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Simplified Models for Obtaining Monthly Average Hourly Global Solar Radiation from Daily Radiation Data at Four Main Regions in Thailand

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บทคัดย่อ

พลังงานแสงอาทิตย์ได้กลายเป็นแหล่งพลังงานทางเลือกที่สำคัญเนื่องจากเป็นพลังงานที่สะอาด ปราศจากการปล่อยมลพิษ และเป็นมิตรต่อผู้ใช้ อย่างไรก็ตาม การใช้ระบบพลังงานแสงอาทิตย์อย่างมีประสิทธิภาพนั้นจำเป็นต้องทราบข้อมูลรังสีอาทิตย์ที่แม่นยำและมีความเชื่อถือได้ ซึ่งไม่สามารถทำได้ด้วยการวัดจากภาคพื้นดินได้ครอบคลุมทุกพื้นที่ ดังนั้น การศึกษานี้จึงมีวัตถุประสงค์ในการสร้างแบบจำลองอย่างง่ายสองแบบจำลอง ได้แก่ แบบจำลอง Collares-Pereira and Rabl (CPR) และแบบจำลอง CPR ร่วมกับแบบจำลอง Liu and Jordan (CPR-JL) เพื่อประมาณค่ารังสีรวมรายชั่วโมงเฉลี่ยต่อเดือนจากรังสีรวมรายวัน ตำแหน่งของดวงอาทิตย์ และรังสีอาทิตย์นอกบรรยากาศโลก โดยใช้ข้อมูลจากภูมิภาคต่าง ๆ 4 ภูมิภาคหลักในประเทศไทย ได้แก่ เชียงใหม่ (18.78°N 98.98°E) นครปฐม (13.82°N 100.04°E) อุบลราชธานี (15.25°N 104.87°E) และสงขลา (7.20°N 100.60°E) ในช่วงปี พ.ศ. 2538 - 2566 หลังจากนั้น ทำการตรวจสอบประสิทธิภาพของแบบจำลองทั้งสองด้วยข้อมูลในปี พ.ศ. 2567 โดยใช้ตัวชี้วัดทางสถิติ ได้แก่ ค่ารากที่สองของค่าเฉลี่ยความแตกต่างยกกำลังสอง (Root Mean Square Difference, RMSD) ค่าความเอนเอียงเฉลี่ย (Mean Bias Difference, MBD) และค่าสัมประสิทธิ์การตัดสินใจ (Coefficient of Determination, R^2) จากผลลัพธ์แสดงให้เห็นว่า แบบจำลอง CPR มีความสอดคล้องกับค่าที่วัดได้จริงมากที่สุด ดังนั้นจึงแนะนำให้ใช้แบบจำลอง CPR สำหรับประมาณค่ารังสีอาทิตย์รายชั่วโมงเฉลี่ยต่อเดือนในพื้นที่อื่นที่มีลักษณะภูมิอากาศใกล้เคียงกับพื้นที่ที่ศึกษา

ABSTRACT

Solar energy has become a significant alternative renewable energy source due to its clean, emission-free, and user-friendly characteristics. However, an efficient utilization of solar energy system requires accurate and reliable solar radiation data, which could not be fulfilled by the ground measurement. Therefore, this study aims to evaluate two simplified models including Collares-Pereira and Rabl (CPR)

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model and the CPR model combined with Liu and Jordan (CPR-JL) model for estimating a monthly average hourly global solar radiation from monthly average daily global solar radiation, solar geometry, and extraterrestrial solar radiation using the data from four different regions across Thailand, namely Chiang Mai (18.78°N, 98.98°E), Nakhon Pathom (13.82°N, 100.04°E), Ubon Ratchathani (15.25°N, 104.87°E), and Songkhla (7.20°N, 100.60°E) for a period of the year 1995 - 2023. Subsequently, a performance of these models was investigated through statistical indicators such as Root Mean Square Difference, (RMSD), Mean Bias Difference, (MBD), and the coefficient of determination, (R^2) using the data of the year 2024. The Results indicated that CPR model provided the best agreement between the measured and calculated monthly average hourly global solar radiation. Thus, this is recommended to apply this model for gathering the hourly average data in other regions, which have similar climate characteristics to the studied locations.

คำสำคัญ: แบบจำลอง Collares-Pereira และ Rabl แบบจำลอง Liu และ Jordan รังสีรวม แบบจำลอง รังสีอาทิตย์
Keywords: Collares-Pereira and Rabl Model, Liu and Jordan Model, Global Solar Radiation, Model, Solar Radiation

INTRODUCTION

The Sun, our closest star, is a spherical gaseous self-gravitating body consisting mainly of hydrogen. It is located at the center of the solar system, on average 1.5×10^{11} m from the Earth. At the inner core of the Sun, the gravitational force creates a pressure, which generates nuclear fusion that turns hydrogen into helium. In this process, a portion of the mass is converted into an abundant amount of electromagnetic radiation (Widén and Munkhammar, 2019). This makes the Sun as a primary source of radiant energy in the solar system.

Solar Radiation refers to electromagnetic waves of various wavelengths, which people generally call sunlight. However, these electromagnetic waves do not only include light, but also compose of other radiation ranged from gamma rays to radio waves (Janjai, 2014). This radiation supports the survival of all living things through natural processes such as photosynthesis and the water cycle.

Solar energy is mostly preferred due to being safe, clean, free, limitless and non-polluting (Ayvazoğluyüksel and Filik, 2017). This energy is mainly utilized via two methods: photovoltaic power generation, which converts solar radiation into an electricity (Kalogirou, 2023; Jiang *at el*., 2025) and heat conversion from solar energy. Among these, photovoltaic power generation is the most widely adopted and efficient approach in reliable PV systems (Satpathy *et al*., 2021) and the design of solar energy systems in a region performing solar radiation evaluation is essential for attaining suitable information (Khorasanizadeh *et al*., 2014). Therefore, data collection of global solar radiation at each location is very important because it varies depending on diurnal and seasonal position of the sun relative to the Earth (Akarslan *et al.,* 2014), which affects to an identification of investment, system design, planning and continuity of the solar energy system (Teke *et al*., 2015). However, the measurement of solar radiation was not easily available due to a high instrument cost and maintenance including calibration requirements

(Nik *et al.,* 2012). This makes an estimation of solar radiation using various models became a great interest at present.

Solar radiation at the Earth's surface consists of two components: direct solar radiation, which travels in a straight line from the Sun and diffuse solar radiation, which results from the scattering of sunlight by atmospheric constituents in the atmosphere. Total or global solar radiation is the sum of the direct and diffuse solar radiation, both of which arrive at the surface from all directions. The global solar radiation reaching to the Earth's surface is therefore affected by various atmospheric constituents. These parameters change with both space and time (Madhlopa, 2006). There were different models developed for calculating global solar radiation using a variety of parameters such as an extraterrestrial solar radiation, sunshine duration, mean temperature, maximum temperature, soil temperature, relative humidity, number of rainy days, altitude, latitude, total precipitation, cloudiness, and evaporation (Ahmad and Tiwari, 2011). It was also found that Hollands and Huget (1983) developed a probabilistic model to characterize the variation of a clearness index (K_t), which is defined as the ratio of global solar radiation at the Earth's surface to the extraterrestrial solar radiation. This index effectively quantifies the impact of atmospheric conditions or cloud cover on the solar radiation.

In general, most of the available solar radiation data were collected in a daily format. However, for solar energy applications, it is necessary to obtain data in hourly resolution. There were models established for the estimation of hourly global solar radiation for example, the Whillier (1956) or Liu and Jordan (1960) model, the Collares-Pereira and Rabl (1979) model, and the Jain (1984) model which uses the normal distribution form. Ayvazoğluyüksel and Filik (2017) studied six models to derive the monthly hourly average global solar radiation from the daily global solar radiation in Çanakkale, northwestern Turkey. The most accurate model was the Collares-Pereira and Rabl modified by Gueymard (CPRG), which was recommended to be used for obtaining the monthly average hourly global solar radiation in other similar climate areas. In addition, Benchrifa *et al*. (2021) presented an equation for gathering the global solar radiation using the Collares-Pereira and Rabl model in Morocco. The results showed that the purposed model was the most adaptive model to predict the average monthly hourly global solar radiation for use as a solar energy database in this area.

For Thailand, there were a few models for obtaining the hourly global solar radiation and these models required atmospheric or relevant parameters. Therefore, the objective of this work was to develop models for estimating the monthly average hourly global solar radiation based on the Collares-Pereira and Rabl (CPR) model and the CPR model combined with the Liu and Jordan (CPR-JL) model, which were models that did not require other atmospheric variables as mentioned before. The monthly average hourly global solar radiation was derived from the monthly average daily global solar radiation together with the solar position and the extraterrestrial solar radiation, which were often available or calculated. The results obtained from both models were then compared with the measurement from a pyranometer to determine the best model for estimating monthly average hourly global solar radiation across four main regions of Thailand.

MATERIALS AND METHODS

In this section, the details of the measuring site, the data collection and calculation, the model development as well as the model validation was described as follows.

1. Monitoring station sites

Thailand locates between latitudes of 5° 37'N and 20° 28'N and longitudes 97° 21'E and 105° 37'E (Jomwinyan, 2017). It has a tropical climate with different seasonal weather changes in each region. In this study, the ground-based monitoring stations representing four main regions of Thailand were selected as shown in Table 1.

Table 1 Location of measuring stations in the research

Stations	Coordinates of the location
Northern Meteorological Center, Chiang Mai Province	18.78°N 98.98°E
Silpakorn University, Nakhon Pathom Province	13.82°N 100.04°E
Northeastern Meteorological Center, Ubon Ratchathani Province	15.25°N 104.87°E
Southern Meteorological Center, Songkhla Province	7.20°N 100.60°E

2. Data acquisition

The global solar radiation data from the four measuring stations (Table 1) were collected using a pyranometer CM21 manufactured by Kipp&Zonen and a DX2000 data logger from Yokogawa. Measurements were recorded every second during 7:00 - 17:00 local time and subsequently was averaged to obtain both hourly (7:00 - 7:59 AM, 8:00 - 8:59 AM, etc.) and daily data for each station, covering the period of 30 years from 1995 to 2024. The data were processed to compute monthly hourly averages by averaging all measurements taken within each hour across valid days of the month. This yielded 120 data points for the year, representing monthly average hourly values across 12 months. The daily global solar radiation was further aggerated into the monthly average data by dividing the total monthly radiation by the number of days in each respective month, yielding 12 monthly data points per year for each station. The collected data were divided into two datasets for developing the model from 1995 to 2023 and evaluating a performance of the model using the independent data of 2024 in order to avoid a potential bias from self-assessment of the data.

3. Model Formulation

A simplified model of the monthly average hourly global solar radiation was formulated as a function of the daily global solar radiation collected by the measurement, solar position, and the extraterrestrial equation encompassing the year of 1995 to 2023, which were calculated described as follow (Iqbal, 1983). The model was developed using long-term data to accurately capture climatological patterns and variability of global solar radiation across Thailand.

3.1 Solar Position and Extraterrestrial Radiation

- Hourly Extraterrestrial Solar Radiation can be obtained by using this equation.

$$I_o = I_{sc} E_o (\sin\delta \sin\phi + \cos\delta \cos\phi \cos\omega_i) \quad (1)$$

Where I_o is an hourly extraterrestrial solar radiation (MJ $m^{-2}hr^{-1}$)

I_{sc} is a solar constant for hourly radiation (4,917.96 × 10^3 J $m^{-2}hr^{-1}$)

ϕ is a latitude of the measuring site (degrees)

E_o is an Earth–Sun distance correction factor (-) and δ is a solar declination (degrees), which can be calculated using the following equations.

$$E_0 = 1.000110 + 0.034221 \cos\Gamma + 0.001280 \sin\Gamma + 0.000719 \cos 2\Gamma + 0.000077 \sin 2\Gamma \quad (2)$$

$$\delta = \begin{pmatrix} 0.006918 - 0.399912 \cos\Gamma + 0.070257 \sin\Gamma - 0.006758 \cos 2\Gamma + \\ 0.000907 \sin 2\Gamma - 0.002697 \cos 3\Gamma + 0.00148 \cos 3\Gamma \end{pmatrix} (180/\pi) \quad (3)$$

Where Γ is a day angle (radians) calculated from the following equation.

$$\Gamma = 2\pi(d_n - 1)/365 \quad (4)$$

Where d_n is the day number of the year and ω_i is the hour angle (degrees), which can be calculated from

$$\omega_i = 15(12 - ST) \quad (5)$$

when ST is the solar time (hour).

- Daily Extraterrestrial Solar Radiation

This daily data can be calculated from the summation of hourly extraterrestrial solar radiation, as shown in Equation (1) from sunrise to sunset during a whole day by:

$$H_o = \int_{sr}^{ss} I_o \, dt \quad (6)$$

The monthly average hourly extraterrestrial solar radiation ($\overline{I}_o$) in MJ m^{-2} $hr^{-1}$was computed by summing the hourly data from Equation (1) for the same specific hour of the day across all days in a month and then divided by the number of days as expressed in Equation (7). Similarly, the monthly average daily extraterrestrial solar radiation ($\overline{H}_o$) in MJ m^{-2} day^{-1} was calculated by averaging the daily values obtained from Equation (6) for each day of the month. This was done by summing the daily values from the first to the last day of the month and dividing by the total number of days in that month as shown in Equations (7) and (8).

$$\bar{I}_o = \frac{1}{N}\sum_{i=1}^{N} I_{oi} \quad (7)$$

$$\bar{H}_o = \frac{1}{N}\sum_{i=1}^{N} H_{oi} \quad (8)$$

3.2 Collares-Pereira and Rabl or CPR Model

The first model used in this work was based on the work of Collares-Pereira and Rabl (1979), which presented a relationship between the monthly average daily global solar radiation and the solar position to estimate the monthly average hourly global solar radiation. The CPR model was expressed in the following form.

$$\frac{\bar{I}/\bar{H}}{\bar{I}_0/\bar{H}_0} = a + b\cos\omega_i \quad (9)$$

where

$$a = a' \sin\left(\bar{\omega}_{ss} - \omega_{ss_{min}}\right) + a''$$

$$b = b' \sin\left(\bar{\omega}_{ss} - \omega_{ss_{min}}\right) + b'' \quad (10)$$

$\omega_{ss_{min}}$ was the minimum sunset hour angle (degrees) considered equal to 81° for these four sites of the measurement and ω_{ss} was the sunset hour angle (degrees), which was performed using the following equation.

$$\omega_{ss} = \cos^{-1}(-\tan\delta\tan\phi) \quad (11)$$

The coefficients a and b were derived as a function of coefficients a' a'' b' and b' for each station obtained from our previous work (Runghathaithum *et al.,* 2025) as shown in Table 2.

Table 2 The coefficients a' a'' b' and b' for each station applied in the work.

Stations	a'	a''	b'	b''
Chiang Mai	-0.722	0.732	0.767	0.386
Nakhon Pathom	-0.544	0.652	0.634	0.452
Ubon Ratchathani	-1.407	0.721	1.284	0.405
Songkhla	-0.914	0.730	0.927	0.393

3.3 Collares-Pereira and Rabl with Liu and Jourdan or CPR-JL Model

The CPR-JL model was an extended model developed by integrating the concept of the Liu and Jordan model (1960) expressed in Equation (12) with the Collares-Pereira and Rabl model (1979). This CPR-JL model represented the ratio between the monthly average hourly and monthly average daily global solar radiation as shown in Equation (13).

$$r_d = \frac{\bar{I}_d}{\bar{H}_d} = \frac{\bar{I}_0}{\bar{H}_0} = \frac{\pi}{24}\left(\frac{\cos\omega_i - \cos\omega_{ss}}{\sin\omega_{ss} - \frac{\pi}{180}\omega_{ss}\cos\omega_{ss}}\right) \quad (12)$$

where $\bar{I}_d$ was the monthly average hourly diffuse solar radiation and $\bar{H}_d$ was the monthly average daily diffuse solar radiation.

$$\frac{\bar{I}}{\bar{H}}=\frac{\pi}{24}(a+b\cos\omega_{\mathrm{i}})\left(\frac{\cos\omega_{\mathrm{i}}-\cos\omega_{\mathrm{ss}}}{\sin\omega_{\mathrm{ss}}-\frac{\pi}{180}\omega_{\mathrm{ss}}\cos\omega_{\mathrm{ss}}}\right) \quad (13)$$

4. Model Performance Evaluation

To verify a performance of the developed model for estimating the monthly average hourly global solar radiation, a comparison between the data calculated from the purposed model and that obtained from the measurement using the data of the year 2024 was investigated. Two statistical indicators, namely the root mean square difference (RMSD) and the mean bias difference (MBD) were evaluated expressed in Equations (14) and (15).

$$\mathrm{RMSD}=\frac{\sqrt{\frac{\sum_{\mathrm{i}=1}^{\mathrm{N}}\left(\bar{\mathrm{I}}_{\mathrm{model,i}}-\bar{\mathrm{I}}_{\mathrm{meas,i}}\right)^2}{\mathrm{N}}}}{\frac{\sum_{\mathrm{i}=1}^{\mathrm{N}}\bar{\mathrm{I}}_{\mathrm{meas,i}}}{\mathrm{N}}}\times 100\% \quad (14)$$

$$\mathrm{MBD}=\frac{\frac{\sum_{i=1}^{N}\left(\bar{\mathrm{I}}_{\mathrm{model,i}}-\bar{\mathrm{I}}_{\mathrm{meas,i}}\right)}{N}}{\frac{\sum_{\mathrm{i}=1}^{\mathrm{N}}\bar{\mathrm{I}}_{\mathrm{meas,i}}}{\mathrm{N}}}\times 100\% \quad (15)$$

Where $\bar{\mathrm{I}}_{\mathrm{model,i}}$ was the monthly average hourly global solar radiation calculated from the model (MJ m^{-2} hr^{-1}), $\bar{\mathrm{I}}_{\mathrm{meas,i}}$ was the monthly average hourly global solar radiation obtained from the measurements (MJ m^{-2} hr^{-1}), and N was the total number of the data.

RESULTS AND DISCUSSION

This section presented results of the model performance consisting of an assessment of the CPR model, the assessment of the CPR-JL model, and a comparative analysis of the accuracy between the two models.

1. Performance Evaluation of the CPR Model

The comparisons for four stations between the measured values and those estimated by the CPR model and the summary of the static indicators were presented in Figure 1 and Table 3, respectively.

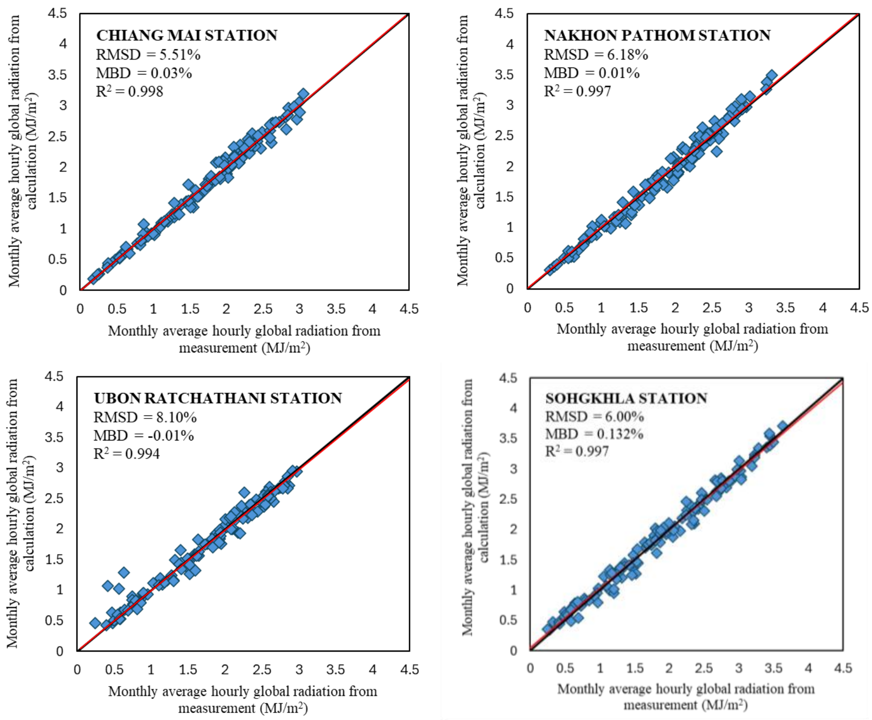

Figure 1 The comparisons of the monthly average hourly global radiation calculated from the CPR model and the measurement for four stations.

Table 3 Statistical indicators including a coefficient of the determination (R^2) investigated by the CPR model

Stations	RMSD (%)	MBD (%)	R^2
Chiang Mai	5.51	0.03	0.998
Nakhon Pathom	6.18	0.01	0.997
Ubon Ratchathani	8.10	-0.01	0.994
Songkhla	6.00	0.13	0.997

The results from Figure 1 showed that the monthly average hourly global solar radiation estimated from the CPR model and that collected from the instruments were in good agreement, which can be observed from the trend line (red line) almost superimposed with the half line (black line). From the analyze of the statistical indicators in Table 2, it was found that the RMSD were 5.51%, 6.18%, 8.10%, and 6.00%, while the MBD were 0.03%, 0.01%, -0.01%, and 0.13% for Chiang Mai, Nakhon Pathom, Ubon Ratchathani, and Songkhla stations, respectively. Considering to the MBD, most stations excepted Ubon Ratchathani delivered positive values meaning that the CPR model slightly overestimated the monthly average hour data.

2. Performance Evaluation of the CPR-JL Model

As same as the CPR model, the comparisons between the values from the CPR-JL model and that obtained from the measurement for four stations were presented in Figure 2 and the discrepancy in terms of the RMSD and the MBD was summarized in Table 4.

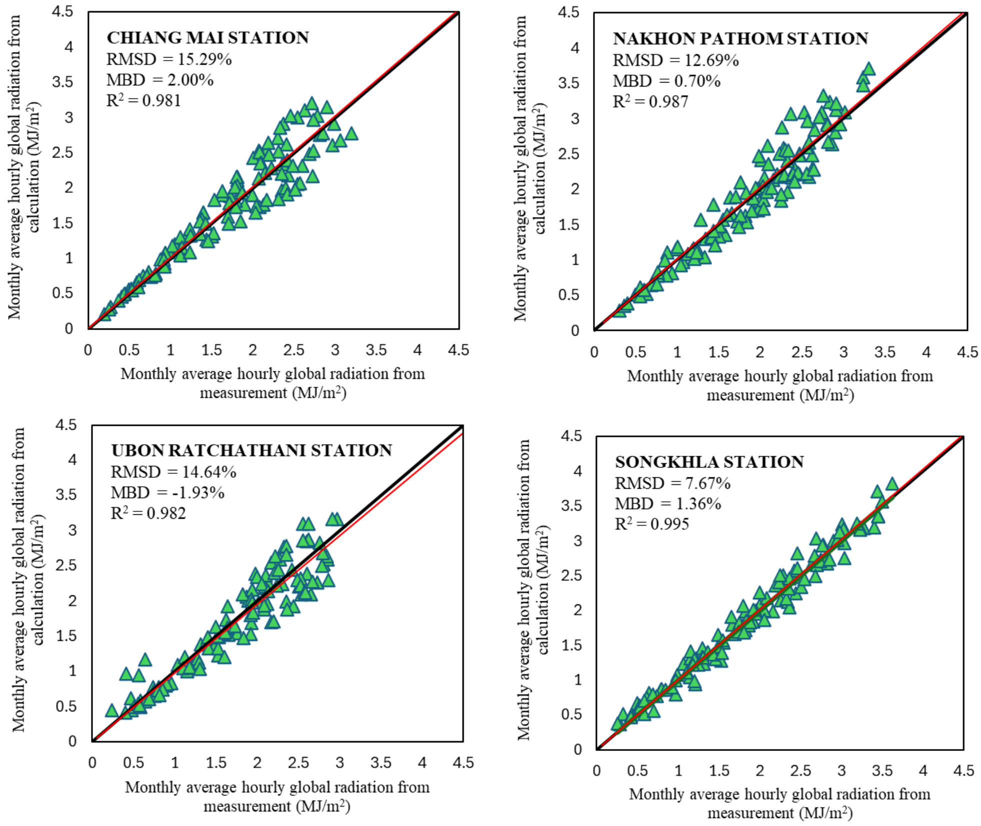

Figure 2 The comparisons between monthly average hourly global solar radiation obtained from the CPR-JL model with the actual values at each station.

The scatter plots in Figure 2 between the measured values and that estimated by the CPR-JL model showed that both datasets still depicted a good argument representing by the trend line (red) closely aligned with the half line (1:1) (black). However, the plots exhibited a higher dispersion compared to the CPR model leading to the higher RMSD and MBD. The RMSD was found to be 15.29%, 12.69%, 14.64%, and 7.67%, while the MBD were 2.00%, 0.70%, -1.93%, and 1.36% for Chiang Mai, Nakhon Pathom, Ubon Ratchathani, and Songkhla, respectively. The overestimation of the data performed by the CPR-JL was still observed comparing to the measurement.

Table 4 Summary of statistical indicators for the performance evaluation of the CPR-JL model

Stations	RMSD (%)	MBD (%)	R^2
Chiang Mai	15.29	2.00	0.981
Nakhon Pathom	12.69	0.70	0.987
Ubon Ratchathani	14.67	-1.93	0.982
Songkhla	7.67	1.36	0.995

Although the CPR-JL model is often regarded as structurally more sophisticated, it estimated the ratio of $\frac{\bar{I}_0}{\bar{H}_0}$ using only hour angle (Equation (12)). In contrast, the CPR model calculates $\frac{\bar{I}_0}{\bar{H}_0}$ based on Equations (1)–(5), incorporating a more complete representation of solar geometry. The results indicated that the CPR model yields more consistent and accurate predictions when applied to the solar radiation data over Thailand. This suggests that, under relatively stable tropical atmospheric conditions, the additional geometric detail in the CPR model enhances its applicability for the estimation of monthly average hourly global solar radiation.

CONCLUSIONS

In this work, the models for estimating the monthly average global solar radiation, which can be utilized in different applications in solar energy system, was purposed. Two models, the CPR and CPR-JL models, were selected due to no atmospheric parameters need. The monthly average daily global solar radiation, position of the sun and extraterrestrial solar radiation were delivered into the models. The model formulation was analyzed using the long-term data from 1995 to 2023 (30 years) at four main regions of Thailand. After that, the performance of the models was investigated by comparing with the data from the measurement of 2024 and reported in terms of two statistic indicators, RMSD and MBD. The results indicated that the monthly average hourly global solar radiation calculated from the CPR model (RMSD: 5.51 - 8.10%, MBD: -0.01 - 0.13%) consistently outperformed the CPR-JL model (MBD: 7.67 - 15.29%, MBD: -1.93 - 2.00%) for all stations as evidenced by lower RMSD and MBD values. Therefore, it can be concluded that the CPR model is more suitable for estimating monthly average hourly global solar radiation. This model can be effectively applied to energy planning and photovoltaic system design in Thailand as well as in other tropical countries with similar climate conditions. However, relatively small seasonal variation in the solar radiation due to the tropical climate, incorporating a seasonal analysis (e.g., dividing the data into dry, rainy, and cool seasons) could further enhance the model's applicability for future energy policy development.

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