British Journal of Applied Science & Technology
11(2): 1-8, 2015, Article no.BJAST.19129
ISSN: 2231-0843

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Comparison of Empirical Models for the Estimation of Monthly Global Solar Radiation at Nigde in Turkey

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Authors' contributions

This work was carried out in collaboration between all authors. Author AK designed the study, performed the statistical analysis, wrote the protocol, and wrote the first draft of the manuscript and managed literature searches. Authors MG and AG managed the analyses of the study and literature searches. All authors read and approved the final manuscript.

Article Information

DOI: 10.9734/BJAST/2015/19129
Editor(s):
(1) Vijay Kumar Thakur, School of Mechanical and Materials Engineering, Washington State University, USA.
(2) Singiresu S. Rao, Prof. at Department of Mechanical and Aerospace Engineering, University of Miami, Coral Gables, USA.
Reviewers:
(1) Anonymous, Mohamed Premier University, Morocco.
(2) Anonymous, University of Malaya, Malaysia.
(3) Antipas T. S. Massawe, Department of Chemical & Mining Engineering, University of Dar es Salaam, Tanzania.
(4) Shahzad Sultan, Chinese University of Hong Kong, China.
Complete Peer review History: http://sciencedomain.org/review-history/10455

Original Research Article

Received 26th May 2015
Accepted 31st July 2015
Published 9th August 2015

ABSTRACT

Aims: Comprehension of the local solar radiation is important for many applications of solar energy systems. The global solar radiation on horizontal surface at the location of interest is the most critical input parameter employed in the design and prediction of the performance of solar energy systems.

Study Design: In this study, 3 empirical sunshine based models are compared correlating the monthly mean daily global solar radiation on a horizontal surface with monthly mean sunshine records for Nigde, Turkey

Place and Duration of Study: Department of Mechanical Engineering, Akdeniz University and Nigde University, 2014-2015

Methodology: Models are compared using coefficient of determination (R^2), the root mean square error (RMSE), the mean bias error (MBE) and the t-statistic.

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Results: The results show that the models fitted the data satisfactorily.
Conclusion: The models can be utilized to estimate the specific global solar radiation on monthly basis.

Keywords: Global solar radiation; Sunshine method; statistical parameter; t-statistic.

1. INTRODUCTION

One of the most important renewable energy sources is solar energy which is considered to be a safe, effective and economic energy resource, as it has the potential to be one of the major energy sources in the near future. There are quite a lot of factors that affect the amount of solar energy (or solar radiation) available on the earth's surface which depend on astronomical, physical, meteorological and geographical parameters such as extraterrestrial radiation, atmospheric transmittance, latitude, inverse relative distance between the Earth and the Sun, sunset hour angle, the actual duration of sunshine, relative humidity, ambient temperature and cloudiness at relevant locations [1].

For the optimal design and prediction of the solar system performance, and the design and selection of solar energy conversion systems, the knowledge of accurate global solar radiation data is extremely important [1]. In spite of the importance of solar radiation measurements; cost, maintenance, and calibration requirements of the measuring equipment make it difficult to attain necessary information. In places where no measured values are available, a common application has been to determinate this parameter by appropriate correlations which are empirically established using the measured data [2]. Several empirical formulas have been developed to calculate the global solar radiation based on three main parameters; sunshine hours, temperature-based models, and cloud-based models [1].

Based on sunshine records, there are many studies published about estimation of monthly mean global solar radiation for different regions of the world in the literature [3-6]. The first correlation for estimating monthly mean daily global solar radiation on horizontal surface was carried out by Angstrom [7] this regression equation related monthly average daily radiation to clear day radiation in a given location and average fraction of possible sunshine hours. In order to overcome the difficulty in obtaining the clear day solar radiation data, Prescott [8] suggested using the extraterrestrial radiation to replace it, and the modification in this way resulted in the formation of the Angstrom-Prescott method, which has been the most convenient and widely used correlation for estimation of solar radiation based on sunshine duration. Following this, numerous empirical models have been derived from this model to estimate monthly mean daily radiation from commonly observed meteorological data [1].

Besharat et al. [9] collected and reviewed empirical models available in the literature for estimating global solar radiation in order to classify them into four categories, i.e., sunshine-based, cloud-based, temperature-based and other meteorological parameter-based models.

The objective of this study is to figure out and examine in contrast various models for the estimation of the monthly average daily global radiation on a horizontal surface from bright sunshine hours and to select the most appropriate model for Nigde. In this study, 3 empirical sunshine based models are compared by using 4 statistical methods correlating the monthly mean daily global solar radiation on a horizontal surface with monthly mean sunshine records for Nigde, Turkey. For this purpose, models are compared using coefficient of determination (R^2), the root mean square error (RMSE), the mean bias error (MBE) and the t-statistic. The values of the monthly average daily global radiation on a horizontal surface used in the present study are taken from Turkish State Meteorological Service (TSMS) in the periods between 2001 and 2010.

2. MATERIALS AND METHODS

The most commonly used parameter for estimating global solar radiation is sunshine duration, and the previous studies have indicated that the models based on sunshine hours can provide more accurate estimations of solar radiation than those based on air temperature [10,11]. Consequently, this study mainly focused on the sunshine based models. It must be noted that the models based on air temperature may be used in case of location without sunshine data measurement.

The regression models proposed in the literature are given in Table 1. The correlation models in Table 1, are the most acceptable and widely used correlation for the estimation of solar radiation based on sunshine duration.

Table 1. Regression models proposed in the literature

Models	Mod. no.	Regression equation
Logarithmic	1	$H/H_0 = a + b \cdot \log\left(S/S_0\right)$
Exponential	2	$H/H_0 = a + b \cdot \exp\left(S/S_0\right)$
Exponent	3	$H/H_0 = a\left(S/S_0\right)^b$

The other required parameters such as extraterrestrial radiation and maximum possible sunshine hours are worked out using the standard following relations Duzen and Aydin [12];

$$H_0 = (\frac{24x60}{\pi})I_{SC}d_r[\cos(\varphi)\cos(\delta)\sin(\omega_s) + \omega_s \sin(\varphi)\sin(\delta)] \quad (1)$$

$$d_r = 1 + 0.033\cos(\frac{2\pi}{365}J) \quad (2)$$

$$\delta = 0.4093\sin\left[\frac{2\pi}{365}(248 + J)\right] \quad (3)$$

$$\omega_s = \arccos[-\tan(\varphi)\tan(\delta)] \quad (4)$$

Where d_r relative earth-sun distance, δ solar declination (rad), ω_s sunset hour angle (rad), φ latitude (rad), and J is the number of days of the year starting from the first of January, I_{sc} is the solar constant as 0.082 MJ/m^2/min (1367 W/m^2) [12].

For a given month, the monthly average day length (S_o) can be computed by using the following equation [2]:

$$S_o = \frac{2\omega_s}{15} \quad (5)$$

In this study, three regression models based on sunshine duration are examined and validated to predict monthly mean daily global solar radiation on a horizontal surface, and are listed in Table 2.

Table 2. Regression results and R^2

Models	Regression equation	R^2
Logarithmic	$H/H_0 = 0.7463 + 0.1848 \cdot \log\left(S/S_0\right)$	0.9382
Exponential	$H/H_0 = 0.4857 + 0.4694 \cdot \exp\left(S/S_0\right)$	0.9483
Exponent	$H/H_0 = 0.7513\left(S/S_0\right)^{0.2836}$	0.9402

2.1 Model Evaluation

The relative ability of the different models to predict the global radiation on horizontal surfaces is tested. The performance of the individual models is determined by utilizing different statistical methods. There are a lot of studies in literature, which deal with the evaluation and comparison of solar radiation estimation models. In this study, in order to evaluate the efficiency and accuracy of the estimated data, the following statistical estimators are used; MBE, RMSE, the correlation coefficient (R^2), and t-statistic to test the linear relationship between predicted and measured values.

The MBE provides information on the long-term performance of a model. A low MBE value is more desirable. A negative value gives the average amount of underestimation in the calculated value. So, one handicap of MBE is that overestimation of an individual observation may cancel underestimation in a separate observation. The value of RMSE is always positive, representing zero in the ideal case. The normalized RMSE gives information on the short-term performance of the correlations by allowing a term-by term comparison of the actual deviation between the predicted and measured values. The smaller the value, the better the model's performance is. The coefficient of determination (R^2) can be used to test determining the linear relation between calculated and measured values, and the correlation coefficient, R^2, should approach to 1. The t-statistic is given as a function of widely used root mean square error and mean bias error. In this paper, we used the t-statistic test in conjunction with the RMSE and MBE errors, for the evaluation and comparison of models, assuming that the smaller the value of t, the better the model performance is. To determine the significance of a model statistically, the absolute value of the calculated t must be less than the critical t value, taken from standard statistical tables.

These performance indices are calculated using the following equations:

$$R^2 = \frac{\sum_{i=1}^{n}(Y_{i,m} - Y_{i,c})^2}{\sum_{i=1}^{n}(Y_{i,m} - \overline{Y}_{i,c})^2} \tag{6}$$

$$MBE = \frac{1}{n}\sum_{i=1}^{n}(Y_{i,m} - Y_{i,c}) \tag{7}$$

$$RMSE = \frac{1}{n}\sqrt{\sum_{i=1}^{n}(Y_{i,m} - Y_{i,c})^{2}} \tag{8}$$

$$t = \sqrt{\frac{(n-1)MBE^2}{RMSE^2 - MBE^2}} \tag{9}$$

where $Y_{i,m}$, $Y_{i,c}$, $\overline{Y}_{i,c}$ and n are the measured clearness index $\left({H_m}/{H_0}\right)$, calculated clearness index $\left({H_c}/{H_0}\right)$, the average of the measured clearness index and the number of observations respectively.

2.2 Observed Climate Data

Turkey lies in a sunny belt between 36° and 42°N latitudes and is geographically well situated with respect to solar energy potential. Nigde situated in the Central Anatolia Region of Turkey. Nigde is situated on the borderline of a semi-arid cold climate and a dry-summer continental climate. Nigde lies on the borderline between a cold semi-arid climate and a dry-summer continental climate. Nigde has hot and dry summers and cold and snowy winters. The climate in the mentioned city could be described as having dry and hot summers and cold, snowy winters Most of the precipitation is during late spring. The rainy season is spring. In this study, the measured global radiation data (MJ/m^2 day) as well as the sunshine duration (h), are obtained from TSMS. Solar data measured by the TSMS in the years of 2001-2010 for a sunny site in Turkey are used (Fig. 1). The measurements are taken using the pyranometer. Solar map of Nigde has shown in Fig. 2. Nigde's yearly average total sunshine duration to be 2759 h and the yearly average solar radiation is 1935 kWh/m^2 yr (5.3 kWh/m^2 day). Detailed geography, and the time period from which data were used for establishing the models are given in Table 3.

The monthly average daily extraterrestrial radiation (H_o) and maximum possible sunshine duration (S_o) for each month of the Nigde city in Turkey are calculated from the fundamental mathematical expressions.

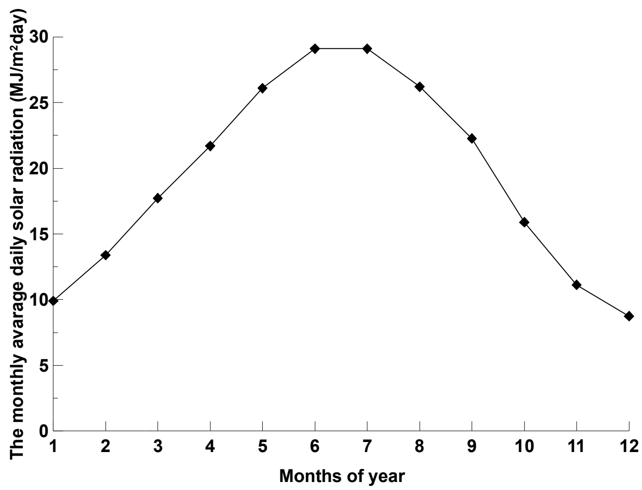

Fig. 1. The measured monthly mean daily global solar radiation in Nigde

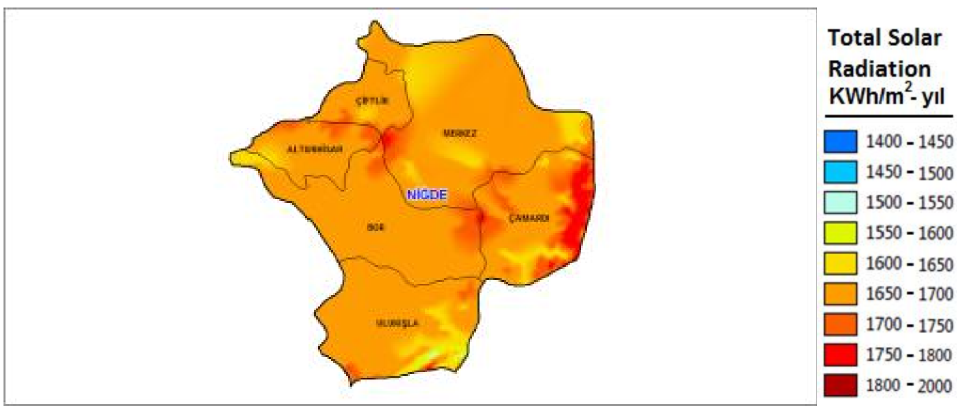

Fig. 2. Solar Map of Nigde, Turkey

Table 3. Geographic and data records period of the Nigde station

Site	Latitude(N)	Longitude(E)	Altitude(m)	Average Sunshine Duration (h/day)	Data series for evaluating model
Nigde	37.59	34.42	1250	7.6	2001/2010

3. RESULTS AND DISCUSSION

Three empirical sunshine based models are compared correlating the monthly mean daily global solar radiation on a horizontal surface with monthly mean sunshine records for Nigde, Turkey. Models are compared using coefficient of determination (R^2), the root mean square error (RMSE), the mean bias error (MBE) and the t-statistic.

As shown in Table 2, the highest coefficient of determination (R^2) of the calculated and measured clearness index (H/Ho) at the Nigde station is obtained as 0.9483 with exponential regression model, while the lowest value of correlation coefficient acquired by logarithmic regression as 0.9382.

For Nigde the best result in sunshine based models is acquired for exponent model, the ideal values of statistical tests such as MBE, and RMSE are 0. In this study the lowest values of the MBE, and RMSE are derived by the exponent regression model as -0,0977, and 0,3547, respectively for the Nigde station (Table 4).

Table 4. The MBE, RMSE, and t-statistic values of the equations developed

		Jan.	Feb.	March	April	May	June	July	August	Sept.	Oct.	Nov.	Dec.
MBE	Logarithmic	-0.2229	-0.6142	0.0146	0.6597	0.4907	0.1676	-0.0743	0.1326	-0.5935	-0.0765	0.2054	0.0471
	Exponential	-0.0471	-0.4163	-0.1608	0.4729	0.2169	0.2297	0.2297	0.8525	0.3809	0.3809	-0.2163	0.1136
	Exponent	-0.1736	-0.5569	-0.0977	0.6160	0.4262	0.1696	-0.0319	0.1706	-0.5841	-0.1101	0.1841	0.1099
RMSE	Logarithmic	0.6353	0.9848	0.6154	1.2014	0.8364	1.2067	1.2706	0.8015	1.0732	0.4828	0.3567	0.4336
	Exponential	0.7624	1.0608	0.6733	1.1864	0.7035	1.1121	1.3523	0.8578	0.9438	0.5234	0.3629	0.6043
	Exponent	0.6619	0.9901	0.6287	1.1944	0.7984	1.1852	1.2430	0.8034	1.0516	0.4887	0.3547	0.4554
t-statistic	Logarithmic	1,12403	2,39361	0,07119	1,97108	2,17338	0,42075	0,17573	0,50325	1,991262	0,48143	2,11298	0,327816
	Exponential	0,18569	1,28000	0,73782	1,30386	0,97231	0,63329	0,51709	26,86220	1,32330	3,18323	2,22688	0,57420
	Exponent	0,81537	2,04084	0,47193	1,80593	1,89387	0,43376	0,07702	0,65191	2,00385	0,69371	1,82168	0,74603

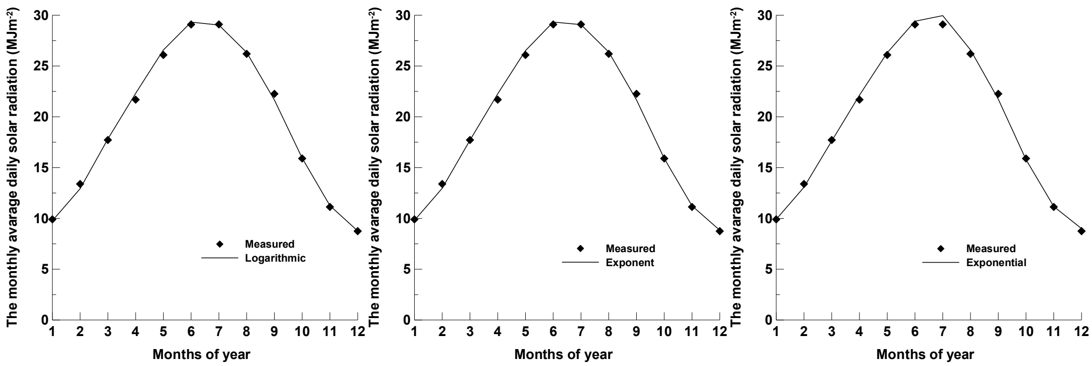

Fig. 3. Comparison of empirical models with measured values

For all three models in each month, t statistics are calculated (Table 4). The best performance can be found by selecting the lowest t values. For logarithmic model, March, June and July were the months with best performance and February, May and November with the worst. For the exponential model, January, July and December are the months with best performance and August, October and November with the worst. For exponent model, March, June and July were the months with best performance and February, September and November with the worst. Comparing the results in terms of t-statistic, the logarithmic and exponent models give generally the best results while the exponential model exhibits worse performance than the other models.

A general comparison of the results reveal that all the regression equations gave very good results. (Fig. 3 above) The third degree and exponent models gave the best estimate and have smaller errors for the monthly values. The logarithmic model performed worse than the other models, giving the largest t-statistic error.

4. CONCLUSION

In this study, 3 empirical sunshine based models are compared correlating the monthly mean daily global solar radiation on a horizontal surface with monthly mean sunshine records for Nigde, Turkey. A general comparison of the results reveal that all the regression equations gave very good results. The results of this study also show that the t-statistic is used as the best indicator; this indicator depends on both, and is more effective for determining the model performance. The agreement between the estimated and the measured data were noteworthy and the method was recommended for use in Nigde, Turkey.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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