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Research article

Intercomparison of Diffuse Fraction Models for Hourly Solar Radiation Partitioning under Tropical Monsoon Conditions in Kamphaeng Phet, Thailand

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Abstract

Accurate estimation of diffuse and direct solar radiation components is essential for solar energy applications, particularly in regions where only global horizontal irradiance (GHI) data are available. This study presents an intercomparison of three widely used diffuse fraction models—Orgill–Hollands, Erbs et al., and Reindl et al.—for hourly solar radiation partitioning under tropical monsoon conditions in Kamphaeng Phet, Thailand. One year of quality-controlled ground-based GHI data was used to estimate diffuse horizontal irradiance (DHI) and direct normal irradiance (DNI) using each model. The analysis was conducted at annual, diurnal, and seasonal scales, with additional evaluation based on the relationship between diffuse fraction and clearness index. The results indicate that all models capture the overall behavior of solar radiation components; however, noticeable differences in magnitude arise, particularly within intermediate clearness index ranges where atmospheric conditions exhibit high variability. Seasonal analysis indicates higher diffuse radiation during the monsoon period and higher direct radiation during the non-monsoon period, reflecting the influence of cloud cover and atmospheric moisture. Among the selected models, the Reindl formulation exhibited lower inter-model variability under varying sky conditions, reflecting differences in model structure and sensitivity to atmospheric conditions. However, because no measured DHI or DNI observations were available, these results should be interpreted as differences in model behavior rather than evidence of superior predictive performance. These findings emphasize the importance of model selection in solar radiation partitioning and offer practical guidance for solar energy applications in tropical regions where only GHI measurements are available.

Keywords: diffuse fraction; solar radiation partitioning; clearness index; tropical monsoon climate; global horizontal irradiance; diffuse solar radiation models

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1. Introduction

Accurate characterization of solar radiation components is essential for solar energy applications, including photovoltaic (PV) system design, solar thermal systems, and building energy analysis. Although global horizontal irradiance (GHI) is the most widely measured solar radiation variable, many engineering and scientific applications require its separation into diffuse horizontal irradiance (DHI) and direct normal irradiance (DNI). This requirement arises because the diffuse and direct components contribute differently to energy conversion processes and strongly influence the performance of solar energy systems. The fundamental relationships among global, diffuse, and direct radiation were first established by Liu and Jordan (1960) and later refined through improved correlations for hourly and daily solar radiation distributions (Collares-Pereira & Rabl, 1979).

In many regions, however, long-term measurements of DHI and DNI are limited due to the higher cost and complexity of the required instrumentation. Consequently, diffuse fraction models have become widely used for estimating solar radiation components from GHI data. These models express the diffuse fraction, defined as the ratio of diffuse to global radiation, primarily as a function of the clearness index. Among the most commonly used models are those developed by Orgill and Hollands (1977), Erbs et al. (1982), and Reindl et al. (1990), which have been extensively applied in solar energy studies due to their simplicity and practical applicability.

The model proposed by Orgill and Hollands (1977) introduced a piecewise linear relationship between diffuse fraction and clearness index for hourly conditions. Erbs et al. (1982) extended this concept by developing polynomial correlations that can be applied across multiple temporal scales. Reindl et al. (1990) further improved the estimation by incorporating solar geometry, recognizing that atmospheric scattering depends not only on atmospheric transparency but also on solar position. The models used in this study, namely the Orgill–Hollands, Erbs et al. and Reindl et al. models, were selected for their historical significance and simplicity, and they continue to serve as benchmark empirical models of partitioning hourly solar radiation. The Orgill–Hollands model is one of the earliest piecewise correlations for hourly diffuse radiation, while the Erbs et al. model is a popular polynomial form for a wide range of clearness index conditions. The Reindl et al. model was selected because it is an extension of the clearness index based approaches but incorporates solar geometry in order to take into account the effect of solar position on diffuse radiation estimation. These three models thus provide useful progression from simple clearness-index-only formulations to a formulation with an additional physical parameter. Their continued use in model comparison studies also makes them useful reference models to assess model-to-model variability in data-limited situations.

Tropical and monsoon climates present particular challenges for solar radiation partitioning due to their highly variable atmospheric conditions. Frequent transitions between clear, partly cloudy, and overcast skies, combined with high humidity and cloud variability, lead to significant fluctuations in diffuse radiation. Chandrasekaran and Kumar (1994) showed that diffuse fraction correlations at a tropical site differ from those in temperate regions, and that seasonal analysis improves model performance. Similarly, Okogbue et al. (2009) reported strong variability in clearness index and diffuse fraction at a tropical location, with predominantly cloudy conditions throughout the year. Hakemzadeh et al. (2020) further demonstrated that diffuse radiation modeling under tropical conditions is highly sensitive to atmospheric variability and requires careful model selection.

Recent research has attempted to improve diffuse fraction estimation by incorporating additional predictors or advanced modeling techniques. Ruiz-Arias et al.

(2010) proposed a model applicable under all sky conditions, while Kuo et al. (2014) showed that including solar altitude and temporal variables enhances model accuracy. Skartveit et al. (1998) introduced corrections for variability and surface effects, highlighting the importance of additional parameters in diffuse radiation modeling. In addition, previous studies have emphasized the influence of solar geometry and temporal resolution on diffuse radiation estimation (Posadillo & López Luque, 2009; Engerer, 2015; Liu et al., 2020). More recent approaches have employed clustering and machine learning techniques. Yin et al. (2023) demonstrated that classifying sky conditions improves model performance, while Krieger et al. (2024) and Gevorgian et al. (2025) showed that artificial intelligence methods can enhance prediction accuracy. Nevertheless, empirical models remain widely used because of their simplicity, interpretability, and suitability for applications with limited data availability (Krieger et al., 2024).

In Thailand and other tropical regions, solar radiation characteristics are strongly influenced by monsoon systems. Exell (1976) reported that solar radiation in Thailand exhibits significant seasonal variability, with lower values during the rainy season due to increased cloud cover. More recent studies have confirmed the high variability of solar radiation in tropical environments. Chawphongphang et al. (2022) analyzed global and diffuse radiation in Bangkok and demonstrated the influence of atmospheric conditions on radiation variability. Phaisathit et al. (2025) further showed that diffuse fraction estimation in Thailand can be improved by incorporating atmospheric parameters, highlighting the importance of region-specific modeling.

Although these studies provide valuable insights into solar radiation behavior in tropical regions, systematic intercomparison of widely used diffuse fraction models under inland tropical monsoon conditions remains limited. In many practical applications, a single model is often used without evaluating the impact of model selection on the estimated radiation components. However, differences among models can lead to variations in DHI and DNI, which in turn affect solar energy assessments and system performance analysis. Previous studies have shown that model selection can significantly influence radiation partitioning, particularly under varying sky conditions (Marques Filho et al., 2016; Lee et al., 2017; Mirzabade et al., 2021).

Kamphaeng Phet, located in the lower northern region of Thailand, provides a representative case for investigating these issues. The region experiences a tropical monsoon climate characterized by distinct seasonal transitions between monsoon and non-monsoon periods. These seasonal variations influence cloud cover, atmospheric moisture, and solar radiation characteristics, making the region suitable for evaluating diffuse fraction models under diverse sky conditions.

In this study, an intercomparison of three widely used diffuse fraction models—Orgill–Hollands, Erbs et al., and Reindl et al.—is conducted for hourly solar radiation partitioning under tropical monsoon conditions in Kamphaeng Phet, Thailand. Using one year of quality-controlled ground-based GHI data, the study aims to quantify differences in estimated diffuse and direct radiation components across multiple temporal scales. Specifically, the objectives are: (1) to evaluate the annual mean characteristics of DHI, DNI, and diffuse fraction derived from different models; (2) to analyze the diurnal variation of estimated diffuse radiation; (3) to examine seasonal differences between monsoon and non-monsoon conditions; and (4) to assess model-to-model deviations as a function of clearness index under varying sky conditions. These analyses provide insight into model - dependent variability and contribute to the selection of appropriate diffuse fraction models for solar energy applications in tropical regions.

2. Materials and Methods

2.1 Study area and solar radiation data

This study was conducted in Kamphaeng Phet, located in the lower northern region of Thailand, which is characterized by a tropical monsoon climate. The climate of the region is strongly influenced by seasonal wind circulation, resulting in two distinct periods: the monsoon season (May-October) and the non-monsoon season (November-April). These seasonal variations significantly affect cloud cover, atmospheric moisture, and solar radiation characteristics, making the region suitable for investigating solar radiation partitioning under different sky conditions.

Global horizontal irradiance (GHI) data were obtained from a ground-based pyranometer installed at the study site. The instrument was installed in December 2024 and operated continuously throughout the year 2025. The measurements were recorded at high temporal resolution and aggregated into hourly values for analysis.

Since direct measurements of diffuse and direct radiation were not available, only GHI data were used as the primary input for estimating diffuse horizontal irradiance (DHI) and direct normal irradiance (DNI) using diffuse fraction models. This approach is widely adopted in solar radiation studies where only global radiation data are available (Boland et al., 2008; Dervishi & Mahdavi, 2012).

The global horizontal irradiance (GHI) data used in this study were collected using an SMP10-V pyranometer manufactured by Kipp and Zonen (Netherlands), classified as an ISO 9060 Secondary Standard/Class A instrument. The pyranometer was installed horizontally at a ground-based solar radiation monitoring station located at Kamphaeng Phet Rajabhat University, Kamphaeng Phet Province, Thailand (16.445°N, 99.512°E), under unobstructed sky conditions to minimize shading effects. The solar radiation monitoring system operated continuously throughout the year 2025 using an HIOKI LR8431-20 data logger. Irradiance measurements were initially recorded at 5-second intervals and subsequently processed into hourly average datasets for analysis. To lower measurement uncertainty and preserve steady long-term instrument performance, routine maintenance procedures, such as routine inspection and cleaning of the sensor dome, were carried out in accordance with manufacturer recommendations.

2.2 Data quality control

Prior to analysis, the solar radiation dataset underwent a quality-control procedure to remove physically unrealistic and inconsistent observations. Only daytime records with positive solar elevation angles were retained for analysis. Data screening included detection of negative irradiance values, excessively high irradiance values (above physically plausible extraterrestrial limits) and missing and incomplete observations. Hourly values affected by obvious instrumental anomalies or irregular fluctuations were excluded from the dataset. The quality-control procedure followed commonly adopted practices for ground-based irradiance measurements in solar radiation studies (Boland et al., 2008; Gueymard & Ruiz-Arias, 2016). The procedures were applied to improve the reliability and consistency of the hourly GHI dataset used for diffuse fraction model intercomparison.

2.3 Solar geometry and clearness index

Solar geometry parameters were calculated based on the geographical location of the study site. The solar zenith angle (θ_Z) was determined for each hourly observation using standard astronomical relationships.

The extraterrestrial solar radiation on a horizontal surface (G_0) was calculated as a reference value representing solar radiation at the top of the atmosphere. The clearness index (k_t), which indicates atmospheric transparency, was then defined as shown in equation (1):

$$k_t = GHI / G_0 \quad (1)$$

where GHI is the measured global horizontal irradiance and G_0 is the extraterrestrial irradiance.

The clearness index is widely used in solar radiation studies as a key parameter for describing sky conditions ranging from cloudy to clear sky (Erbs et al., 1982; Reindl et al., 1990; Okogbue et al., 2009).

2.4 Diffuse fraction models

In this study, three widely used empirical models were selected for estimating the diffuse fraction (k_d): Orgill and Hollands (1977), Erbs et al. (1982), and Reindl et al. (1990). These models have been extensively applied in solar radiation studies due to their simplicity, reliability, and applicability to hourly time scales.

The Orgill–Hollands (1977) model expresses the diffuse fraction as a piecewise linear function of the clearness index. The Erbs et al. (1982) model employs polynomial relationships to represent different atmospheric conditions, while the Reindl et al. (1990) model incorporates solar geometry to improve estimation accuracy.

These models were originally developed using datasets from temperate and mixed climates but have since been applied in diverse climatic regions. Their performance may vary depending on atmospheric conditions, particularly in tropical environments characterized by high variability (Boland et al., 2008; Dervishi & Mahdavi, 2012).

A summary of the mathematical formulations, applicable clearness index ranges, and key characteristics of the selected diffuse fraction models is presented in Table 1.

2.5 Estimation of solar radiation components

The diffuse fraction models adopted in this study were based on the formulations proposed by Orgill and Hollands (1977), Erbs et al. (1982), and Reindl et al. (1990), as summarized in Table 1. Diffuse horizontal irradiance (DHI) and direct normal irradiance (DNI) were subsequently estimated following standard solar radiation decomposition procedures commonly used in solar energy studies (Iqbal, 1983).

Table 1. Summary of diffuse fraction models and their applicable clearness index ranges

Model	Diffuse fraction formulation (k_d)	Applicable range of k_t	Notes
Orgill–Hollands (1977)	$k_d = 1 - 0.249\,k_t$	$k_t \le 0.35$	Simple piecewise linear formulation
	$k_d = 1.557 - 1.84\,k_t$	$0.35 < k_t \le 0.75$	
	$k_d = 0.177$	$k_t > 0.75$	
Erbs et al. (1982)	$k_d = 1 - 0.09\,k_t$	$k_t \le 0.22$	Widely used empirical model for hourly applications
	$k_d = 0.9511 - 0.160\,k_t + 4.388\,k_t^2 - 16.638\,k_t^3 + 12.336\,k_t^4$	$0.22 < k_t \le 0.80$	
	$k_d = 0.165$	$k_t > 0.80$	
Reindl et al. (1990)	$k_d = 1.02 - 0.254\,k_t + 0.0123\sin(\theta_z)$	$k_t \le 0.30$	Includes solar geometry effects
	$k_d = 1.4 - 1.749\,k_t + 0.177\sin(\theta_z)$	$0.30 < k_t \le 0.78$	
	$k_d = 0.486\,k_t - 0.182\sin(\theta_z)$	$k_t > 0.78$	

These formulations were used to estimate the diffuse fraction (k_d) for hourly solar radiation partitioning in this study.

The diffuse horizontal irradiance (DHI) was estimated from the diffuse fraction as shown in equation (2):

$$DHI = k_d \times GHI \tag{2}$$

The direct normal irradiance (DNI) was then calculated as shown in equation (3):

$$DNI = (GHI - DHI) / \cos\theta_z \tag{3}$$

where θ_z is the solar zenith angle.

This method ensures consistency in estimating solar radiation components, allowing direct comparison between models.

2.6 Temporal analysis

To ensure consistency with the results presented in this study, the analysis was performed at three temporal scales: annual, diurnal, and seasonal.

Annual mean values of DHI, DNI, and diffuse fraction were calculated using the full dataset for 2025. Diurnal variation was analyzed using hourly averages between 07:00 and 17:00 local time, representing the primary period of solar radiation.

Seasonal analysis was conducted by dividing the dataset into monsoon (May–October) and non-monsoon (November-April) periods. This classification reflects the dominant climatic conditions and enables comparison of solar radiation behavior under different atmospheric regimes (Chandrasekaran & Kumar, 1994; Okogbue et al., 2009).

2.7 Model intercomparison

The intercomparison of diffuse fraction models was performed by analyzing differences in estimated DHI and DNI across all temporal scales. Relative deviations among models were evaluated to quantify model-to-model variability.

In addition, the relationship between model deviations and clearness index was examined to assess model performance under different sky conditions. This analysis provides insight into how each model responds to changes in atmospheric transparency and cloud conditions.

3. Results and Discussion

3.1 Annual characteristics of solar radiation components

The annual mean characteristics of diffuse horizontal irradiance (DHI), direct normal irradiance (DNI), and diffuse fraction estimated from the three diffuse fraction models are summarized in Table 2. Although all estimates are derived from the same GHI dataset, systematic differences in solar radiation partitioning are evident among the models.

Table 2. Annual mean values of estimated diffuse horizontal irradiance (DHI) and direct normal irradiance (DNI) obtained from different diffuse fraction models

Model	Annual Mean DHI ($W m^{-2}$)	Annual Mean DNI ($W m^{-2}$)	Diffuse fraction
Orgill–Hollands	187.72	345.66	0.46
Erbs	186.28	347.18	0.45
Reindl	190.72	334.95	0.46
Ensemble mean	188.24	342.59	0.46

The annual diffuse fraction ranges from 0.45 to 0.46, indicating a relatively balanced contribution between diffuse and direct radiation components under tropical conditions. This range is consistent with previous observations in tropical and humid environments, where persistent cloud cover and atmospheric moisture enhance diffuse radiation (Okogbue et al., 2009; Marques Filho et al., 2016). Such values are typically higher than those reported in arid or temperate regions, highlighting the strong influence of atmospheric conditions on solar radiation partitioning. The observed diffuse fraction values are also broadly consistent with previous studies conducted in Thailand, where cloud cover and atmospheric moisture associated with the tropical monsoon climate were found to enhance the diffuse component of solar radiation (Exell, 1976; Chawphongphang et al., 2022).

The estimated DHI values show relatively small variation among the models, while DNI exhibits greater differences. This behavior is expected, as DNI is derived as the residual component of GHI after subtracting DHI. Consequently, even minor discrepancies in diffuse fraction estimation can lead to amplified differences in direct irradiance. Similar patterns have been reported in previous model comparison studies, where diffuse estimates tend to agree more closely than direct irradiance values (Dervishi & Mahdavi, 2012; Gueymard & Ruiz-Arias, 2016).

Among the models, the Reindl formulation yields slightly higher DHI values compared to the others. This can be attributed to its inclusion of solar geometry, which allows the model to better account for variations in atmospheric scattering under different solar positions (Reindl et al., 1990; Kuo et al., 2014). In contrast, the Erbs model tends to produce slightly higher DNI values, reflecting its sensitivity to clearness index under clearer sky conditions. These differences indicate that model formulation plays a significant role in determining long-term solar radiation characteristics, even when the results are aggregated over an entire year.

3.2 Diurnal variation of diffuse radiation

The mean diurnal variation of estimated diffuse horizontal irradiance (DHI) is presented in Figure 1. The analysis was based on hourly global horizontal irradiance (GHI) measurements recorded using a ground-based SMP10-V pyranometer at Kamphaeng Phet, Thailand during 2025. Hourly DHI values were estimated using the selected diffuse fraction models and subsequently averaged between 07:00 and 17:00 local time to obtain the mean diurnal profiles.

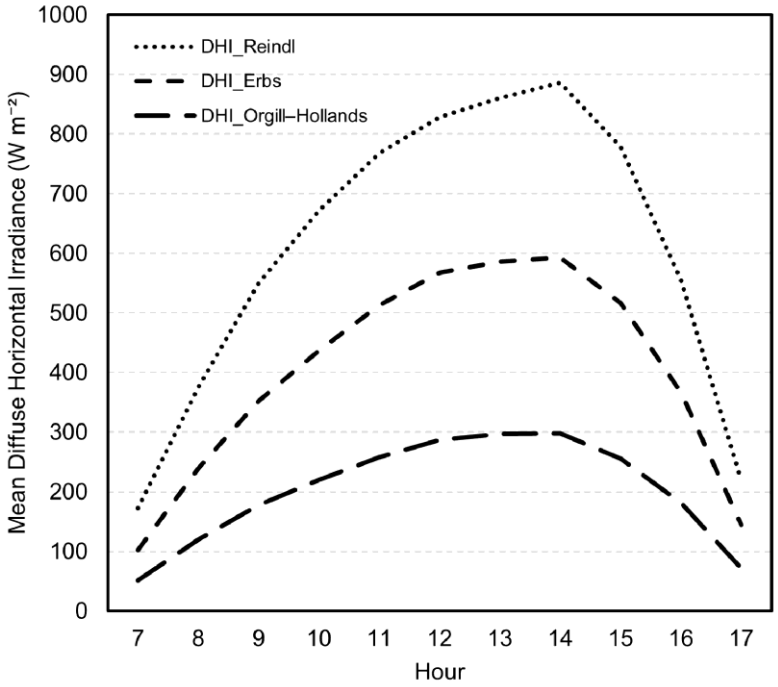


Figure 1. Mean diurnal variation of estimated diffuse horizontal irradiance (DHI) derived from different diffuse fraction models in Kamphaeng Phet, Thailand

All three models exhibit a consistent bell-shaped diurnal pattern, with diffuse radiation increasing after sunrise, reaching a maximum during early afternoon, and decreasing toward sunset. This pattern reflects the combined effects of solar elevation, atmospheric path length, and scattering processes governing the formation of diffuse radiation throughout the day (Liu & Jordan, 1960; Collares-Pereira & Rabl, 1979).

Despite the similarity in overall shape, differences in magnitude are observed, particularly during morning and late afternoon hours. The Reindl model consistently produces higher DHI values during periods of low solar elevation. This behavior is directly related to the inclusion of solar zenith angle in the model formulation, which enhances diffuse radiation estimates when the sun is close to the horizon. Similar effects have been documented in studies that incorporate solar geometry into diffuse fraction modeling (Skartveit et al., 1998; Ruiz-Arias et al., 2010).

The mean diurnal profiles are shown in Figure 1, but the hourly observations showed large variations during the year due to the changes in cloud cover, atmospheric moisture and seasonal monsoon effects. An averaging procedure was followed to emphasize the characteristic diurnal behavior of each model and to minimize the effect of short-term variations caused by transient atmospheric conditions.

During midday hours, when solar elevation is highest and atmospheric conditions are relatively stable, the differences among models become minimal. In this period, the clearness index dominates the behavior of diffuse radiation, resulting in strong agreement among the models. Comparable diurnal convergence has been reported in tropical environments, where atmospheric conditions tend to stabilize around solar noon (Chandrasekaran & Kumar, 1994; Hakemzadeh et al., 2020).

The results indicate that model sensitivity varies throughout the day, with the greatest differences occurring during transitional periods of solar elevation. This finding is particularly important for applications requiring high temporal resolution, such as photovoltaic performance analysis and short-term solar forecasting, where sub-hourly variability can significantly influence model performance (Engerer, 2015).

3.3 Seasonal variability under monsoon and non-monsoon conditions

Seasonal variations in solar radiation components are presented in Table 3 and Figure 2, showing clear differences between monsoon and non-monsoon periods.

Table 3. Seasonal mean values of estimated DHI, DNI, and diffuse fraction during monsoon and non-monsoon seasons

Season	Model	Mean DHI ($W m^{-2}$)	Mean DNI ($W m^{-2}$)	Diffuse Fraction
Monsoon	Orgill–Hollands	204.32	273.15	0.52
	Erbs	204.53	272.25	0.52
	Reindl	202.48	268.61	0.51
	Ensemble mean	203.78	271.34	0.51
Non-monsoon	Orgill–Hollands	169.48	428.23	0.40
	Erbs	166.23	432.50	0.39
	Reindl	177.81	410.49	0.42
	Ensemble mean	171.17	423.74	0.40

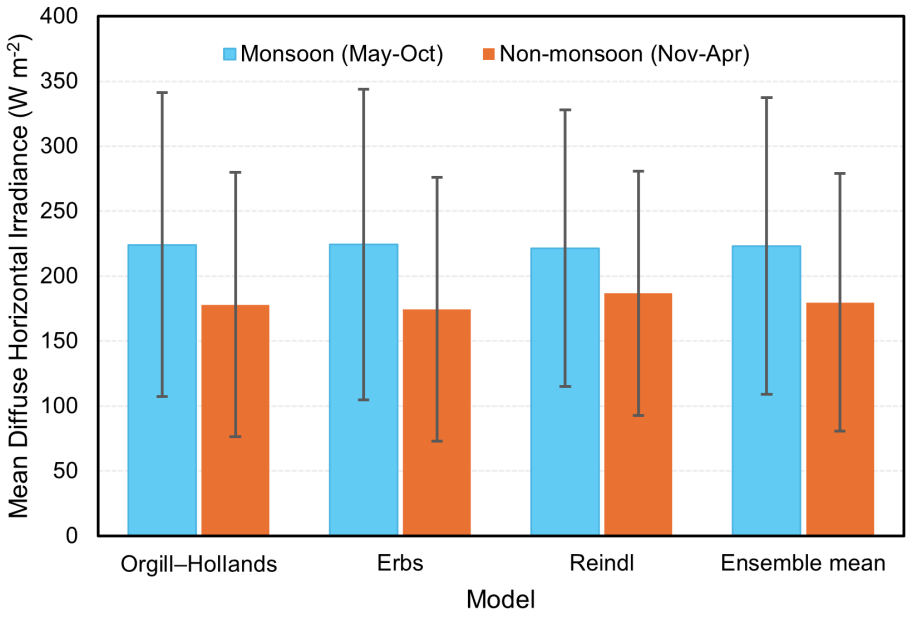


Figure 2. Seasonal comparison of mean diffuse horizontal irradiance (DHI) during monsoon (May–October) and non-monsoon (November-April) seasons estimated using different diffuse fraction models in Kamphaeng Phet, Thailand. Error bars represent one standard deviation of hourly DHI values within each season.

During the monsoon season, diffuse radiation dominates the solar radiation regime, with diffuse fraction values ranging from 0.51 to 0.52. Correspondingly, mean DHI values are high, while DNI values are relatively low. This behavior reflects the influence of extensive cloud cover, high humidity, and enhanced multiple scattering processes characteristic of tropical monsoon climates (Exell, 1976; Chawphongphang et al., 2022). The relatively large standard deviations demonstrate a significant intra-seasonal variability in diffuse radiation, which arises from the variability of cloud cover, atmospheric moisture and the rapidly changing weather conditions typical of tropical monsoon climates. These findings are also consistent with previous observations in Thailand. Exell (1976) reported a significant reduction of solar radiation during the rainy season on account of increased cloudiness. Chawphongphang et al. (2022) showed increased diffuse radiation under humid and cloudy atmospheric conditions in Bangkok. Thus, the larger diffuse fraction during the monsoon season in Kamphaeng Phet is a manifestation of a common characteristic of solar radiation regimes in tropical Thailand.

The statistical comparison presented in Table 4 shows that the percentage differences among the diffuse fraction models were generally small, ranging from 4.18% to 5.15% relative to the Reindl model. The Orgill–Hollands and Erbs formulations produced slightly lower DHI estimates, as reflected by the negative MBE values. RMSE values below 30 W m^{-2} indicate reasonable agreement among the models despite differences in their mathematical formulations. These results suggest that model-related uncertainty is relatively modest under average atmospheric conditions, although larger deviations may occur under rapidly changing sky conditions characteristic of tropical monsoon climates.

In contrast, the non-monsoon season is characterized by lower diffuse fraction values (0.39-0.42) and significantly higher DNI values, indicating a shift toward direct-dominated radiation under clearer atmospheric conditions. This seasonal transition is consistent with observations from other tropical regions, where solar radiation is strongly modulated by monsoon dynamics (Okogbue et al., 2009; Hakemzadeh et al., 2020).

Although all models capture this seasonal contrast, differences in magnitude remain evident. The Reindl model tends to produce slightly higher diffuse radiation values under non-monsoon conditions, while the Orgill–Hollands model yields higher DNI values. These variations reflect differences in model sensitivity to atmospheric transparency and solar geometry. The effect of solar geometry is especially important in the non-monsoon season when cloud cover is lower and direct solar radiation is a larger fraction of the total irradiance. Under such conditions, models that include the position of the sun may be better at accounting for changes in the atmospheric scattering pathways, resulting in a somewhat different partitioning between the diffuse and direct components of radiation.

The results demonstrate that seasonal atmospheric forcing plays a dominant role in solar radiation partitioning, whereas model selection primarily affects the quantitative magnitude of the estimated components. This finding underscores the importance of considering both climatic conditions and model characteristics when analyzing solar radiation in tropical regions.

3.4 Model-to-model differences as a function of clearness index

The relationship between model deviations and clearness index (k_t) is shown in Figure 3, providing insight into model behavior under different sky conditions.

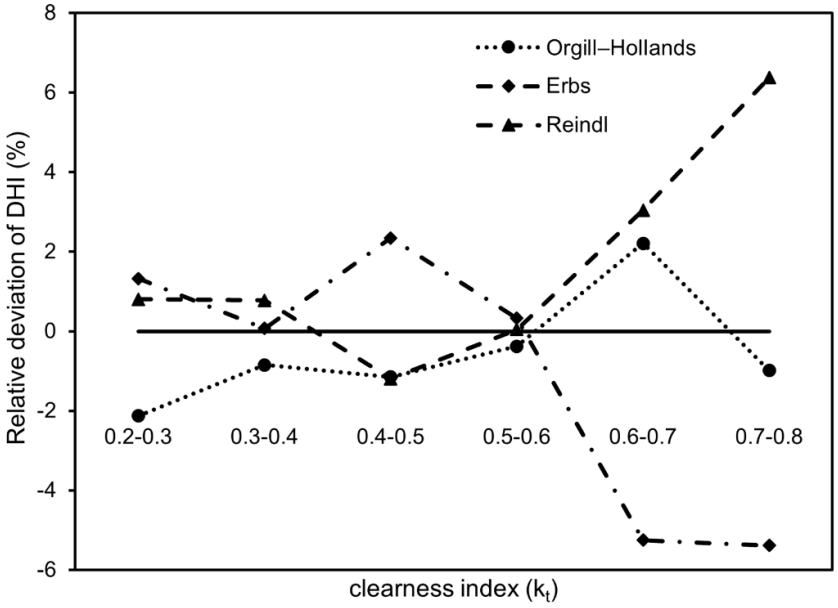


Figure 3. Relative deviations of estimated DHI among diffuse fraction models as a function of clearness index (k_t)

The results reveal that model agreement is strongly dependent on atmospheric conditions, particularly on the combined influence of clearness index and solar geometry, which has been widely reported in previous studies (Posadillo & López Luque, 2009; Liu et al., 2020). Under low k_t values (0.2-0.4), corresponding to overcast conditions, the Orgill–Hollands model tends to underestimate diffuse radiation relative to the ensemble mean, while the Erbs and Reindl models show slightly positive deviations. This behavior reflects differences in how each model represents diffuse radiation under highly scattering conditions (Boland et al., 2008; Salhi et al., 2020).

In the intermediate k_t range (0.4-0.6), representing partly cloudy conditions, model deviations converge toward zero. This indicates strong agreement among models and suggests that diffuse fraction formulations are most reliable when both direct and diffuse components contribute significantly to global radiation. Similar findings have been reported in studies highlighting improved model performance under moderate atmospheric conditions (Dervishi & Mahdavi, 2012; Yin et al., 2023).

At higher k_t values (0.6-0.8), corresponding to clear-sky conditions, model behavior diverges again. The Reindl model exhibits positive deviations, indicating higher diffuse estimates, while the Erbs model shows negative deviations. This divergence reflects differences in model structure and sensitivity to atmospheric transmissivity (Erbs et al., 1982; Reindl et al., 1990).

A possible explanation for this behavior is that the Reindl model accounts for solar geometry explicitly through the solar zenith angle, allowing the diffuse fraction to respond to atmospheric transparency changes as well as to changes in the position of the sun. Under clear sky conditions, when the contribution of atmospheric scattering depends on small variations in solar elevation, direct beam radiation is dominant. Consequently, the Reindl model retains slightly more diffuse radiation than the models based only on the clearness index. In contrast, the Erbs and Orgill–Hollands formulations rely primarily on empirical relationships with clearness index and therefore may respond less effectively to variations in solar geometry. Such differences are particularly significant under tropical monsoon conditions, where rapid transitions from clear to cloudy sky can affect the relative contributions of the direct and diffuse components of radiation.

These results confirm that model uncertainty is strongly dependent on sky conditions, with the largest discrepancies occurring under extreme atmospheric regimes. The observed differences among diffuse fraction models may also have practical implications for solar energy applications. Differences in estimated DHI and DNI may influence calculations of solar resource availability, PV system performance, and solar energy yield assessment. In tropical monsoon climates, cloud cover changes rapidly and diffuse radiation can be a significant part of total irradiance. Therefore, differences in model formulation may contribute to variations in predicted energy production. Accordingly, the choice of a diffuse fraction model is an important aspect for the characterization of the solar radiation and the reliability of PV system design, performance assessment and long term energy forecasting.

The estimated hourly DHI values were used to calculate the statistical indicators such as RMSE, MBE and mean difference for a more quantitative comparison of the selected diffuse fraction models. Since no measured DHI observations were available, the analysis focused on the agreement between models rather than on direct validation with observations. As a reference, the Reindl model (including the effects of clearness index and solar geometry) was used. Therefore, the reported RMSE and MBE values should be

interpreted as indicators of inter-model agreement and consistency rather than measures of predictive accuracy. The statistical comparison results are summarized in Table 4.

Table 4. Inter-model statistical comparison among diffuse fraction models based on estimated hourly DHI values. The reported RMSE, MBE, and Mean Difference values represent inter-model agreement and consistency rather than validation against measured DHI observations.

Comparison	RMSE ($W m^{-2}$)	MBE ($W m^{-2}$)	Mean Difference (%)
Orgill–Hollands vs Reindl	27.05	-2.88	-4.18
Erbs vs Reindl	28.99	-4.44	-5.15

As shown in Table 4, the statistical comparison indicates moderate differences among the selected diffuse fraction models. Both the Orgill–Hollands and Erbs models produced slightly lower DHI estimates than the Reindl model, as reflected by the negative MBE values. The relatively small RMSE values suggest reasonable agreement among the models under tropical monsoon conditions, although discrepancies become more evident during intermediate sky conditions associated with variable cloud cover and atmospheric scattering effects.

3.5 Implications for solar radiation modeling in tropical regions

The combined results from annual, diurnal, seasonal, and clearness-index analyses underscore the importance of diffuse fraction model selection in study area. Although all models provide reasonable estimates, their differences can lead to variations in DHI and DNI that may affect solar energy applications.

In local conditions with high atmospheric variability, models that include additional physical parameters, such as solar geometry, may better represent diffuse radiation variations as atmospheric conditions change. A similar pattern has also been reported in Thailand. Phaisathit et al. (2025) demonstrated that diffuse fraction estimation could be enhanced by incorporating more atmospheric information into the model definition. Atmospheric variables were not considered in the present study, but the relatively lower inter-model variability of the Reindl model indicates that the inclusion of additional physical information, such as the solar geometry, may improve the representation of diffuse radiation under tropical atmospheric conditions. This observation aligns with previous studies demonstrating improved performance of multi-parameter models compared to single-variable approaches (Ruiz-Arias et al., 2010; Kuo et al., 2014).

Although direct validation with measured DHI and DNI data was not available, the present intercomparison suggests that the Reindl model provides a physically consistent representation of diffuse radiation partitioning under tropical monsoon conditions in Kamphaeng Phet. This conclusion is supported by its relatively lower inter-model variability, physically consistent seasonal behavior, and explicit incorporation of solar geometry through the solar zenith angle. The Reindl model considers atmospheric transparency and solar position and provides a more physically representative description of the diffuse radiation variability than the formulations based on the clearness index alone. Nevertheless, this interpretation should be regarded as an assessment of model suitability and consistency rather than definitive evidence of superior predictive accuracy.

However, empirical models based solely on clearness index remain valuable due to their simplicity and ease of implementation, particularly in regions where only GHI data are available (Mirzabade et al., 2021; Krieger et al., 2024). The trade-off between model complexity and practical applicability should therefore be carefully considered in solar energy studies.

The ensemble mean approach adopted in this study provides a robust representation of diffuse radiation behavior by reducing model-specific biases. This approach is particularly useful in tropical regions where direct measurements of diffuse radiation are limited, and model uncertainty is significant. It is worth mentioning that the present study is based on an inter-comparison of diffuse fraction models, not on a direct validation using observed diffuse horizontal irradiance (DHI) or direct normal irradiance (DNI) data. Only global horizontal irradiance (GHI) measurements were available at the study site, and therefore the estimated DHI and DNI values were fully based on empirical model formulations. Therefore, the results mainly reflect the model-to-model variability for tropical monsoon conditions, and not the absolute model performance. Although this approach is commonly adopted in data-limited regions, the absence of ground-truth DHI and DNI observations makes it difficult to assess the actual predictive performance of each model. Therefore, the results of this study should be interpreted as a comparison of the model behavior and sensitivity in different atmospheric conditions, rather than as a definitive validation of model superiority.

Overall, the findings emphasize that both atmospheric conditions and model formulation must be considered when selecting diffuse fraction models for solar radiation partitioning. The results provide valuable guidance for improving the accuracy of solar resource assessment and energy system analysis in tropical monsoon regions.

4. Conclusions

This study presented a comprehensive intercomparison of three widely used diffuse fraction models—Orgill and Hollands, Erbs et al., and Reindl et al.—for estimating solar radiation components under tropical monsoon conditions in Kamphaeng Phet, Thailand. Using one year of quality-controlled ground-based global horizontal irradiance (GHI) data, the study evaluated model performance across annual, diurnal, and seasonal scales, as well as under varying atmospheric conditions characterized by the clearness index.

The results demonstrate that all three models are capable of representing the general behavior of solar radiation partitioning under tropical conditions. The estimated diffuse horizontal irradiance (DHI) exhibits consistent patterns across models, indicating that the clearness index remains a reliable predictor of diffuse radiation. However, differences in model formulation led to variations in magnitude, particularly in intermediate atmospheric conditions. These differences become more pronounced in the estimation of direct normal irradiance (DNI), where small discrepancies in diffuse fraction propagate into larger deviations in direct radiation.

The diurnal analysis reveals that all models capture the expected daily pattern of diffuse radiation, with maximum values occurring near solar noon. Nevertheless, variations among models are evident, especially during periods of high solar elevation, where the inclusion of solar geometry in the Reindl model leads to comparatively lower diffuse estimates. This suggests that models incorporating additional physical parameters may better represent atmospheric processes under certain conditions.

Seasonal analysis further highlights the strong influence of monsoon dynamics on solar radiation components. During the monsoon period, increased cloud cover and

atmospheric moisture result in higher diffuse radiation and reduced direct radiation. In contrast, the non-monsoon period is characterized by clearer sky conditions, leading to higher direct irradiance. Although all models reflect this seasonal trend, differences in magnitude indicate that model selection can affect the interpretation of seasonal solar energy potential.

The relationship between diffuse fraction and clearness index confirms the well-established inverse correlation between atmospheric transparency and diffuse radiation. However, the transition region between cloudy and clear-sky conditions remains a critical source of model uncertainty. The intercomparison results show that model deviations are largest in this intermediate range, where atmospheric variability is most pronounced. This finding underscores the importance of careful model selection when analyzing solar radiation under partially cloudy conditions.

From a practical perspective, the results suggest that the choice of diffuse fraction model can influence solar energy assessments, particularly in tropical regions characterized by high atmospheric variability. While simpler models based solely on clearness index offer ease of implementation, models that incorporate solar geometry exhibit different responses to varying sky conditions compared with models based solely on clearness index. However, because no measured DHI or DNI observations were available for validation, the present study cannot definitively determine which model provides the highest predictive accuracy. Nevertheless, the Reindl model exhibited physically consistent behavior among the evaluated formulations and may serve as a useful reference model for diffuse radiation partitioning under the tropical monsoon conditions examined in this study.

Overall, this study highlights the need for region-specific evaluation of diffuse fraction models, particularly in tropical monsoon climates. The findings provide useful guidance for selecting appropriate models for solar radiation partitioning when only GHI data are available. Future work may focus on incorporating additional atmospheric parameters or advanced modeling approaches to further improve estimation accuracy under complex sky conditions. One limitation of this study is that the intercomparison was based on model-derived estimates of DHI and DNI without direct observational validation. Therefore, the results should be interpreted as differences in model behavior rather than evidence of predictive accuracy. Another limitation is that the analysis is based on one year observations (2025). The data set covers a full year cycle with monsoon and non-monsoon seasons, but the diffuse and direct radiation characteristics are likely to be affected by year-to-year changes in cloud cover and atmospheric conditions. The results are therefore representative of the time period investigated, not of long term climatological conditions. Future studies with measured DHI and DNI observations and multi-year data sets would be useful to better understand the behavior of diffuse radiation as well as the applicability of models under tropical monsoon climate.

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6. Authors' Contributions

Supawat Wisitsirikun: Conceptualization, methodology, data curation, formal analysis, investigation, writing original draft preparation, and writing—review and editing.

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7. Conflicts of Interest

The author declares no conflict of interest.

8. AI Declaration

AI-assisted tools (e.g., ChatGPT) were used during the preparation of this manuscript to support language refinement and improve clarity of expression. All scientific content, analysis, and interpretations were developed and verified by the author. The author takes full responsibility for the accuracy and integrity of the work.

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