Journal of Renewable Energy and Smart Grid Technology, Vol. 17, No. 2, July-December 2022

A Semi-Empirical Model for Calculating Spectral Global Solar Irradiance under Clear Sky Conditions in Thailand

Sunisa Khakhu, Itsara Masiri, Rungrat Wattan* and Serm Janjai

Solar Energy Research Laboratory, Department of Physics, Faculty of Science, Silpakorn University,
Nakhon Pathom 73000, Thailand
***Corresponding author's email:** rungrat.wattan@gmail.com

Received: 31 October 2022, Revised: 19 December 2022, Accepted: 21 December 2022

Abstract

This paper presents the development of a semi-empirical model for calculating spectral global solar irradiance in Thailand. The model expresses the spectral global solar irradiance as an empirical function of atmospheric constituents affecting radiation. To develop the model, global solar spectral irradiance was measured at Chiang Mai (18.78°N, 98.98°E), Ubon Ratchathani (15.25°N, 104.87°E), Nakhon Pathom (13.82°N, 100.04°E) and Songkhla (7.18°N, 100.60°E). Five years (2017-2021) of spectral data from these locations were collected and separated into two groups. The first group (2017-2020) was used for modeling while the second group (2021) was employed for model validation. The validation results revealed that the values of spectral global irradiance calculated from the model and those obtained from the measurements were in good agreement with the discrepancy in terms of mean bias difference and root mean square difference of 0.98% and 9.61%, respectively. These results imply that the developed model performs well in calculating spectral global solar irradiance.

Keywords:
Solar Radiation, Spectral Global Solar Irradiance, Solar Spectrum, Clear Sky

1. Introduction

The spectrum of global solar irradiance is important for the research and application of solar cells, which have different responses for each wavelength of solar radiation [1]. In addition, the global solar spectrum is important information for the development of a selective surface for solar thermal applications [2]. This is because a selective surface is sensitive to the global solar spectrum. Spectral models could be categorized into two types: spectral model under clear sky conditions and spectral model for all- sky conditions. This study focused on the spectral model under clear sky conditions as it might be used in our spectral model for all-sky conditions. The solar spectrum under clear sky conditions gives information on the maximum possible energy available for solar energy applications. In fact, the spectrum of global radiation can be obtained by modeling approach using a radiative transfer model [3-5]. However, the use of a radiative transfer model is generally complicated. Although the information on solar spectrum can be also obtained from the measurements, the measurements are scarce due to the high cost of spectroradiometers [6]. Thus, several researchers have developed a simplified physical model to calculated solar spectrum [7-11]. Some researchers [12-13] proposed spectral models of solar radiance but these models cannot be used directly to calculate global solar spectrum. Most of spectral models treated global solar radiation in two steps. In the first step, the direct and diffuse components of the solar spectrum were modeled. Then the direct and diffuse components were summed to obtain the global solar spectrum, resulting in a complicated modeling process. In addition, the validation of the spectral models in a tropical climate is very limited and the discrepancy between the calculation and the measurement is quite high [14]. Although the validation for other climates, their discrepancies are quite low [15-18], these model could not be used in the tropical climate. Therefore, it is necessary to create a more accurate model for calculating global solar spectrum.

The objective of the present work is to develop a semi-empirical model under clear sky conditions which can then be used to calculate the global spectrum directly for Thailand.

2. Instrument and data

To develop the model, the spectral data of global solar radiation are required. As Thailand can be divided into four main regions, namely, the northern, northeastern, central , and the southern regions, four spectroradiometers were installed at Chiang Mai, Ubon Ratchathani, Nakhon Pathom , and Songkhla, respectively (Fig. 1). These spectroradiometers were regularly calibrated by EKO, the manufacturer. At these stations, AERONET sunphotometers (AErosol RObotic NETwork) were also installed to measure direct solar irradiance at the following wavelengths: 340, 380, 440, 500, 675, 870, 1020 , and 1640 nm. The spectral irradiance values at these wavelengths were sent via the internet to the AERONET headquarters in the USA for processing, and the optical properties of aerosols were obtained. The obtained properties were posted on the AERONET website (https://aeronet.gsfc.nasa.gov/). These sunphotometers were routinely calibrated by AERONET. In this study, data on aerosol optical depth (AOD) at 340, 380, 440, 500, 675, 870 and 1020 nm, as well as precipitable water (W) ozone amount (O_3) and nitrogen dioxide amount (NO_2) were downloaded from the AERONET website and subsequently used for model development. The positions and pictorial view of instruments installed and used in this study are shown in Fig. 1.

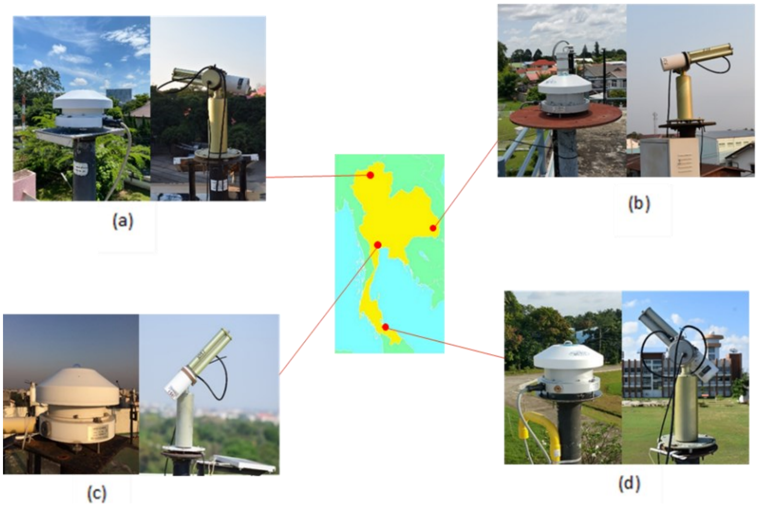

Fig. 1 Positions and pictorial view of instruments installed and used in this study (a) Chiang Mai station, (b) Ubon Ratchathani station, (c) Nakhon Pathom station and (d) Songkhla station.

3. Formulation of the model

Based on the information in Iqbal [19], the atmospheric constituents involved in the model under clear sky conditions are aerosols, ozone, water vapor, and nitrogen dioxide. Therefore, we propose a semi-empirical model, which mean that the physical parameters affecting the spectrum are involved empirically in the model. The proposed model has the following form:

$$\dot{I}_{g,clear,\lambda} = a_0 \dot{I}_{o\lambda} \exp[-(a_1 m_a + a_2 AOD m_a + a_3 k_{w\lambda} W m_a + a_4 k_{o\lambda} O_3 m_a + a_5 k_{g\lambda} m_a + a_6 k_{n\lambda} NO_2 m_a) + a_7] \quad (1)$$

where $\dot{I}_{g,clear,\lambda}$ = spectral global irradiance under clear sky conditions ($Wm^{-2}\mu m^{-1}$);
$\dot{I}_{o\lambda}$ = spectral extraterrestrial irradiance ($Wm^{-2}\mu m^{-1}$);
m_a = air mass (-);
AOD = aerosol optical depth (-);
W = precipitable water (cm);
O_3 = amount of ozone (cm);
NO_2 = amount of nitrogen dioxide (cm);
$k_{w\lambda}$ = spectral extinction coefficient due to water vapour (cm^{-1});
$k_{o\lambda}$ = spectral extinction coefficient due to ozone (cm^{-1});
$k_{g\lambda}$ = spectral extinction coefficient due to gases (-);
$k_{n\lambda}$ = spectral extinction coefficient due to nitrogen dioxide (-); and
a_0 , a_1, a_2, a_3, a_4, a_5, a_6 and a_7 are empirical coefficients.

$k_{w\lambda}$, $k_{o\lambda}$, and $k_{g\lambda}$ were obtained from Iqbal [19]. $k_{n\lambda}$ was acquired from Iqbal [19]. The calculation of m_a was based on the formula proposed by Kasten [21].

The values of empirical coefficients are obtained by fitting the Eq. (1) with the measured data from the four stations. The values of the coefficients for every 0.01 μm are shown in Table 1.

Table 1 Values of empirical coefficients for every 0.01 μm of the proposed model.

wavelength(μm)	Coefficients*							
	a_0	a_1	a_2	a_3	a_4	a_5	a_6	a_7
0.35	0.279	0.479	0.275	0.000	203.850	-17.810	0.000	1.547
0.36	0.276	0.796	0.278	0.000	0.000	-9.382	0.000	1.654
0.37	0.287	0.704	0.260	0.000	0.000	42.213	0.000	1.694
0.38	0.235	0.661	0.248	0.000	0.000	63.254	0.000	1.823
0.39	0.243	0.719	0.263	0.000	0.000	25.462	0.000	1.742
0.40	0.313	0.781	0.273	0.000	0.000	-14.620	0.000	1.493
0.41	0.000	0.714	0.259	0.000	0.000	18.630	0.000	8.907
0.42	0.360	0.663	0.250	0.000	0.000	46.356	0.000	1.531
0.43	0.339	0.676	0.252	0.000	0.000	38.709	0.000	1.894
0.44	0.258	0.298	0.245	0.000	12976.000	-7.984	0.000	1.904
0.45	0.336	0.262	0.244	0.000	622.490	11.647	0.000	1.556
0.46	0.748	0.211	0.238	0.000	315.560	50.158	0.000	0.858
0.47	0.167	0.177	0.236	0.000	220.780	73.495	0.000	2.418
0.48	0.341	0.212	0.239	0.000	137.060	57.980	0.000	1.658
0.49	0.305	0.225	0.244	0.000	91.558	51.971	0.000	1.711
0.50	0.572	0.231	0.235	0.000	62.958	92.888	0.000	1.158
0.51	0.313	0.253	0.246	0.000	50.288	9.627	0.000	1.704
0.52	0.560	0.208	0.241	0.000	41.030	106.020	0.000	1.164
0.53	0.554	0.231	0.247	0.000	31.935	63.466	0.000	1.157
0.54	0.212	0.222	0.248	0.000	27.337	105.590	0.000	2.199
0.55	0.329	0.230	0.253	0.000	24.255	57.593	0.000	1.714
0.56	0.355	0.221	0.256	0.000	20.454	103.640	0.000	1.623
0.57	0.256	0.220	0.260	0.000	18.091	89.135	2.759	2.003
0.58	0.509	0.217	0.259	0.000	18.102	181.010	0.177	1.284
0.59	0.293	0.075	0.246	0.000	22.912	438.080	0.223	1.833
0.60	0.300	-0.039	0.255	0.000	25.955	469.340	0.079	1.800
0.61	0.180	-0.017	0.253	0.000	24.491	912.460	0.000	2.303
0.62	0.311	-0.004	0.256	0.000	27.457	698.650	0.000	1.718
0.63	0.232	-0.015	0.256	0.000	33.143	1164.900	0.000	2.042

wavelength(μm)	Coefficients*							
	a_0	a_1	a_2	a_3	a_4	a_5	a_6	a_7
0.65	0.322	-0.134	0.252	0.000	50.057	949.780	0.000	1.684
0.67	0.176	45.654	0.283	-2.000	66.136	-1289.000	1.248	2.269
0.69	0.255	-0.598	0.239	3.250	119.220	6034.500	-0.409	1.922
0.71	0.273	0.069	0.314	0.000	160.150	0.000	-0.053	1.838
0.73	0.472	-0.057	0.308	0.000	324.700	0.000	0.023	1.385
0.75	0.282	-0.107	0.278	0.000	411.290	0.000	-2.116	1.813
0.77	0.271	1.094	0.290	-4.800	959.800	0.000	-99.450	1.846
0.79	0.131	0.716	0.351	0.000	0.000	0.000	0.560	2.608
0.81	0.237	0.751	0.371	0.000	0.000	0.000	0.035	2.055
0.83	0.392	0.764	0.401	0.000	0.000	0.000	0.051	1.529
0.85	0.168	0.685	0.378	0.000	0.000	0.000	0.041	2.343
0.87	0.426	0.670	0.401	0.000	0.000	0.000	-1.031	1.361
0.89	0.164	0.694	0.399	0.000	0.000	0.000	0.004	2.346
0.91	0.091	0.858	0.454	0.000	0.000	0.000	0.014	3.012
0.93	0.019	1.078	0.452	0.000	0.000	0.000	0.005	4.430
0.95	0.025	1.171	0.501	0.000	0.000	0.000	0.006	4.381

* The values of the coefficients of the proposed model for every 1 nm are available on request.

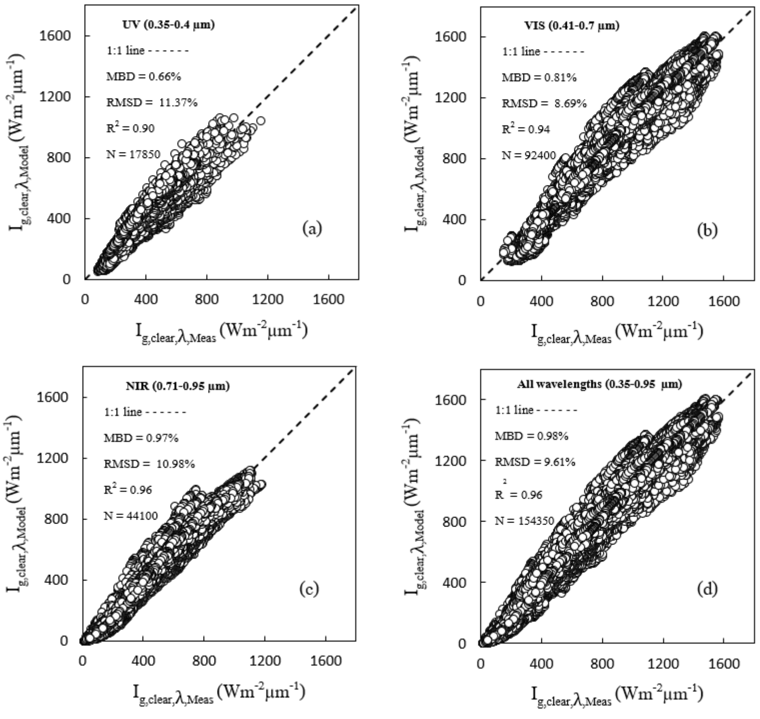

Fig. 2 The comparison result of the spectral values calculated from the model ($I_{g,clear,\lambda,Model}$) and those from the measurements ($I_{g,clear,\lambda,Meas}$); (a) in the ultraviolet wavelengths (UV band), (b) in the visible wavelengths (VIS band), (c) in the near-infrared wavelengths (NIR band), and (d) in all wavelengths. (RMSD = percentage of root mean square difference relative to mean measured value, MBD = percentage of mean bias difference relative to mean measured value, R^2 = coefficient of determination and N = number of data.)

4. Validation of the model

In validating the model, the obtained model (Eq.1) was used to compute the spectral global irradiance under clear sky conditions at the four stations for the year 2021. The results were compared with the spectral from the measurements. The comparison of the spectral values calculated from the model and measurements is shown in Fig. 2. As can be seen, for the UV and NIR wavelengths, the RMSD and MBD are relatively high as the sensitivities of the measurements in these wavelengths are not high. Meanwhile, the VIS wavelengths have the lowest RMSD, which may be due to the fact that there are more data (N= 92400) and the sensitivities of the instrument in these wavelengths are higher than those in UV and NIR wavelengths. However, for the whole data, RMSD and MBD are 9.61% and 0.98%, respectively, and are actually quite low. The comparison for each station is shown in Fig 3. From this figure, it can be clearly seen that the RMSD and MBD values are quite low. Examples of the global spectral solar irradiance from the model and that from the measurements at different times at each monitoring stations are shown in Fig. 4. From Fig. 4, it can be observed that the spectrum from the model agree well with that from the measurements, indicating that the model presents quite accurate solar spectrum values.

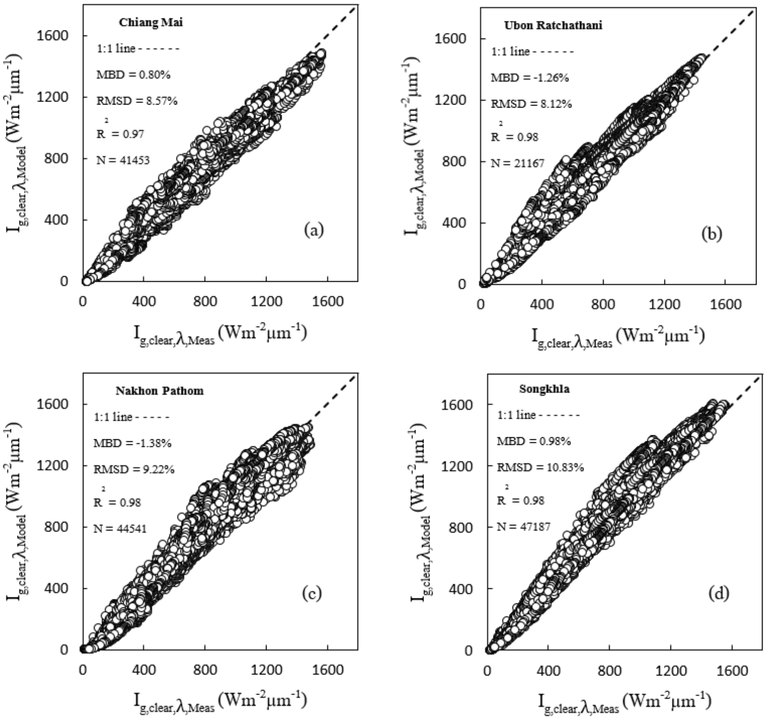

Fig. 3 The comparison of the spectral values calculated from the model ($I_{g,clear,\lambda,Model}$) and measurements ($I_{g,clear,\lambda,Meas}$) at the four stations for the year 2021 for all wavelengths (a) Chiang Mai station, (b) Ubon Ratchathani station, (c) Nakhon Pathom station, and (d) Songkhla station.

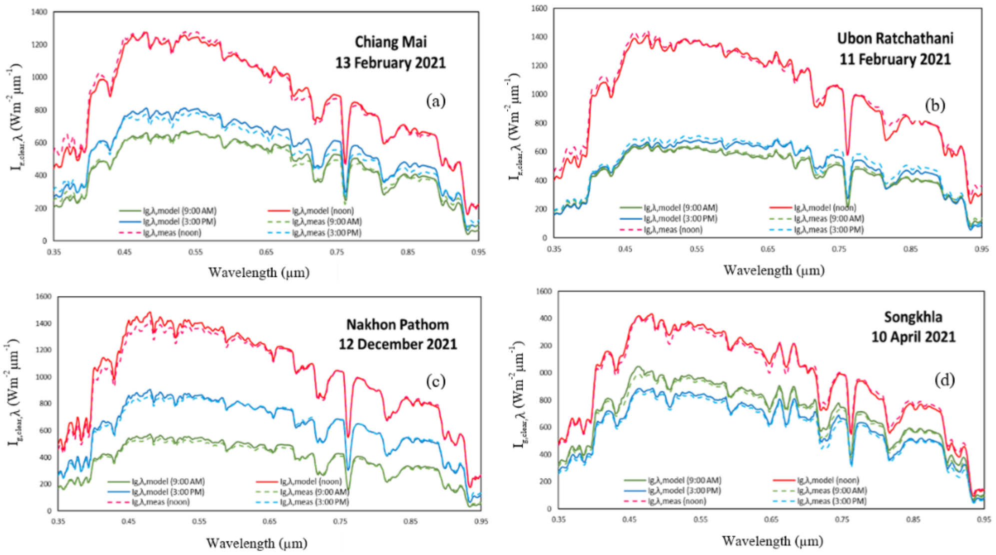

Fig. 4 Examples of spectral global solar irradiance calculated from the model ($I_{g,\lambda,model}$) and the measurement ($I_{g,\lambda,meas}$) at the solar monitoring stations at 9 AM, noon and 3 PM. (a) Chiang Mai station, (b) Ubon Ratchathani station, (c) Nakhon Pathom station, and (d) Songkhla station.

5. Conclusion

A semi-empirical model for calculating spectral global irradiance in Thailand under clear sky conditions was developed in this work. The model expresses the spectrum as an empirical function of various atmospheric constituents namely aerosol optical depth, ozone amount, precipitation water, and the amount of nitrogen dioxide. The model was validated against the independent data and the validation results show good agreement between the spectrum calculated from the model and that obtained from the measurements. The discrepancies in terms of RMSD and MBD reach 9.61% and 0.98%, respectively for the whole data.

Acknowledgments

This study was financially supported by the Silpakorn University Research, Innovation and Creativity Administration Office (SURIC) (formerly named Silpakorn Research and Development Institute). The author and co-authors of this paper would like to thank SURIC for this support.

References

[1] Green, M. A. (1982). *Solar Cells: Operating Principles, Technology and System Applications.* New South Wales, Australia: University of New South Wales.

[2] Duffie, J. A., Beckman, W. A. & Blair N. (2020). *Solar Engineering of Thermal Processes, Photovoltaics and Wind* (5th Edition). New York, United States: Wiley.

[3] Mayer, B. & Kylling, A. (2005). Technical note: The libRadtran software package for radiative transfer calculations - description and examples of use. *Atmospheric Chemistry and Physics, 5*(7), 1855-1877.

[4] Ricchiazzi, P., Yang, S., Gautier C., & Sowle D. (1998). SBDART: a research and teaching software tool for plane-parallel radiative transfer in the earth's atmosphere. *Bulletin of the American Meteorological Society, 79*(10), 2101-2114.

[5] Kneizys, F. X., Shettle, E. P., Abreu, L. W., Chetwynd, J. H., Anderson, G. P., Gallery, W. O., Selby, J. E. A. & Clough, S. A. (1988). *In Users Guide to Lowtran 7*. MA, United States: Air Force Geophysics Laboratory.

[6] Myers, R. D. (2013). *Solar Radiation Practical Modeling for Renewable Energy Applications* (1st Edition). Florida, United States: CRC Press.

[7] Leckner, B. (1978). The spectral distribution of solar radiation at the earth's surface. *Solar Energy, 20*(2), 143-150.

[8] Brine, D. T. & Iqbal M. (1983). Solar spectral diffuse irradiance under cloudless skies. *Solar Energy, 30*(5), 447-453.

[9] Bird, R. E. & Riodan C. (1986). Simple solar spectral model for direct and diffuse irradiance on horizontal and tilted planes at the Earth's surface for cloudless atmospheres. *Journal of Climate and Applied Meteorology, 25*(1), 87–97.

[10] Gueymard, C. A. (2001). Parameterized transmittance model for direct beam and circumsolar spectral irradiance. *Solar Energy, 71*(5), 325–346.

[11] Torres-Ramírez, M., Elizondo, D., García-Domingo, B., Nofuentes, G. & Talavera, D.L. (2015). Modelling the spectral irradiance distribution in sunny inland locations using an ANN-based methodology. *Energy, 86*, 323-334.

[12] Rocco, J. D., Bourke, P. D., Patterson, C. B. & Kider, J. T. (2020). Real-time spectral radiance estimation of hemispherical clear skies with machine learned regression models. *Solar Energy, 204*, 48-63.

[13] Gueymard, C. A. & Kocifaj, M. (2022). Clear-sky spectral radiance modeling under variable aerosol conditions. *Renewable and Sustainable Energy Reviews, 168,* 1-17.

[14] Kittitanadet, P., Masiri, I. & Janjai, S. (2016, June 8-10). *Comparison of direct normal irradiance models under clear sky condition at Nakhon Pathom*, Conference on Energy Network of Thailand (E-NETT), Wangchan Riverview hotel, Phitsanulok, Thailand.

[15] Jacovides, C. D., Kaskaoutis, D. G., Tymvios, F. S. & Asimakopoulos, D. N. (2004). Application of SPTRAL2 parametric model in estimating spectral solar irradiance over polluted Athens atmosphere. *Renewable Energy, 29*, 1109-1119.

[16] Madkour, M. A., El-Metwally, M. & Hamed, A. B. (2006). Comparative study on different models for estimation of direct normal irradiance (DNI) over Egypt atmosphere. *Renewable Energy, 31,* 361-382.

[17] Gueymard, C. A. (2008). Prediction and validation of cloudless shortwave solar spectra incident on horizontal, tilted, or tracking surfaces. *Solar Energy, 82,* 260-271.

[18] Koussa, M., Saheb-Koussa, D. & Hadji, S. (2017). Experimental investigation of simple solar radiation spectral model prefermences under a Mediterranean Algerian's climate. *Energy, 120,*751-773.

[19] Iqbal, M. (1983). *An introduction to solar radiation.* New York, USA: Academic Press.

[20] Gueymard, C. A. (1995). *SMART2, A Simple Model of the Atmospheric Radiative Transfer of Sunshine: Algorithms and performance assessment.* Florida, USA: University of Central Florida

[21] Kasten, F. (1966). A new table and approximation formula for the relative optial air mass. *Archiv für Meteorologie, Geophysik und Bioklimatologie, Serie B, 14*, 206-223.