Comparison of Sunshine Based Models for Estimating Global Solar Radiation in Uyo, Nigeria

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Abstract: A comparison has been made using sunshine hours of the monthly average daily global solar radiation in Uyo (Longitude 05.02^{o}N, Latitude 7.55^{o}E) using six different sunshine-based models. The values of the measured and the estimated global solar radiation models were tested using the root mean square error (RMSE), the mean bias error (MBE) and the mean percentage error (MPE); coefficient of determination, R^2 and correlation coefficient, r were also calculated. From the results obtained, Fagbenle's Model is most suitable for estimating monthly average daily global solar radiation for Uyo and other locations with similar geographic and climatic conditions. The maximum and minimum values of the monthly average daily global solar radiation on a horizontal surface in Uyo are 16.25MJm^{-2}day^{-1} and 10.36MJm^{-2}day^{-1} respectively, while the total global solar radiation is 169.75MJm^{-2}day^{-1}. The study, design and utilization of solar energy conversion devices depend to a greater extend on the monthly average daily global solar radiation data so determined.

Key words: Global solar radiation, sunshine-based models, energy conversion, climatic conditions

1. Introduction

A good working knowledge of the global solar radiation for a particular location is essential for proper prediction, design and the study of the performance of the solar energy systems to be installed in that geographic location. The global solar radiation data for a given location can be obtained by the use of measuring instruments, like a pyranometer. Many developing countries, including Nigeria do not have solar radiation measuring instruments, thus the unavailability of reliable global solar radiation data in many locations within the country (Massaquoi, 1988, Ezekwe, 1988, Podesta *et al.*, 2004, Sanusi and Abisove, 2011). In the absence of standard measured solar radiation data from reliable measuring instruments, there is therefore a need to study and compare different empirical models to predict and estimate global solar radiation at the location of interest using available weather parameters. Several empirical models have been developed to calculate global solar radiation using various parameters (Moon, 1940, Fritz and Mcdonald, 1949, Fritz, 1957, Drummond and Vowinckel, 1957). These parameters include the sunshine hours (Angstrom, 1924, Black, 1958, Swartman and Ogunlade, 1967, Smith, 1976) the relative humidity and sunshine hours (Reddy, 1971) and the sunshine duration, relative humidity, maximum temperature, water vapour pressure, mean sea level and the ratio of water vapour pressure to the mean sea level pressure (Abdalla, 1994). Among all such parameters, sunshine hours are the most widely and commonly used. The models employing this common and important parameter are called sunshine-based models. Sunshine-based models use only bright sunshine hours as input parameter while others use additional climatological data together with bright sunshine hours (Ahmad and Ulfat, 2004). The objective of this work is to compare the different modified Angstrom models and determine the one that would be most suitable for estimating global solar radiation using sunshine hours in Uyo, Nigeria.

2. Theory

The model for estimating the monthly average daily global solar radiation that is simple and widely used was first developed by Angstrom and later modified by Prescott (Duffie and Beckman, 1994),

$$\frac{\bar{H}}{\bar{H_o}} = a + b\frac{\bar{n}}{\bar{N}} \qquad (1)$$

where $\bar{H}$ is the monthly average daily global solar radiation on a horizontal surface (MJm^{-2}day^{-1}); $\overline{H_o}$ is the monthly average extraterrestrial solar radiation on a horizontal surface (MJm^{-2}day^{-1}); $\bar{n}$ is the monthly average daily number of hours of bright sunshine ; $\bar{N}$ is the monthly average daily maximum number of hours of possible sunshine; a and b are regression constants, the value of monthly average daily extraterrestrial solar radiation on a horizontal surface $\overline{Ho}$ may be calculated from the expression by Duffie and Beckman (1994),

$$\bar{H}_o = \frac{24}{\pi} I_{sc} \left(1 + 0.033 cos\frac{360 d_n}{365}\right)$$
$$\left(cos\phi cos\delta sin\omega_s + \frac{2\pi\omega_s}{360} sin\phi sin\delta\right) \qquad (2)$$

The recommended value of the solar constant I_{sc} is 1367Wm^{-2} (Frohlich and Brusa, 1981), ϕ is the geographical latitude in degrees; d_n is the day number of the year, ranging from 1 on January 01 to 365 on December 31. The sunset hour angle ω_s and the solar declination δ are given by equations (3) and (4) respectively:

$$\omega_s = cos^{-1}(-tan\phi tan\delta) \qquad (3)$$

$$\delta = 23.45 sin\left(360\frac{284 + d_n}{365}\right) \qquad (4)$$

The monthly average day length $\bar{N}$ is given by equation (5):

$$\bar{N} = \frac{2}{15} cos^{-1}(-tan\phi tan\delta) = \frac{2}{15}\omega_s \quad (5)$$

Sunshine-based global solar radiation models have been developed, equations (6 -11). Rietveld (1978) proposed a solar radiation model for all places in the world that yields particularly superior results for cloudy conditions when $\frac{\bar{n}}{\bar{N}} < 0.4$

$$\frac{\bar{H}}{\bar{H}_o} = 0.18 + 0.62\frac{\bar{n}}{\bar{N}} \qquad (6)$$

Glover and McCulloch (1958) included the latitude ϕ (degrees) effect and presented the following correlation, as reviewed by Iqbal (1983),

$$\frac{\bar{H}}{\bar{H}_0} = 0.29 cos\phi + 0.52\frac{\bar{n}}{\bar{N}} \qquad for \phi < \ 60^o \qquad (7)$$

Fagbenle (1990) proposed a model for rain forest zone of Nigeria, expressed as:

$$\frac{\bar{H}}{\bar{H}_o} = 0.28 + 0.39\frac{\bar{n}}{\bar{N}} \qquad (8)$$

Turton (1987) developed a model for humid tropical countries as:

$$\frac{\bar{H}}{\bar{H}_o} = 0.3 + 0.4\frac{\bar{n}}{\bar{N}} \qquad (9)$$

Akpabio and Etuk (2002) developed a model for Onne, Nigeria as:

$$\frac{\bar{H}}{\bar{H}_o} = 0.23 + 0.38\frac{\bar{n}}{\bar{N}} \qquad (10)$$

Augustine and Nnabuchi (2009) developed a model for Warri expressed as:

$$\frac{\bar{H}}{\bar{H}_o} = 0.29 + 0.42\frac{\bar{n}}{\bar{N}} \qquad (11)$$

The error or deviation of the estimated values from the measured values is determined based on statistical parameters such as the root mean square error (RMSE), the mean bias error (MBE) and mean percentage error (MPE) (equations 12-14). Coefficient of determination, R^2 (equation 15) is most often seen as a number between 0.0 and 1.0, used to describe how well a regression line fits a set of data. R^2 near 1.0 indicates that a regression line fits the data well, while

an R^2 closer to 0.0 indicates that a regression line does not fit the data very well. Coefficient of correlation, r (equation 16) is used to test the linear relationship between estimated and measured values. The value of r is between -1.0 and +1.0, the + and – signs are used for positive linear correlations and negative linear correlations, respectively.

$$MBE = \frac{1}{n}\sum_i^n (H_e - H_m) \qquad (12)$$

$$RMSE = \left\{\frac{1}{n}\sum_i^n(H_e - H_m)^2\right\}^{1/2} \qquad (13)$$

$$MPE(\%) = \frac{1}{n}\sum_i^n\left(\frac{H_e - H_m}{H_m}\right) \times 100 \qquad (14)$$

$$R^2 = 1 - \frac{\sum_i^n(H_m - H_e)^2}{\sum_i^n(H_m - \bar{H}_m)^2} \qquad (15)$$

$$r = \frac{n\sum_i^n H_e H_m - \sum_i^n H_e \sum_i^n H_m}{\sqrt{n(\sum_i^n H_e^2) - (\sum_i^n H_e)^2}\ \sqrt{n(\sum_i^n H_m^2) - (\sum_i^n H_m)^2}}$$
$$(16)$$

where n is the number of observations, H_m is the measured global radiation, H_e is the estimated global radiation and $\bar{H}_m$ is the mean measured global radiation.

3. Materials and Methods
The monthly average daily data for sunshine hours and the global solar radiation for Uyo were obtained from the Nigerian Meteorological Agency, Lagos. The data obtained covered a period of ten years (1998 – 2007). The monthly average values of the measured solar radiation and sunshine hours for the ten years were calculated and compared. The necessary meteorological and solar radiation parameters were calculated from equations (1 – 5). Six different sunshine hours based solar radiation models (equations 6 – 11) were selected based on their relationship with geographical information of Uyo and used for the estimation. Assessment and comparison of the six selected models were based on some statistical parameters given by equations (12 – 16).

4. Results and Discussion
The calculated values of measured monthly average daily global solar radiation on a horizontal surface $\bar{H}$, extraterrestrial solar radiation $\bar{H}_0$, clearness index K_T, bright sunshine hours $\bar{n}$, the day length $\bar{N}$ and possible fraction of sunshine $\bar{n}/\bar{N}$, are presented in Table 1. This is similar to the results obtained by Agbo *et al.,* (2012) and Okundamiya and Nzeako (2010). From Table 1, it can be seen that the maximum monthly average daily global radiation, $\bar{H}$ for Uyo is 16.25MJm^{-2}day^{-1} occurring in the month of February while the minimum radiation of 10.36MJm^{-2}day^{-1}

occurs in August. This is due to the highest number of bright sunshine hours (4.99) attainment in the month of February and the lowest bright sunshine hours (1.99) in the month of August respectively. Also, February is the peak of dry season and August is characterized by heavy rainfall. The total annual global solar radiation is 169.75MJm^{-2}day^{-1}. The radiation obtained throughout the year is high and can be very useful for solar energy conversion devices. Table 2 shows the monthly average daily global solar radiation estimated from the models of Rietveld (1978), Glover and McCulloch (1958), Fagbenle (1990), Turton (1987), Akpabio and Etuk (2002), Augustine and Nnabuchi (2009), and the measured data.

Table 1: Monthly Mean Global Radiation and Meteorological data for Uyo

Month	$\bar{H}$ (MJm^{-2}day^{-1})	$\bar{Ho}$ (MJm^{-2}day^{-1})	$K_T = \bar{H}/\bar{Ho}$	$\bar{n}$ (hours)	$\bar{N}$ (hours)	$\bar{n}/\bar{N}$
Jan	14.23	34.31	0.415	4.91	11.74	0.4182
Feb	16.25	36.22	0.449	4.99	11.85	0.4211
Mar	14.67	37.58	0.39	3.79	11.97	0.3166
Apr	14.44	37.47	0.385	4.17	12.11	0.3443
May	14.72	36.28	0.406	4.22	12.23	0.3451
Jun	13.66	35.35	0.386	3.06	12.29	0.249
Jul	11.65	36.59	0.327	2.18	12.26	0.1778
Aug	10.36	36.62	0.283	1.99	12.16	0.1637
Sep	13.85	37.19	0.372	2.97	12.03	0.2469
Oct	14.63	36.43	0.402	2.89	11.89	0.2431
Nov	16.15	34.69	0.466	4.08	11.76	0.3469
Dec	15.14	33.55	0.451	4.13	11.71	0.3527

Table 2: Measured and Estimated Values of Monthly Average Daily Global Radiation using Different Models for Uyo in MJm^{-2}day^{-1}.

Month	Rietveld Model	Glover and McCulloch Model	Fagbenle Model	Turton Model	Akpabio and Etuk Model	Augustine and Nnabuchi Model	H$_{measured}$
Jan	15.07	17.37	15.2	16.03	13.34	15.98	14.23
Feb	15.98	18.4	16.09	16.97	14.13	16.91	16.25
Mar	14.14	17.04	15.16	16.03	13.16	15.9	14.67
Apr	14.74	17.53	15.52	16.4	13.52	16.28	14.44
May	14.29	16.99	15.04	15.89	13.1	15.78	14.72
Jun	11.82	14.79	13.33	14.13	11.48	13.95	13.66
Jul	10.62	13.95	12.78	13.58	10.89	13.34	11.65
Aug	10.31	13.7	12.59	13.38	10.7	13.14	10.36
Sep	12.39	15.52	13.99	14.83	12.04	14.64	13.85
Oct	12.05	15.13	13.65	14.47	11.74	14.28	14.63
Nov	13.71	16.28	14.41	15.22	12.55	15.11	16.15
Dec	13.38	15.85	14.01	14.8	12.21	14.7	15.14
Total	158.5	192.55	171.77	181.73	148.86	180.01	169.75

Table 3: Statistical Tests for the Comparison of Estimated Data from various Models

Statistical Test	Rietveld	Glover and McCulloch	Fagbenle	Turton	Akpabio and Etuk	Augustine and Nnabuchi
MBE	-0.9375	1.9000	0.1683	0.9983	-1.7408	0.8550
MPE (%)	-0.5522	1.1193	0.0992	0.5881	-1.0255	0.5037
RMSE	3.2476	6.5818	0.5831	3.4583	6.0304	2.9618
R^2	0.9948	0.9785	0.9998	0.9941	0.9820	0.9957
r	0.9968	0.9985	0.9977	0.9990	1.0002	0.9996

Shown in Table 3 are the statistical tests of MBE, MPE, RMSE, R^2, and r for the assessment and comparison of the selected models for the entire period. From Table 3 also, it is obvious that the MBE in Fagbenle's model is the closest to zero (0.1683) indicating that the model is more efficient than the others. For the rest of the models, the MBE is close to and above 1.0, showing that these models are less

efficient for Uyo. MPE for all the models is less than 5.0%, suggesting that all the models can be used for estimating solar radiation (Ahmad *et al.*, 2004) for Uyo and other locations with similar climatological conditions (Ugwu and Ugwuanyi, 2011), but it is very clear that the MPE in Fagbenle's model is smaller than that of others implying that the model is better. RMSE indicates that there is error in the estimated data of the

different models when compared with the measured data. This error is the least and the closest to zero (0.5831) in Fagbenle's model, revealing that the model is the most suitable. R^2 values for all the models are very close to 1.0, but with the closest (0.9998) from Fagbenle's model. This means that the regression lines fit the estimated data from all the models very well. The correlation coefficient, r values are acceptable for all the models, since they are very close to 1.0. This shows that the measured and the estimated solar radiation are linearly dependent.

From the statistical test results of the six models (Table 3), it can be seen that the Fagbenle model has the values of MBE, MPE and RMSE very close to zero, and R^2 and r values very near to 1.0 as required (Namrata *et al.*, 2012 and Udounwa *et al.*, 2013), and it estimates with an accuracy of 98.82%. Therefore, it can be said that the model of Fagbenle is most suitable for estimating monthly average daily global solar radiation for Uyo. Rietveld and Akpabio and Etuk models indicate under-estimation of the measured data, but with accuracies of 92.90% and 85.97% respectively.

Glover and McCulloch, Turton, and Augustine and Nnabuchi models indicate over estimation of the measured values, but with accuracies of 88.16%, 93.41% and 94.30% respectively. It can therefore be seen that all the selected models perform above an accuracy of 85% and hence could be used for estimation of monthly average daily global solar radiation in Uyo

and other geographical locations with similar climatic conditions. Fagbenle's model is found to be of better performance than the model of Augustine and Nnabuchi proposed for Warri with the same latitude as Uyo. This might be due to the fluctuations in the measured data obtained for the two locations (Warri and Uyo) which may be attributed to the period under study, that is, 17years and 10years respectively. Figure 1 shows the variation of $\bar{n}/\bar{N}$, sunshine hours-to-day length, and K_T, the clearness index for Uyo. The dip in the months of June − October indicates poor sky conditions where the values of $\bar{n}/\bar{N}$ and K_T reach the minimum in August as 0.1637 and 0.283 respectively. This poor sky condition is attributed to less sunshine hours and heavy overcast within the period. A plot of the estimated values of the monthly average daily global solar radiation (Sanusi and Abisoye, 2011) using the different models (equations 6-11) and the measured values is illustrated in Figure 2. Close examination of Figure 2 shows that there is a good agreement between the measured data and the data obtained from the models of Fagbenle, and Augustine and Nnabuchi. The measured solar radiation and the result of the estimated Fagbenle's model are presented in Fig. 3. From Fig. 3, and also as reported by Poudyal *et al.*, (2012) and Quansah *et al.*, (2014) similarly, the predicting regression model of Fagbenle could be employed for the estimation of global solar radiation in the similar climatic locations.

Fig.1: Variation of n/N with KT

Fig.2: Comparison of Monthly Average Daily Global Radiation Using Different Models
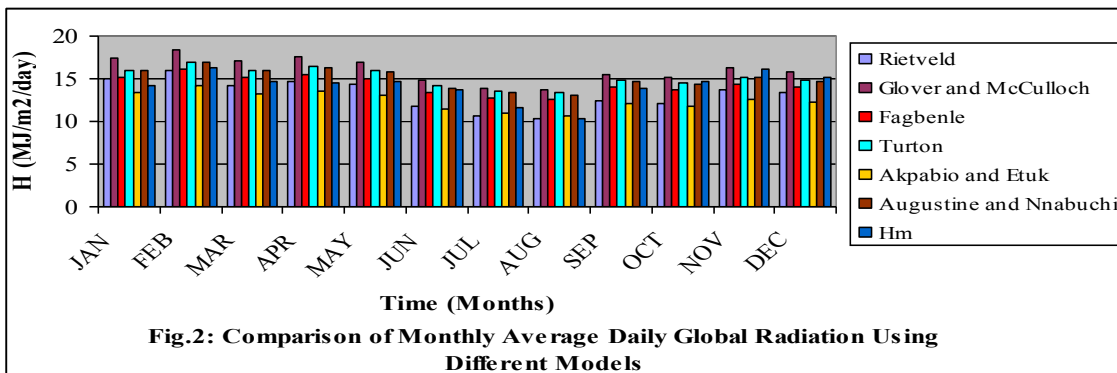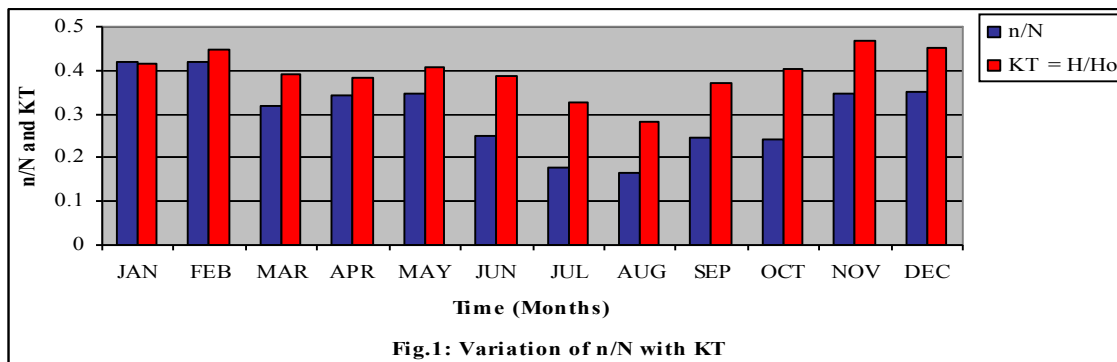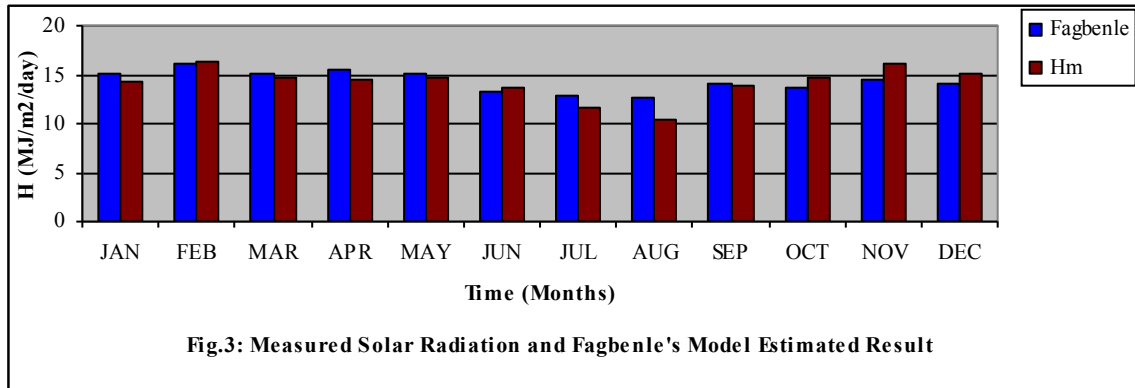
Fig.3: Measured Solar Radiation and Fagbenle's Model Estimated Result

5. Conclusion

Six different sunshine-based models were selected and used for the estimation of monthly average daily global solar radiation for Uyo and the results compared. The results from these models clearly show that the model of Fagbenle is most suitable for the estimation of the global solar radiation in Uyo. This is because there is an excellent agreement between the data estimated by this model and the measured one. It can therefore be concluded that Fagbenle's model can be conveniently used to estimate solar radiation in Uyo and other locations with similar climatic conditions where there is an absence of standard measured solar radiation data from a reliable measuring instrument.

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12/1/2014