Model for Development of Solar Energy Potential in Nigeria

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ABSTRACT

This study explored the potential of developing solar energy as a viable option in Nigeria. Sunshine-hours data recorded at six synoptic meteorological stations in the country, namely: Sokoto (12.9^0N, 5.2^0E), Maiduguri (11.9^0N, 13.1^0E), Ilorin (8.4^0N, 4.5^0E), Ikeja (6.6^0N, 3.3^0E), Port-Harcourt (5.0^0N, 6.9^0E) and Enugu (6.5^0N, 7.6^0E). over the period 1996-2010 were used. A set of Angstrom constants were obtained and averaged in order to develop the linear regression model for estimation of solar radiation in Nigeria. This model has potential for generating ground observation data of solar radiation at any given location in the country using sunshine hours as the only required input. An Angstrom model of monthly average Clearness Index with normalized sunshine duration was then developed for each of the six meteorological stations. The resulting linear regression model was applied in estimating monthly average daily solar radiation. Regression analysis between computed and measured radiation data was applied to assess the reliability of the generated Angstrom constants. The results generally show a high degree of agreement between the two variables, with correlation coefficients ranging from 0.72 to 0.94. Angstrom constants obtained at the six meteorological stations were thereafter averaged in order to develop a linear regression model for estimating solar radiation in Nigeria. The model developed is $H = H_o(0.21 + 0.42N)$ for which H is the estimated solar radiation in Nigeria , H_o, the extraterrestrial solar radiation and N is the relative sunshine. Solar radiation values obtained using this model were noted to be in good agreement with those developed for each of the six meteorological stations.

Keywords: *Solar Radiation; Angstrom Constants; Sunshine Hours; Clearness Index; Linear Regression Model*

1. Introduction

The sun, is the absolute source of solar radiation, is a sphere of intensely hot gaseous matter with a diameter of about $1.39 \times 10^9 m$, a total mass of $1.99 \times 10^{30} kg$, and on average $1.5 \times 10^{11} m$ away from earth (Duffie & Beckman, 2013). The 3 sun radiates energy radially from an effective surface temperature of about 5760K as electromagnetic radiation known as 'solar 4 energy' or sunshine (Musa *et al*., 2012). The sun is the source of most energy on the earth and is a primary factor in determining the thermal environment of a locality. Solar energy is a renewable resource, and is environmentally friendly, available just about everywhere on earth. The added advantage of solar energy is that it is provided for free and is not susceptible to price fluctuations associated with fossil fuels. Solar radiation may be harnessed for use either as solar thermal or 8 photovoltaic. Solar energy may be harnessed and used for various purposes including domestic use such as cooking, heating, and lighting.

The need to explore the potential of renewable energy in Nigeria cannot be over emphasized. The energy sector in Nigeria comprises four main subsectors: hydropower, biomass (fuel wood), natural gas and oil, the country's energy needs are mainly derived from fuel wood, which accounts for 82.2% of the total energy demand . Hydropower 0.4%, natural gas 6.8 % and oil 10.6% [9]. The severe deforestation being experienced in the country is a direct result of fuel wood demands and the clearing of vast expanses of land for agricultural production. This had serious repercussions on soil erosion, frequency and intensity of flash floods, siltation of water bodies, and reduction of greenhouse gas sink capacity.

The country's high dependence on fuel wood calls for concerted effort by all Nigerians to explore and exploit alternative sources of energy in order to arrest deforestation, and thus curb further environmental degradation. This study as an attempt of assessing Nigeria's potential for developing solar energy as an option is viable, noting that the search for alternative energy sources is in line with Nigeria Energy Policy.

Some major studies on solar radiation in Nigeria include those done by Adeola, Aro, & Akinpelu, (2017); Estimation of Global Solar Radiation in Ibadan, Nigeria using Angstrom - Prescott and Glover - Mcculloch‟s Model by; (Ogolo, 2014); Estimation of GSR in Nigeria using a modified Angstrom model and the trend analysis of the allied meteorological components ; Innocent *et al*. (2015); Estimation of GSR in Gusau, Nigeria Musa, Zangina, & Aminu (2012); Solar Radiation Models and Information for Renewable Energy Applications by Falayi & Rabiu (2012); Estimation of GSR in Maiduguri, Nigeria Using Angstrom Model Elom & Nnamdi (2012); Solar radiation in Onitsha : A correlation with average temperature; Gana & Akpootu (2013b); Estimation of GSR using four sunshine based models in Kebbi, North-Western, Nigeria

3. Materials and Methods

Various climate models have been developed for use in predicting the monthly average global solar radiation, the first obtained through the well-known Angstrom equation (Angstrom, 1924) [1]. This equation is given as

$$\frac{H}{H_0} = a + b\frac{S}{S_0}, \qquad (1)$$

This relates monthly average daily global radiation to the average daily sunshine hours, and is given by the following expression:

where: H is the monthly average daily global radiation on a horizontal surface (MJ·m^{-2}·day^{-1}), H_0 is the monthly average daily extraterrestrial radiation on a horizontal surface (MJ·m^{-2}·day^{-1}), S is the monthly average daily number of hours of bright sunshine, S_0 is the monthly average daily maximum number of hours of possible sunshine (or day length), a and b are regression constants. Equation (1) has been noted to predict global solar radiation in several locations on earth with a high degree of accuracy.

Global solar radiation H represented as [2]:

$$H = K_T\, H_0 \qquad (2)$$

where K_T is the Clearness Index (the degree of transparency of the atmosphere to the passage of solar radiation) and H_o is the extraterrestrial solar radiation on a horizontal surface. H_o is only a function of latitude and is independent of other location-specific parameters. The daily clearness index K_T is also given as $\frac{H}{H_0}$., ratio of the daily global radiation on a horizontal surface to the daily extraterrestrial radiation on a horizontal surface. Because of attenuation, H is very much dependent on the location of the place on the earth's surface; and its value is less than extraterrestrial irradiation, H_0.

The extraterrestrial solar radiation on a horizontal surface is calculated from the following Equation (3):

$$H_0 = \frac{24 \times 3600 I_{sc}}{\pi}\left[1 + 0.033\cos\left(\frac{360n}{365}\right)\right] \times \left[\cos\phi\cos\delta\sin\omega_s + \frac{2\pi\omega_s}{360}\sin\phi\sin\delta\right] \quad (3)$$

where n is the Julian day number, I_{sc} is the solar constant with a value of 1367 Wm^{-2}, is the latitude of the location, δ is the declination angle:

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

and ω_s is the sunset hour angle:

$$\omega_s = \cos^{-1}(-\tan\phi\tan\delta) \quad (5)$$

The maximum possible sunshine duration N is given by:

$$N = \frac{2}{15}\omega_s \quad (6)$$

In order to determine the value of H in Equation (1), sunshine-hours data recorded over the period 1996-2010 were collected from six synoptic meteorological stations: Sokoto, Maiduguri, Ilorin, Ikeja, Port-Harcourt and Enugu. using the Camp-Bell Stokes Sunshine Recorder.

The Data on incident radiation in $MJm^{-2}day^{-1}$ was collected by the Gunn-Bellan Spherical Pyranometer. An Angstrom model of monthly average Clearness Index with normalized sunshine duration was then developed for each of the six meteorological stations.
Values of H_o and S were calculated for each month using Equations (3) and (6), respectively. The regression coefficients a and b in Equation (1) were computed from a plot of H/H_o and S/S_o, with a as the intercept on the H/H_o axis and b as the gradient.

Differences between estimated and measured values of solar radiation were determined by the Mean Bias Error (MBE), the Root Mean Square Error (RMSE), and the Mean Percentage Error (MPE), given by the following respective expressions:

$$MPE(\%) = \frac{1}{n}\sum_{1}^{n}\left(\frac{(H_{cal} - H_{meas})}{H_{meas}}\right) \times 100 \quad (7)$$

Root Mean Square Error (RMSE)

$$RMSE = \left[\frac{1}{2}\sum_{1}^{n}\left(H_{cal} - H_{meas}\right)^2\right]^{\frac{1}{2}} \tag{8}$$

4. Results and Discussions

The selected stations across the country is as shown in Figure 1. Table **1** shows some of its Geographical characteristics, its location, altitude and vegetation type(s) of the stations.

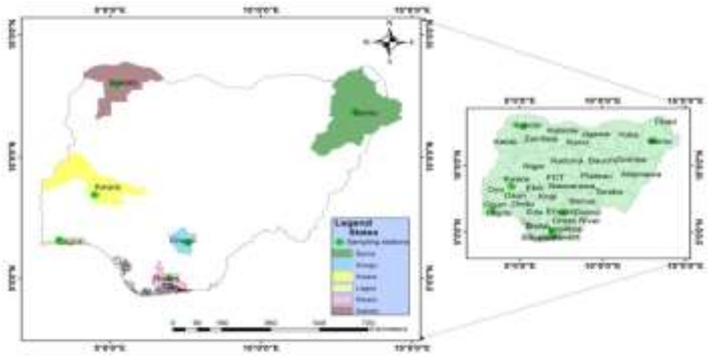

Figure 1: Study Stations

Table 1 Geographical characteristics of the selected site

Stations	Latitude (North)°	Longitude (East)°	Altitude (meters)	Vegetation Type
SOKOTO	12.92	5.21	269	Savanna/Thorn Scrub
MAIDUGURI	11.85	13.08	325	Sudan Savanna/ Southern Sahel
ILORIN	8.44	4.50	335	Forest and Savanna
IKEJA	6.58	3.32	45	Dry low land rainforest
PORT-HARCOURT	5.01	6.95	20	Rainforest

ENUGU	6.47	7.57	132	Tropical rainforest vegetation /Guinea savanna vegetation

The data analysis results showed that maximum and minimum solar radiation values were observed in March, November and July/August respectively. Values of regression constants of Equation (2), along with the correlation coefficients (RC) and the values of the MBE, RMSE and MPE for the six meteorological stations are summarized in **Table 2**.

Results presented in **Table 2** show that regression coefficients (RC) are higher than 0.70, implying a good fitting between the Clearness Index H/H_o and N, the relative possible number of sunshine hours S/S_o. Furthermore, there is a remarkable agreement between the measured and calculated values of global radiation for the six locations as attested by very low values of RMSE and MPE. Negative and positive values of MPE respectively show slight overestimation and underestimation of H

Comparison between measured and calculated H using Equation (2), along with regression constants given in **Table 2**, indicate that the percentage error for a single month rarely exceeds ±2% at any of the six meteorological stations. For example, the calculated annual average daily solar radiation value at Sokoto using Equation (2) is 16.2 $MJ.m^{-2}\cdot day^{-1}$ while the measured value is 16.8 $MJ.m^{-2}\cdot day^{-1}$. The corresponding values for Ilorin and Enugu are 15.4 $MJ.m^{-2}\cdot day^{-1}$ and 14.1 $MJ.m^{-2}\cdot day^{-1}$, and 15.1 $MJ.m^{-2}\cdot day^{-1}$ and 14.0 $MJ.m^{-2}\cdot day^{-1}$, respectively. **Table 3** gives a summary of global for measure and calculated radiation for Sokoto, Maiduguri, Ilorin, Ikeja, Portharcourt and Enugu meteorological stations.
From the results highlighted in **Table 3**, the following simple first order Angstrom correlations models may be developed for use in estimating values of H_h at each of the respective six meteorological stations:

1) Sokoto $H = H_0(0.33 + 0.46N)$ ……………......... (10)

2) Maiduguri $H = H_0(0.29 + 0.56N)$ …………………… (11)

3) Ilorin $H = H_0(0.08 + 0.19N)$ ……………......... (12)

4) Ikeja $H = H_0(0.25 + 0.63N)$ ……………......... (13)

5) Port-harcourt $H = H_0(0.07 + 0.12N)$ ……………......... (14)

6) Enugu $H = H_0(0.28 + 0.58N)$ ……………......... (15)

From Equations (10)-(15) that neither a nor b vary with latitude or altitude in any systematic manner. However, the values of the sum of the regression constants a + b, which represent the maximum Clearness Index ((N) = 1), averaged over the period of analysis, are found to be almost equal for Sokoto, Maiduguri, Ikeja, and Enugu are 0.79, 0.84, , 0.88, and 0.85, respectively, 0.27 and 0.19 respectively for Ilorin and Port-harcourt meteorological stations. Averaged results for linear regression models for the six selected stations were used in developing the linear regression model for estimating solar radiation in Nigeria:

$$H = H_0(0.21 + 0.42N) \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (16)$$

Equation (16) was then used in estimating H for the six locations, and in all cases the Mean Percentage Error lesser than ±10%. This is indicative of a fairly good results

Table 2: Regression constants of Equation (2) for the selected locations and the corresponding values of RC,MBE,RMSE and MPE

Station	Degree of Correlation(RC)	Regression constants a	b	a +b	MBE	RMSE	MPE (%)
Sokoto	0.83	0.33	0.46	0.79	-0.3025	0.4278	1.79
Maiduguri	0.72	0.29	0.55	0.84	0.61778	0.8736	4.12
Ilorin	0.93	0.08	0.19	0.27	0.17139	0.2424	1.13
Ikeja	0.91	0.25	0.63	0.88	-0.4169	0.5896	3.83
Port-Harcourt	0.88	0.07	0.12	0.19	-0.0589	0.0730	0.43
Enugu	0.94	0.27	0.58	0.85	0.1744	0.2467	1.23

Stations	Sokoto		Maiduguri		Ilorin		Ikeja		Port Harcourt		Enugu	
Month	H_{cal} (MJm^{-2})	H_{meas} (MJm^{-2})	H_{cal} (MJm^{-2})	H_{meas} (MJm^{-2})	H_{cal} (MJm^{-2})	H_{meas} (MJm^{-2})	H_{cal} (MJm^{-2})	H_{meas} (MJm^{-2})	H_{cal} (MJm^{-2})	H_{meas} (MJm^{-2})	H_{cal} (MJm^{-2})	H_{meas} (MJm^{-2})
JAN	14.10	15.68	14.10	14.22	14.30	14.07	10.80	10.76	13.40	12.30	13.90	14.27
FEB	17.20	17.56	17.20	15.43	16.90	17.20	10.80	12.34	15.30	13.76	15.40	15.89
MAR	17.70	18.76	17.70	17.04	17.20	17.00	12.80	13.06	14.10	13.25	16.60	15.30

APR	19.00	19.04	19.00	17.91	18.30	17.02	13.10	13.29	13.70	12.76	14.70	14.39
MAY	16.60	18.18	16.60	16.59	17.50	15.60	12.70	11.94	12.90	12.37	15.30	14.70
JUN	17.80	17.52	17.80	14.66	13.30	13.90	11.20	10.28	11.50	10.86	14.10	13.62
JUL	14.50	15.34	14.50	13.27	12.80	12.05	7.60	8.14	7.90	9.24	12.50	11.62
AUG	14.70	14.29	14.70	12.08	12.50	11.71	5.10	7.35	8.80	9.04	11.30	11.12
SEP	15.00	16.26	15.00	14.82	14.50	14.63	6.90	8.95	9.10	10.47	13.10	13.00
OCT	16.60	17.02	16.60	15.62	16.50	16.36	8.50	10.32	10.20	12.12	14.70	14.34
NOV	14.90	16.65	14.90	14.87	17.10	16.95	10.20	11.80	11.50	13.24	16.70	15.71
DEC	16.50	15.52	16.50	13.22	14.90	15.18	10.70	12.13	12.80	12.98	15.00	15.13

Table 3. Measure and calculated Global Solar Radiation

5. Conclusions

The study has shown that maximum and minimum solar radiation in Nigeria take place in March/October and July/August respectively. Therefore the optimum time for using solar energy is during the month of March and October.

The study also resulted in the development of respective Angstrom linear regression models for each of the six selected meteorological stations, which culminated in the development of the Angstrom model for Nigeria given by Equation (16).

A fairly good agreement (MPE $\leq \pm 10\%$) was noted between measured values and calculated values of solar radiation at the six selected meteorological stations, which makes Equation (16) useful for estimating solar radiation in Nigeria.

Since knowledge of the amount of irradiance reaching any point on the earth's surface is critical in the design solar systems, the model we have developed may help the Nigeria Government to develop realistic energy policies and programmes based on sound scientific knowledge.

In Nigeria, where there is abundant sunlight and a large rural population without proper infrastructure to develop an electricity grid, use of PV is seen as an attractive option because of its modular features, namely: its ability to generate electricity at the point of use, its low maintenance requirements and its nonpolluting characteristics.

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