

Assessment of Global Horizontal Irradiance Data Quality and Calibration Uncertainty in a Tropical Monsoon Region: A Case Study in Kamphaeng Phet, Thailand

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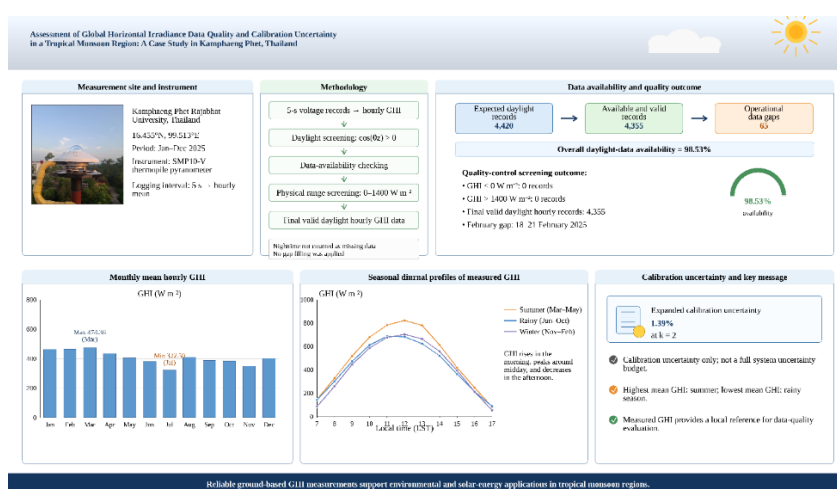
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GRAPHIC ABSTRACT



ABSTRACT

Ground-based solar radiation data are useful for environmental studies and solar-energy assessment, especially in tropical monsoon regions where sky conditions change throughout the year. This study investigated the quality and variability of hourly global horizontal irradiance (GHI) measured at Kamphaeng Phet Rajabhat University, Thailand, from January to December 2025. GHI was measured using an SMP10-V thermopile pyranometer. The instrument recorded data every 5 s, and the data were later averaged into hourly values. The dataset was checked by separating daylight hours, assessing data availability, and applying preliminary physical range screening. Nighttime periods were not treated as missing data, and no gap filling was performed. During the study period, 4,420 daylight hourly records were expected. Of these, 4,355 records were available and passed the physical range screening, giving an overall daylight-data availability of 98.53%. The record-weighted annual mean hourly GHI was 404.63 W/m². Monthly mean GHI ranged from 322.50 W/m² in July to 474.36 W/m² in March. The seasonal results showed that mean GHI was highest in summer and lowest in the rainy season. The rainy season also showed the highest relative variability because atmospheric conditions were more variable during this period. The pyranometer calibration certificate reported an expanded calibration uncertainty of 1.39% at k=2. These results provide a local reference for measured GHI characteristics and data-quality evaluation in a tropical monsoon environment.

HIGHLIGHTS

- Ground-based hourly GHI data were assessed under a tropical monsoon climate
- Daylight-data availability reached 98.53% after preliminary quality screening
- Monthly mean GHI ranged from 322.50 to 474.36 W/m² during 2025
- Seasonal variability was strongest during the rainy season
- Calibration uncertainty was reported as 1.39% at k=2

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1. INTRODUCTION

Reliable solar radiation data are important for environmental studies and solar-energy applications. They are used in solar resource assessment, photovoltaic system planning, climate-related analyses, and the validation of satellite-based or model-derived irradiance products. Among solar radiation variables, global horizontal irradiance (GHI) is widely used because it represents the total shortwave solar radiation received on a horizontal surface. However, surface GHI changes throughout the day and year due to solar geometry, atmospheric attenuation, cloud cover, aerosols, and seasonal conditions (Garg and Datta, 1993; Reynolds et al., 1975). Therefore, measured GHI data must be carefully checked before they are used in scientific or engineering applications.

Ground-based measurements remain an important source of local solar radiation information. They provide direct observations at a specific site and are often used as reference data for evaluating satellite products, reanalysis datasets, and solar radiation models (Sengupta et al., 2018; Sander et al., 2026). However, the quality of ground-based solar radiation data can be affected by instrumental and environmental factors, including calibration, sensor response, leveling, dome cleanliness, shading, logger performance, timing problems, missing records, and local atmospheric variability. For this reason, solar radiation measurements should include post-measurement validation and quality-control procedures (Hay, 1993). Physical limits, consistency checks, and data-availability assessment are commonly used to identify unrealistic or unreliable observations (Younes et al., 2005; Long and Shi, 2008; Daniel-Durandt and Rix, 2023). Missing or flagged records can also affect the calculation of monthly radiation statistics, especially when gaps occur within a short period (Roesch et al., 2011).

Quality assurance is also needed when interpreting measured irradiance data. A reliable dataset depends not only on data screening, but also on instrument selection, calibration, maintenance, and station setup (Silva et al., 2019). From an uncertainty perspective, measurement errors can affect solar-energy analysis and model evaluation (Myers et al., 1989; Myers, 2005). Calibration uncertainty provides traceability for the instrument under calibration conditions, but it should not be interpreted as the total uncertainty of a complete field measurement system. Other factors, such as logger accuracy, installation

conditions, cosine response, temperature response, and maintenance practices, may also contribute to field measurement uncertainty.

Solar radiation assessment is more challenging in tropical monsoon regions because atmospheric conditions can change significantly throughout the year. Cloud cover, humidity, aerosols, rainfall patterns, and wet-dry seasonal shifts affect the amount of solar radiation reaching the ground. In Thailand, early work showed that solar radiation is influenced by the monsoon climate, with higher values generally found during drier periods and lower values during cloudy or rainy periods (Exell, 1976). Later studies developed empirical and atmospheric-parameter-based approaches for estimating solar radiation in Thailand and showed that model performance depends on local climatic conditions and proper calibration (Waewsak and Chancham, 2010; Khakhu et al., 2022; Wattan et al., 2023). Recent studies have also reported strong solar radiation variability under tropical conditions in Thailand (Chawphonphang et al., 2022; Phaisathit et al., 2025). These findings highlight the need for local ground-based measurements and transparent data-quality assessment.

Although solar radiation has been studied in Thailand, site-specific ground-based GHI datasets are still important for inland areas where local climate, cloud conditions, and surrounding environments may differ from those of the major urban, coastal, or long-established monitoring stations. Kamphaeng Phet is located in northern Thailand and has a tropical monsoon climate with distinct seasonal changes. Local GHI measurements from this area can support solar resource assessment, environmental analysis, and future comparison with satellite-based or modelled radiation products. At the same time, the reliability of the dataset must be clearly described through measurement-system information, data-availability assessment, quality screening, and uncertainty reporting.

Therefore, this study aims to assess the data quality and calibration uncertainty of hourly GHI measured at Kamphaeng Phet Rajabhat University, Thailand, during January-December 2025. The study uses ground-based observations from an SMP10-V thermopile pyranometer and applies daylight identification, data-availability checking, and preliminary physical range screening. The specific objectives are to: (1) describe the measurement system and calibration information; (2) quantify daylight-data availability, operational data gaps, and preliminary

quality-control outcomes; (3) analyze monthly, seasonal, and diurnal characteristics of measured hourly GHI; and (4) discuss the scope of the reported calibration uncertainty and the main limitations of the dataset. The results provide a local reference for measured GHI characteristics and data-quality assessment in the tropical monsoon environment.

2. METHODOLOGY

2.1 Study area and measurement system

Measurements were carried out at Kamphaeng Phet Rajabhat University, Kamphaeng Phet, Thailand (16.455°N, 99.513°E; approximately 80 m above sea level), an inland area with a tropical monsoon climate. Global horizontal irradiance (GHI) was measured on a horizontal platform with an open sky view using an SMP10-V thermopile pyranometer (OTT HydroMet/Kipp and Zonen, serial number 242042). The instrument was classified as ISO 9060 Class A* and was calibrated on 03 July 2024 according to ISO 9847:2023, Clause 6, Type A1. A sensitivity of 11.34

$\mu\text{V (W/m}^2\text{)}^{-1}$ and an expanded calibration uncertainty of 1.39% at $k=2$ were reported in the calibration certificate. Instrument calibration and documentation are essential elements of quality assurance for solar radiation measurements (Myers, 2005; Silva et al., 2019).

The pyranometer was connected to a HIOKI LR8431-20 Memory HiLogger using the original manufacturer-supplied cable, which was not extended. The analog voltage output was recorded every 5 s. The SMP10-V was operated using its factory output range, where 0 V represents -200 W/m^2 and 1 V represents $2,000 \text{ W/m}^2$. GHI was calculated as:

$$\text{GHI} = 2,200 \times V - 200 \quad (1)$$

Where; GHI is expressed in W/m^2 and V is the recorded voltage in volts. The 5-s measurements were averaged to hourly values for analysis. The measurement period covered January-December 2025. Key system details are summarized in Table 1.

Table 1. Measurement system and data acquisition details

Item	Description
Measurement variable	Global horizontal irradiance (GHI)
Site	Kamphaeng Phet Rajabhat University, Thailand; 16.455°N, 99.513°E; approximately 80 m a.s.l.
Pyranometer	SMP10-V thermopile pyranometer; OTT HydroMet / Kipp and Zonen; serial number 242042; ISO 9060 Class A*
Installation and calibration	Installed on 26 December 2024; calibrated on 03 July 2024 according to ISO 9847:2023, Clause 6, Type A1
Calibration information	Sensitivity=11.34 $\mu\text{V (W/m}^2\text{)}^{-1}$; expanded calibration uncertainty=1.39% at $k=2$
Data acquisition	HIOKI LR8431-20 Memory HiLogger; analog voltage output; 5-s sampling; hourly mean aggregation
Factory output range	0 V = -200 W/m^2 ; 1 V = $2,000 \text{ W/m}^2$
Signal cable	Original manufacturer-supplied cable; less than approximately 15 m; no extension
Measurement period	January-December 2025

2.2 Data processing and daylight-data availability

The 5-s voltage records were converted to GHI using Equation (1), grouped by hour, and averaged to obtain hourly mean GHI. No missing values were estimated or filled, because missing and flagged records can affect derived monthly radiation statistics (Roesch et al., 2011). Daylight hours were identified using solar geometry, as described in Section 2.3. An hourly interval was treated as daylight when the solar elevation angle was greater than 0° at the midpoint of the interval. Only daylight records were used for data-availability calculations, quality-control statistics, and subsequent analysis. Nighttime periods were not

counted as missing data. For each month, N_{expected} was obtained from the number of expected daylight intervals, while $N_{\text{available}}$ was obtained from the hourly GHI dataset. Daylight-data availability and operational data gaps were calculated as:

$$\text{Data availability (\%)} = \frac{N_{\text{available}}}{N_{\text{expected}}} \times 100 \quad (2)$$

$$\text{Operational data gap (\%)} = \frac{N_{\text{expected}} - N_{\text{available}}}{N_{\text{expected}}} \times 100 \quad (3)$$

Available daylight records were screened using the physical range criterion of $0 \leq \text{GHI} \leq 1,400 \text{ W/m}^2$. Records outside this range were classified as invalid

daylight records, while records within the range were retained as final valid records.

2.3 Solar geometry and theoretical constraints

Solar geometry was used to identify daylight periods and to provide a theoretical reference for interpreting measured GHI. The solar zenith angle, θ_z , was calculated at the midpoint of each hourly interval from the site latitude, solar declination, and solar hour angle, following standard solar-geometry relationships (Garg and Datta, 1993):

$$\cos(\theta_z) = \sin(\phi) \sin(\delta) + \cos(\phi) \cos(\delta) \cos(\omega) \quad (4)$$

Where; ϕ is the site latitude, δ is the solar declination, and ω is the solar hour angle. Intervals for which $\cos(\theta_z) > 0$ were classified as daytime, whereas intervals with $\cos(\theta_z) \leq 0$ were classified as nighttime. The extraterrestrial horizontal irradiance, G_o , was calculated as a theoretical reference:

$$G_o = I_{sc} E_o \cos(\theta_z) \quad (5)$$

Where; G_o is the extraterrestrial horizontal irradiance, I_{sc} is the solar constant ($1,361 \text{ W/m}^2$) and E_o is the Earth-Sun distance correction factor. The correction factor was calculated from the day number, n , as:

$$E_o = 1 + 0.033 \cos\left(\frac{360n}{365}\right) \quad (6)$$

The value of G_o was used only as a theoretical reference (Garg and Datta, 1993). It was not used as an automatic rejection threshold, and solar-geometry calculations were not used to fill missing records or adjust measured GHI values.

2.4 Quality control and data classification

A rule-based quality-control framework was applied after voltage conversion and hourly aggregation. The procedure included daylight screening, data-availability checking, and physical range screening. Rule-based screening using physical limits and consistency checks is commonly used to improve the reliability of solar-radiation datasets (Hay, 1993; Younes et al., 2005; Long and Shi, 2008).

Each hourly interval was assigned to one of four categories. Hours with $\cos(\theta_z) \leq 0$ were classified as nighttime periods. Expected daylight hours without recorded GHI were classified as operational data gaps. Available daylight records below 0 W/m^2 or above

$1,400 \text{ W/m}^2$ were classified as invalid daylight records. Records within this range were retained as valid records. Similar reporting of missing or unreliable records is commonly used in irradiance data-quality assessment (Daniel-Durand and Rix, 2023; Sander et al., 2026). Monthly classification results are summarized in Table 3 and Figure 2.

The present QC procedure did not apply clear-sky correction, temporal smoothing, temporal-consistency testing, or adjustment of individual observations. More comprehensive QC frameworks may include these procedures, but they were outside the scope of this study (Ameen et al., 2018; Pashiardis and Kalogirou, 2016; Perez-Astudillo et al., 2018).

2.5 Statistical evaluation metrics

The statistical analysis was based on the final valid hourly GHI records. For seasonal analysis, summer was defined as March-May, the rainy season as June-October, and winter as November-February. For the seasonal diurnal profile, final valid hourly GHI records were grouped by local clock hour within each season, and the mean GHI was calculated for each hour. The common hourly interval from 07:00 to 17:00 local time was used to compare seasons.

Monthly and seasonal GHI characteristics were evaluated using the number of valid records, mean, standard deviation, minimum, maximum, and coefficient of variation. The mean GHI was calculated as:

$$\text{Mean GHI} = \frac{\sum \text{GHI}_i}{N} \quad (7)$$

Where; GHI_i is the GHI value for each valid hourly record and N is the number of valid records. The standard deviation was calculated as:

$$\text{SD} = \sqrt{\frac{\sum (\text{GHI}_i - \text{GHI}_{\text{mean}})^2}{N-1}} \quad (8)$$

The coefficient of variation was used to compare relative variability among months and seasons (Sander et al., 2026):

$$\text{CV}(\%) = \frac{\text{SD}}{\text{Mean GHI}} \times 100 \quad (9)$$

Monthly data availability and operational data gaps were evaluated using Equations (2) and (3). All statistical calculations used valid daylight records only, and no missing values were replaced before analysis.

3. RESULTS AND DISCUSSION

3.1 Monthly characteristics of global horizontal irradiance

The monthly descriptive statistics of the final valid daylight hourly global horizontal irradiance (GHI) records are presented in Table 2. A total of 4,355 valid hourly records were used. The record-weighted annual mean hourly GHI was 404.63 W/m², with a standard deviation of 289.37 W/m² and a coefficient of variation of 71.51%. These values represent valid daylight-hour means only and should not be interpreted as 24-h mean irradiance or daily solar irradiation.

Monthly mean GHI ranged from 322.50 W/m² in July to 474.36 W/m² in March. January through March had the highest monthly mean values, while July had the lowest mean (Figure 1). Mean GHI decreased from April to July, with a 32.0% reduction from March to July, before increasing again in August. This pattern suggests that monthly GHI was influenced by both solar geometry and month-to-month atmospheric variability, consistent with previous findings for Thailand and other tropical monsoon environments (Garg and Datta, 1993; Exell, 1976; Chawphongphang et al., 2022; Wattan et al., 2023).

Table 2. Monthly statistics of final valid daylight hourly GHI

Month	n	Mean GHI (W/m ²)	SD (W/m ²)	Minimum (W/m ²)	Maximum (W/m ²)	CV (%)
Jan	329	463.96	257.66	36.67	829.59	55.53
Feb	264	465.01	284.45	13.49	923.78	61.17
Mar	360	474.36	300.35	1.76	944.50	63.32
Apr	387	435.78	332.88	0.20	1,025.26	76.39
May	401	405.17	315.48	0.20	1,058.14	77.86
Jun	389	380.70	277.04	5.69	1,017.83	72.77
Jul	402	322.50	257.04	0.20	1,016.34	79.70
Aug	402	410.58	309.94	1.42	1,044.72	75.49
Sep	362	389.06	289.39	1.03	1,110.76	74.38
Oct	372	384.45	281.41	0.20	1,004.41	73.20
Nov	346	349.54	252.40	2.84	895.50	72.21
Dec	341	402.58	252.57	7.97	824.40	62.74
Overall	4,355	404.63	289.37	0.20	1,110.76	71.51

Note: Overall statistics were calculated from pooled final valid daylight hourly records.

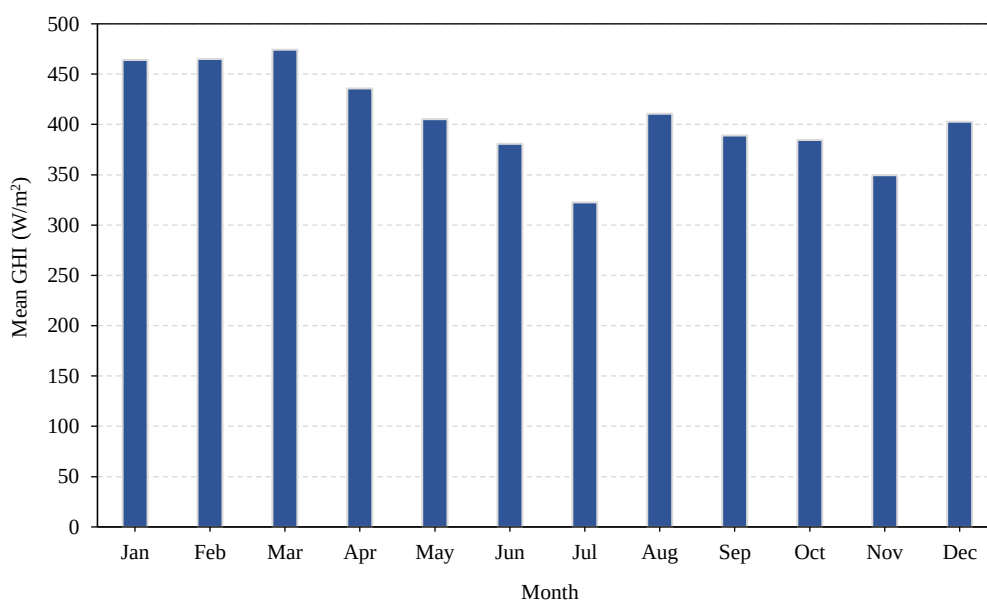


Figure 1. Monthly mean hourly GHI from final valid daylight records

3.2 Data availability and preliminary quality-control outcomes

The monthly availability of daylight data and preliminary quality-control results are shown in Table 3. Based on the solar-geometry criterion, 4,420 daylight hourly records were expected during the study period. Of these, 4,355 records were available, giving an overall daylight-data availability of 98.53%. The remaining 65 records (1.47%), were classified as operational data gaps.

Monthly availability ranged from 85.71% in February to 100.00% in March, October, November,

and December. The lowest availability occurred in February because 44 expected daylight records were unavailable during the interruption between 18 and 21 February 2025 (Figure 2). Since no gap filling was applied, the February statistics were calculated only from available valid daylight records and should be interpreted with this reduced temporal coverage in mind (Roesch et al., 2011). The exact cause of the interruption could not be confirmed from the hourly dataset; therefore, it was reported as an operational data gap rather than a specific sensor, cable, communication, or logger failure.

Table 3. Monthly daylight-data availability and preliminary QC outcomes

Month	Expected	Available	Gaps	Availability (%)	Gap (%)	GHI < 0	GHI > 1400	Final valid
Jan	341	329	12	96.48	3.52	0	0	329
Feb	308	264	44	85.71	14.29	0	0	264
Mar	360	360	0	100.00	0.00	0	0	360
Apr	390	387	3	99.23	0.77	0	0	387
May	403	401	2	99.50	0.50	0	0	401
Jun	390	389	1	99.74	0.26	0	0	389
Jul	403	402	1	99.75	0.25	0	0	402
Aug	403	402	1	99.75	0.25	0	0	402
Sep	363	362	1	99.72	0.28	0	0	362
Oct	372	372	0	100.00	0.00	0	0	372
Nov	346	346	0	100.00	0.00	0	0	346
Dec	341	341	0	100.00	0.00	0	0	341
Overall	4,420	4,355	65	98.53	1.47	0	0	4,355

Note: Expected daylight records were defined as hourly intervals with $\cos(\theta_z) > 0$. Operational data gaps refer to unavailable records within expected daylight periods. No gap filling was applied. The physical range criterion was $0 \leq \text{GHI} \leq 1,400 \text{ W/m}^2$.

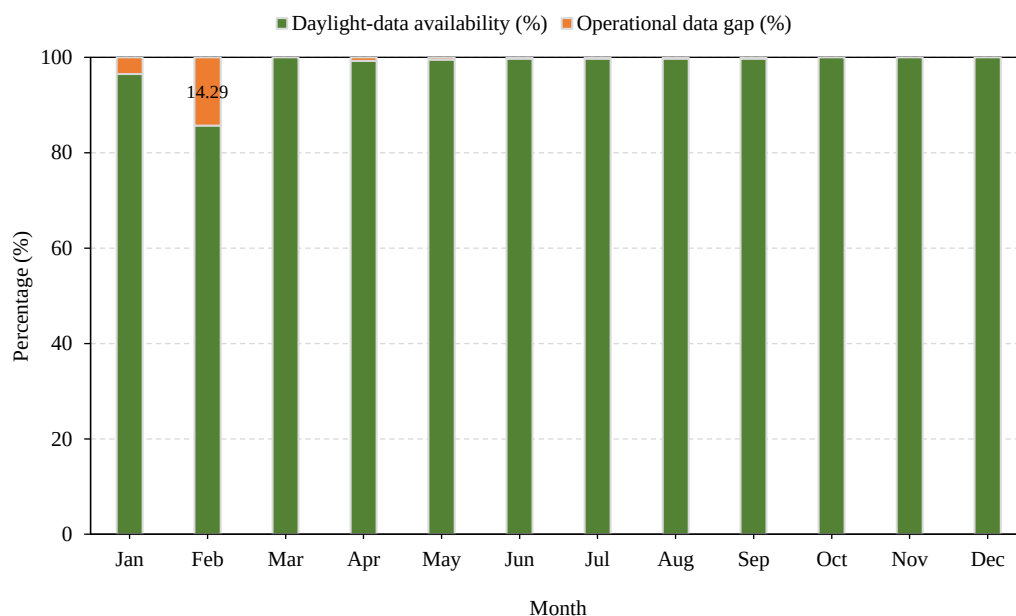


Figure 2. Monthly daylight-data availability and operational gaps

All available daylight records passed the preliminary physical range screening. No record was below 0 W/m² or above 1,400 W/m²; therefore, all 4,355 available daylight records were retained for subsequent analysis. Nighttime periods were excluded from the availability calculation and were therefore not treated as missing data. The use of daylight identification and physically plausible range limits is consistent with established approaches for solar-radiation data validation (Hay, 1993; Long and Shi, 2008; Ameen et al., 2018).

3.3 Monthly and seasonal variability of hourly GHI

The monthly coefficient of variation (CV) of the final valid daylight hourly GHI records is displayed in

Figure 3. The monthly CV ranged from 55.53% in January to 79.70% in July. January showed relatively lower variability, while higher CV values from April to October indicated a wider spread of hourly GHI relative to the monthly mean. July had both the lowest monthly mean GHI and the highest CV, indicating strong relative variability during that month.

Seasonal statistics are presented in Table 4. Summer had the highest mean hourly GHI, at 437.19 W/m², while the rainy season had the lowest mean, at 377.09 W/m². The rainy-season mean was approximately 13.8% lower than the summer mean. The rainy season also had the highest CV, at 75.51%, whereas winter had the lowest CV, at 63.52%.

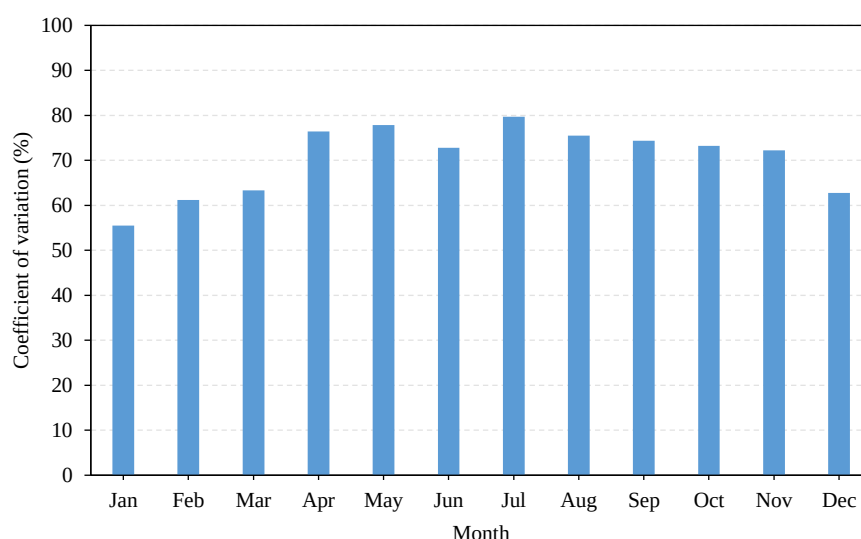


Figure 3. Monthly coefficient of variation of final valid daylight hourly GHI

Table 4. Seasonal statistics of final valid daylight hourly GHI

Season	Months	n	Mean GHI (W/m ²)	SD (W/m ²)	CV (%)
Summer	Mar-May	1,148	437.19	317.85	72.70
Rainy	Jun-Oct	1,927	377.09	284.72	75.51
Winter	Nov-Feb	1,280	416.90	264.83	63.52
Overall	Jan-Dec	4,355	404.63	289.37	71.51

Note: Seasonal statistics were calculated from pooled final valid daylight hourly records.

The lower mean GHI and higher relative variability during the rainy season were consistent with more variable atmospheric attenuation, likely including changes in cloud cover. Short periods of clearer sky could still produce high irradiance within the same day, leading to a wider spread of hourly GHI values. In contrast, the lower CV in winter suggests

more stable hourly radiation conditions. Since all valid daylight hours were included, the CV values reflect both diurnal changes in solar elevation and short-term atmospheric variability. These results indicate that seasonal GHI differences were influenced by solar geometry and varying atmospheric conditions (Garg and Datta, 1993; Exell, 1976; Chawphongphang et al., 2022; Wattan et al., 2023).

3.4 Seasonal diurnal profiles of measured GHI

The seasonal diurnal profiles of the hourly GHI measured between 07:00 and 17:00 local time are displayed in Figure 4. Each point represents the mean measured GHI at the same local hour within each season; therefore, the profiles represent seasonal mean diurnal patterns rather than annual averages or individual daily observations.

GHI increased from morning to around midday in all seasons and then decreased during the afternoon. The summer profile had the highest midday value, reaching 821.50 W/m² at 12:00 local time. Winter also

peaked at 12:00, with a mean GHI of 703.63 W/m². In the rainy season, the highest mean value was 686.83 W/m² at 11:00, and the profile showed a flatter peak between 11:00 and 13:00. The summer profile was generally higher from late morning to early afternoon, while the winter profile showed lower early-morning and late-afternoon values due to seasonal changes in solar elevation and day length (Garg and Datta, 1993; Exell, 1976). Because only measured GHI records were used, Figure 4 provides a direct description of seasonal diurnal surface irradiance at the study site.

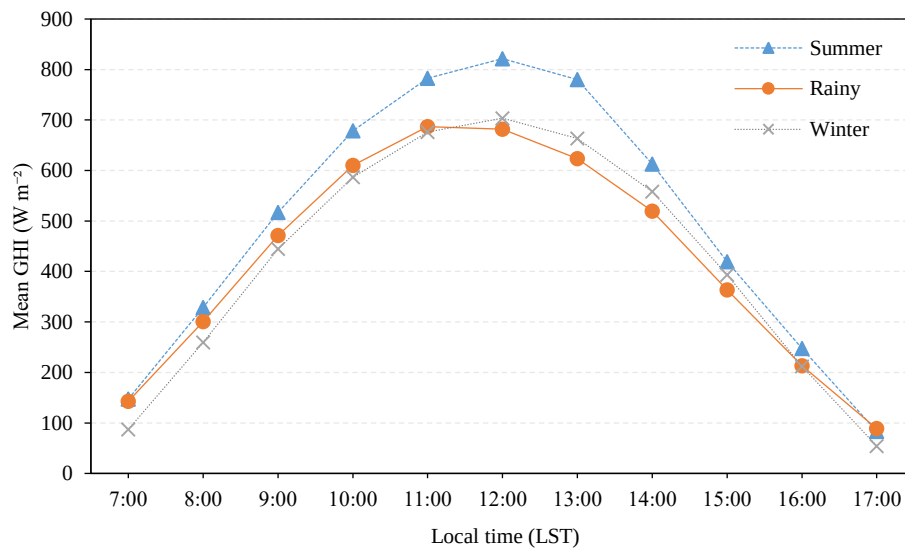


Figure 4. Seasonal diurnal profiles of measured hourly GHI

3.5 Calibration uncertainty and study limitations

The SMP10-V pyranometer calibration certificate reported an expanded calibration uncertainty of 1.39% at $k=2$. This value provides traceability for the measured GHI values under the stated calibration conditions, but it should not be interpreted as the total uncertainty of the complete

measurement system. Other factors, including logger input accuracy, instrument levelling, dome cleanliness, cosine response, temperature response, and maintenance conditions, may also affect field measurement uncertainty (Myers et al., 1989; Myers, 2005; Silva et al., 2019). Table 5 summarizes the calibration-uncertainty scope and study limitations.

Table 5. Calibration uncertainty and study limitations

Aspect	Status in the present study	Implication
Pyranometer calibration uncertainty	Expanded calibration uncertainty of 1.39% at $k=2$	Provides traceability for the calibrated SMP10-V pyranometer
Combined system uncertainty	Not calculated	The total uncertainty of the complete measurement system was not quantified
Data logger input uncertainty	Not included in the uncertainty calculation	May contribute to field measurement uncertainty
Field operating conditions	Levelling, dome cleanliness, cosine response, temperature response, and maintenance effects were not quantified separately	These factors may affect field measurements
Daylight screening	Applied using the criterion $\cos(\theta_z) > 0$	Nighttime intervals were excluded from daylight-data analysis

Table 5. Calibration uncertainty and study limitations (cont.)

Aspect	Status in the present study	Implication
Physical range screening	Applied using $0 \leq \text{GHI} \leq 1,400 \text{ W/m}^2$	No available daylight record was rejected by this criterion
Clear-sky consistency test	Not applied	Subtle anomalies relative to expected clear-sky conditions were not evaluated
Temporal-consistency test	Not applied	Short-duration irregularities were not assessed separately
Missing-data treatment	No gap filling was applied	Statistics were calculated from available final valid records only
Temporal coverage	January–December 2025	Interannual variability was not assessed
Spatial coverage	One measurement site in Kamphaeng Phet	Results represent local conditions and may not apply directly to other locations

Note: The 1.39% value is the pyranometer calibration uncertainty, not the combined system uncertainty.

The main limitations were the one-year observation period, the single measurement site, the absence of a full combined uncertainty budget, and the use of preliminary QC screening only. The results describe local conditions in Kamphaeng Phet and may not directly represent areas with different terrain, aerosol conditions, cloud regimes, or surrounding obstructions (Garniwa et al., 2024; Sander et al., 2026). Clear-sky and temporal-consistency tests were not applied, although they are commonly used in more comprehensive QC frameworks (Ameen et al., 2018; Long and Shi, 2008; Perez-Astudillo et al., 2018; Pashiardis and Kalogirou, 2016). No gap filling was applied, so missing records, especially during 18-21 February 2025, remained operational data gaps.

4. CONCLUSION

This study assessed the data quality and calibration uncertainty of hourly GHI measured at Kamphaeng Phet Rajabhat University, Thailand, during 2025. After daylight screening, data-availability checking, and preliminary physical range screening, 4,355 final valid daylight hourly records were retained for analysis. The record-weighted annual mean hourly GHI was 404.63 W/m^2 . Monthly mean GHI ranged from 322.50 W/m^2 in July to 474.36 W/m^2 in March. Seasonal analysis showed the highest mean GHI in summer and the lowest in the rainy season, while the rainy season had the highest relative variability.

The data-availability assessment showed that 4,355 of 4,420 expected daylight hourly records were available, giving an overall daylight-data availability of 98.53%. The remaining 65 records, or 1.47%, were classified as operational data gaps, mainly during 18-21 February 2025. No available daylight record was below 0 W/m^2 or above $1,400 \text{ W/m}^2$, and nighttime periods

were not treated as missing data. The pyranometer calibration certificate reported an expanded calibration uncertainty of 1.39% at $k=2$. This value provides traceability for the calibrated instrument but does not represent the total uncertainty of the complete field measurement system. Future work should include longer observations, additional stations, a full uncertainty budget, and comprehensive QC tests.

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AUTHOR CONTRIBUTIONS

Conceptualization, S.W.; Methodology, S.W. and S.P.; Validation, S.P.; Formal Analysis, S.W.; Investigation, S.W.; Resources, S.P.; Data Curation, S.W.; Writing-Original Draft Preparation, S.W.; Writing-Review and Editing, S.W. and S.P.; Visualization, S.W.; Supervision, S.W.

DECLARATION OF CONFLICT OF INTEREST

The authors declare no conflict of interest.

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