

Angstrom Constants for Estimating Solar Radiation in Sokoto, North-Western, Nigeria.

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Abstract

Detailed information about the availability of solar radiation on horizontal surface is essential for the optimum design and study of solar energy conversion system. For Sokoto (Latitude 13.00°N, Longitude 5.25°E and altitude 304 meters above sea level), the economical and efficient application of solar energy seems inevitable because of abundant sunshine available throughout the year. In this paper, a new set of constants for Angstrom-type correlation for first, second and third order, to estimate monthly average daily global solar radiation, has been obtained using global solar radiation and sunshine hours data for the period (1990-2005), capable of generating solar radiation at any given location and other surrounding towns of similar meteorological conditions. These results are then compared with other three models and the calculated global solar radiation data. The calculated global solar radiation for Sokoto (1990-2005), North-Western, Nigeria will enable the solar energy researchers to use the estimated data with confidence, because of its good agreement with the three applied models. Moreover, the maximum monthly average sunshine hours and calculated global solar radiation for Sokoto (1990-2005) on a horizontal surface are found to be 8.99 hours and 24.33MJ/m²/day respectively, and this occurred in the months of November and June. To test for the performance of statistical significance of the models, mean bias error (MBE), root mean square error (RMSE), mean percentage error (MPE) and t-test values were adopted, however, the MBE, RMSE and MPE gives a fairly good estimates while the results shows that at both confidence level of 95% and 99% for Sokoto, they are significant.

Keywords: Angstrom constants, Sunshine Hours, NIMET, Global Solar Radiation, Sokoto.

1. INTRODUCTION

SOLAR energy is a free, clean and inexhaustible source of energy. Its effective harnessing and utilization are of importance to the world especially at this time of rising fuel costs and environmental effects such as depletion of the ozone layer and greenhouse effect [1].

Knowledge of local solar radiation is essential to many applications including architectural designs, solar energy systems, crop growth models, hydrological models, and design of irrigation systems [2], [3].

The sunshine duration at a given site depends on the topography of the site and the prevailing meteorological conditions, such as the clearness of the sky and the height above sea level, water vapor content, air temperature, pressure, humidity, wind direction and force, etc. [4],[5].

Solar radiation data are a fundamental input for solar energy applications such as photovoltaic, solar-thermal systems and passive solar design. The data should be reliable and readily available for design, optimization and performance evaluation of solar technologies for any particular location. Unfortunately, for many developing countries, solar radiation measurements are not easily

The data of the monthly mean of daily global solar radiation and sunshine duration from Nigeria Meteorological Agency (NIMET) Abuja, Nigeria for Sokoto location were

available because of not being able to afford the measuring equipments and techniques involved. Therefore, it is necessary to develop methods to estimate the solar radiation on the basis of the more readily available meteorological data. [6].

[7] developed correlation with solar radiation using sunshine hours for Kano with the regression coefficients $a=0.413$ and $b=0.241$ for all the months between 1980- 1984, [8] developed a correlation with solar radiation using sunshine hours in Northern Nigeria with regression coefficients $a=0.2$ and $b=0.74$, [9] developed a model for estimation of global solar radiation in Bauchi with regression coefficients $a=0.24$ and $b=0.46$. Other workers (e.g. [10], [11], [12], [13], [14], [15]) developed theoretical and empirical correlations of broad applicability to provide solar data for system design in most Nigeria cities. They observed that the regression coefficients are not universal but depends on the climatic conditions [16]. Accurate modeling depends on the quality and quantity of the measured data used and is a better tool for estimating the global solar radiation of location where measurements are not available [17].

collected and utilized. The data obtained cover a period of fifteen years (1990-2005) for Sokoto (Latitude 13.00°N, Longitude 5.25°E and altitude 304 meters). The main objective

of this paper was to develop a linear regression model for estimating solar radiation using global solar radiation and

sunshine hours for Sokoto.

2. METHODOLOGY

The first correlation proposed for estimating the monthly average daily global radiation is based on the method of Angstrom [18]. The original Angstrom-Prescott type regression equation-related monthly average daily radiation to clear day radiation in a given location and average fraction of possible sunshine hours:

$$\frac{H}{H_o} = a + b \left(\frac{S}{S_o} \right) \quad (1)$$

where H is the monthly average daily global radiation on a horizontal surface ($\text{MJm}^{-2}\text{day}^{-1}$), H_o the monthly average daily extraterrestrial radiation on a horizontal surface ($\text{MJm}^{-2}\text{day}^{-1}$), S the monthly average daily hours of bright sunshine, S_o the monthly average day length, and "a" and "b" values are known as Angstrom constants and they are empirical.

The values of the monthly average daily extraterrestrial irradiation (H_o) can be calculated from the following equation (2) [19]:

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

Where I_{sc} is the solar constant ($=1367 \text{ W m}^{-2}$), ϕ the latitude of the site, δ the solar declination, w_s the mean sunrise hour angle for the given month, and n the number of days of the year starting from the first of January.

The solar declination (δ) and the mean sunrise hour angle (w_s) can be calculated by the following equations (3) and (4), respectively in [20]:

$$\delta = 23.45 \sin \left(360 \frac{284 + n}{365} \right) \quad (3)$$

$$w_s = \cos^{-1} (-\tan \phi \tan \delta) \quad (4)$$

For a given month, the maximum possible sunshine duration (monthly average day length (S_o)) can be computed by using the following equation (5) [19]

$$S_o = \frac{2}{15} w_s \quad (5)$$

Then, the monthly mean of daily global radiation H was normalized by dividing with monthly mean of daily extraterrestrial radiation H_o . We can define clearness index

(K_T) as the ratio of the observed/measured horizontal terrestrial solar radiation (H), to the calculated/predicted horizontal/extraterrestrial solar radiation (H_o) [21]

$$K_T = \frac{H}{H_o} \quad (6)$$

In this study, H_o and S_o were computed for each month by using Equations (2) and (5), respectively. The regression coefficients a and b in Equation (1) have been obtained from the graph of $\frac{H_{cal}}{H_o}$ versus $\frac{S}{S_o}$. The values of the monthly

average daily global radiation H and the average number of hours of sunshine were obtained from monthly measurements covering a period of 15 years. The regression coefficient a and b from the calculated monthly average global solar radiation has been obtained from the relationship given as [22]:

$$a = -0.110 + 0.235 \cos \phi + 0.323 \left(\frac{S}{S_o} \right) \quad (7)$$

$$b = 1.449 - 0.553 \cos \phi - 0.694 \left(\frac{S}{S_o} \right) \quad (8)$$

To compute estimated values of the monthly average daily global radiation H_{Cal} , the values of computed a and b from equations (7) and (8) were used in Equation (1) [23].

The three regression models used in this study are:

1. [24] included latitude effect and presented the correlation

$$\frac{H}{H_o} = 0.29 \cos \phi + 0.52 \left(\frac{S}{S_o} \right) \quad (9)$$

where ϕ is the latitude of the location under study.

2. [25] examined several published values of regression coefficient for Angstrom-type relations and suggested use of the following correlation:

$$\frac{H}{H_o} = 0.18 + 0.62 \left(\frac{S}{S_o} \right) \quad (10)$$

3. [26] developed the following third- order correlation based on the data of bright sunshine hours and global radiation for 48 locations around the world [27]:

$$\frac{H}{H_o} = 0.16 + 0.87 \left(\frac{S}{S_o} \right) - 0.61 \left(\frac{S}{S_o} \right)^2 + 0.349 \left(\frac{S}{S_o} \right)^3 \quad (11)$$

In this study, the validity of the estimated global solar radiation data was statistically tested by mean bias error (MBE), root mean bias error (RMSE), mean percentage error (MPE%) and t-test (t) and are defined as follows:

$$MBE = \frac{\sum_{i=1}^n [(\bar{H}_{i,cal} - \bar{H}_{i,meas})]}{n} \quad (12)$$

4. RESULTS AND DISCUSSION

The extraterrestrial solar radiation H_o (MJ/m²/day) and the monthly day length S_o (hr) were computed for each month using equations (2) and (5), the input parameters for the calculation of the mean monthly global solar radiation for Sokoto (1990- 2005) are shown in the Table 1. It was observed that sunshine duration is above 60 percent throughout the year with exception of the months of July- August (Table 1). Using these parameters, the regression constants 'a' and 'b' evaluated as 0.429 and 0.302 respectively. Substituting these values into equation (1), the simple first order Angstrom-type empirical correlation for the estimation developed for Sokoto is as follow:

$$RMSE = \left\{ \frac{\sum_{i=1}^n (\bar{H}_{i,cal} - \bar{H}_{i,meas})^2}{n} \right\}^{\frac{1}{2}} \quad (13)$$

$$MPE = \frac{\sum_{i=1}^n \frac{(\bar{H}_{i,meas} - \bar{H}_{i,cal}) \times 100}{\bar{H}_{i,meas}}}{n} \quad (14)$$

$$t = \left[\frac{(n-1) - (MBE)^2}{(RMSE)^2 - (MBE)^2} \right]^{\frac{1}{2}} \quad (15)$$

where $\bar{H}_{i,cal}$ and $\bar{H}_{i,meas}$ is the *i*th calculated and measured global solar radiation values and *n* is the total number of observations. In general, a low RMSE is desirable. The positive MBE shows overestimation while a negative MBE indicates underestimation [28].

$$\frac{H_{cal}}{H_o} = 0.429 + 0.302 \left(\frac{S}{S_o} \right) \quad (16)$$

The coefficient of regression, R^2 , (97.73) obtained for this analysis shown in Fig.1, i.e., the model best fits the data. The

value of $\frac{H_{cal}}{H_o}$ (= 0.5981) corresponding to the lowest value

of $\frac{S}{S_o}$ (= 0.5739) and H_{cal} (23.23MJ/m²/day) in the month of

August is an indication of poor sky condition. These conditions correspond to the general wet or rainy season (June – September) observed in Nigeria during which there is much cloud cover.

Table 1. Calculated monthly mean of global solar radiation and input parameters of monthly mean average of global solar radiation for Sokoto (1990 - 2005).

Months	Hcal	H ₀	S	S ₀	Hcal/H ₀	S/S ₀
Jan	18.75	29.22	7.85	11.25	0.6416	0.6978
Feb	19.80	31.60	7.41	11.43	0.6267	0.6482
Marc	21.52	34.15	7.73	11.73	0.6303	0.6591
Apri	23.33	38.26	7.29	12.11	0.6098	0.6020
May	24.20	39.54	7.57	12.46	0.6121	0.6077
Jun	24.33	38.73	8.29	12.71	0.6281	0.6523
Jul	22.90	37.99	7.46	12.76	0.6028	0.5848
Aug	23.23	38.84	7.22	12.58	0.5981	0.5739
Sept	23.90	38.96	7.49	12.25	0.6134	0.6112
Oct	22.98	36.44	7.85	11.89	0.6307	0.6605
Nov	20.98	31.85	8.99	11.53	0.6586	0.7798
Dec	18.29	28.32	8.08	11.29	0.6461	0.7157

Table 2. Summary of monthly mean average of regression constants, extraterrestrial solar radiation, measured and calculated values, measured and calculated clearness index and relative percentage error for Sokoto (1990 - 2005).

Months	a	b	H ₀	H _{meas}	Hcal	H _{meas} /H ₀	Hcal/H ₀	Error %
Jan	0.34	0.43	29.22	20.95	18.75	0.7170	0.6416	10.52
Feb	0.33	0.46	31.60	23.01	19.80	0.7281	0.6267	13.93
Marc	0.33	0.45	34.15	24.64	21.52	0.7215	0.6303	12.65
Apri	0.31	0.49	38.26	24.39	23.33	0.6374	0.6098	4.33
May	0.32	0.49	39.54	22.73	24.20	0.5749	0.6121	-6.47
Jun	0.33	0.46	38.73	21.48	24.33	0.5546	0.6281	-13.26
Jul	0.31	0.50	37.99	19.84	22.90	0.5223	0.6028	-15.41
Aug	0.30	0.51	38.84	19.03	23.23	0.4900	0.5981	-22.06
Sept	0.32	0.49	38.96	19.87	23.90	0.5100	0.6134	-20.29
Oct	0.33	0.45	36.44	21.3	22.98	0.5846	0.6307	-7.89
Nov	0.37	0.37	31.85	21.54	20.98	0.6763	0.6586	2.62
Dec	0.35	0.41	28.32	20.61	18.29	0.7279	0.6461	11.24

Table 3. Monthly average global solar radiation estimation from various models for Sokoto (1990-2005).

Month	Ho	Hcal/Ho	S/So	Hcal	Glover and McCulloch (1958)	Bahel			
						Rietveld (1978)	et al (1987)	Equation 17	Equation 18
Jan	29.22	0.6416	0.6978	18.75	18.86	17.90	17.20	18.69	18.73
Feb	31.60	0.6267	0.6482	19.80	19.58	18.39	17.78	19.74	19.79
Marc	34.15	0.6303	0.6591	21.52	21.35	20.10	19.41	21.45	21.51
Apri	38.26	0.6098	0.6020	23.33	22.79	21.17	20.62	23.37	23.32
May	39.54	0.6121	0.6077	24.20	23.67	22.01	21.42	24.22	24.19
Jun	38.73	0.6281	0.6523	24.33	24.08	22.64	21.88	24.25	24.31
Jul	37.99	0.6028	0.5848	22.90	22.28	20.61	20.13	23.00	22.88
Aug	38.84	0.5981	0.5739	23.23	22.56	20.81	20.36	23.39	23.21
Sept	38.96	0.6134	0.6112	23.90	23.39	21.78	21.18	23.91	23.89
Oct	36.44	0.6307	0.6605	22.98	22.81	21.48	20.73	22.90	22.97
Nov	31.85	0.6586	0.7798	20.98	21.91	21.13	20.16	21.16	20.96
Dec	28.32	0.6461	0.7157	18.29	18.54	17.66	16.94	18.27	18.28

Table 4. The equation with regression and Statistical indicator for Sokoto (1990-2005)

a	B	MBE	RMSE	MPE (%)	r	R ²	t
0.429	0.302	0.4021	2.7075	40.2124	0.9886	0.9773	0.4981

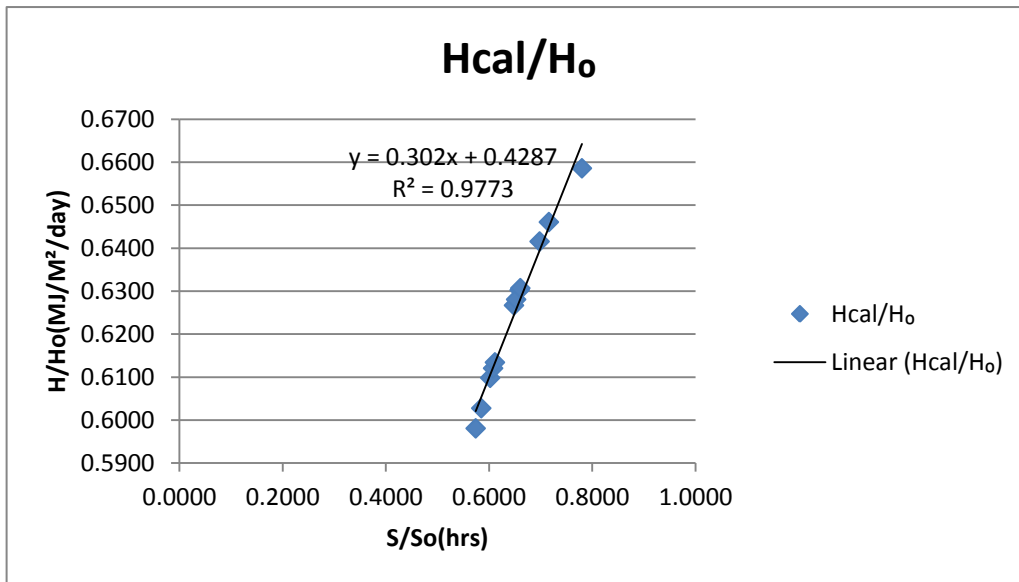


Figure 1: Variation of clearness index with respect to sunshine duration of first-order for Sokoto (1990 - 2005)

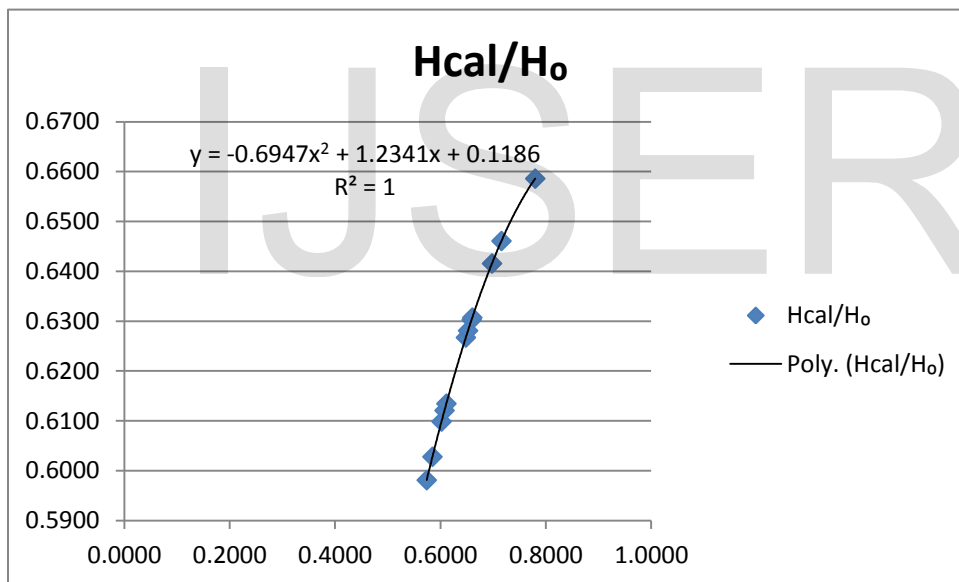


Figure 2: Variation of clearness index with respect to sunshine duration of second-order for Sokoto (1990 - 2005)

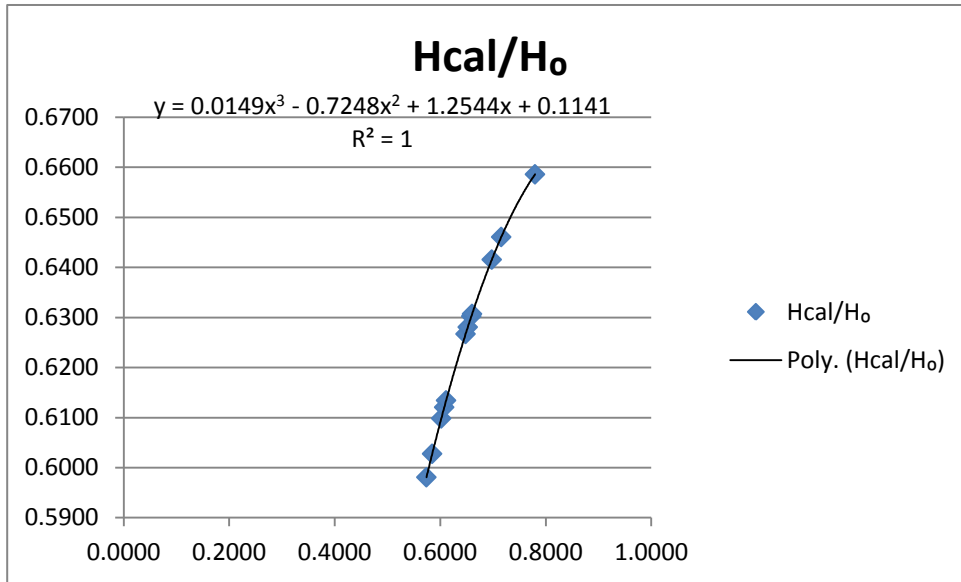


Figure 3: Variation of clearness index with respect to sunshine duration of third-order for Sokoto (1990 - 2005)

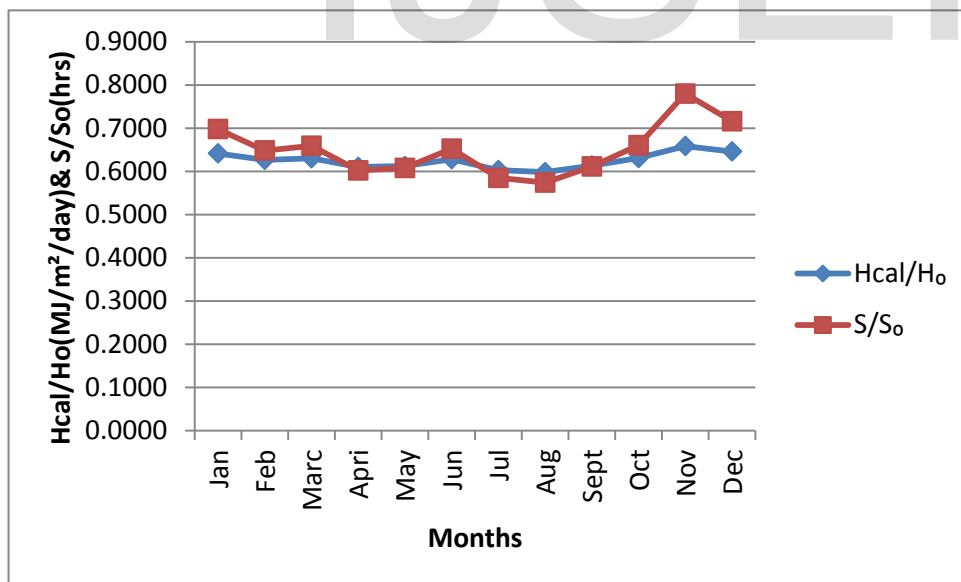


Figure 4: Correlation of monthly variation of Hcal/Ho and S/So for Sokoto (1990 - 2005)

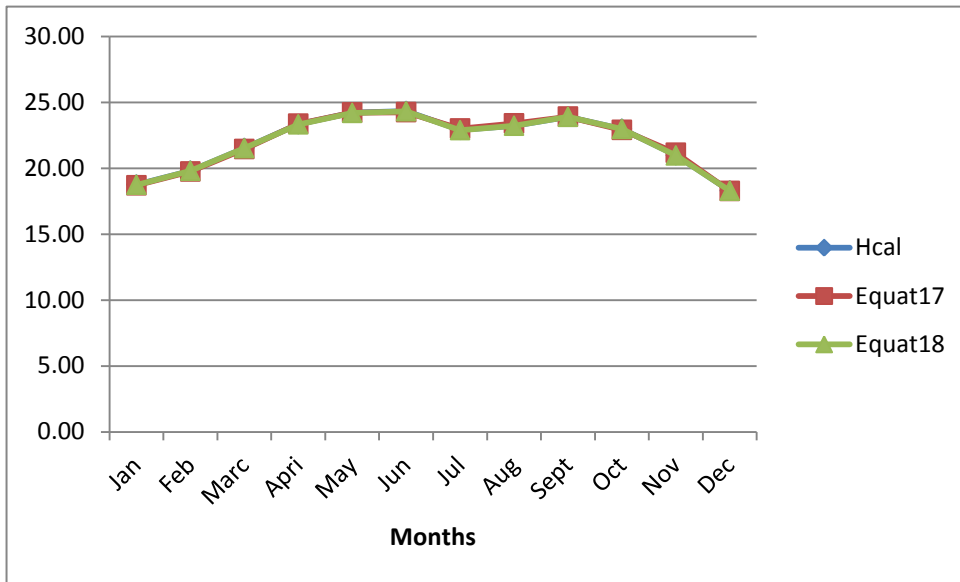


Figure 5. Estimated value of monthly average daily global solar radiation from equations (17) and (18), and comparison with calculated data for Sokoto (1990-2005).

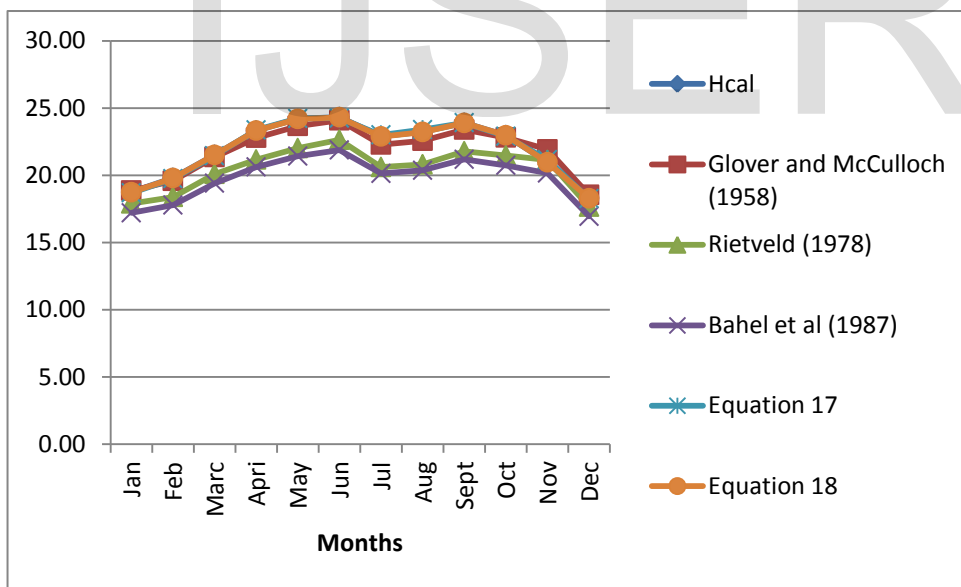


Figure 6: Comparison of the calculated value of monthly average daily global solar radiation from various models, compared with the calculated value for Sokoto (1990-2005).

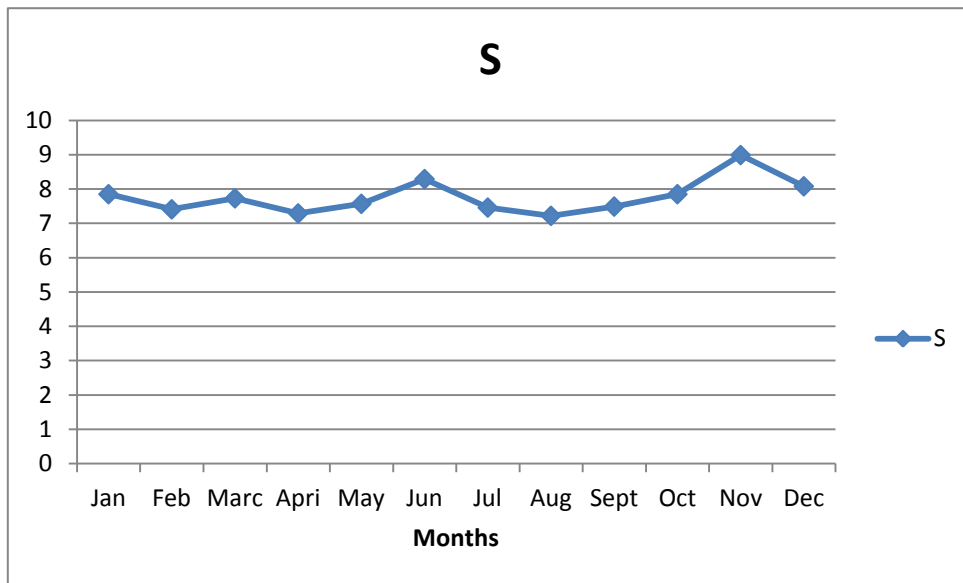


Figure 7: Maximum monthly average sunshine hours (S) for Sokoto (1990 - 2005)

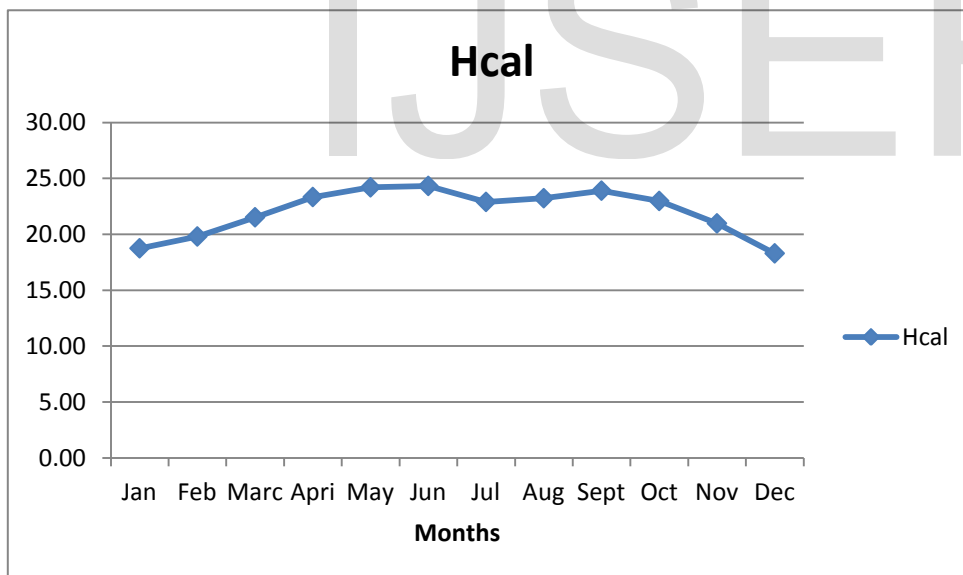


Figure 8: Maximum monthly average calculated global solar radiation(Hcal) for Sokoto (1990 - 2005)

The values of the regression constants is 0.429 and 0.302 are in close agreement with different research work in Nigeria among which include [29], [30], [31]. The sum of regression coefficient (a + b) is interpreted as transmissivity of the atmosphere for global solar radiation under perfectly clear

sky condition [32]. Similarly, the intercept 'a' is interpreted as the transmissivity of an overcast atmosphere. It is therefore important to examine the regression relation we have developed and compare it with others in terms of the value of the atmospheric transmissivity under skies. The value

obtained for Sokoto is 0.73, which compares favourably with the value of 0.68-0.85 as clear sky transmissivity of most tropical regions [33], [34], [35], [16], [30], [31] and [36].

The regression constants (Table.2), **a** and **b** of different months were evaluated from equations (7) and (8). To compute the calculated values of the mean monthly average global solar radiation H_{cal} , the values of **a** and **b** were inserted into equation (1) and the correlation may be used to compute H_{cal} at other locations having the same altitude. Looking at these values of measured and calculated clearness indexes; it is observed that both of them had the lowest values in the month of August. (Throughout the year)

$$\frac{H_{meas}}{H_o} (= 0.4900), \quad \frac{H_{cal}}{H_o} (= 0.5981) \text{ with } H_{meas} (19.03$$

MJ/m²/day) and H_{cal} (= 23.23 MJ/m²/day) which can be traced to the meteorological conditions and also the relative percentage error for each month was estimated. The errors ranged between the following minima and maxima values: (-22.06%, 13.93%) for Sokoto.

Moreover, the second and third-order polynomials were also developed for Sokoto (Fig. 2 and 3) as follow:

$$\frac{H_{cal}}{H_o} = 0.119 + 1.234 \left(\frac{S}{S_o} \right) - 0.695 \left(\frac{S}{S_o} \right)^2 \quad (17)$$

$$\frac{H}{H_o} = 0.114 + 1.254 \left(\frac{S}{S_o} \right) - 0.725 \left(\frac{S}{S_o} \right)^2 + 0.015 \left(\frac{S}{S_o} \right)^3 \quad (18)$$

The correlation of monthly variation of calculated clearness index and sunshine fraction for Sokoto for the period of fifteen years (Fig.4). Though there is similarity in both patterns, however, there is significance difference in the values of both parameters. It is observed clearly that there is a defined trough in the curves for the months of July – August. This is an indication that the atmospheric condition of Sokoto and its environs was at a poor state in which the sky was not clear. The value of the clearness index and the relative sunshine duration in the Table 1 were observed to be 0.5981 and 0.5739 respectively. The results suggest that the rainfall in Sokoto is at peak during the month of July – August when the sky is cloudy and the solar radiation is fairly low. However, just immediately after the August minimum, the clearness index and the relative sunshine duration increased remarkably with the cloud cover crossing over the clearness index. Both the values of clearness index and relative sunshine duration in November reached peaks at 0.6586 and 0.7798 respectively. This implies that a clear sky will obviously fell within the dry season and hence a high solar radiation is experienced. Obviously, this is generally the dry season period in Nigeria.

The monthly average global solar radiation estimated using equations (9), (10) and (11) for Sokoto (1990-

2005) are shown in Table 3, along with the values of calculated global solar radiation and the estimated values from the models of [24], [25], [26]. It is very encouraging to observe a good agreement between calculated global solar radiation and the estimated values obtained from the three models.

The values of monthly average global solar radiation estimated by equation (17) and (18) are plotted with the calculated values in Figure 5 and then compared with the three models in Figure 6. The development of the Angstrom-type correlation of the first, second and third order will enable the solar energy researchers to use the estimated data with confidence, because of its good agreement. These correlations will also be useful for the places with similar climatic conditions and having no facilities of recording the global solar radiation data.

A close observation of Figure 7 and 8 shows that the maximum values of the monthly average sunshine hours and monthly average calculated global solar radiation for Sokoto (1990 - 2005) on a horizontal surface are 8.99 hours and 24.33MJ/m²/day respectively, and this occurred in the months of June and November. This occurrence is expected at these months for a very clear sky condition and that a very high monthly average sunshine hour is obtained because it has a high clearness index.

Another point worthy of note is that the minimum values of monthly average sunshine hours and monthly average calculated global solar radiation for Sokoto (1990 - 2005) on a horizontal surface are 7.09 hours and 18.29MJ/m²/day respectively and they occurred in the months August and December. The months it occurs are also well expected as a result of poor sky condition.

The result presented in Table 4 shows that coefficient of determinations (R^2) and correlation coefficients (r) are both higher than 0.97 respectively, indicating a good fitting between the clearness index H_{cal}/H_o and the relative possible number of sunshine hours S/S_o . Furthermore, there is a close agreement between the measured and calculated values of global radiation for Sokoto as attested by low values of RMSE and MPE.

The station was statistically tested at the $(1- \alpha)$ confidence levels of significance of 95% and 99%. For the critical t-value, i.e., at α level of significance and $(n-1)$ degree of freedom, the calculated t-value must be less than the critical value ($t_{critical} = 2.20$, $df=11$, $P < 0.05$) and ($t_{critical} = 3.12$, $df=11$, $P < 0.01$). It is observed that at $t_{cal} < t_{critical}$ value for Sokoto, t-values are both significant at levels of degree of freedom to the $t_{critical}$ value.

5. CONCLUSION

Sokoto is blessed with abundant sunlight and large rural dwellers lived in villages without proper infrastructure to develop an electricity grid, the use of photo voltaic (PV) is

seen as attractive alternative because of its modular features, namely, its ability to generate electricity at the point of use, its low maintenance requirements and its non-polluting characteristics.

The maximum and minimum values of calculated global solar radiation and sunshine hours in Sokoto are found to be in the range 18.29 – 24.33(MJ/m²/day) i.e. 18.29 ≤ Hcal ≤ 24.33 for (7.09-8.99hours) indicating a promising solar radiation for Sokoto. It is therefore concluded that development of the Angstrom-type correlation of the first, second and third order for Sokoto, North-Western, Nigeria will enable the solar energy researchers to use the estimated data with confidence, because of its good agreement. These correlations will also be useful for the places with similar climatic conditions and having no facilities of recording the

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