A NEW MODEL TO ESTIMATE GLOBAL SOLAR RADIATION ON HORIZONTAL SURFACE IN ESKİŞEHİR

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ABSTRACT

Global solar radiation is the key factor for providing information about solar energy availability of the region, therefore, this parameter should be known for efficient planning and projection of solar energy systems. Since the measurement of global solar radiation is not available in many sites, estimation of this parameter has come into prominence in recent years. In this study, global solar radiation on horizontal surface is estimated by using seven daily global solar radiation decomposition (DGSRD) models in Eskişehir. Then, a new DGSRD model is established based on daily clearness index, solar altitude angle, solar hour angle and sunrise hour angle. The considered models are evaluated based on statistical analysis methods. It is observed that the new model has better accuracy than the other considered DGSRD models.

1. INTRODUCTION

With increasing concern on dependence on fossil fuels and environmental issues, alternative energy resources have gathered wide interest in recent years [1]. Since solar energy is known as a sustainable, reliable, environmentally friendly, pollution free and abundant energy source at the Earth's surface, photovoltaic (PV) systems are recommended to be used in electricity generation in place of fossil fuels [2]. Therefore, people are concentrating on studies and applications of PV systems these days to meet increasing energy demands of countries [3].

Global solar radiation data has a crucial role on solar energy conversion systems for optimum design because accurate information on availability of the solar resources for the considered application is generally required [4]. The data received at any point on the globe is necessary in the design phase of the solar technology and accelerates its deployment by reducing the investment decision uncertainty [5]. Despite the considered importance of gathering global solar radiation data, measurement of such data is generally not possible in many meteorological stations because solar radiation data can be measured with a high-cost equipment [6]. Therefore, global solar radiation estimation techniques have come into prominence to obtain relevant data by performing appropriate correlations between measured parameters.

In some solar studies, hourly global solar radiation data on horizontal surfaces are required for the regions where measured daily global solar radiation values are available [7]. At this point, daily global solar radiation decomposition (DGSRD) models are preferred to obtain hourly global solar radiation values from the measured daily global solar radiation values on horizontal surface. The existing DGSRD models are divided into three main groups [8]. The first kind of models considers the solar hour angle, day length and solar time [9-14]. The second kind of models assumes that there is a random variation in weather conditions and axial symmetric distribution between hourly global solar radiation of morning and afternoon times [15-18]. Finally, the third kind of models completely considers neither the variability of hourly solar radiation, nor the randomness of weather conditions [19].

In this study, hourly global solar radiation values on horizontal surface are estimated by using seven different DGSRD models for seven months in Anadolu University İki Eylül Campus. Then, a new DGSRD model is established by modifying the first group models. Within the scope of this aim, Curve Fitting toolbox of Matlab is used to fit the measured data. The measured values of global solar radiation are obtained from the first-class pyranometer placed in Renewable Energy Research Home (RERH) as actual photo given in Figure 1.

Fig. 1. RERH placed in Anadolu University İki Eylül Campus.

The parameters of the pyranometer used in the PV system to measure the global solar radiation values are given in Table 1.

Table 1. Datasheet values of the pyranometer.

ISO 9060 classification	First class
Response time 95 % (sec)	18
Sensitivity (μV/W.m^{-2})	Approx. 7~14
Impedance (Ω)	Approx. 20~140
Operating temperature range (°C)	-40 to +80
Irradiance range (W/m^2)	0 - 4000
Wavelength range (nm)	285 to 3000

2. DGSRD MODELS

Global solar radiation is a primary driver for solar energy applications because electricity generation from PV panel is directly affected by solar radiation [20]. Unfortunately, there are no continuous local solar radiation data due to the limited number of recording stations, cost and maintenance of devices in most cases [21]. Thus, when hourly global solar radiation values are needed, DGSRD models can be used to obtain hourly global solar radiation values from the daily global solar radiation values. At that point, choosing the appropriate DGSRD models for the considered region is vital to perform an efficient global solar radiation estimation.

2.1. Selected Models

In this study, Whillier [9], CPR [11], CPRG [12], Gueymard [14], Jain [15], Baig et al. [17] and Shazly [18] models are selected to estimate hourly global solar radiation values from the daily value for the considered region. Among these models, Whillier, CPR, CPRG and Gueymard models are included in the first group models. In addition, Jain, Baig et al. and Shazly models are considered in the second group models. The mathematical expressions of the considered models are shown in Table 2.

2.2. New Model Proposed by Modifying Whillier Model

In Whillier model, the formula to calculate hourly solar radiation from daily values is given as:

$$\frac{I}{H} = \frac{\pi}{24} \cdot \frac{\frac{24}{\pi}\sin\frac{\pi}{24}\cos W - \cos W_s}{\sin W_s - \frac{\pi W_s}{180}\cos W_s} \cdot \frac{k_t}{K_t} \qquad (1)$$

The ratio of clearness indexes (k_t /K_t) is constant in the assumption of Whillier model. This assumption is reasonable on overcast days, but there will be larger errors on clear days and partly cloudy days. Therefore, it is necessary to introduce a correction term to explain the complex weather conditions.

The hourly clearness index (k_t) can be related to the solar hour angle (W), solar altitude angle (h), solar azimuth angle (α) and temperature (t). As an initial case, correction factor is defined as:

$$\frac{k_t}{K_t} = x + y \cdot \cos W \qquad (2)$$

where

$$x = a + b \cdot \sin(W_s - 60^\circ)$$
$$y = c - d \cdot \sin(W_s - 60^\circ) \qquad (3)$$

Also, a shifting term is added to newly proposed model to increase the accuracy. Shifting term depends on h and K_t such as:

$$\Gamma(h, K_t) = e \cdot \sin(h) + f \cdot K_t$$
(4)

Then, the proposed model is obtained as:

$$\frac{I}{H} = Ratio \cdot \left(x + y \cdot \cos W\right) + \Gamma(h, K_t) \qquad (5)$$

where

$$Ratio = \frac{\pi}{24} \cdot \frac{\frac{24}{\pi}\sin\frac{\pi}{24}\cos W - \cos W_s}{\sin W_s - \frac{\pi W_s}{180}\cos W_s} \quad (6)$$

Table 2. The selected DGSRD models to estimate hourly global solar radiation values in İki Eylül Campus of Eskişehir.

Model Name	Mathematical Expression	
Whillier Model	$\frac{I}{H} = \frac{\pi}{24} \cdot \frac{\frac{24}{\pi}\sin\frac{\pi}{24}\cos W - \cos W_s}{\sin W_s - \frac{\pi W_s}{180}\cos W_s}$	(7)
CPR Model	$\frac{I}{H} = \frac{\pi}{24} \frac{(a + b\cos W)(\cos W - \cos W_s)}{\sin W_s - \frac{\pi W_s}{180}\cos W_s}$	(8)
CPRG Model	$\frac{I}{H} = \frac{(a + b\cos W)r_o}{a + 0.5 \cdot b \cdot \frac{\frac{\pi W_s}{180} - \sin W_s \cos W_s}{\sin W_s - \frac{\pi W_s}{180}\cos W_s}}$	(9)
Gueymard Model	$\frac{I}{H} = r_o \frac{1 + q\left(\frac{a_2}{a_1}\right)\left(\frac{24}{\pi}\right)\left(\sin W_s - \frac{\pi W_s}{180}\cos W_s\right)r_o}{1 + q\left(\frac{a_2}{a_1}\right)\frac{\frac{\pi W_s}{180}\left(0.5 + \cos^2 W_s\right) - 0.75\sin 2W_s}{\sin W_s - \frac{\pi W_s}{180}\cos W_s}}$	(10)
Jain Model	$\frac{I}{H} = \frac{1}{(0.192S_0 + 0.461)\sqrt{2\pi}}\exp\left(-\frac{(t_s - 12)^2}{2(0.192S_0 + 0.461)^2}\right)$	(11)
Baig et al. Model	$\frac{I}{H} = \frac{1}{2(0.21S_0 + 0.26)\sqrt{2\pi}}\left(\exp\left(-\frac{(t_s - 12)^2}{2(0.21S_0 + 0.26)^2}\right) + \cos\left(\frac{\pi(t_s - 12)}{S_0 - 1}\right)\right)$	(12)
Shazly Model	$\frac{I}{H} = \frac{1}{2.2(0.174S_0 + 0.768)\sqrt{2\pi}}\left(\exp\left(-\frac{(t_s - 12)^2}{2(0.174S_0 + 0.768)^2}\right) + 1.2\cos\left(\frac{\pi(t_s - 12)}{S_0 - 0.65}\right)\right)$	(13)

The parameters of the new model are obtained by using Curve Fitting toolbox of Matlab. As a result, these parameters are found as shown; $a = 0.4937$, $b = 0.7097$, $c = 0.6327$, d = 0.5056, $e = -0.01914$ and $f = -0.2329$.

3. SIMULATION AND RESULTS

The selected and new DGSRD models are performed to estimate hourly global solar radiation values from the measured daily global solar radiation values from March to September of 2016. The accuracy of the DGSRD models is evaluated by using some statistical analysis methods. These analysis methods are shown as:

$$MAE = \frac{1}{n}\sum_{i=1}^{n}\left(\left|c_i - m_i\right|\right) \quad (14)$$

$$\%rMAE = \frac{\sum_{i=1}^{n}\left(\left|c_i - m_i\right|\right)}{\sum_{i=1}^{n} m_i} \cdot 100 \quad (15)$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(c_i - m_i\right)^2} \quad (16)$$

$$\%rRMSE = \sqrt{\frac{\sum_{i=1}^{n}\left(c_i - m_i\right)^2}{\sum_{i=1}^{n}\left(c_i\right)^2}} \cdot 100 \quad (17)$$

where c_i is the i^{th} calculated global solar radiation data, m_i is the i^{th} measured global solar radiation data and n is the number of data. The accuracy of the considered models is obtained by considering measured hourly global solar radiation values obtained from the pyranometer placed in RERH. The results are shown in Table 3. Table 3 indicates that the new model has the lowest MAE, RMSE, %rMAE and %rRMSE values, which results in the highest accuracy. When MAE values are considered, the new model is followed by CPR and then Baig et al. models in terms of accuracy. In addition, RMSE values show that the second and third highest accuracy belongs to CPRG and CPR models respectively. Finally, according to Table 3, it is concluded that Whillier model has the lowest accuracy due to having the highest statistical analysis values in each case.

Comparison of the new and considered DGSRD models based on % rMAE and % rRMSE values is seen in Figure 2 and Figure 3 respectively. These figures indicate that the new model performs better than the considered seven DGSRD models. It is analysed that the estimated values of CPR, CPRG and Baig et al. models are very close to each other, which causes that all these models follow the new model closely in terms of accuracy. However, Whillier and Jain models have the lowest accuracy with much higher statistical results than the other considered DGSRD values. Therefore, we recommend our new model to be performed to estimate hourly global solar radiation for the regions that have similar climatic conditions with the considered region.

Table 3. The accuracy of the considered DGSRD models.

Stat. Method	**Whillier Model**	**CPR Model**	**CPRG Model**	**Gueymard Model**	**Jain Model**	**Baig et al. Model**	**Shazly Model**	**New Model**
MAE	49.3799	44.7884	44.8096	45.0296	47.2885	44.8089	45.3157	44.7067
RMSE	83.5327	77.4664	77.4392	77.6730	82.4604	77.6511	78.1722	77.3370
% rMAE	19.1977	17.4127	17.4209	17.5065	18.3847	17.4207	17.6177	21.8072
% rRMSE	19.9748	18.5242	18.5177	18.5736	19.7184	18.5684	18.6930	18.4933

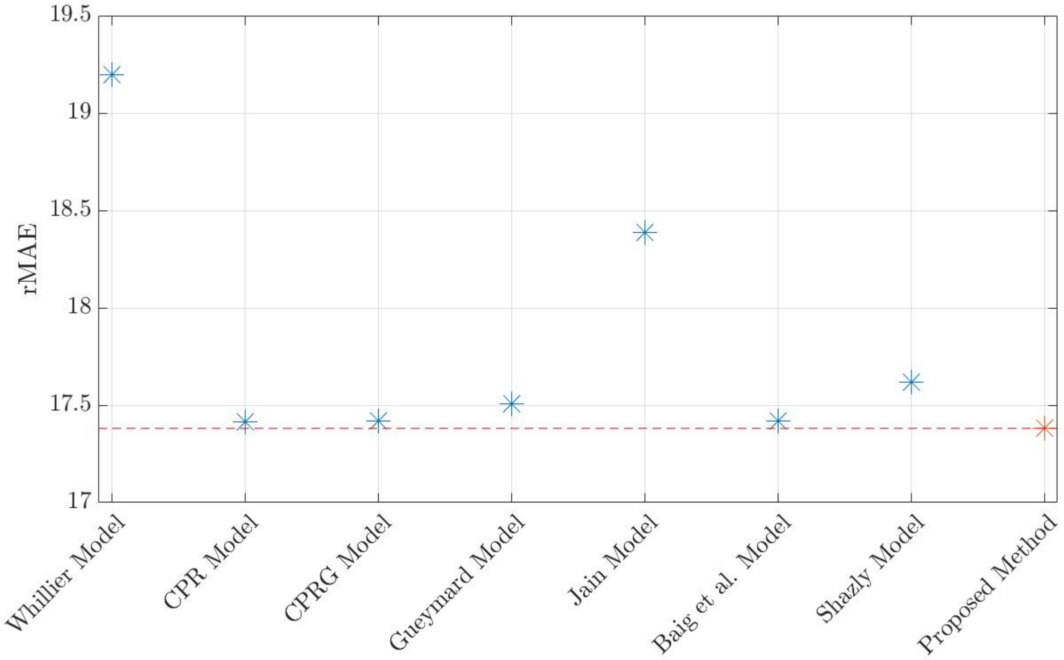

Figure 2. Comparison of the new and considered DGSRD models based on % rMAE values.

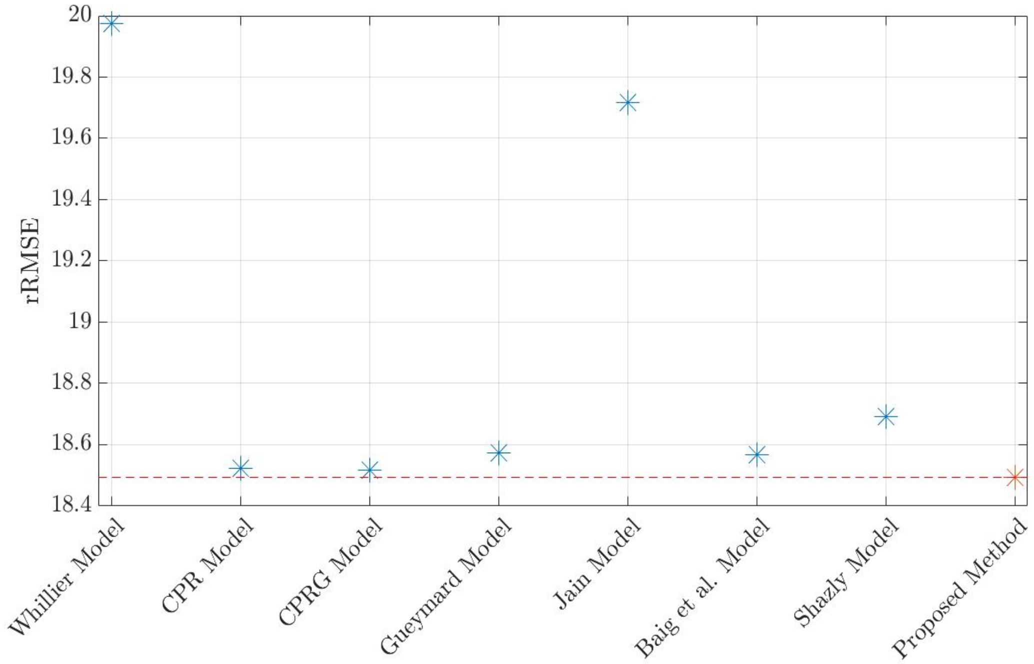

Figure 3. Comparison of the new and considered DGSRD models based on % rRMSE values.

Figure 4 and Figure 5 shows the estimated hourly global solar radiation values of the DGSRD models for a day in March and August respectively.

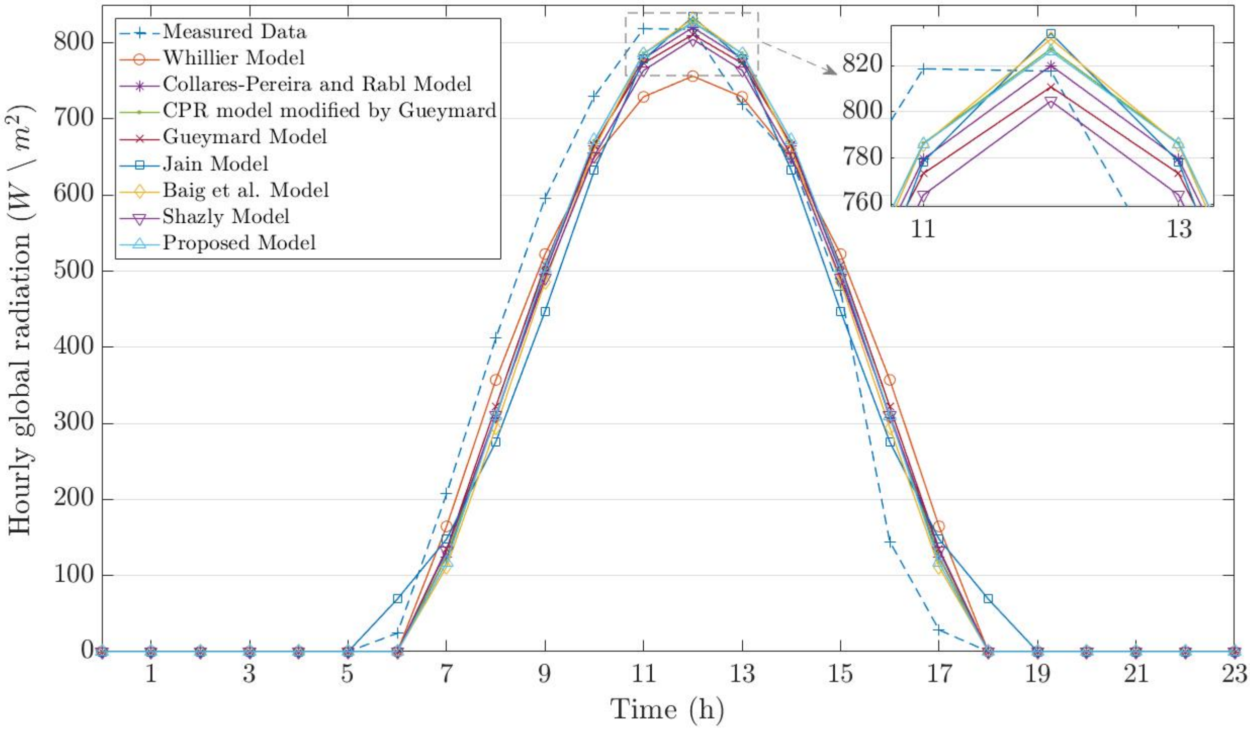

Figure 4. Estimated hourly global solar radiation values of DGSRD models for a day in March.

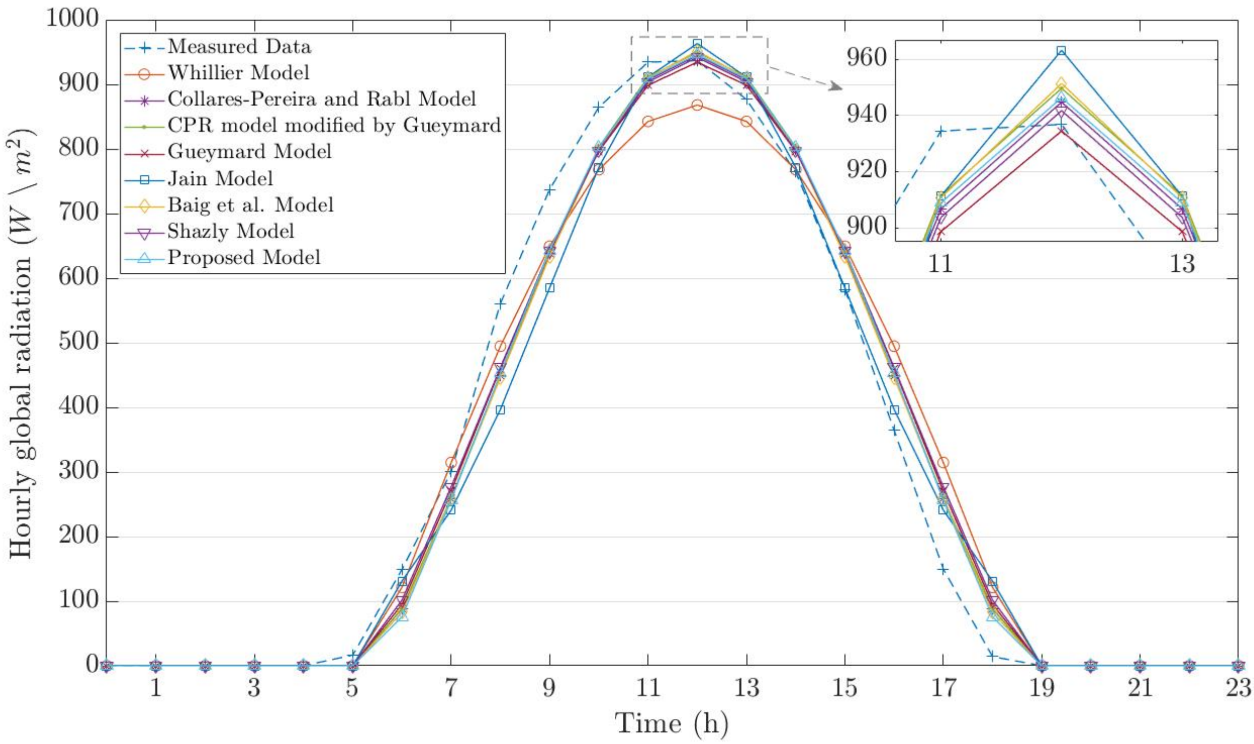

Figure 5. Estimated hourly global solar radiation values of DGSRD values for a day in August.

4. CONCLUSION

In this study, the selected DGSRD models are performed to obtain hourly global solar radiation values from the measured daily global solar radiation values in Anadolu University İki Eylül Campus. Then, a new model is established by modifying Whillier model. The accuracy of the models is evaluated by using statistical analysis methods. The results indicate that our new model has higher accuracy than the other selected models for the considered region.

Therefore, this new model can be used to estimate hourly global solar radiation values in similar regions.

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Nomenclature

I	Hourly global solar radiation on horizontal surface (W/m^2)
H	Daily global solar radiation on horizontal surface (W/m^2)
I/H	Ratio of hourly to daily global solar radiation on horizontal surface (unitless)
W	Solar hour angle (degree)
W_s	Sunrise hour angle (degree)
k_t	Hourly clearness index (unitless)
K_t	Daily clearness index (unitless)
h	Solar altitude angle (degree)
S_0	Day length (hour)
t_s	Solar time (hour)
MAE	Mean absolute error (W/m^2)
$rMAE$	Relative mean absolute error (%)
$RMSE$	Root mean square error (W/m^2)
$rRMSE$	Relative root mean square error (%)

References

[1] Ayvazoğluyüksel, Ö. and Başaran Filik, Ü., Power output forecasting of a solar house by considering different cell temperature methods, 10th International Conference on Electrical and Electronics Engineering, Bursa, 2017.

[2] Bayrakçı, H. C., Demircan, C. and Keçebaş A., The development of empirical models for estimating global solar radiation on horizontal surface: A case study, *Renewable and Sustainable Energy Reviews*, Vol. 81, 2018, pp. 2771-2782.

[3] Ayvazoğluyüksel, Ö. and Başaran Filik, Ü., Estimation of monthly average hourly global solar radiation from the daily value in Çanakkale, Turkey, *Journal of Clean Energy Technologies*, Vol. 5, No. 5, 2017, pp. 389-393.

[4] Yıldırım, H. B., Çelik, Ö., Teke, A. and Barutçu, B., Estimating daily global solar radiation with graphical user interface in Eastern Mediterranean region of Turkey, *Renewable and Sustainable Energy Reviews*, Vol. 82, 2018, pp. 1528-1537.

[5] Sengupta, M., Habte, A., Kurtz, S. et al., *Best practices handbook for the collection and use of solar resource data for solar energy applications*, Technical Report NREL/TP-5D00-63112, 2015.

[6] Loghmari, I., Timoumi, Y. and Messadi, A., Performance comparison of two global solar radiation models for spatial interpolation purposes, *Renewable and Sustainable Energy Reviews*, Vol. 82, 2018, pp. 837-844.

[7] Wan Nik, W. B., Ibrahim, M. Z., Samo, K. B. and Muzathik, A. M., Monthly mean hourly global solar radiation estimation, *Solar Energy*, Vol. 86, 2012, pp. 379-387.

[8] Yao, W., Li, Z., Xiu, T., Lu, Y. and Li, X., New decomposition models to estimate hourly global solar radiation from the daily value, *Solar Energy*, Vol. 120, 2015, pp. 87-99.

[9] Whillier, A., The determination of hourly values of total solar radiation from daily summations, *Archiv für Meteorologie, Geophysik und Bioklimatologie*, Vol. 7, 1956, pp. 197 - 204.

[10] Liu, B. Y. H. and Jordan, R. C., The interrelationship and characteristic distribution of direct, diffuse and total solar radiation, *Solar Energy*, Vol. 4, No. 3, 1960, pp. 1-19.

[11] Collares-Pereira, M. and Rabl, A., The average distribution of solar radiation-correlations between diffuse and hemispherical and between daily and hourly insolation values, *Solar Energy*, Vol. 22, No. 2, 1979, pp. 155-164.

[12] Gueymard, C., Mean daily averages of beam radiation received by tilted surfaces as affected by the atmosphere, *Solar Energy*, Vol. 37, No. 4, 1986, pp. 261-267.

[13] Garg, H. P. and Garg, S. N., Improved correlation of daily and hourly diffuse radiation with global radiation for Indian

stations, *Solar & Technology*, Vol. 4, No. 2, 1987, pp. 113-126.
[14] Gueymard, C., Prediction and performance assessment of mean hourly global radiation, *Solar Energy*, Vol. 68, No. 3, 2000, pp. 285-303.
[15] Jain, P. C., Comparison of techniques for the estimation of daily global irradiation and a new technique for the estimation of hourly global irradiation, *Solar & Wind Technology*, Vol. 1, No. 2, 1984, pp. 123-134.
[16] Jain, P. C., Estimation of monthly average hourly global and diffuse irradiation, *Solar & Wind Technology*, Vol. 5, 1988, pp. 7-14.
[17] Baig, A., Akhter, P. and Mufti, A., A novel approach to estimate the clear day global radiation, *Renewable Energy*, Vol. 1, No. 1, 1991, pp. 119-123.
[18] Shazly, S. M. E., Estimation of hourly and daily global solar radiation at clear days using an approach based on modified version of Gaussian distribution, *Advances in Atmospheric Sciences*, Vol. 13, No. 3, 1996, pp. 349-358.
[19] Newell, T. A., Simple models for hourly to daily radiation ratio correlations, *Solar Energy*, Vol. 31, No. 3, 1983, pp. 339-342.
[20] Besharat, F., Dehghan, A. A. and Faghih A. R., Empirical models for estimating global solar radiation: A review and case study, *Renewable and Sustainable Energy Reviews*, Vol. 21, 2013, pp. 798-821.
[21] Gairaa K., Khellaf, A., Messlem, Y. and Chellali, F., Estimation of the daily global solar radiation based on Box-Jenkins and ANN models: A combined approach, *Renewable and Sustainable Energy Reviews*, Vol. 57, 2016, pp. 238-249.