctuations in irradiance, leading to deviations from the idealized geometric profile. This behavior is consistent with findings from validation studies of clear-sky irradiance models, which demonstrate that atmospheric variability remains a major source of uncertainty in solar radiation estimation [1, 3]. Therefore, while solar geometry provides a physically meaningful baseline for describing diurnal patterns, atmospheric processes introduce variability that should be considered in practical applications.

The seasonal variation in model performance shown in Fig. 3 further highlights the influence of regional atmospheric conditions on the accuracy of the geometry-based GHI estimation model. The pre-monsoon period exhibited the lowest normalized errors, with an rRMSE of 34.74% and an rMAE of 27.13%, indicating comparatively better model performance under relatively clear atmospheric conditions. In contrast, the wet monsoon season showed the highest normalized errors, with an rRMSE of 43.77% and an rMAE of 33.85%, reflecting the greater influence of cloud variability and atmospheric moisture. These results are consistent with previous studies conducted in tropical and monsoon-influenced regions, where cloud activity and humidity are important factors affecting solar radiation model performance [8, 9].

The dry season exhibited intermediate model performance, with an rRMSE of 36.92% and an rMAE of 30.57%, lying between the pre-monsoon and wet monsoon values. This intermediate behavior reflects the combined influence of solar geometry and seasonal atmospheric conditions on model accuracy. While solar position changes gradually throughout the year, atmospheric conditions—particularly cloud cover, humidity, and aerosol loading—can vary more abruptly, leading to seasonal differences in estimation error. These findings underscore the importance of evaluating geometry-based irradiance models across different seasonal conditions in tropical climates.

The relationship between measured GHI and the cosine of the solar zenith angle, as shown in Fig. 4, indicates that solar geometry provides a physically interpretable first-order approximation of hourly irradiance variability. The observed linear dependence indicates that a moderate portion of GHI variability can be explained by geometric factors alone, consistent with the reported R^2 value. This result is consistent with previous studies demonstrating that regression-based approaches using solar geometry can effectively reproduce the dominant diurnal structure of solar radiation [4, 6]. The use of the cosine of the solar zenith angle is particularly appropriate because it directly represents the projection of solar irradiance onto a horizontal surface, making it both physically meaningful and computationally efficient.

Model performance statistics presented in Table 2 support the interpretation of the geometry-based regression model as a physically interpretable baseline estimation approach. The very small Mean Bias Error (MBE) indicates that the model does not introduce substantial systematic overestimation or underestimation when averaged over the full annual dataset. Because the ordinary least-squares regression includes an intercept and was evaluated on the same dataset used for model fitting, the residuals sum to approximately zero, resulting in a near-zero annual MBE. This property reflects negligible mean systematic bias but does not imply small point-to-point errors, as indicated by the substantially larger RMSE and MAE values. This suggests that the regression formulation captures the central tendency of the observed irradiance values, although substantial short-term variability remains unresolved [22]. However, the magnitude of the Root Mean Square Error (RMSE) reflects residual variability that

cannot be explained by solar geometry alone. This residual error is primarily associated with atmospheric influences, including cloud variability and changes in atmospheric transmissivity, which are not explicitly included in the model formulation. Part of the remaining estimation uncertainty may be attributed to unresolved atmospheric variability and residual measurement limitations under rapidly changing sky conditions.

Seasonal performance results shown in Fig. 3 and Table 4 provide further insight into the strengths and limitations of the geometry-based model. Improved model performance during the pre-monsoon period is consistent with clearer atmospheric conditions, where the influence of solar geometry is more dominant and atmospheric disturbances are relatively limited. Under such conditions, the assumption that irradiance variability is primarily controlled by solar position is more appropriate, resulting in relatively lower error values [8, 9]. In contrast, the increased errors observed during the wet monsoon season highlight the limitations of the model in capturing complex atmospheric processes. Frequent cloud formation, rapid variations in cloud optical properties, and increased atmospheric moisture introduce variability that cannot be adequately represented by a simple geometric relationship.

These seasonal differences in model performance are consistent with previous studies conducted in tropical regions, where solar radiation models often exhibit reduced accuracy during periods of high atmospheric variability [8, 9]. The higher relative errors observed during the wet season suggest that additional atmospheric parameters, such as cloud fraction or humidity, may be necessary to improve model performance under such conditions. However, incorporating such variables would increase model complexity and reduce the simplicity and transparency that characterize the geometry-based approach.

The simple and physically interpretable baseline model based on the geometry-based framework was intentionally designed, but the inclusion of atmospheric variables such as cloud fraction, humidity, aerosol concentration and atmospheric water vapor can improve the predictive accuracy [1–3, 15–20]. The model needs only limited input data, has low computational complexity and preserves the dominant geometric relationship controlling the hourly irradiance variability [4, 6]. Hence the proposed formulation should be considered as a baseline reference framework and not as a complete all-sky irradiance prediction system. Previous studies indicate that models incorporating additional atmospheric or data-driven predictors can achieve improved predictive performance compared with geometry-only formulations, particularly under highly variable atmospheric conditions [1–3, 15–20]. However, the simplicity and physical interpretability of the present framework make it useful for investigating the dominant influence of solar geometry on surface irradiance and for providing a benchmark reference for future irradiance estimation model development.

The moderate statistical performance observed in the present study is physically consistent with the use of a geometry-only formulation under highly variable tropical atmospheric conditions. Although more advanced irradiance estimation approaches may achieve lower prediction errors through the incorporation of additional atmospheric predictors, the present model provides a transparent first-order representation of the dominant geometric control on hourly irradiance variability [18–20]. The moderate coefficient of determination ($R^2 = 0.61$) and relatively high normalized error values are physically consistent with the strong influence of rapidly varying atmospheric conditions under tropical monsoon climates. Furthermore, the use of hourly averaged observations inherently smooths atmospheric fluctuations associated with transient cloud passages and rapid irradiance changes. As a result, the proposed formulation is more appropriate for representing dominant diurnal and seasonal irradiance behavior rather than detailed short-duration atmospheric processes under highly variable sky conditions. Previous empirical irradiance estimation studies have similarly reported reduced predictive accuracy under highly variable atmospheric and tropical climatic conditions [15–20].

A principal advantage of the proposed framework is its combination of low input requirements and physical interpretability. Because the formulation relies primarily on solar geometry, departures from the baseline relationship can be interpreted as atmosphere-related variability rather than being embedded within a highly parameterized predictive structure. This characteristic makes the framework useful as a transparent benchmark for evaluating more advanced irradiance models [4, 6].

In the context of recent advances in data-driven modeling, the role of physically based baseline models remains critically important. The use of machine learning techniques, including deep learning approaches, has been widespread for solar irradiance forecasting [15–17] since they can capture complex nonlinear relationships between irradiance and meteorological variables. However, these models often lack physical transparency and require large training datasets, which may limit their applicability in certain regions. In contrast, geometry-based models provide a clear and interpretable framework that can serve as a reference for evaluating the added value of more complex approaches. Comparing advanced models against a physically meaningful baseline allows for a more robust assessment of model performance and helps determine whether increased complexity leads to meaningful improvements in accuracy.

The high-resolution one-year dataset used in this study also represents a valuable contribution to solar radiation research in tropical regions. Continuous ground-based measurements covering a complete annual cycle provide detailed insights into both diurnal and seasonal variability, which are not easily captured using short-term or incomplete datasets. In Southeast Asia, where long-term solar radiation observations remain limited, such datasets are essential for improving solar resource assessment, validating satellite-derived irradiance products, and supporting the development of region-specific solar radiation models.

From a practical perspective, the findings of this study have important implications for solar energy applications. Accurate characterization of hourly GHI is essential for photovoltaic system design, energy yield prediction, and grid integration analysis [1–3, 5]. Understanding seasonal variability in solar radiation can improve system optimization and enhance the reliability of solar energy generation. In particular, recognizing periods of increased variability, such as during the wet monsoon season, can inform strategies for energy storage, load management, and hybrid system design.

The present study provides useful insights into hourly solar irradiance behavior under tropical monsoon conditions, but several limitations should be acknowledged. The results are based on measurements from a single ground-based station in Kamphaeng Phet Province; therefore, their direct generalization to other climatic or geographic regions may be limited. However, the study area is representative of tropical monsoon conditions typical in many areas of Thailand and Southeast Asia where seasonal variations in cloud

cover and atmospheric moisture strongly influence surface irradiance behavior. Thus, the dataset reported in this study is a useful reference for studying the first-order variability of irradiance under tropical atmospheric conditions. Seasonal differences in morning irradiance may also reflect atmospheric effects beyond cloud cover alone. During dry-season periods, increased aerosol loading, biomass-burning aerosols, haze formation, or morning fog may reduce atmospheric transmissivity during early hours of the day, leading to lower irradiance despite relatively clearer sky conditions. Moreover, the short-term variability in irradiance due to cloud dynamics and change of transmissivity of the atmosphere is not well captured by the geometric model as the atmospheric variables are not explicitly considered in the model formulation. Such limitations have been reported in previous empirical and geometry-based studies on irradiance estimation [1–3, 15–20]. Future studies should extend the analysis to multiple measurement sites and independent datasets from different climatic regimes to better assess model transferability and regional applicability. Multi-site investigations would also allow more comprehensive comparisons between geometry-based, empirical, clear-sky, and machine-learning-based irradiance estimation approaches under varying atmospheric conditions.

Overall, results suggest that solar geometry is a physically meaningful basis for explaining GHI diurnal variability, while there is substantial contribution from atmospheric processes under monsoon conditions. The geometry-based regression model offers a simple and interpretable baseline for irradiance analysis, but its predictive power is limited under highly variable sky conditions. These results indicate the combined effect of solar geometry and atmospheric variability on surface irradiance behaviour in a tropical monsoon climate.

5. Conclusion

This study presented a one-year analysis of hourly Global Horizontal Irradiance (GHI) based on high-resolution ground-based pyranometer measurements in Kamphaeng Phet, Thailand, a region characterized by a tropical monsoon climate. The results demonstrate that the diurnal variation of GHI exhibits a well-defined bell-shaped pattern primarily governed by solar geometry, with irradiance increasing after sunrise, peaking around local solar noon, and decreasing toward sunset. This consistent diurnal structure confirms the dominant role of solar position, particularly the solar zenith angle, in controlling the temporal distribution of surface solar radiation. The analysis showed clear seasonal variability associated with monsoon-related atmospheric conditions and solar geometry. The pre-monsoon period exhibited the highest irradiance levels, reflecting relatively clear atmospheric conditions and higher solar elevation. During the wet monsoon season, the irradiance was lower and more variable, because of frequent cloud formation and increased atmospheric moisture. The dry season showed intermediate irradiance characteristics resulting from the combined influence of solar geometry and atmospheric conditions. The results emphasize the relevance of considering deterministic geometric factors and dynamic atmospheric processes in the characterization of the solar radiation in tropical environments.

The geometry-based linear regression model showed that solar position parameters can explain a moderate portion of hourly GHI variability. The model provided a physically interpretable first-order representation of the main diurnal behavior of GHI with negligible systematic bias, although relatively high error values indicate limitations under variable atmospheric conditions. However, the scale of the estimation errors, especially in the wet monsoon season, demonstrates the limitations of geometry-only methods in accounting for the complex atmospheric variability. The results support the use of solar geometry as a baseline for irradiance estimation, while demonstrating that additional atmospheric parameters are required to improve predictive performance under highly variable conditions.

The one-year ground-based dataset provides a useful reference for solar radiation characterization, satellite-derived irradiance validation, and regional solar resource assessment in data-sparse tropical environments. The proposed geometry-based framework also offers a simple and physically interpretable baseline for comparison with more advanced empirical, clear-sky, and data-driven irradiance estimation approaches. The main limitations of this study are the use of data from a single measurement site and the absence of explicit atmospheric predictors in the geometry-based model. In future work, the analysis will be extended to multiple stations, atmospheric variables will be added, and the baseline framework presented here will be compared with empirical, clear-sky and machine learning-based models on independent data sets.

The results indicate that solar geometry provides a physically interpretable first-order description of hourly GHI variability under tropical monsoon conditions. However, under mixed sky conditions, atmospheric effects cause substantial short-term fluctuations. The proposed framework can be useful as a baseline reference for solar radiation estimation, empirical model development, satellite validation, and future solar energy applications in the tropical region.

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Author Contributions:

Supawat Wisitsirikun: Conceptualization, Methodology, Data curation, Software, Formal analysis, Writing – original draft, Visualization.

Declaration of Interest Statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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