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Research article

Analysis of Zenith Sky Radiance in the Tropics: A Case Study of Chiang Mai and Nakhon Pathom, Thailand

Worapan Kanchanachat*, Itsara Masiri and Serm Janjai

Department of Physics, Faculty of Science, Silpakorn University, Nakhon Pathom 7300, Thailand

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Abstract

Zenith sky radiance data collected at two sites: Chiang Mai station (18.78°N, 98.98°E) and Nakhon Pathom station (13.81°N, 100.04°E) in Thailand, were analyzed and used to develop a model. When analyzing the zenith sky radiance under all sky conditions, it was found that the diurnal variations of zenith sky radiance at both stations presented a similar pattern. The zenith sky radiance increased in the morning, peaked at noon, and decreased in the afternoon. The highest seasonal variation of zenith sky radiance occurred in the summer season (mid-February to mid-May) and the lowest value was in the winter season (mid-October to mid-February). The solar altitude, latitude of the location, and cloud cover affected variation of zenith sky radiance. For the modeling, the measurement data at Nakhon Pathom station were used for model development to estimate hourly zenith sky radiance under clear sky condition as a function of solar altitude. The hourly zenith sky radiance under clear sky condition data collected at Chiang Mai and Nakhon Pathom stations were employed to validate the accuracy of the model. The results showed that the measured and estimated hourly zenith sky radiance under clear sky conditions were in reasonable agreement, with root mean square error (RMSE) of 30.17% and mean bias error (MBE) of 7.48%. This model can be used to estimate zenith sky radiance data when measurement is not available and can be utilized to evaluate the maximum performance of solar energy applications.

Keywords: zenith sky radiance; measurement data; clear sky model; tropical environment

1. Introduction

It has been well-recognized that greenhouse gases are emitted through burning fossil fuels. Therefore, a goal of developing a modern building is to reduce the utilization of conventional electricity energy from fossil fuels (Chwieduk, 2017). The installation of solar photovoltaic (PV) for electricity energy generation is one of the applications of renewable energy. Generally, PV panels are always inclined at an angle to the latitude of the location to receive maximum solar energy. Unfortunately, the rooftop area of the modern building has a limited area to install PV panels. This has led to the development and installation of PV panels at a vertical external wall known as building integrated photovoltaics (BIPVs)

*Corresponding author: E-mail: topmarch12@gmail.com
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(Yu et al., 2021; Li et al., 2023). In urban areas, most modern buildings have obstructed PV panels. One approach to obtaining the solar irradiance on BIPVs obstructed by a nearby building is by integrating the absolute sky radiance (Li et al., 2013).

The most accurate measurement of absolute sky radiance comes from a sky scanner. However, sky scanner on-station measurements are not obtainable due to the need for calibration and the price is very high. To fill the gap, the 15 CIE general standard skies model was proposed to estimate the sky radiance in terms of relative sky radiance under clear sky to overcast sky. Zenith sky radiance is a part of the model that is used to convert relative sky radiance to absolute sky radiance. Details of the model can be found in Darula & Kittler (2002).

Some works have been studied to estimate zenith sky radiance. For example, the study at a high latitude in Pamplona, Spain revealed that the zenith sky radiance varies with solar altitude and sky conditions (Torres et al., 2010). In contrast with Spain, Thailand is located in a tropical area where the environment is quite different from that at high latitudes. Hence, this study had two main objectives. The first objective was to analyze in detail the diurnal and seasonal variations of the zenith sky radiance under all sky conditions at two different measurement stations located in the tropics. The second objective was to develop a model of the zenith sky radiance under clear sky condition as a function of solar altitude.

2. Materials and Methods

Ground-based measurements of the zenith sky radiance data and clear sky identification were conducted at two stations located in a tropical environment, Thailand, namely Chiang Mai station (18.78°N, 98.98°E), situated in the mountainous area of northern Thailand, with an average elevation of 312 m above sea level, and Nakhon Pathom station (13.82°N, 100.04°E), set in the flat low-land of central Thailand, with an average elevation of 72 m above sea level, as shown in Figure 1. In this study, data collected from both sites during 8:00 to 16:00 in local time were used. The details of instruments used in this study and the methodology are as follows.

2.1 Zenith sky radiance data

A sky scanner (model: MS-321LR) (Figure 1), which was calibrated and manufactured by EKO company in Japan, was used to collect zenith sky radiance data at both stations. The sky scanner employs two different sensors consisting of sky radiance and sky luminance, over 145 points (shown in Figure 2) covering the sky dome, located in a two-axis tracking system for the required azimuth angles and altitude angles. The sky radiance data of this sky scanner ranged from 0 to 300 W/m^2 sr. Each scanning time was about 4 min and the measurements were taken every 30 min. Sky scanning sequence number 145 (Figure 3) was considered the zenith sky radiance which was used in this study.

2.2 Clear sky identification

Sky images obtained from a sky camera (model: PVS-100) from PRIDE company and another sky camera (model: ASI-16) from EKO company in Japan (Figure 1) were taken every 30 min to correspond with the sky scanner and were used to identify clear sky. These cameras are automatic cameras with a fish eye objective and 180° field of view that capture

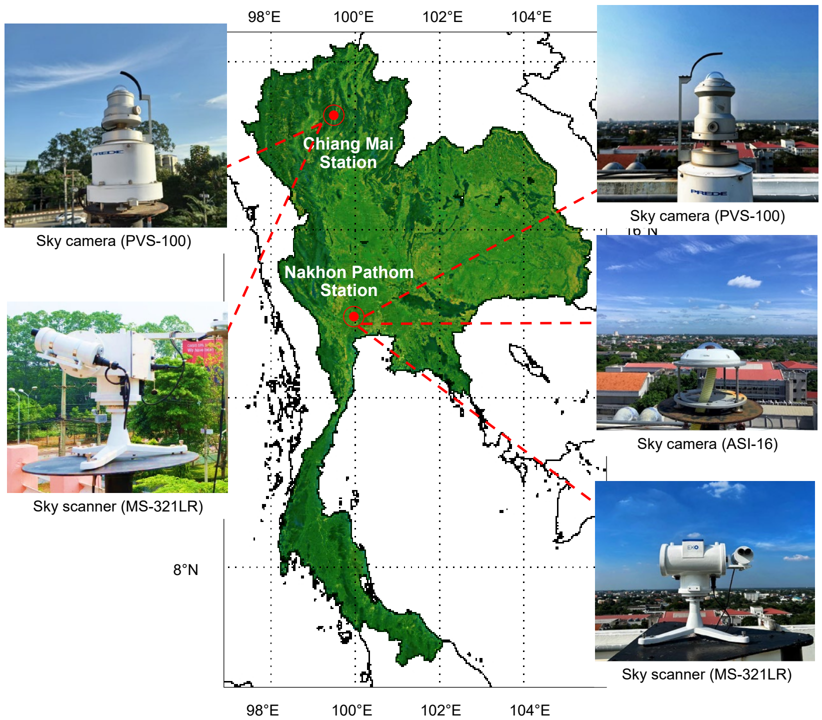

Figure 1. Map of Thailand showing the locations at Chiang Mai station and Nakhon Pathom stations and measurements together with the elevation

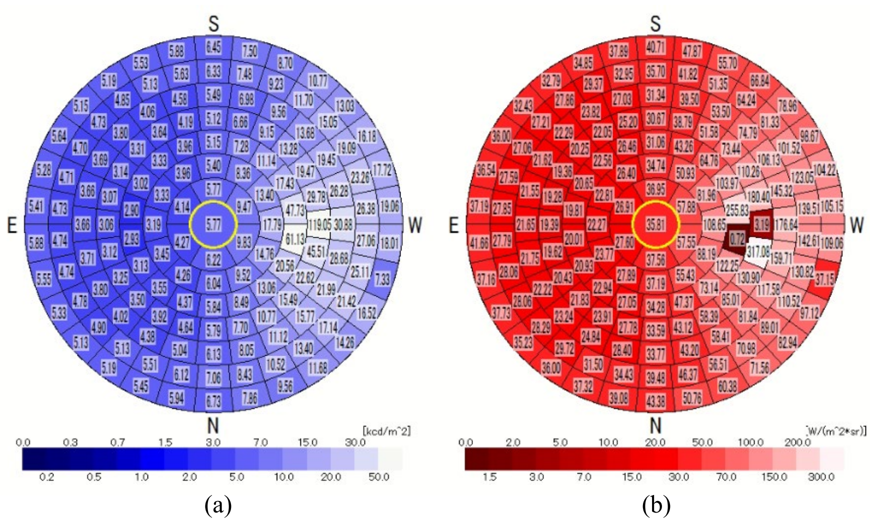

Figure 2. Examples of sky luminance (a) and sky radiance (b) from the EKO sky scanner

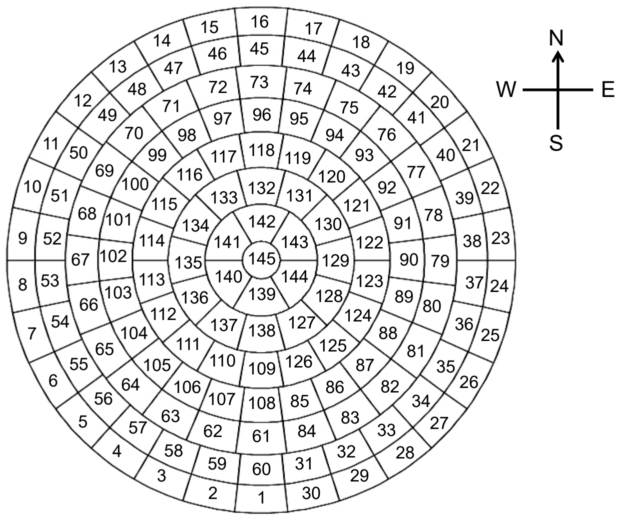

Figure 3. The 145 measurement points of the EKO sky scanner

images of the sky. To identify the zenith sky radiance under clear sky conditions, very clear image with no clouds were used and these images were selected by human observation. A sample of the image with a clear sky used in this study can be seen in Figure 4.

Figure 4. Example of sky image under clear sky condition from the EKO sky camera

2.3 Formulation of the model

In the last decade, some research efforts were focused on developing mathematical models of hourly zenith sky luminance as a function of altitude angle with 3rd-degree polynomials (Soler & Gopinathan, 2004). This study was concentrated on the estimation of hourly zenith sky radiance under clear sky condition due to easy to model (cancel out the effect of clouds) and the maximum electric conversion of the PV panels was carried out by solar irradiance under clear sky condition. Zenith sky radiance collected from Nakhon Pathom station in 2016 was employed to determine the parameter for model adjustments. The relationship between hourly zenith sky radiance and solar altitude is shown in Figure 5.

From Figure 5, the best fit with 3rd-degree polynomial was established as follows:

$$R_z = 0.0008\alpha^3 - 0.0690\alpha^2 + 2.9288\alpha - 10.5170 \quad (1)$$

Where R_z is hourly zenith sky radiance under clear sky condition (W/m^2 sr), and α is solar altitude (degrees).

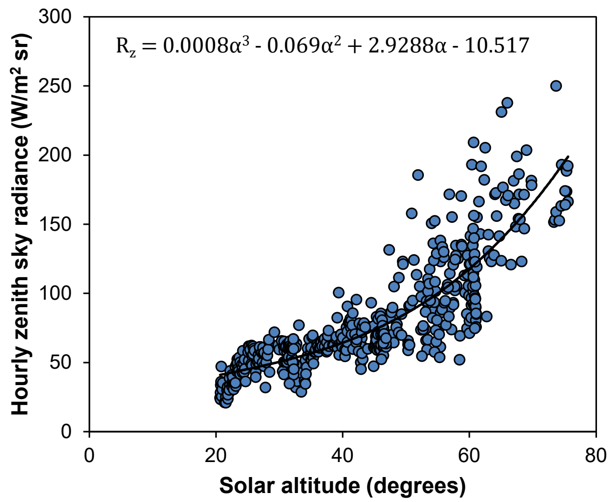

Figure 5. The relationship between hourly zenith sky radiance under clear sky condition and solar altitude

2.4 Validation of the model

The zenith sky radiance measured at Chiang Mai station in 2016 and Nakhon Pathom station between August 2023 and September 2024 were used for model validation. There were indicators that represent mathematical model accuracy. In equations (2) and (3), root mean square error (RMSE) and mean bias error (MBE) were employed for validation of the model accuracy:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(R_{z,model} - R_{z,means})^2 / N}{\sum_{i=1}^{N} R_{z,means} / N}} \times 100 \quad (2)$$

$$\text{MBE} = \frac{\sum_{i=1}^{N}(R_{z,model} - R_{z,means})^2 / N}{\sum_{i=1}^{N} R_{z,means} / N} \times 100 \quad (3)$$

where $R_{z,model}$ is hourly zenith sky radiance under clear sky condition from model (W/m^2 sr), $R_{z,means}$ is hourly zenith sky radiance under clear sky condition from measurement (W/m^2 sr), and N is total number of the data (-). A negative MBE value indicates the underestimation in the estimated zenith sky radiance, whereas a positive value indicates the overestimation. RMSE provides an error of a model, when this value close to zero would indicate a perfect model.

3. Results and Discussion

3.1 Diurnal variation of zenith sky radiance

The monthly average hourly zenith sky radiance under all sky conditions at two stations in 2016 is shown in Figure 6. We only present a curve for 8:00-9:00 (representing morning), 12:00-13:00 (representing noon), and 15:00-16:00 (representing afternoon). It can be seen from Figure 5 that the zenith sky radiance at both sites increased from the morning to reach the peak at noon and then decreased in the afternoon according to sun position in terms of solar altitude. The solar altitude varies with the time of the day. Every day, the solar altitude is equal to 0° when the sun rises and increases to 90° around noon then decreases to 0° again when the sun sets.

3.2 Seasonal variation of zenith sky radiance

Figure 7 illustrates the monthly average daily variation in zenith sky radiance for 2016, highlighting its seasonal changes. The results from both stations show similar patterns across the different seasons, which were driven by the sun's declination. As the Earth orbits the sun, its axial tilt causes the sun’s position in the sky to shift, leading to seasonal variations. During the summer (mid-February to mid-May) and rainy season (mid-May to mid-October), the sun’s declination is around 0 degrees. However, zenith radiance is higher in summer due to clearer skies, while cloud cover, which reduces the zenith sky radiance, can be seen in the rainy season. In winter (mid-October to mid-February), when the sun’s declination reaches -23.5 degrees, the lowest zenith sky radiance is observed as the sun is lower in the sky. In addition to solar declination, the latitude of the measurement site plays a role in zenith sky radiance. Nakhon Pathom, located at a lower latitude, recorded the highest values, while Chiang Mai, at a higher latitude, showed the lowest values. Thus, zenith sky radiance was affected by solar declination, cloud cover, and the location’s latitude.

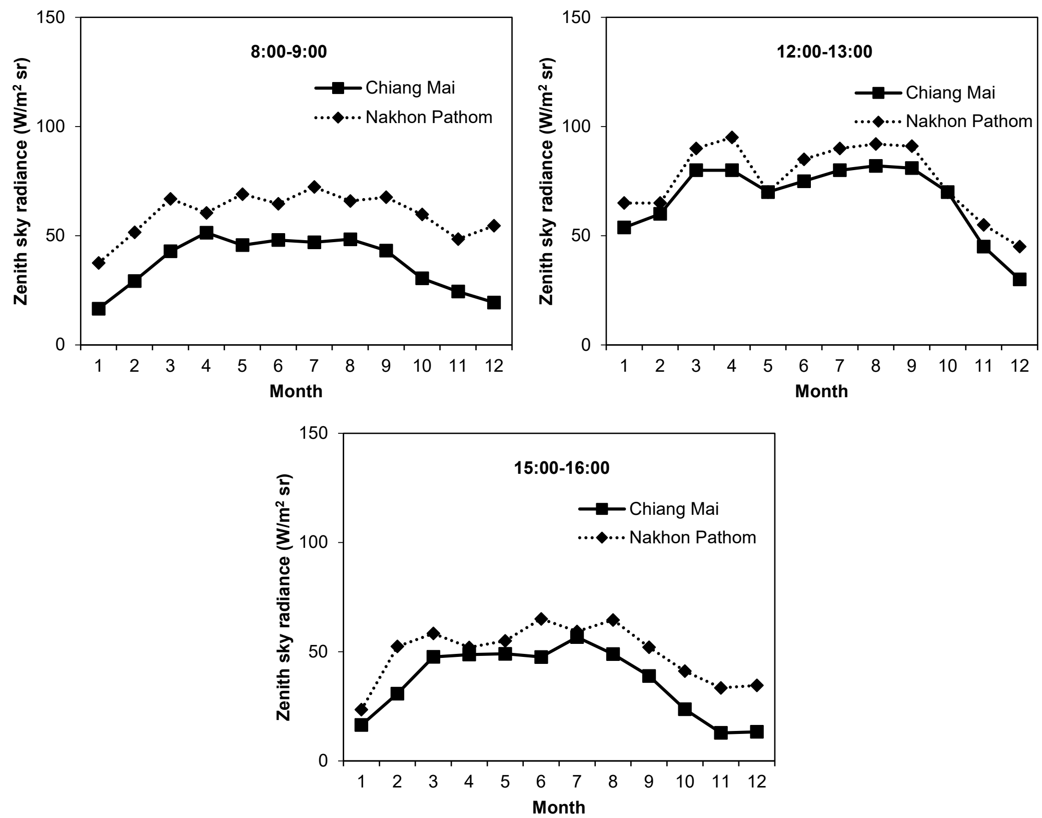

Figure 6. Monthly average hourly zenith sky radiance for morning (8:00-9:00), noon (12:00-13:00), and afternoon (15:00-16:00)

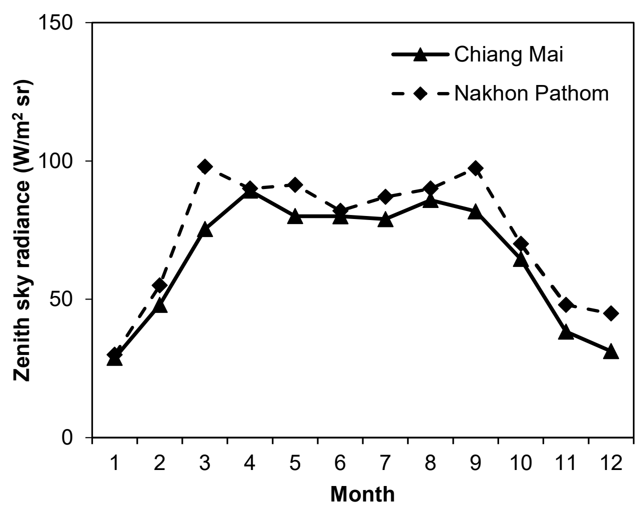

Figure 7. Monthly average daily zenith sky radiance

3.3 Validation result

The hourly zenith sky radiance under clear sky condition at Chiang Mai station obtained from the model was compared with the hourly zenith sky radiance under clear sky condition data from measurements. However, the data obtained from the Chiang Mai station in 2016 represented historical measurements. Therefore, data collected from the Nakhon Pathom station between August 2023 and September 2024 were included for comparison. The result of the comparison is shown in Figure 8. It can be observed that the hourly zenith sky radiance under clear sky condition from the model were in reasonable agreement with the data from the measurement, with RMSE of 30.17% and overestimated with MBE of 7.48%.

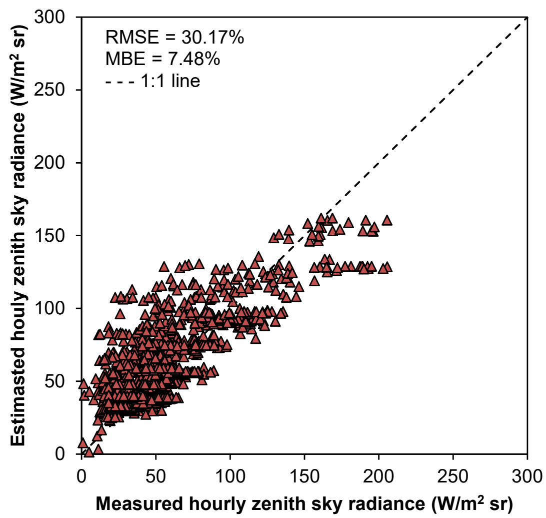

Figure 8. Comparison of the measured hourly zenith sky radiance under clear sky condition versus the estimated hourly zenith sky radiance under clear sky condition from the model

4. Conclusions

Thailand is situated in a tropical environment characterized by rapid cloud movement. In this study, we analyzed the diurnal and seasonal variations of zenith sky radiance measured by a sky scanner under all sky conditions at two sites: Chiang Mai station and Nakhon Pathom station in Thailand, during 2016. The diurnal variations of the zenith sky radiance increased in the morning, peaked at noon, and decreased in the afternoon. The most significant seasonal variation in zenith sky radiance was observed during the summer months of mid-February to mid-May, when radiance levels were at their highest. Conversely, the lowest values were recorded during the winter season, from mid-October to mid-February. The analyses also indicated that solar altitude, latitude, and cloud cover significantly affected these variations. Additionally, hourly zenith sky radiance under clear sky conditions was estimated as a function of solar altitude. The accuracy of the model showed reasonable agreement, with a root mean square error (RMSE) of 30.17% and a mean bias error (MBE) of 7.48%.

5. Acknowledgements

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6. Authors' Contributions

Worapan Kanchanachat: Data analysis, writing – original draft preparation, methodology, conceptualization, writing – reviewing and editing, and software.
Itsara Masiri: Conceptualization, methodology, and writing – reviewing.
Serm Janjai: Supervision and project administration.

7. Conflicts of Interest

The authors delcare that there is no conflict of interest in this study.

ORCID

Worapan Kanchanachat https://orcid.org/ 0009-0001-0777-0564

Itsara Masiri https://orcid.org/0009-0000-6639-6931

Serm Janjai https://orcid.org/0000-0002-8797-4283

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