ANALYSIS OF SOLAR ENERGY PARAMETERS IN BIDA, NIGERIA

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Abstract

The monthly daily average solar energy parameters measured in Bida (9.1°N, 6.02°E) for a period of thirteen years (2000 – 2012) were obtained from the Nigerian Meteorological Agency Bida, Niger State. These data which include Gunn-Bellani solar radiation, sunshine hour duration, relative humidity, rainfall, wind speed, maximum and minimum temperatures were analysed using both single-variable and multi-variable regression techniques of the Angstrom type to generate several regression equations (models) that were used to estimate the total solar radiation reaching a horizontal surface in Bida. The statistical error methods of the mean bias error (MBE), root mean square error (RMSE), mean percentage error (MPE) and T-test were used to test the performances of these models. The correlation coefficient (R) and coefficient of correlation (R^2) were also determined for each model. Based on the highest values of correlation coefficient (R) and coefficient of determination (R^2) and least RMSE value, the equation (model 9) that outperformed the rest is:

$$\frac{H}{Ho} = -0.568 + 0.669\left(\frac{\bar{n}}{\bar{N}}\right) + 0.033\left(\bar{T}_{max}\right) - 0.020\left(\bar{T}_{min}\right) + 0.022(\bar{R}).$$

This model is recommended for designers and engineers of solar energy and other renewable energy devices in this area.

Keywords: Gunn-Bellani solar radiation, sunshine hours, relative humidity, rainfall, wind speed, maximum and minimum temperatures, temperature ratio.

Introduction

Solar energy is the clean, abundant, renewable and sustainable energy resource from the sun which reaches the earth inform of light and heat

(Nwokoye, 2006; Okonkwo and Nwokoye, 2011). Solar energy is not evenly distributed on the surface of the earth. The net amount of the sun's energy received on the average, in a day, varies significantly with geographical locations and weather patterns. Nigeria is privileged to be one of the nations of the world with abundant sunshine per day due to its tropical location.

The utilization of solar energy is important in a developing nation like Nigeria where there is an acute shortfall in electricity generation and distribution. The knowledge of the available solar radiation at a place is essential in selecting and designing suitable solar energy systems for that location. Unfortunately, for many developing countries, solar radiation measurements are not widely available due to the high cost of the required equipment and the techniques involved (Ahmed et al, 2009). Only in a few designated locations like airports and meteorological stations are solar radiation data available.

Most of these stations lack the right instrument (e.g. pyranometer) for direct measurement of solar radiation but rather use an alternative device like the Gunn-Bellani radiometer which provides a time-integrated assessment of radiation falling on a black body by measuring the volume of liquid distilled by the radiation (Mungai, 2007). It has therefore become a common phenomenon to develop empirical equations of the Angstrom-type correlating the global solar radiation on a horizontal surface with the meteorological data at the location of interest, where solar radiation measurements are not carried out.

Angstrom (1924) developed the earliest equation correlating the ratio of the measured mean daily global solar radiation $\overline{H}_M$ ($MJm^{-2}day^{-1}$) and mean clear sky solar radiation $\overline{H}_C$ ($MJm^{-2}day^{-1}$) with the relative sunshine duration $\frac{\overline{n}}{\overline{N}}$ given as:

$$\frac{\overline{H}_M}{\overline{H}_C} = a' + b'\left(\frac{\overline{n}}{\overline{N}}\right) \tag{1}$$

where $\overline{n}$ and $\overline{N}$ are the monthly mean daily bright sunshine hours and the maximum possible monthly mean daily sunshine hours (or the day length), respectively. a' and b' are regression constants. The Angstrom equation was modified by Prescott (1940) to:

$$\frac{\overline{H}_M}{\overline{H}_O} = a + b\left(\frac{\overline{n}}{\overline{N}}\right) \tag{2}$$

by replacing clear sky radiation $\overline{H}_C$ with extraterrestrial radiation $\overline{H}_O$ ($MJm^{-2}day^{-1}$). The ratio $\frac{\overline{H}_M}{\overline{H}_O}$ is referred to as the clearness index ($\overline{K}_T$) of the sky.

A large number of researchers have conducted studies on regression analysis based on this Angstrom-Prescott model and developed equations involving either single variable or multivariable data (in a linear, multi-linear or even nonlinear manner) to estimate the amount of solar radiation at different locations around the world. Among these are Arinze and Obi (1983), Sambo (1985), Awachie and Okeke (1990), Babatunde and Aro (1990), Aliu and Sambo (1991), Akinbode (1992), Akpabio (1992), Iheonu (2001), Burari and Sambo (2001), Burari, et al. (2001), Udo (2002), Akpabio and Etuk (2003), Sanusi (2004), Akpabio, et al. (2005), Hussaini et al. (2005), Falayi and Rabiu (2005), El-sebaii and Trabea (2005), Togrul (2009), Chukwuemeka and Nnabuchi (2009), Augustine and Nnabuchi (2010), Abdulazeez, et al. (2010), Tijjani (2011), Chukwu and Nwachukwu (2012) and Medugu et al. (2013). However, no previous study of this nature has been conducted in Bida.

Therefore, the first aim of this study is to develop both one-parameter and multiple-parameter regression models (equations) for predicting solar radiation in Bida using meteorological data such as Gunn-Bellani solar radiation, sunshine hour duration (n), maximum and minimum air temperature, temperature ratio, rainfall, wind speed and relative humidity. The second aim is to test the performance of the generated models with the statistical comparison methods of mean bias error (MBE), root mean square error (RMSE), mean percentage error (MPE) and the paired-samples T-test to determine the best model for Bida and other locations having the same geographical and climatic indices.

MATERIALS AND METHODS

The meteorological data consisting of monthly daily average Gunn-Bellani solar radiation, maximum and minimum temperatures, sunshine hour duration, rainfall, wind speed and relative humidity spanning a period of thirteen years (2000 – 2012) were obtained from the Nigerian Meteorological Agency Bida, Niger state. The Gunn-Bellani solar radiation data in millimetres were converted to $MJm^{-2}day^{-1}$ using a conversion factor of 1.216 ($MJm^{-2}day^{-1}$) proposed by Ododo (1994).

The values of the mean extraterrestrial solar radiation $\overline{H}_O$ and day length $\overline{N}$ as in equation (2) were calculated for the fifteenth day of the month as given by Igbal (1983), Duffie and Beckman (1991) and Nwokoye (2006):

$$\overline{H}_O = \frac{24}{\pi} I_{sc} E_o \left(\frac{\pi}{180} w_s \sin\varphi \sin\delta + \cos\varphi \cos\delta \sin\omega_s \right) \quad (3)$$

where I_{sc} is the solar constant in (MJm^{-2}-day), expressed as:

$$I_{sc} = \frac{1367 * 3600}{1000000} \mathrm{MJm^{-2}\,day^{-1}} \quad (4)$$

E_o is the eccentricity correction factor, expressed as:

$$E_o = 1 + 0.033 \cos\left(\frac{360N}{365}\right) \quad (5)$$

w_s is the hour angle, expressed as:

$$w_s = \cos^{-1}(-\tan\varphi\tan\delta)$$

(6)

φ and δ are the latitude and declination angles respectively.

$$\delta = 23.45\sin\left(360\left(\frac{N+284}{365}\right)\right) \tag{7}$$

where N is the characteristic day number for each month

The mean day length $\overline{N}$ is expressed as:

$$\overline{N} = \frac{2}{15}w_s \tag{8}$$

The Angstrom-type regression equations were obtained by correlating the measured global solar radiation data with the meteorological data either as one-parameter or multiple-parameter regression analysis using the IBM SPSS20 computer programme. The accuracy of the estimated values was tested by calculating the Mean Bias Error (MBE), Root Mean Square Error (RMSE), and Mean Percentage Error (MPE). Finally, Paired Samples Test (T-Test) was performed on the measured and estimated values of solar radiation to ascertain the degree of variance between each pair using the IBM SPSS20.

The expressions for the MBE ($MJm^{-2}day^{-1}$), RMSE ($MJm^{-2}day^{-1}$), and MPE (%) as stated by El-Sebaii and Trabea (2005) are:

$$MBE = \frac{\left[\Sigma\left(\overline{H}_{i,cal}-\overline{H}_{i,meas}\right)\right]}{n} \tag{9}$$

$$RMSE = \left[\frac{\Sigma\left(\overline{H}_{i,cal}-\overline{H}_{i,meas}\right)^2}{n}\right]^{1/2} \tag{10}$$

$$MPE = \frac{\left[\Sigma\left(\frac{\overline{H}_{i,meas}-\overline{H}_{i,cal}}{\overline{H}_{i,meas}}\times 100\right)\right]}{n} \tag{11}$$

where $\overline{H}_{i,cal}$ and $\overline{H}_{i,meas}$ are the ith calculated and measured values of solar radiation respectively, n is the total number of observations.

MBE provides information on the long-term performance of models. A positive and a negative value of MBE indicate the average amount of over estimation and under estimation in the calculated values, respectively. One drawback of this test is that over estimation in one observation is cancelled by under estimation in another observation.

RMSE provides information on short-term performance of the models. It is always positive. The demerit of this parameter is that a single value of high error leads to a higher value of RMSE.

MPE test provides information on long-term performance of the examined regression equations. A positive and a negative value of MPE indicate the average amount of over estimation and under estimation in the calculated values, respectively. It is recommended that a zero value for MBE is ideal while a low RMSE and low MPE are desirable (Igbal, 1983; Halouani, et al. 1993; Akpabio and Etuk, 2003; Almorox et al., 2005; Che et al., 2007).

RESULTS AND DISCUSSION

Table 1 shows the monthly mean daily values of the meteorological data used in this study and the predicted total monthly mean daily global solar radiation for Bida. It was observed that the highest and lowest air temperatures are obtained in the months of March and December, respectively. It was also shown that the highest and lowest values of the fraction of sunshine occurred in the month of November and August, respectively. The high value of the fraction of sunshine could be attributed to the very high mean daily sunshine hours obtained due to a high clearness index in the month of November (Augustine and Nnabuchi, 2010). This trend is also followed by the global solar radiation which is highest in November and lowest in August.

Table 1 Monthly Daily Average Meteorological data for Bida

Month	$\overline{T}_{max}$ (°C)	$\overline{T}_{min}$ (°C)	$\frac{\overline{T}_{min}}{\overline{T}_{max}}$ (θ)	$\overline{R}$	$\overline{W}$ (ms^{-1})	$\frac{\overline{RH}}{100}$	$\overline{n}$ (hrs)	$\overline{N}$ (hrs)	$\frac{\overline{n}}{\overline{N}}$	$\overline{H}_M$ (MJm^{-2}day^{-1})	$\overline{H}_O$ (MJm^{-2}day^{-1})	$\overline{K}_T = \frac{\overline{H}_M}{\overline{H}_O}$	H_P (MJ m^{-2}day^{-1})
Jan.	35.5	21.3	0.60	0.0	3.0	0.34	6.9	11.5	0.6012	18.6	32.3	0.5744	19.53
Feb.	38.0	25.3	0.67	0.0	3.3	0.35	7.0	11.7	0.5971	21.0	34.7	0.6044	20.74
Mar.	39.2	26.7	0.68	0.1	3.4	0.40	6.9	12.0	0.5757	21.7	37.2	0.5840	21.12
Apr.	37.5	26.2	0.70	1.6	3.9	0.58	6.8	12.2	0.5543	20.4	38.0	0.5370	20.84
May	34.9	25.0	0.72	4.5	4.3	0.70	6.1	12.4	0.4935	19.3	37.6	0.5135	19.47
Jun.	32.4	23.5	0.73	6.2	4.2	0.78	5.9	12.5	0.4695	18.2	36.7	0.4944	18.06
Jul.	31.2	23.3	0.75	7.1	3.5	0.83	5.5	12.5	0.4392	16.0	36.9	0.4330	16.36
Aug.	30.6	23.0	0.75	7.7	3.4	0.84	4.5	12.3	0.3630	15.0	37.6	0.3993	14.80
Sep.	31.3	22.8	0.73	7.2	4.1	0.83	5.1	12.0	0.4254	16.9	37.1	0.4551	16.76
Oct.	33.1	23.0	0.69	3.8	3.8	0.78	7.1	11.8	0.5988	19.7	35.3	0.5599	19.67
Nov.	35.9	21.7	0.60	0.2	3.2	0.56	8.4	11.6	0.7242	21.9	32.7	0.6703	21.80
Dec.	35.9	20.1	0.56	0.0	3.1	0.39	7.2	11.5	0.6290	20.3	31.4	0.6456	19.77

Table 2 shows the regression equations (models) developed for this study. Models 1 and 2 are linear and quadratic one-parameter regression with fraction of sunshine, respectively. Model 3 is a multi-linear three-parameter regression with fraction of sunshine, rainfall and temperature ratio. Model 4 is a multi-linear three-parameter regression with fraction of sunshine, wind speed and temperature ratio. Model 5 is a multi-linear three-parameter regression with fraction of sunshine, relative humidity and temperature ratio. Model 6 is a multi-linear four-parameter regression with fraction of sunshine, rainfall, wind speed and relative humidity. Model 7 is a multi-linear four-parameter regression with fraction of sunshine, rainfall, wind speed and temperature ratio. Model 8 is a multi-linear four-parameter regression with fraction of sunshine, wind speed, relative humidity and temperature ratio. Model 9 is a multi-linear four-parameter regression with fraction of sunshine, maximum temperature, minimum temperature and rainfall. Model 10 is a multi-linear five-parameter regression with fraction of sunshine, rainfall, wind speed, relative humidity and temperature ratio. Model 11 is a multi-linear five-parameter regression with fraction of sunshine, rainfall, wind speed, relative humidity and minimum temperature. Model 12 is a multi-linear six-parameter regression with fraction of sunshine, rainfall, wind speed, relative humidity, maximum temperature and minimum temperature. Model 13 is a multi-linear regression with fraction of sunshine$\left(\frac{\bar{n}}{\bar{N}}\right)$, rainfall, wind speed, relative humidity, temperature ratio and product of these parameters.

Table 2 Regression equations (models) used for the analysis

1. $\frac{\bar{H}}{\bar{H}o} = 0.111 + 0.794\left(\frac{\bar{n}}{\bar{N}}\right)$
2. $\frac{\bar{H}}{\bar{H}o} = 0.025 + 1.125\left(\frac{\bar{n}}{\bar{N}}\right) - 0.308\left(\frac{\bar{n}}{\bar{N}}\right)^2$
3. $\frac{\bar{H}}{\bar{H}o} = 0.392 + 0.552\left(\frac{\bar{n}}{\bar{N}}\right) - 0.005(\bar{R}) - 0.197(\theta)$
4. $\frac{\bar{H}}{\bar{H}o} = 0.400 + 0.632\left(\frac{\bar{n}}{\bar{N}}\right) + 0.018(\bar{W}) - 0.391(\theta)$
5. $\frac{\bar{H}}{\bar{H}o} = 0.333 + 0.635\left(\frac{\bar{n}}{\bar{N}}\right) - 0.060(\overline{RH}) - 0.146(\theta)$
6. $\frac{\bar{H}}{\bar{H}o} = 0.098 + 0.858\left(\frac{\bar{n}}{\bar{N}}\right) + 0.012(\bar{R}) + 0.022(\bar{W}) - 0.222(\overline{RH})$
7. $\frac{\bar{H}}{\bar{H}o} = 0.430 + 0.498\left(\frac{\bar{n}}{\bar{N}}\right) - 0.006(\bar{R}) + 0.024(\bar{W}) - 0.333(\theta)$
8. $\frac{\bar{H}}{\bar{H}o} = 0.358 + 0.599\left(\frac{\bar{n}}{\bar{N}}\right) + 0.027(\bar{W}) - 0.080(\overline{RH}) - 0.275(\theta)$
9. $\frac{\bar{H}}{\bar{H}o} = -0.568 + 0.669\left(\frac{\bar{n}}{\bar{N}}\right) + 0.033(\bar{T}_{max}) - 0.020(\bar{T}_{min}) + 0.022(\bar{R})$
10. $\frac{\bar{H}}{\bar{H}o} = 0.302 + 0.684\left(\frac{\bar{n}}{\bar{N}}\right) + 0.005(\bar{R}) + 0.027(\bar{W}) - 0.136(\overline{RH}) - 0.240(\theta)$
11. $\frac{\bar{H}}{\bar{H}o} = 0.198 + 0.736\left(\frac{\bar{n}}{\bar{N}}\right) + 0.005(\bar{R}) + 0.028(\bar{W}) - 0.167(\overline{RH}) - 0.003(\bar{T}_{min})$
12. $\frac{\bar{H}}{\bar{H}o} = -0.630 + 0.871\left(\frac{\bar{n}}{\bar{N}}\right) + 0.034(\bar{R}) + 0.006(\bar{W}) - 0.154(\overline{RH}) + 0.031(\bar{T}_{max}) - 0.017(\bar{T}_{min})$
13. $\frac{\bar{H}}{\bar{H}o} = 0.160 + 0.866\left(\frac{\bar{n}}{\bar{N}}\right) + 0.025(\bar{R}) + 0.044(\bar{W}) - 0.229(\overline{RH}) - 0.220(\theta) - 0.011\left(\frac{\bar{n}}{\bar{N}} \times \bar{R} \times \bar{W} \times \overline{RH} \times \theta\right)$

Table 3 shows the result of the statistical error tests on each of the models. It was observed that model 12 which combines fraction of sunshine, rainfall, wind speed, relative humidity, maximum temperature and minimum temperature, has the highest values of correlation coefficient R and coefficient of determination R^2. The R^2 value of 0.986 indicates that 98.6% of the clearness index is accounted for by model 12. Again, it was observed that model 12 has the highest and lowest values of MBE and MPE respectively, indicating serious overestimation and underestimation on a long-term basis. Again, the P-value of less than 0.05 ($P<0.05$) indicates a significant variance between the measured and estimated solar radiation.

It was also observed that model 9, which combines fraction of sunshine, maximum temperature, minimum temperature and rainfall, ranked second in terms of the values of R and R^2 but obtained the lowest RMSE value, indicating higher accuracy. From the R^2 value, 98.3% of the clearness index can be accounted for by model 9. Again, the P-value is greater than 0.05 ($P>0.05$), indicating no significant variance between the measured and estimated values of solar radiation. However, the MBE and MPE values show slight underestimation and overestimation of 12% and 59.7%, respectively.

Model 13 which combines fraction of sunshine$\left(\frac{\bar{n}}{\bar{N}}\right)$, rainfall, wind speed, relative humidity, temperature ratio and product of these parameters, ranked third in terms of R and R^2 values and second in terms of RMSE value. The MBE and MPE values show slight overestimation and underestimation, respectively. The P-value indicates no significant variance between the measured and estimated values.

Table 3 Statistical error indicators of the models

Models	R	R²	MBE	RMSE	MPE	P-value (T-TEST)
1	0.973	0.946	0.002914	0.645139	-0.11257	0.977
2	0.973	0.947	0.002954	0.636454	-0.08629	0.980
3	0.982	0.965	0.007302	0.524714	-0.13854	0.992
4	0.981	0.962	-0.00214	0.543264	-0.10254	0.949
5	0.983	0.966	-0.00993	0.514215	-0.04494	0.904
6	0.985	0.971	0.089874	0.470955	-0.52444	0.569
7	0.986	0.973	-0.00614	0.461555	-0.03521	0.916
8	0.987	0.975	0.088646	0.443644	-0.51249	0.549
9	0.991	0.983	-0.12136	0.394816	0.597146	0.269
10	0.988	0.976	-0.08508	0.436081	0.420072	0.477
11	0.986	0.973	-0.02477	0.451907	0.060934	0.809
12	0.993	0.986	0.349941	0.481119	-1.85967	0.005
13	0.989	0.977	0.003879	0.413969	-0.08063	0.958

The monthly variation of sunshine hours is shown in Fig.1. It was observed that the highest and lowest levels of sunshine hours occurred in the month of November and August, respectively. This is consistent with the clear and overcast skies prevalent in the months of November and August, respectively.

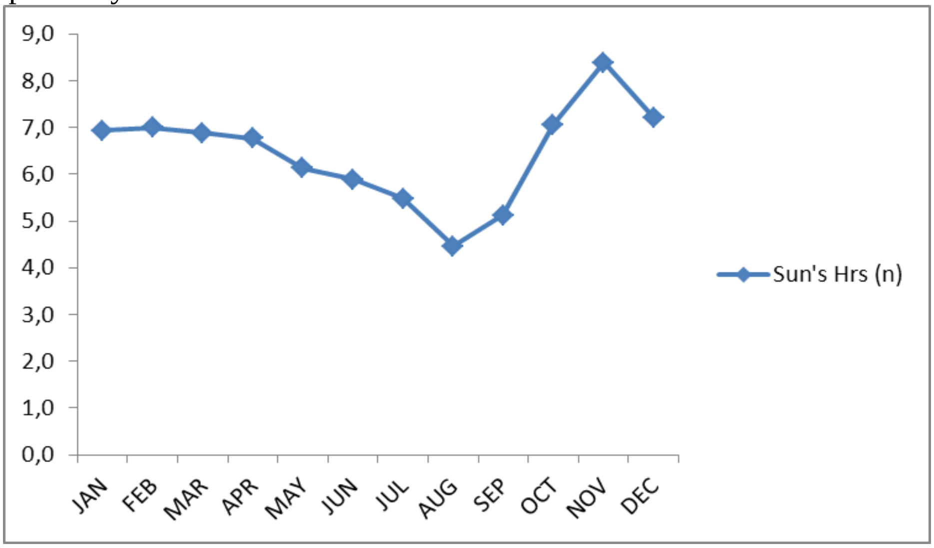

Fig.1. Monthly variation of Sunshine Hours for Bida

Figures 2 – 13 show how the measured solar radiation compares with each of the models indicated. It is observed in Figures 2 and 3 that models 1 and 2 gave the same results with slight underestimation in the months of February, March and December and slight overestimation in the months of July and October. In Fig. 4, model 3 overestimated the measured value in the months of January and July, and gave 100% estimation for the rest of the year.

From Figures 5 and 6, it is shown that model 4 underestimated the measured between February and March while model 5 has slight overestimation in January and July, and slight underestimation in June and December. In Fig. 7, model 6 show slight overestimation in January and July and underestimation in December. From Fig. 8, it is indicated that model 7 slightly overestimated the measured value in the months of January and April and underestimated in February.

For model 8 (Fig. 9), there is slight overestimation in January and April, and 100% estimation in other months. In Fig. 10, model 9 show very little underestimation in the month of February and 100% estimation for the rest months of the year. Models 10 and 11 (Figures 11 and 12), gave similar results with slight overestimation in January and slight underestimation in December. From Fig. 13, it is observed that model 12 has slight overestimation in the months of January, April, May and July. As shown in Fig. 14, model 13 has slight overestimation and underestimation in the months of January and December, respectively.

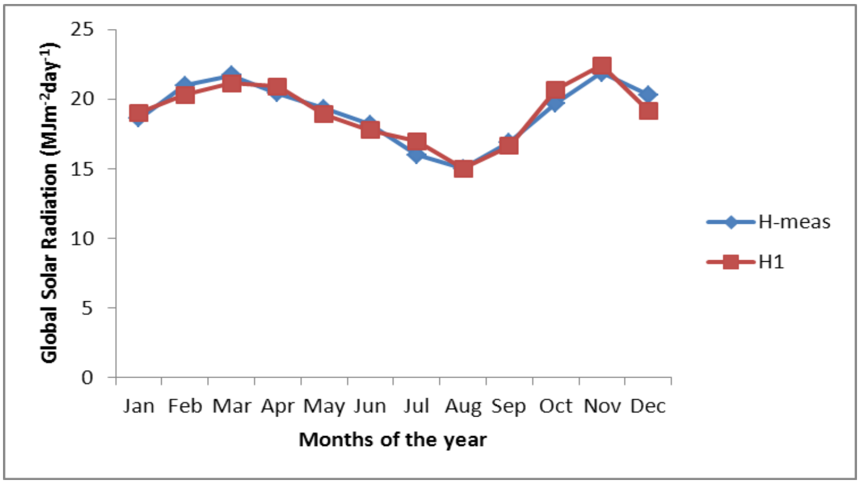

Fig.2. Comparison between model 1 and measured solar radiation for Bida

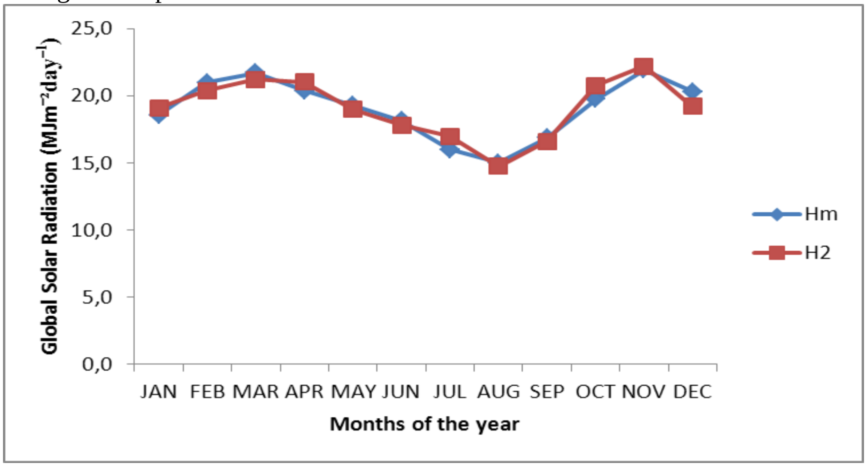

Fig.3. Comparison between model 2 and measured solar radiation for Bida

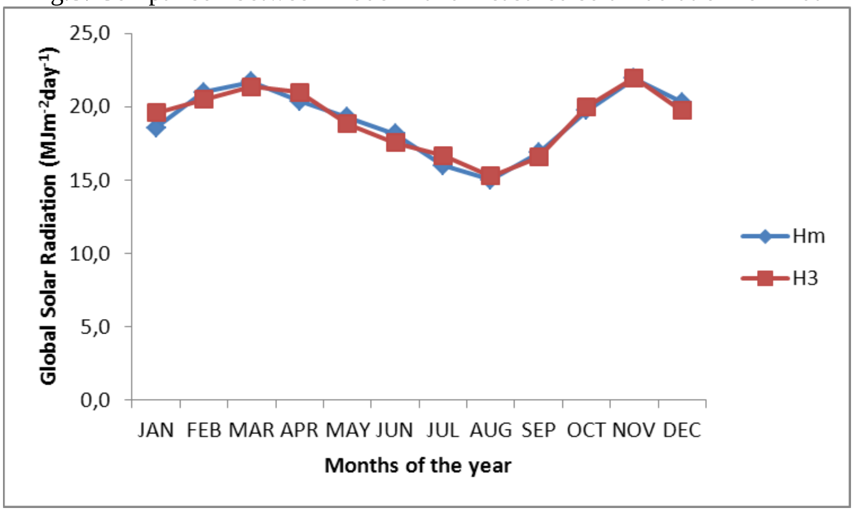

Fig.4. Comparison between model 3 and measured solar radiation for Bida

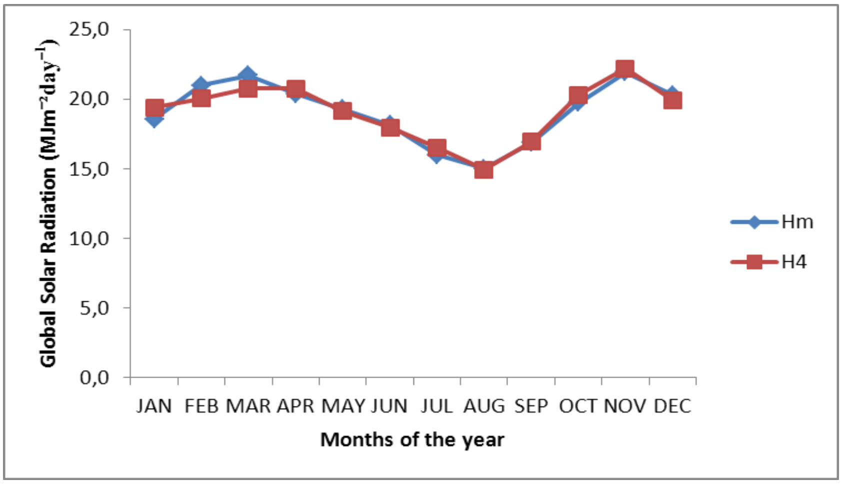

Fig.5. Comparison between model 4 and measured solar radiation for Bida

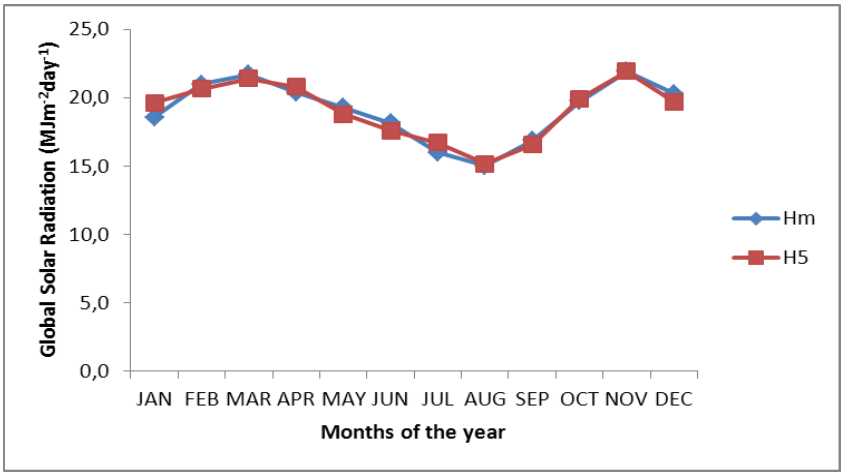

Fig. 6 Comparison between model 5 and measured solar radiation for Bida

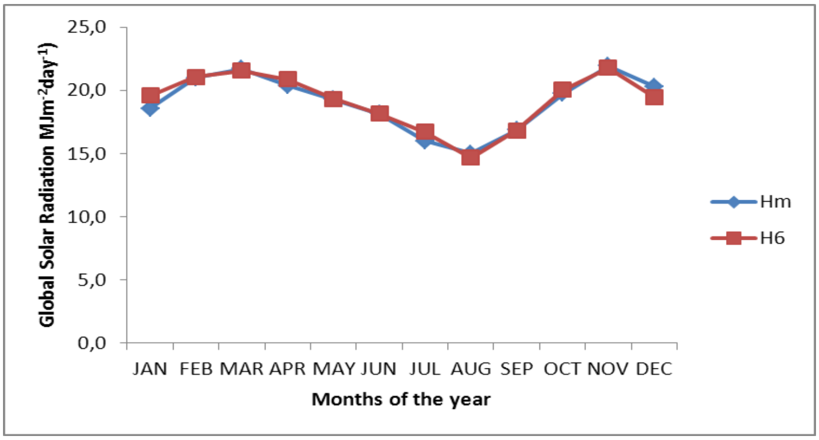

Fig.7. Comparison between model 6 and measured solar radiation for Bida

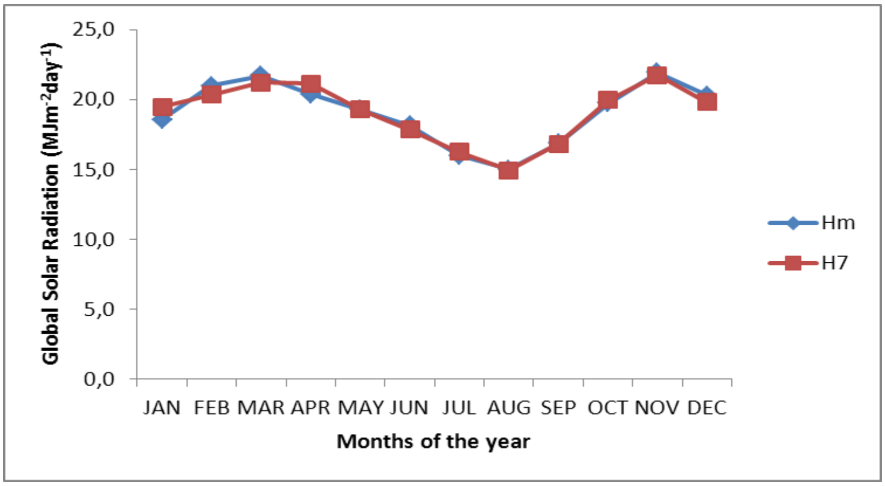

Fig.8. Comparison between model 7 and measured solar radiation for Bida

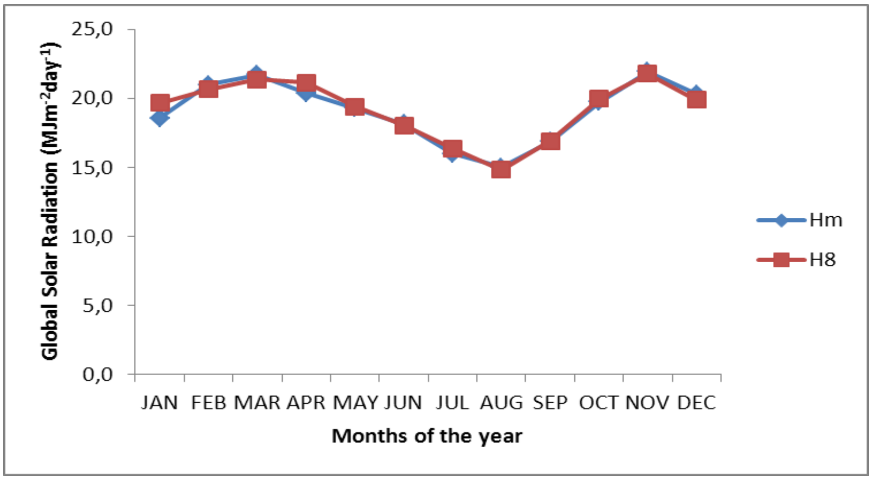

Fig.9. Comparison between model 8 and measured solar radiation for Bida

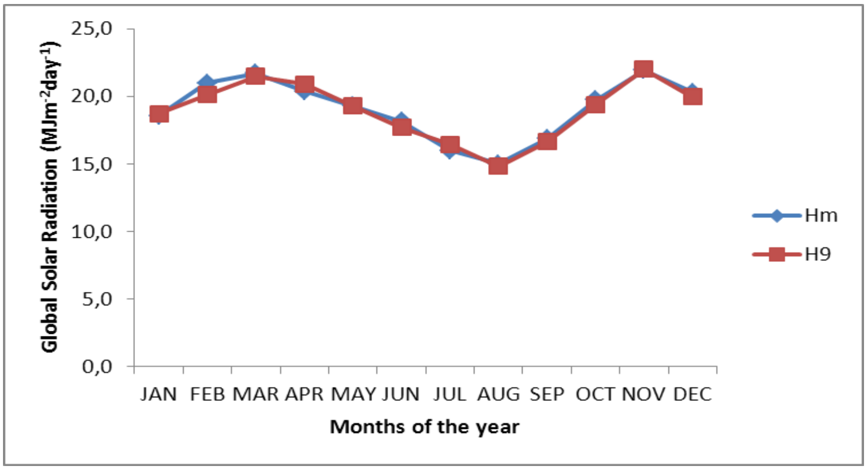

Fig.10. Comparison between model 9 and measured solar radiation for Bida

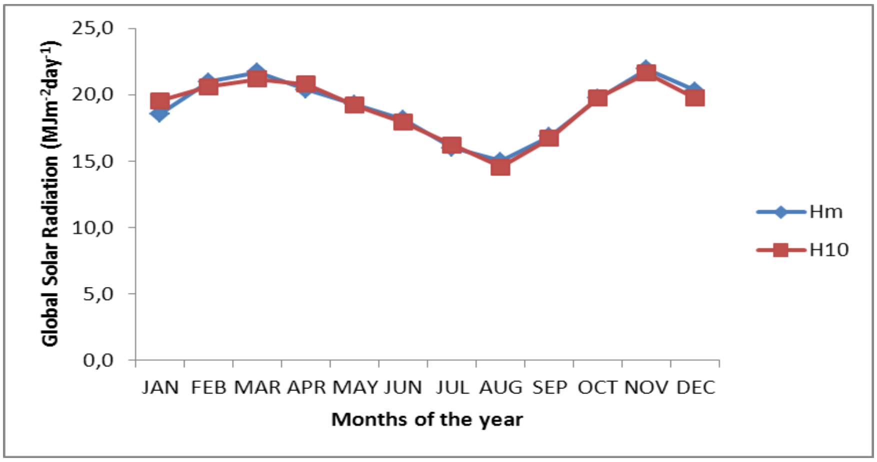

Fig.11. Comparison between model 10 and measured solar radiation for Bida

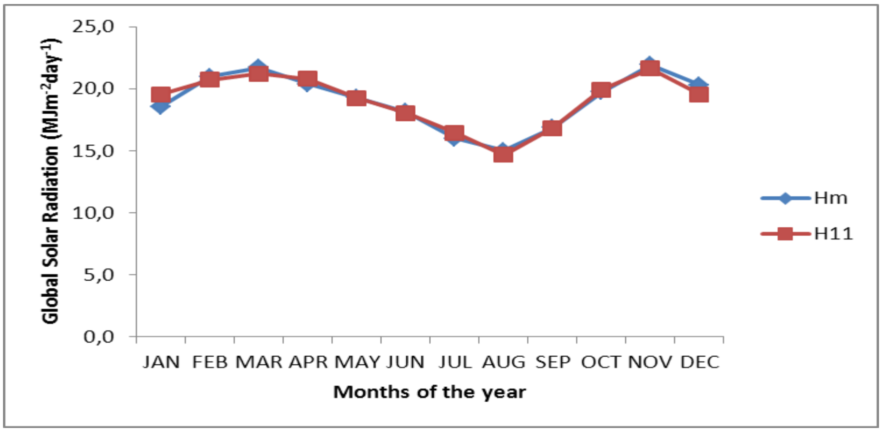

Fig.12. Comparison between model 11 and measured solar radiation for Bida

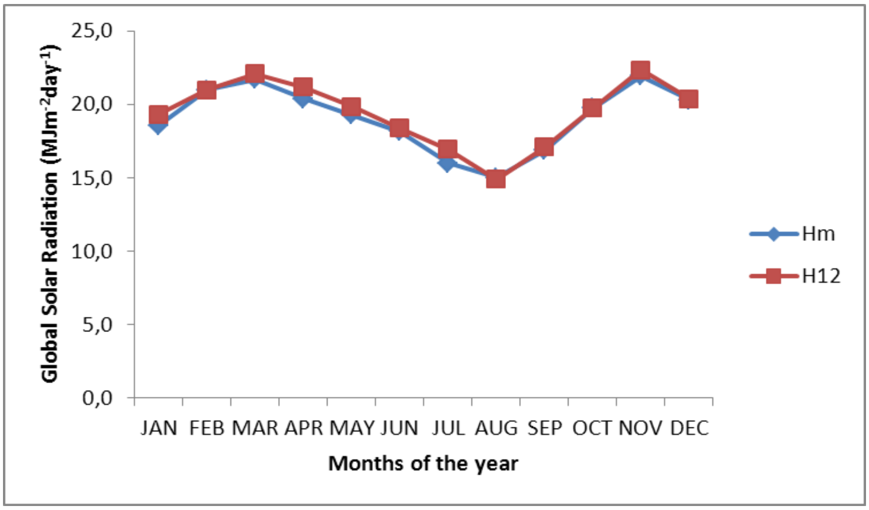

Fig.13. Comparison between model 12 and measured solar radiation for Bida

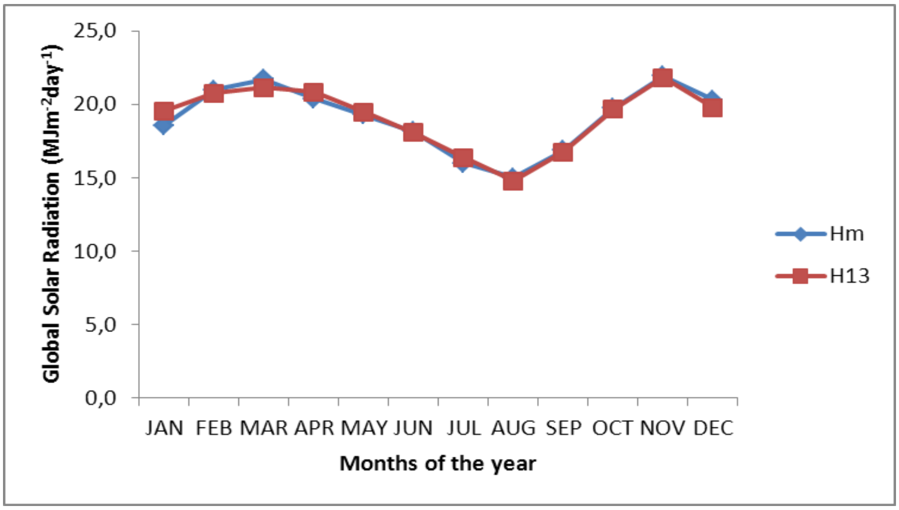

Fig.14. Comparison between model 13 and measured solar radiation for Bida

From figures 3 – 9, it is observed that model 9 (as shown in Fig.10) is the best model for estimating the global solar radiation for Bida from January to December.

Conclusion

The computer software program IBM SPSS 20 was used to develop several linear and multi-linear regression models for Bida. Based on the values of the correlation coefficient and coefficient of determination and least RMSE value the equation (model 9):

$$\frac{\overline{H}}{\overline{H_O}} = -0.568 + 0.669\left(\frac{\overline{n}}{\overline{N}}\right) + 0.033\left(\overline{T}_{max}\right) - 0.020\left(\overline{T}_{min}\right) + 0.022(\overline{R})$$

has been found suitable for predicting the monthly mean daily solar radiation in Bida from January to December.. The values of the correlation coefficient, R, determination coefficient R^2, MBE, RMSE, MPE and T-test obtained for model 9 as indicated in Table 3 are: 0.991, 0.983, -0.12136, 0.394816, 0.597146 and 0.269 respectively.

This model will provide useful information for designers and engineers of solar energy and other renewable energy devices in this area.

Acknowledgements

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