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Estimation of Global Solar Radiation in Owerri Nigeria Using Empirical Models

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ABSTRACT

In this research, measured meteorological data, empirical models were used to estimate the global solar radiation in Owerri, Nigeria. The global solar radiation data was correlated with the relative sunlight duration, relative humidity, and maximum temperature for Owerri, Nigeria, using Angstrom and Page's linear regression model. Additional multiple linear regression models were produced to examine the relationship between the amount of solar energy received worldwide and other climatic factors, such as the maximum temperature and relative humidity. The Nigerian climatic Agency (NIMET) in Abuja provided the climatic characteristics for this study for the 11-year period between 2011 and 2021. Four statistical error indicators—Mean Bias Error (MBE), Root Mean Square Error (RMSE), Mean Percentage Error (MPE), and t-stat—were used to verify the data' statistical validity. Although certain models correlate more strongly than others, the results demonstrate a strong relationship between the predicted mean worldwide solar radiation and the measured mean global solar radiation using the established models. Based on the t-statistic results, the optimum empirical equation for city was assessed. The best model for Owerri is $H_2 = H_O\left(-0.496 + 0.599\left(\frac{n}{N}\right) + 0.025(T_{max})\right)$ with t − stat value of 0.79. The global solar radiation intensity obtained with these models can be used in the design, analysis and performance estimation of solar energy conversion systems which is gradually but steadily gaining ground in Nigeria and the world at large.

Keywords: Solar Radiation, Empirical model, Temperature, relative humidity, sunshine hour, Owerri.

INTRODUCTION

Solar energy which is the radiant light and heat from the sun, has been harnessed by humans since ancient times using a range of ever evolving technologies such as solar heating, photovoltaics, solar thermal energy, solar architecture and artificial photosynthesis. [1], stated that, solar energy in effect is the light radiant heat from the sun. It therefore drives the earth's climate, plant, marine and terrestrial life and cycles. Solar radiation and other secondary resources of energy such as wind and tidal power accounts for most of the available renewable energy on earth. The energy is in turn captured in form of heat or electricity and like any other source of energy can be put to various uses. Solar energy is fast becoming an alternative to other renewable sources of energy. Currently, the dominant energy source used in Nigeria is oil and its derivatives, accounting for 85% of the total energy consumption except in the rural areas where biomass in the form of fuel, wood dominates [2]. Energy trends indicate that world oil production will reach peak and start a long downward slide some day when the fossil fuel and gas would have exhausted. The environmental consequences of harnessing these non-renewable energy sources are assuming alarming proportions. Oil extraction in Nigeria has created many ecological problems that the inhabitants of the Niger Delta region of Nigeria are beginning to think that coming from the oil rich area is a curse rather than a blessing [3]. With a view to finding solutions to energy shortage and with the environmental degradation the country is facing, solar energy is now considered to be the most effective and economical alternative energy [4]. The energy from the sun could play a key role in decarbonizing the global economy alongside improvements in energy efficiency and imposing costs on greenhouse gas emitters [5]. For a country like Nigeria, the economical and efficient application of solar energy seems inevitable because of abundant sunshine available throughout the year. It is estimated that Nigeria receives on her land area an annual insolation that is four thousand times the annual production of crude oil [6]. However, only a negligible part of this abundant solar energy potential has been tapped by Nigeria. Harnessing solar energy presents several problems. One of the main problems is the collection of solar power.

Information on the amount of global solar radiation is one of the primary variables for determining solar energy production in a region. In Nigeria, only few stations have been measuring daily solar radiation on a consistent basis. Therefore, it is important to develop method to estimate the global solar radiation using climatological parameters such as sunshine hours, relative humidity, maximum and minimum temperature, cloud cover and geographical location. Several empirical formulae have been developed to calculate the global solar radiation using various parameters. These statistical relationships between daily global solar irradiation and other climatic variables provide a practical way to calculate daily global irradiation [7].

METHODOLOGY

The data for this work was collected from Nigeria Meteorological Agency (NIMET) Abuja. The climate parameter data collected are; measured daily global radiation (H_m), the daily extra-terrestrial solar radiation on a horizontal surface (H_o), the daily maximum temperature (T_{max}), the daily maximum number of hours of possible sunshine (N), the daily number of hours of bright sunshine (n) and daily relative humidity (RH). The data collected covered a period of eleven years (2011−2021) for Owerri. The global solar radiation data supplied by NIMET were converted to useful form *Mjm^{-2}day^{-1}* using conversion factor of *1.216* proposed by [8]. The linear regression model used in correlating the measured global solar radiation data is given $\frac{\bar{H}}{H_c} = a + b\left(\frac{n}{N}\right)$ as proposed by angstrom [9] and later modified by Page [10]:

$$\frac{\bar{H}}{\bar{H}_o} = a + b\left(\frac{n}{N}\right) \quad (1)$$

Where n is the monthly average daily hours of bright sunshine, N is the monthly average day length, (a and b) values are known as Angstrom empirical constant or regression coefficients, $\bar{H}$ is the monthly average daily global radiation on a horizontal surface, $\bar{H}_o$ is the daily extraterrestrial solar radiation on a horizontal surface given by [8] as;

$$H_o = \frac{24}{\pi} I_{SC}\epsilon_o \left[\frac{\pi}{180}\ \omega sin\emptyset sin\delta + cos\emptyset cos\delta sin\omega_s\right] \quad (2)$$

where I_{SC} − the solar constant,
ϵ_o− the eccentricity correction factor of the earth's orbit,
$\emptyset$ − the latitude
δ - the solar declination angle
ω_s − the sunset hour angle

The expressions for I_{SC} , ϵ_o , δ, and ω are given by same Iqbal (1983) as:

$$I_{SC} = \frac{1367\times3600}{1000000}\ mjm^{-2}day^{-1} \quad (3)$$

$$\epsilon_o = 1 + 0.033\ cos\left(\frac{360d_n}{365}\right) \quad (4)$$

Equations for the solar declination angle (δ) and the sunset hour angle (ω_s) are given as

$$\delta = 23.45\sin\left[\frac{360(284+d_n)}{365}\right][°] \quad (5)$$

$$\omega_s = cos^{-1}(-\tan\emptyset\tan\delta) \quad (6)$$

Table 1: Meteorological Data and Global Solar Radiation for Owerri

S/N	MONTH	H_o (MJ $m^{-2}day^{-1}$)	H_m (MJ $m^{-2}day^{-1}$)	n (hrs)	N (hrs)	K	n/N	T_{MAX} (°C)	RH (%)
1	January	34.17	20.09	6.35	11.59	0.59	0.55	29.57	74.36
2	February	36.14	20.38	6.16	11.74	0.56	0.52	29.90	76.77
3	march	37.66	19.57	6.01	11.96	0.52	0.50	29.07	83.84
4	April	37.65	18.20	5.45	12.20	0.48	0.45	29.10	84.88
5	May	36.55	16.87	5.51	12.39	0.46	0.44	28.62	85.64
6	June	35.59	15.08	5.37	12.46	0.42	0.43	27.20	87.13
7	July	35.82	13.58	3.87	12.43	0.38	0.31	26.51	87.07
8	August	36.78	13.28	3.79	12.28	0.36	0.31	26.51	86.68
9	September	37.22	13.90	4.47	12.06	0.37	0.37	26.89	87.10
10	October	36.32	15.40	4.94	11.80	0.42	0.42	27.38	86.75
11	November	34.50	17.59	5.53	11.61	0.51	0.48	28.36	84.40
12	December	33.35	19.13	6.64	11.55	0.57	0.57	28.91	81.15

Multiple linear regression and correlation analysis of four parameters ($\frac{H_m}{H_{cal}}$, $\frac{n}{N}$, T_{max} and RH) were employed to estimate the global solar radiation in this work. Where $\frac{H_m}{H_{cal}}$ is the clearness index, $\frac{n}{N}$ is monthly mean fraction of sunshine radiation, T_{max} is the monthly mean maximum temperature and RH is the relative Humidity. SPSS

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computer software program was used in evaluating the model parameters. The accuracy of the estimated values was tested by calculating the mean Bias Error (MBE), Root Mean Square Error (RMSE), Mean Percentage Error (MPE) and t-stat. the expression for (MBE), (RMSE), (MPE) and t-stat were obtained from Chukwuemeka and Nnabuchi, Falayi *et al.*, and stone, [11] [12] [13] respectively and it is given as follows:

$$MBE = \frac{[\Sigma(H_{cal}-H_m)]}{n} \quad (7)$$

$$RMSE = \frac{\sqrt{[\Sigma(H_{cal}-H_m)^2]}}{n} \quad (8)$$

$$MPE = \frac{\left[\frac{H_m-H_{cal}}{H_m}\times 100\right]}{n} \quad (9)$$

$$t-stat = \sqrt{\frac{(n-1)\,MBE^2}{RMSE^2-MBE^2}} \quad (10)$$

Were H_{cal} and H_m is the calculated (predicted) and measured values and n is total number of observations. [5] have recommended that the ideal value of MBE is zero. The Root Mean Square Error (RMSE) provides information on the short – term comparisons of the deviation performance of the correlations by allowing a term by term between the calculated and measure values. The MPE gives long term performance of the examined regression equations, a positive MPE value provides an indication of some amount of overestimation in the estimated values. Negatives values indicate underestimation. A low value of MPE is desirable as proposed by [14]. For t-stat, the smaller the value of t – stat of a model, the better is the model's performance.

RESULTS AND DISCUSSION

The values for fraction of sunshine duration, maximum temperature, relative humidity and clearness index are presented in Table 1. Table 2 contains summaries of various linear regression analysis and statistical indicators, obtained from the application of Equation (1) to the monthly mean values for the three variables.

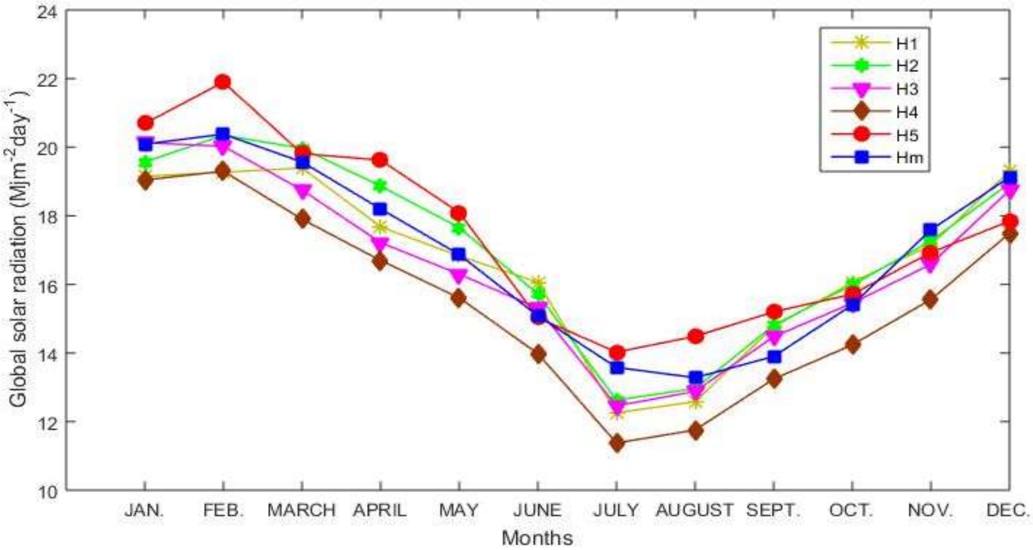

Figure 1: Comparison between measured and calculated values of global solar radiation

Figure 1 shows the comparison between the measured and calculated values of global solar radiation. It is clear that the coefficient of determination R^2, MBE, RSME, MPE and t-stat vary from one variable to another variable.

ONE VARIABLE CORRECTION

The correlation coefficient of 0.96 exists between the clearness index and monthly mean daily fraction of sunshine with a coefficient of determination of 0.92 which implies that 92% of the global solar radiation can be predicted using the fraction of sunshine.

$$H_1 = H_O\left(0.06 + 0.91\left(\frac{n}{N}\right)\right) \quad (11)$$

TWO VARIABLES CORRELATIONS

The correlation coefficient of 0.97 exists between the clearness index and maximum temperature with a coefficient of determination of 0.95 which implies that 95% of the global solar radiation can be predicted using the fraction of sunshine and maximum temperature.

$$H_2 = H_O\left(-0.496 + 0.559\left(\frac{n}{N}\right) + 0.025(T_{max})\right) \quad (12)$$

The correlation coefficient of 0.98 exists between the clearness index and relative humidity with a coefficient of determination of 0.96 which implies that 96% of the global solar radiation can be predicted using the fraction of sunshine and relative humidity.

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$$H_3 = H_O\left(0.657 + 0.688\left(\frac{n}{N}\right) - 0.006(RH)\right) \quad (13)$$

The correlation coefficient of 0.95 exists between the clearness index, maximum temperature and relative humidity with a coefficient of determination of 0.97 which implies that 97% of the global solar radiation can be predicted using the maximum temperature and relative humidity.

$$H_5 = H_O\left(-0.279 + 0.045(T_{max}) - 0.006(RH)\right) \quad (14)$$

THREE VARIABLE CORRELATIONS

The correlation coefficient of 0.98 exists between the clearness index and monthly mean daily fraction of sunshine, maximum temperature and relative humidity with a coefficient of determination of 0.97 which implies that 97% of the of the global solar radiation can be predicted using the fraction of sunshine, the maximum temperature and relative humidity.

$$H_4 = H_O\left(0.187 + 0.543\left(\frac{n}{N}\right) + 0.015(T_{max}) - 0.005(RH)\right) \quad (15)$$

Table 2: Regression equation and statistical indicators

Equations	R	R^2	MBE	RMSE	MPE	t-stat
$H_1 = H_O\left(0.06 + 0.91\left(\frac{n}{N}\right)\right)$	0.96	0.92	-0.22	0.77	1.15	0.97
$H_2 = H_O\left(-0.496 + 0.599\left(\frac{n}{N}\right) + 0.025(T_{max})\right)$	0.97	0.95	0.14	0.59	-0.83	0.79
$H_3 = H_O\left(0.657 + 0.688\left(\frac{n}{N}\right) - 0.006(RH)\right)$	0.98	0.96	-0.39	0.65	2.28	2.54
$H_4 = H_O\left(0.187 + 0.543\left(\frac{n}{N}\right) + 0.015(T_{max}) - 0.005(RH)\right)$	0.98	0.97	-1.40	1.47	8.51	11.04
$H_5 = H_O\left(-0.279 + 0.045(T_{max}) - 0.006(RH)\right)$	0.95	0.91	0.52	0.99	-3.31	2.06

BEST PERFORMED EMPIRICAL EQUATION

From the five (5) equations developed for Enugu, the best performed empirical equation is $H_2 = H_O\left(-0.496 + 0.599\left(\frac{n}{N}\right) + 0.025(T_{max})\right)$ which has the least t-stat value of 0.79.

CONCLUSION

This work shows that in the absence of global solar radiation data, reliable estimates can be made from easily available meteorological observations of possible sunshine hours, temperature and relative humidity along with extraterrestrial solar radiation using different models we developed. The best model for Owerri is $H_1 = H_O\left(0.2 + 0.77\left(\frac{n}{N}\right)\right)$ with t – stat value of 0.79. The models show that global solar radiation for Owerri is good for the estimation of global solar radiation within the regions. The global solar radiation intensity obtained with these models can be used in the design, analysis and performance estimation of solar energy conversion systems which is gradually but steadily gaining ground in Nigeria and the world at large.

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