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Research Article

Empirical Models for Estimation of Global Solar Radiation in Enugu Nigeria Using Measured Meteorological Data

Chima Abraham Iheanyichukwu[1],Nwodo Emeka[2] ,Ayantunji Benjamin Gbenro[3] and Haruna Mohammed Shehu[3]

[1,2]*Department of Industrial Physics Enugu State University of Science and Technology,*
[3,4]*National Space Research and Development Agency*
Corresponding email address:Abraham.chima@esut.edu.ng .08066922634

ABSTRACT: *Global solar radiation is an important parameter necessary for most ecological models and serves as input for different photovoltaic conversion systems. Hence, it is of economic importance to renewable energy sources. In this study, linear regression model of Angstrom and Page was employed to correlate the global solar radiation data with relative sunshine duration, relative humidity and maximum temperature for Enugu, Nigeria. Other multiple linear regression models were obtained to check the correlation of global solar radiation with sunshine duration combined with other meteorological parameters, which include maximum temperature and relative humidity. The meteorological parameters used for this work were obtained from the Nigeria meteorological agency (NIMET) Abuja for the period of 11 years from 2011 to 2021. The results obtained were statistically tested using four statistical error indicators: Mean Bias Error (MBE), Root Mean Square Error, (RMSE), Mean Percentage Error (MPE) and t-stat to establish the validity of the results. The analyses show that there is close correlation between the calculated mean global solar radiation and the measured global solar radiation using the established models, though some models correlate better than others. The best empirical equation for each of the cities was evaluated based on the values of the t – stat. The best model for Enugu is* $H_1 = H_O\left(0.2 + 0.77\left(\frac{n}{N}\right)\right)$ *with t – stat value of 0.11. 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, Enugu*

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1. INTRODUCTION

Solar energy is vital for life on our planet because all other forms of energy depend on it. Solar radiation arriving on earth is the most fundamental renewable energy source in nature. 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. 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 [7]. This energy determines the surface temperature of the earth as well as supplying almost all the energy for natural processes both on its surface and in the atmosphere. It heats up homes and provides energy to grow crops through the process of photosynthesis. Sunshine has traditionally been used for drying all types of things: clothes, agricultural produce, cash crops, and bricks. Profitable use of this energy from the sun has been made in the production of salt.

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 [14]. 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 [14].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[12].

For a country like Nigeria, the economical and efficient application of solar energy seems inevitable because of abundant sunshine available throughout the year. It has been found that there is an estimated 3,000 hours of annual sunshine [4] and average solar radiation received in Nigeria per day is as high as 20 Mj/m^2depending on the time of the year and location [9]. In energy terms, [10] estimates that Nigeria receives on her land area an annual insolation that is four thousand times the annual production of crude oil. 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. Despite the importance of such solar radiation data, there are very few locations in Nigeria where solar radiation is continuously and accurately measured. The problem of lack of data is further compounded by the high cost of solar radiation measuring equipment. However, the operation and maintenance of these instruments are not within the budget estimations of many local meteorological stations. It is therefore necessary to employ solar radiation estimation methods, which use as inputs certain meteorological parameters, such as ambient temperatures, sunshine and relative humidity that are much more readily measured than the solar radiation components.

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2. 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 elevenyears (2011−2021) for Enugu. 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 Ododo[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 [2] and later modified by Page[11]:

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

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 Iqbal (1983) 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:

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

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

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

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

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

TABLE 1: METEOROLOGICAL DATA AND GLOBAL SOLAR RADIATION FOR ENUGU

S/N	MONTH	H_o ($MJm^{-2}day^{-1}$)	H_m ($MJm^{-2}day^{-1}$)	n (hrs)	N (hrs)	K	n/N	T_{MAX} (°C)	RH (%)
1	January	33.70	20.63	5.99	11.75	0.61	0.51	30.69	62.37
2	February	35.81	20.94	5.55	11.84	0.58	0.47	30.66	69.18
3	march	37.49	20.55	4.30	11.98	0.55	0.36	29.58	81.29
4	April	37.68	19.02	4.54	12.12	0.50	0.37	29.44	83.95
5	May	36.67	17.03	4.21	12.23	0.47	0.34	28.84	85.03
6	June	35.91	16.17	3.24	11.72	0.45	0.28	27.59	86.25
7	July	36.14	14.86	3.23	11.75	0.41	0.27	26.9	86.45
8	August	36.96	14.16	3.43	11.90	0.38	0.32	26.84	86.11
9	September	37.23	14.86	3.75	1199	0.40	0.29	27.22	86.52
10	October	36.10	16.59	4.94	11.88	0.46	0.42	27.86	85.61
11	November	34.09	18.76	5.99	11.77	0.55	0.51	28.84	82.63
12	December	32.87	19.94	5.67	11.72	0.61	0.48	29.77	72.79

Multiple linear regression and correlation analysis of four parameters ($\frac{H_m}{H_{cal}}$, $\frac{n}{N}$, $T_{max} and R$H) 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

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sunshine radiation, T_{max} is the monthly mean maximum temperature and RH is the relative Humidity. SPSS 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, [3] [13][6] respectively and it is given as follows:

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

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

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

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

Were H_{cal} and $H_m$is the calculated (predicted) and measured values and n is total number of observations. Che et al. [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 Akpabio and Etuk [1]. For t-stat, the smaller the value of t – stat of a model, the better is the model's performance.

3. RESULTS AND DISCUSSION

Thevalues 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.

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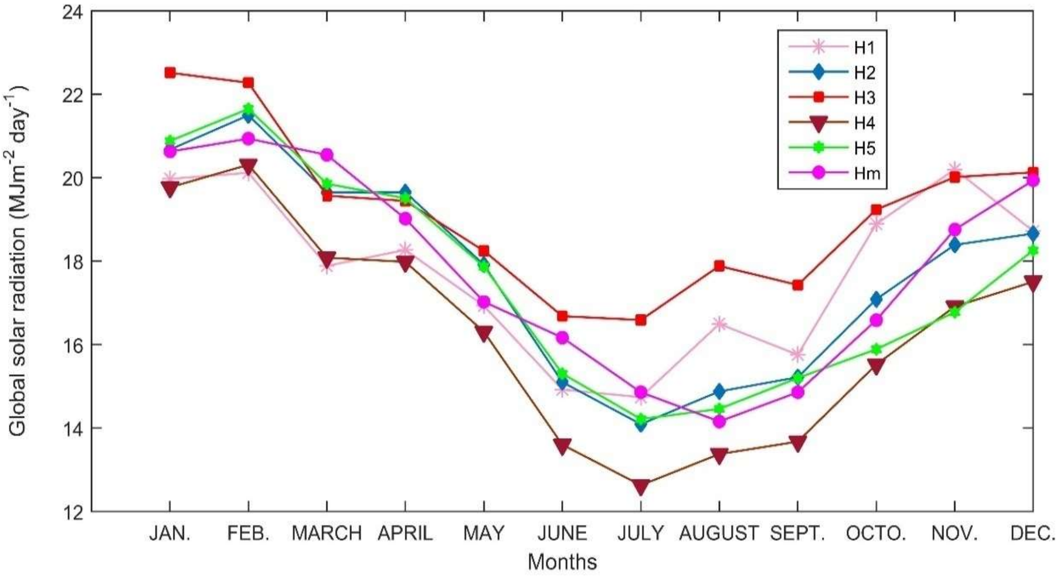

Figure 1: Comparison between measured and calculated values of global solar radiation

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.

3.1. ONE VARIABLE CORRECTION

The correlation coefficient of 0.85 exists between the clearness index and monthly mean daily fraction of sunshine with a coefficient of determination of 0.73 which implies that 73% of the of the global solar radiation can be predicted using the fraction of sunshine.

$$H_1 = H_O\left(0.2 + 0.77\left(\frac{n}{N}\right)\right) \quad (11)$$

3.2. TWO VARIABLES CORRELATIONS

The correlation coefficient of 0.95 exists between the clearness index and maximum temperature with a coefficient of determination of 0.92 which implies that 92% of the of the global solar radiation can be predicted using the fraction of sunshine and maximum temperature.

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$$H_2 = H_O\left(-0.767 + 0.3\left(\frac{n}{N}\right) + 0.04(T_{max})\right) \quad (12)$$

The correlation coefficient of 0.90 exists between the clearness index and relative humidity with a coefficient of determination of 0.81 which implies that 81% of the of the global solar radiation can be predicted using the fraction of sunshine and relative humidity.

$$H_3 = H_O\left(0.678 + 0.470\left(\frac{n}{N}\right) - 0.004(RH)\right) \quad (13)$$

The correlation coefficient of 0.94 exists between the clearness index, maximum temperature and relative humidity with a coefficient of determination of 0.88 which implies that 88% of the of the global solar radiation can be predicted using the maximum temperature and relative humidity.

$$H_5 = H_O(-0.698 + 0.047(T_{max}) - 0.002(RH)) \quad (14)$$

3.3 THREE VARIABLES CORRELATIONS

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

$$H_4 = H_O\left(-0.664 + 0.288\left(\frac{n}{N}\right) + 0.038(T_{max}) - 0.001(RH)\right) \quad (15)$$

TABLE 2: REGRESSION EQUATION AND STATISTICAL INDICATORS

Equations	R	R^2	MBE	RMSE	MPE	t-stat
$H_1 = H_O\left(0.2 + 0.77\left(\frac{n}{N}\right)\right)$	0.85	0.73	-0.05	1.46	-0.42	0.11
$H_2 = H_O\left(-0.767 + 0.3\left(\frac{n}{N}\right) + 0.04(T_{max})\right)$	0.95	0.92	-0.66	0.75	0.21	6.34

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$H_3 = H_O\left(0.678 + 0.470\left(\frac{n}{N}\right) - 0.004(RH)\right)$	0.90	0.81	1.38	1.83	-8.52	3.77
$H_4 = H_O\left(-0.664 + 0.288\left(\frac{n}{N}\right) + 0.038(T_{max}) - 0.001(RH)\right)$	0.96	0.92	-1.48	1.65	8.47	6.74
$H_5 = H_O(-0.698 + 0.047(T_{max}) - 0.002(RH))$	0.94	0.88	-0.30	0.94	1.64	1.12

3.4. BEST PERFORMED EMPIRICAL EQUATION

From the five (5) equations developed for Enugu, the best performed empirical equation is $H_1 = H_O\left(0.2 + 0.77\left(\frac{n}{N}\right)\right)$ which has the least t-stat value of 0.11.

4. 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 Enugu is $H_1 = H_O\left(0.2 + 0.77\left(\frac{n}{N}\right)\right)$ with t – stat value of 0.11. The models show that global solar radiation for Enugu 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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