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Application of Linear Models for Estimation of Global Solar Radiation using Available Meteorological Parameters for Sokoto, Nigeria

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ABSTRACT

Solar radiation data base is an essential pre-requisite for designing, sizing and performance evaluation of any solar energy systems in any part of the globe, even though these data base are not readily available in many localities of both developed and developing countries such as Nigeria. However, modeling techniques can be used to significantly evaluate daily global solar radiation, using other more accomplished available meteorological data. In this study, sunshine hours, relative humidity, minimum and maximum temperatures data for Sokoto location (latitude 13.03^{0}N, Longitude 5.27^{0}E and Altitude 296m) have been obtained from Nigerian meteorological Agency (NIMET) for a period of six years (2007-2012). The data was subjected to eleven different linear models in which the coefficients were obtained using least square error method. The values of global solar radiation estimated by the models were compared with the measured values and tested using some statistical parameters (MBE, NDMBE, MAD, NDMAD, MPE, RMSE, R^2 and t-statistic). The values were generally found to be in close agreement with measured values for the site. However, when only sunshine hours is available among the meteorological parameters, then Angstrom-Prescott model can be used as it shows reasonable agreement with the measured data. It performed better than the models that combine sunshine hours with temperatures; but excellent performance can be achieved by using the models that include sunshine hours, temperatures and natural logarithms of relative humidity. Thus, the resultant correlations and linear regression relations developed may be used for other locations of similar meteorological/geographical characteristics and can also be used to estimate the missing data of solar radiation for the respective sites with existing weather stations.

Key Words: *Global Solar Radiation, Clearness Index, Sunshine Hours, Linear Regression, Statistical test.*

1. INTRODUCTION

Solar energy is freely available and could be easily harnessed to reduce our reliance on hydrocarbon-based energy sources. For feasibility study of the possible use of solar energy or design of any solar energy conversion device, solar radiation data is necessary (Sheriff *et al.*, 2014). Obviously, the best way of knowing the amount of global solar radiation at the site of consideration is to install pyranometer at many locations in the given region and look after their day maintenance and recording, which is a very expensive venture.

In many developing countries, the facility of ground-based measurement of solar radiation is available only at selected sites where as meteorological and hydrological data are available at different parts of the country. Many meteorological stations have for several years been measuring related parameters like the sunshine duration with Campbell Scientific Sunshine Recorder (Medugu *et al.*, 2013). Therefore, the alternative approach is to correlate the global radiation with the meteorological parameters where the data can be collected. The resultant correlation may then be used for locations of similar meteorological characteristics (Augustine and Nnabuchi, 2009; Dehghan *et al.*, 2013).
Among the earliest model developed for estimating global solar radiation was Angstrom model in which sunshine duration and clear sky radiation data were used (Togrul, 2009). Because of problems associated in calculating clear sky radiation

accurately, the Angstrom model was modified by replacing the clear sky radiation with extraterrestrial radiation. The modified model is known as Angstrom-Prescott Model (Ugwuoke and Okeke, 2012; Medugu *et al.*, 2013; Sarsah and Uba, 2013).

So far, various theoretical and empirical models have been developed by a number of researchers with different regression coefficients using different regression techniques for different locations to compute the components of the solar radiation (Burari, 2001; Medugu *et al.*, 2011; Kaya, 2012; Dehghan *et al.*, 2013; Gana and Akpootu, 2013; Innocent *et al.*, 2015).

Some researches where conducted using temperature data as independent variable for the correlation technique (Nwokoye, 2006; Chiemeka, 2008; Falayi and Rabiu, 2008; Okonkwo and Nwokoye, 2014). Some researchers used other factors such as latitude, elevations, relative humidity, soil temperature, number of rainy days, precipitation, cloudiness, evaporation (Bindi and Miglietta, 1991; Elagib and Mansell, 2000; El-Metwally, 2005; Sen, 2007; Aksoy *et al.*, 2010; Sarsah and Uba, 2013; Besharat *et al.*, 2013; Rajesh *et al.*, 2013). Some researchers carried out regression analysis for different models and statistical indices were used to select the best fitted model on the locations (Ugwuoke and Okeke, 2012; Sarsah and Uba, 2013; Ayodele and Ogunjuyigbe, 2015).

The models can be classified based on linearity as linear and non-linear. They can also be classified based on parameters as: sunshine-based, temperature based, humidity based and other meteorological parameters based (Besharat, 2013, Sarsah and Uba, 2013).

From the review, it can be concluded that empirical constants in the models are location dependent. This work aims at comparing various linear models formed for Sokoto (Latitude 13.03^oN Longitude 5.27^oE and altitude $296m$) located in the North-Western Zone of Nigeria.

The sunshine based models to be compared in this work are given by equations 1-2. The model given by equation 1 is the known Angstrom-Prescott model.

$$\frac{\bar{H}_m}{\bar{H}_o} = a_1 + b_1\left(\frac{\bar{n}_d}{\bar{N}_d}\right) \quad \text{……} \quad (1)$$

$$\frac{\bar{H}_m}{\bar{H}_o} = a_2 + b_2\bar{n}_d \quad \text{……} \quad (2)$$

Where: $\bar{H}_m$ is the measured mean daily solar radiation on horizontal surface; $\bar{H}_o$ the mean daily extraterrestrial radiation on horizontal surface; $\bar{n}_d$ the mean daily sunshine hours; $\bar{N}_d$ the average maximum possible daily hours of sunshine or the day length.

The temperature based models are formed by comparing clearness index with mean daily maximum temperature in Celsius scale ($\bar{\theta}_{max}$), mean daily maximum temperature in Kelvin scale ($\bar{T}_{max}$), average temperatures in Celsius scale ($\bar{\theta}_{av}$), average temperatures in Kelvin scale ($\bar{T}_{av}$), and the ratios of average temperatures with maximum temperatures. They are given by equations 3-6.

$$\frac{\bar{H}_m}{\bar{H}_o} = a_3 + b_3\bar{\theta}_{max} \quad \text{……} \quad (3)$$

$$\frac{\bar{H}_m}{\bar{H}_o} = a_4 + b_4\bar{T}_{max} \quad \text{……} \quad (4)$$

$$\frac{\bar{H}_m}{\bar{H}_o} = a_5 + b_5\left(\frac{\bar{\theta}_{av}}{\bar{\theta}_{max}}\right) \quad \text{……} \quad (5)$$

$$\frac{\bar{H}_m}{\bar{H}_o} = a_6 + b_6\left(\frac{\bar{T}_{av}}{\bar{T}_{max}}\right) \quad \text{……} \quad (6)$$

Relative humidity based model was formed as given by equation 7; while other models are formed by combinations of sunshine hours, temperatures and relative humidity. They are given by equations 8-11.

$$\frac{\bar{H}_m}{\bar{H}_o} = a_7 + b_7 \ln RH \quad \text{……} \quad (7)$$

$$\frac{\bar{H}_m}{\bar{H}_o} = a_8 + b_8\left(\frac{\bar{n}_d}{\bar{N}_d}\right) + c_8\left(\frac{\bar{\theta}_{av}}{\bar{\theta}_{max}}\right) \quad \text{……} \quad (8)$$

$$\frac{\bar{H}_m}{\bar{H}_o} = a_9 + b_9\left(\frac{\bar{n}_d}{\bar{N}_d}\right) + c_9\left(\frac{\bar{T}_{av}}{\bar{T}_{max}}\right) \quad \text{……} \quad (9)$$

$$\frac{\bar{H}_m}{\bar{H}_o} = a_{10} + b_{10}\left(\frac{\bar{n}_d}{\bar{N}_d}\right) + c_{10}\left(\frac{\bar{\theta}_{av}}{\bar{\theta}_{max}}\right) + d_{10}\ \ln\overline{RH} \quad \text{……} \quad (10)$$

$$\frac{\bar{H}_m}{\bar{H}_o} = a_{11} + b_{11}\left(\frac{\bar{n}_d}{\bar{N}_d}\right) + c_{11}\left(\frac{\bar{T}_{av}}{\bar{T}_{max}}\right) + d_{11}\ \ln\overline{RH} \quad \text{……} \quad (11)$$

2. MATERIALS AND METHODS

2.1 Measured Meteorological Data

Primary (measured) data of daily Solar radiation, maximum and minimum temperatures, sunshine hours and relative humidity where obtained from Nigerian Meteorological Agency for six years (2007- 2012).

2.2 Determination of Meteorological Variables

Monthly daily average of extraterrestrial solar radiation on horizontal surface, $\overline{H}_o$, is given by Iqbal as cited by Krishna *et al.*, (2013) and Medugu & Yakubu (2011):

$$\overline{H}_o = I_{sc}\frac{24}{\pi}E_o\left(\frac{\pi}{180}w_{ss}\sin\Phi\sin\delta+\cos\delta\cos\Phi\sin w_{ss}\right) \quad \text{.......... (12)}$$

Where: I_{sc} is the hourly solar energy constant; w_{ss}, the sunset hour angle in degrees; Φ, the latitude of the location; δ, the declination; d_n , the n^{th} day of the year i.e. $1 \le d_n \le 365$ $(Jan.1 = 1; Dec.31 = 365)$.

The hourly solar energy constant, I_{sc} in $MJm^{-2}h^{-1}$, is given by:

$$I_{sc} = (G_{sc} \times 3600)/(1 \times 10^6) \quad \text{.......... (13)}$$

Where: G_{sc} is the solar constant and $G_{sc} = 1366.1\ W/m^2$

Solar declination angle, δ is given by:

$$\delta = 23.45\sin[\frac{360}{365}(d_n+284)] \quad \text{.......... (14)}$$

E_o is the earth distance eccentricity and is given by:

$$E_o = 1 + 0.033\cos(\frac{360d_n}{365}) \quad \text{.......... (15)}$$

Sunset hour angle is given by:

$$w_{ss} = \cos^{-1}(-\tan\Phi\tan\delta) \quad \text{.......... (16)}$$

Because 1 hour equals 15^o of the sun travelling through the sky, the maximum possible daylength hours N_d is obtained as:

$$N_d = \frac{2}{15}\cos^{-1}(-\tan\Phi\tan\delta) \quad \text{or}$$

$$N_d = \frac{2}{15}w_{ss} \quad \text{.......... (17)}$$

2.3 Monthly Average Values of Meteorological Variables

The monthly average values of meteorological variables $(\delta, E_o, w_{ss}, N_d, and\ , H_o)$ can be obtained through any of the following ways:

i. calculating the daily values and then find their average;
ii. take the value of the middle day of the month; or
iii. choose a day in the month whose value is closest to the month average value.

The first method is more accurate but very tedious while the second method is least in accuracy among the methods. In this work, the later method was chosen by adopting the monthly recommended days by Klein 1977 as cited by Duffie and Beckman (2013) as shown in Table 1.

Table 1: Monthly Average Days and their Corresponding Day Number

Month	Ave. Day i	Monthly Number	Ave. Day No. d_n
Jan	17	i	17
Feb	16	$31+i$	47
Mar	16	$59+i$	75
Apr	15	$90+i$	105
May	15	$120+i$	135
Jun	11	$151+i$	162
Jul	17	$181+i$	198
Aug	16	$212+i$	228
Sep	15	$243+i$	258
Oct	15	$273+i$	288
Nov	14	$304+i$	318
Dec	10	$334+i$	344

2.4 Statistical Analysis

In order to gain insight into the accuracy and performance evaluation of the models, the following statistical tests parameters were used: mean bias error (MBE), mean absolute deviation (MAD), mean percentage error (MPE), root mean square error (RMSE), coefficient of correlation (r) and t-statistic (t). They are determined using equations 18-23 respectively (Walpole and Myers, 1989).

$$MBE = \frac{1}{n}\sum_{i=1}^{n}(\bar{H}_{i\,meas} - \bar{H}_{i\,calc}) \quad \ldots\ldots (18)$$

$$MAD = \frac{1}{n}\sum_{i=1}^{n}|\bar{H}_{i\,meas} - \bar{H}_{i\,calc}| \quad \ldots\ldots (19)$$

$$MPE = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{(\bar{H}_{i\,meas}-\bar{H}_{i\,calc})}{\bar{H}_{i\,meas}} \times 100\%\right) \quad \ldots\ldots (20)$$

$$RMSE = \left\{\frac{1}{n}\sum_{i=1}^{n}(\bar{H}_{i\,meas} - \bar{H}_{i\,calc})^2\right\}^{1/2} \quad \ldots\ldots (21)$$

$$r = \frac{\sum X_i Y_i - n\bar{X}\bar{Y}}{\left(\sqrt{\sum X_i^2 - n\bar{X}^2}\right)\left(\sqrt{\sum Y_i^2 - n\bar{Y}^2}\right)} \quad \ldots\ldots (22)$$

$$t = \left[\frac{(n-1)MBE^2}{RMSE^2 - MBE^2}\right]^{1/2} \quad \ldots\ldots (23)$$

3.0 RESULTS AND DISCUSSION

Six years data ((2007- 2012) obtained from Nigerian Meteorological Agency (NIMET) for daily Solar radiation, maximum and minimum temperatures, sunshine hours and relative humidity where obtained. The monthly average values calculated are as shown in Table 2.

Table 2: Measured Monthly Daily Average of Some Metrological Variables

Month	Solar Rad. $\bar{H}_m$ (MJ /m^2.day)	Sunshine Hours $\bar{n}_d$, (hours)	Temp max $\bar{\theta}_{max}$ (°C)	Temp min $\bar{\theta}_{min}$, (°C)	Rel. Hum. $\overline{RH}$, (%)
Jan	21.47	8.00	31.83	17.10	22.73
Feb	23.51	8.42	35.97	19.58	18.74
Mar	24.88	7.86	40.80	23.60	18.33
Apr	24.38	7.78	44.10	27.08	31.85
May	22.43	7.30	43.85	27.29	48.76
Jun	20.99	7.98	42.59	25.56	58.27
Jul	19.36	7.26	40.78	23.82	71.37
Aug	18.75	6.44	40.70	22.85	78.10
Sep	19.81	7.64	43.78	23.24	72.85
Oct	21.53	8.90	48.23	23.23	51.70
Nov	22.07	9.00	49.81	20.28	26.74
Dec	21.25	8.86	50.15	17.66	24.69

The monthly average days recommended by Klein as shown in Table 1 were adopted in this work. Based on the monthly average days, monthly average declination angle (d¯_n), earth-distance eccentricity (E¯_o), sunset hour angle (w¯_ss) and maximum day length hours (N¯_d) were calculated using equations 14-17 while extraterrestrial radiation at horizontal surface was calculated using equation 12. The results are as shown in Table 3.

Table 3: Monthly Average Calculated Meteorological Variables

Month	$\bar{d}_n$	$\bar{\delta}$	$\bar{E}_o$	$\bar{w}_{ss}$	$\bar{N}_d$	$\bar{H}_o$
Jan	17	-20.92	1.032	84.90	11.32	30.49
Feb	47	-12.95	1.023	86.93	11.59	33.48
Mar	75	-2.42	1.009	89.44	11.92	36.35
Apr	105	9.41	0.992	92.21	12.29	38.04
May	135	18.79	0.977	94.54	12.61	38.20
Jun	162	23.09	0.969	95.69	12.76	37.89
Jul	198	21.18	0.968	95.17	12.69	37.87
Aug	228	13.45	0.977	93.19	12.43	37.87
Sep	258	2.22	0.991	90.52	12.07	36.78
Oct	288	-9.60	1.008	87.74	11.70	34.17
Nov	318	-18.91	1.023	85.43	11.39	31.10
Dec	344	-23.05	1.031	84.32	11.24	29.50

The parametric equations formed from the method of least squares were solved simultaneously to determine the coefficients of the models. The results obtained gives:

Mod 1: $\bar{H}_m = \bar{H}_o\left[0.0988 + 0.7875\left(\frac{\bar{n}_d}{\bar{N}_d}\right)\right]$

Mod 2: $\bar{H}_m = \bar{H}_o[0.6023 + 0.0026\,\bar{n}_d]$

Mod 3: $\bar{H}_m = \bar{H}_o[0.5939 + 0.000684\,\bar{\theta}_{max}]$

Mod 4: $\bar{H}_m = \bar{H}_o[0.2984 + 0.00103\,\bar{T}_{max}]$

Mod 5: $\bar{H}_m = \bar{H}_o\left[1.9050 - 1.6702\left(\frac{\bar{\theta}_{av}}{\bar{\theta}_{max}}\right)\right]$

Mod 6: $\bar{H}_m = \bar{H}_o\left[0.3235 + 0.3095\left(\frac{\bar{T}_{av}}{\bar{T}_{max}}\right)\right]$

Mod 7: $\bar{H}_m = \bar{H}_o[1.129 - 0.139\,\ln\overline{RH}]$

Mod 8: $\bar{H}_m = \bar{H}_o\left[-0.725 + 1.0876\left(\frac{\bar{n}_d}{\bar{N}_d}\right) + 0.8131\left(\frac{\bar{\theta}_{av}}{\bar{\theta}_{max}}\right)\right]$

Mod 9: $\bar{H}_m = \bar{H}_o\left[-5.2831 + 1.1711\left(\frac{\bar{n}_d}{\bar{N}_d}\right) + 5.2945\left(\frac{\bar{T}_{av}}{\bar{T}_{max}}\right)\right]$

Mod 10: $\bar{H}_m = \bar{H}_o\left[0.7517 + 0.371007\left(\frac{\bar{n}_d}{\bar{N}_d}\right) + 0.000233\left(\frac{\bar{\theta}_{av}}{\bar{\theta}_{max}}\right) - 0.10309\,\ln\overline{RH}\right]$

Mod 11: $\bar{H}_m = \bar{H}_o\left[-1.66929 + 0.621448\left(\frac{\bar{n}_d}{\bar{N}_d}\right) + 2.249364\left(\frac{\bar{T}_{av}}{\bar{T}_{max}}\right) - 0.08213\,\ln\overline{RH}\right]$

The models were used to predict the values of Global Solar Radiation; the measured Monthly Mean Value and the predicted values from the models are as shown in Table 4.

Table 4: Monthly Mean Daily Measured and Predicted Values of Global Solar Radiation

	Meas.	Predicted Values from										
Month	H_m	Mod1	Mod2	Mod3	Mod4	Mod5	Mod6	Mod7	Mod8	Mod9	Mod10	Mod11
Jan	21.47	20.06	19.00	18.77	18.67	18.87	19.11	21.20	20.53	22.47	21.15	21.95
Feb	23.51	22.55	20.90	20.71	20.65	20.72	20.88	24.16	23.27	23.69	24.13	24.29
Mar	24.88	22.48	22.64	22.60	22.60	21.28	22.67	26.34	23.09	22.74	25.33	24.85
Apr	24.38	22.63	23.68	23.74	23.78	21.00	23.73	24.65	23.54	22.46	23.92	23.58
May	22.43	21.22	23.73	23.83	23.87	21.09	23.83	22.47	21.56	20.31	21.62	21.15
Jun	20.99	22.54	23.61	23.61	23.62	21.55	23.63	21.34	23.14	22.37	21.45	21.59
Jul	19.36	20.74	23.52	23.55	23.54	22.17	23.62	20.28	20.35	19.70	19.81	19.55
Aug	18.75	19.25	23.44	23.55	23.54	22.81	23.62	19.80	17.98	17.48	18.76	18.09
Sep	19.81	21.88	22.88	22.95	22.98	22.76	22.94	19.59	21.56	21.71	19.98	20.29
Oct	21.53	23.83	21.37	21.42	21.50	22.86	21.21	19.82	24.03	23.57	21.41	21.80
Nov	22.07	22.42	19.46	19.53	19.62	22.89	19.21	20.89	21.87	20.89	21.95	21.41
Dec	21.25	21.27	18.45	18.53	18.62	22.69	18.22	20.14	20.27	19.82	21.06	20.50

To evaluate the accuracy and performance of the models, the mean bias error (MBE), mean absolute deviation (MAD), mean percentage error (MPE), root mean square error (RMSE), coefficient of correlation (r), coefficient of determination (R^2) and t-statistic (t) were determined using equations 18-23, were $-1 < r = \sqrt{R^2} < 1$. The result obtained is as shown in Table 5.

Table 5: Result for Statistical Error Indicators from the Models

Models	MBE	MAD	MPE	RMSE	t- statistic	r	R^2
Model 1	-0.037	1.325	-0.593	1.512	0.0804	0.5670	0.3215
Model 2	-0.188	2.453	-1.671	2.744	0.2271	-0.0804	0.0065
Model 3	-0.197	2.495	-1.727	2.797	0.2338	-0.0958	0.0092
Model 4	-0.213	2.488	-1.803	2.798	0.2536	-0.0953	0.0091
Model 5	-0.022	2.307	-1.009	2.560	0.0281	-0.4414	0.1948
Model 6	-0.187	2.530	-1.680	2.826	0.2195	-0.0908	0.0082
Model 7	-0.021	0.769	-0.088	0.930	0.0743	0.8998	0.8096
Model 8	-0.063	1.168	-0.522	1.358	0.1549	0.7043	0.4960
Model 9	0.268	1.408	0.996	1.545	0.5850	0.6398	0.4093
Model 10	-0.012	0.348	-0.074	0.415	0.0933	0.9742	0.9490
Model 11	0.115	0.582	0.507	0.662	0.5855	0.9376	0.8791

Mean bias error (MBE) and mean percentage error (MPE) indicate the average amount of over/under estimation of the models. From the results, it can be seen that model 9 and model 11averagely under estimate the solar radiation while all the other models averagely overestimate the radiation.

Mean absolute deviation (MAD) indicate the average accuracy of the model. From the table, model 10 has the least value of MAD and therefore it is the most accurate then followed by model 11. Model 6 has the highest MAD and therefore the least accurate among the models.

Root mean square error (RMSE) provides information on the short term performance of the correlations by allowing a term by term comparison of the actual deviation between the calculated value and the measured value. The smaller the value of the RMSE, the better is the model performance. From the table, model 10 has the least value of RMSE then followed by model 11 then model 7.

The t-statistics is an indication of accuracy of the model. The smaller the value of t, the better is the model performance. From standard statistical tables, at 95% level of significance and degree of freedom (n-1) i.e 11, the critical value of t is 1.796. Therefore, since the calculated value of t in all the models is less than the critical t-value, it can be concluded that all the models can be accepted based on 95% confidence limit.

The coefficient of correlation (r) and coefficient of determination (R^2) indicate the relationship between the measured value and the estimated value. The value of r for models 2-6 are negative which indicate that averagely as measured value increases, the estimated value decreases and vice versa. For the other models, the value of r is positive which indicates that averagely, as measured value increase, the estimated value also increase and vice versa.

For the coefficient of determination, R^2 , the closer the value to unity, the higher the correlation and the better the model. From the table, it can be seen that model 10 has the highest coefficient, followed by model 11 then model 7 then model 1.

4.0 CONCLUSIONS

Based on this studies it can be concluded that simple linear regression techniques can be used to estimate horizontal global solar radiation data for any location of the globe using most commonly available meteorological parameters. The linear regression analysis of the global solar radiation, sunshine durations, temperature and relative humidity data through least square technique that lead to the development of this models showing reasonable agreement with almost all the models.

It can be concluded that, if data for sunshine hours is the only available among the meteorological parameters, then Angstrom-Prescott model can be used as it shows reasonable agreement with the measured data. It is better than the models that combine sunshine hours with temperatures; but excellent performance can be obtained by using the models that include sunshine hours, temperatures and natural logarithms of relative humidity.

The result can be used to estimate daily and monthly mean daily solar radiation for other locations of similar geographical/meteorological characteristics and also can be used to estimate the missing daily/monthly mean daily solar radiation at the respective site with existing weather stations.

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