

AN EVALUATION OF EMPIRICAL CONSTANTS OF TEMPERATURE BASED PREDICTION MODEL FOR EFFICIENT APPLICATIONS OF SOLAR ENERGY TECHNOLOGY IN NORTH WESTERN NIGERIA

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Abstract

The success of solar energy applications depends heavily on the quantity and quality of resource data such as incoming solar radiations (insolations) data. However, in view of the shortcomings and the scarcity of direct observations and measurement it becomes necessary to generate and calibrate empirical relationship capable of estimation using known meteorological variables. In this paper, minimum and maximum ambient temperature (°C) ground measurement data and the monthly average daily global solar radiation on horizontal surface (kW/m²/day) were received from six locations in the North western Nigeria situated 8° and 14° north of the equator and 3.5° and 11° east of meridian. The data was used to derive empirical constants using Angstrom-Prescott model and Micro soft plotter and validate using R², RMSE and CRM. The derived constants are a = 0.373, b = 0.223; a = 0.373, b = 0.223; a = 0.277, b = 0.201; a = 0.624, b = 0.022; a = 0.546, b = 0.085 and a = 0.654, b = 0.195 for Kaduna, Kano, Katsina, Gusau, Sokoto and Yelwa-Yawuri respectively. Validation show high percentages of the R² except in the case of Yelwa-Yawuri location where it has as low as 0.3583 and there is over estimation in the case of Yelwa-Yawuri in Kebbi state as confirmed by CRM being high up to 43.2942. The derived and validated empirical constants values and estimated insolations data are therefore recommended for similar climatic conditions in the design and application of solar energy system, energy efficient buildings and weather forecasting.

Key words: Angstrom-Prescott model, Prediction Empirical constants, insolations, Solar energy.

1.0 Introduction

The quest of generating and using energy in a more efficient and environmental friendly manner without compromising the ability of future generations to meet their needs is enormous. This is usually achieved through sustainable sources such as solar, wind, nuclear, geothermal, biomass and hydro [1, 2]. While, considering the high cost of geothermal power, harmful effect of nuclear power and the inconsistency of hydro and wind power, solar energy seems to be the best solution. The longevity, simplicity and minimal resources used to produce electricity via solar systems make it a highly sustainable technology and ranks high with many advantages including its availability irrespective of location or being in the remote area [3, 5].

The success of solar energy applications depends heavily on the quantity and quality of resource data that are essential for its applications [6]. Abdulsalam *et al.*, [7] considered the prediction of global solar radiation as one of such prerequisite resources for sustainable implementation. This situation can be solved using correlations, which estimate global

radiation from available meteorological parameters, such as sunshine duration hours, daily temperature, relative humidity, etc. 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. Among the reasons for lack of adequate data are problems associated with availability of instruments, their prohibitive cost and that few have only been manufactured for tropical condition [8, 11].

In view of these shortcomings and the scarcity of solar radiation data from direct observations, it become necessary to generate and calibrate empirical relationship that estimate incoming solar radiation as a function of other known meteorological variables such as relative sunshine hour, cloudiness and ambient temperature. Therefore, estimating model based on ambient temperature as developed by Angstrom-Prescott as presented in equation 1 was used in this paper for assessing empirical constants of some locations in Nigeria.

$$\frac{H_s}{H_o} = a + b \left(\frac{\Delta T}{N} \right) \quad (1)$$

where,

- H_s = Monthly average daily global solar radiation on horizontal surface (MJ/m² day)
- H_o = Monthly average daily extraterrestrial radiation (MJ/m² day)
- N = Maximum possible monthly average daily length ($N = 2/15\omega_s$)
- ΔT = Difference between maximum and minimum temperature values.

Nevertheless, Ogolo [12] derived empirical constants a and b for Kano and Lokoja as 0.441, 0.292 and 0.248, 0.509, respectively and expatiated that the a-values are always higher than the b-values of empirical constants of Northern Nigeria. Though, a study in Okundamiya and Nzeako [13] postulated ambient temperature to have the capabilities of overestimates by 5.0% and more appropriate for both wet season of the climatic condition and the sahelian region of Northern Nigeria. Henceforth, Abdulsalam *et al.*, [7] shows there is no significant difference in the monthly variations of insolutions levels.

2.0 Methodology

North western Nigeria situated between latitudes 8° and 14° north of the equator and between longitudes 3.5° and 11° east of meridian was considered for the study being one of the areas with abundant solar radiation [14]. Six locations in the study area were selected for the study namely; Kaduna, Kano, Katsina, Gusau, Sokoto and Yelwa-Yawuri. The minimum and maximum ambient temperature (°C) ground measurement data from the Agricultural meteorological (Agricmet) Stations of Agricultural Development Projects were collected together with the monthly average daily global solar radiation on horizontal surface (kW/m²/day) of all the locations. An ambient temperatures model in equation 1 was employed for the prediction and evaluation of empirical constants. While, equations 2 as used by Angstrom [15] and equations 3 as given by Cooper's equation [15] were used for computing monthly extraterrestrial radiations H_o (kW/m²/day) and declination (δ) of all the locations respectively.

$$H_o = \frac{24 \times 3600 G_{sc}}{\pi} \left\{ 1 + 0.033 \cos \frac{360n}{365} \right\} \{ \cos \theta \cos \delta \sin \omega_s + \frac{\pi \cos \delta}{180} \sin \theta \sin \delta \} \quad (2)$$

where,

- G_{sc} = Solar constant (equivalent to 1367 W/m²)
- θ = Location latitude
- δ = Solar declination
- ω_s = Hour angle
- n = Solar design day

The declination (δ) is the angular position of the sun at solar noon, with respect to the plane of the equator and its value in degrees is given by Cooper’s equation (1969) [16]:

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

where n is the day of year (i.e. n =32 for 1st February) and the declination (δ) varies between -23.45° on December 21 and + 23.45° on 21st June. While, $\omega_s = \cos^{-1} (-\tan\theta \tan\delta)$.

Extraterrestrial Radiations (H_o) of the six Locations of the study area was computed using equation (2) in MJ/m²/day and converted to kWh/m²/day for homogeneity. The study was designed to have the same solar design day (nth) in whole six locations and therefore same solar declination (δ) values, while each location had its own hour angle (ω_s) and maximum monthly average daily length (N) values defined by their locations.

The empirical constants of each of the six location covered in the research were derived based on Microsoft plotter. Monthly ratio of $\frac{H_s}{H_o}$ against that of $\frac{\Delta T}{N}$ for all the six locations were plotted in order to obtain the empirical constants and the trend line that display equation and R-square value on chart using scatter mode plotter.

The mean measured monthly average daily insulations values were compared with the estimated values for all the locations and the outcomes were discussed. Coefficient of determination (R^2) measures a fit between estimated and measured data, Root mean square (RMSE) measure precision while Coefficient of Residual Mass (CRM) indicates either over or under estimations. These were used for validations using Equations 4-6.

$$R^2 = \frac{\sum_1^N (PH_s - MPH_s)^2}{\sum_1^N (MH_s - MMH_s)^2} \tag{4}$$

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^N (MH_s - PH_s)^2} \tag{5}$$

$$CRM = \sum_{i=1}^N PH_s - \sum_{i=1}^N MH_s \tag{6}$$

- where: PHs = predicted insulations values
- MHs = measured insulations values
- MPHs = means of Predicted insulations values
- MMHs = means of measured insulations values
- N = number of observations

3.0 Results and Discussion

The data collected from the field were sorted, analysed and presented in a long term average of 10years ground measurements of ambient temperature and 30years insulations values as presented in Tables 1a – 1c.

Table 1a: Long term average of metrological data for Kaduna and Kano

Months	Kaduna				Kano			
	Ground Ambient Temperature (°C)			Ground Insolations (kWH/m ² /day)	Ground Ambient Temperature (°C)			Ground Insolations (kWH/m ² /day)
	Min	Max	Δ T		Min	Max	Δ T	
January	18.7	30.2	11.5	6.1	13.8	31.1	17.3	5.9
February	16.2	30.4	14.2	6.6	16.6	32.8	16.2	6.6
March	20.0	35.0	15.0	6.8	20.2	36.3	16.1	6.9
April	18.0	35.0	17.0	6.6	24.3	40.1	15.8	7.0
May	19.0	34.0	15.0	6.0	24.7	38.9	14.2	6.6
June	18.0	33.0	15.0	5.6	23.2	34.8	11.6	6.1
July	17.0	32.0	15.0	5.2	21.5	31.8	10.3	5.6
August	16.0	35.0	19.0	5.2	21.0	30.8	9.8	5.6
September	15.0	29.0	14.0	5.6	21.7	32.1	10.4	5.9
October	13.0	32.0	19.0	5.9	20.8	34.4	13.6	6.2
November	28.1	36.8	8.7	6.4	16.3	33.9	17.6	6.1
December	16.4	32.9	16.5	6.1	14.2	30.2	16.0	5.7

Table 1b: Long term Average of metrological data for Katsina and Gusau

Months	Katsina				Gusau			
	Ground Ambient Temperature (°C)			Ground Insolations (kWH/m ² /day)	Ground Ambient Temperature (°C)			Ground Insolations (kWH/m ² /day)
	Min	Max	Δ T		Min	Max	Δ T	
January	10.7	36.9	26.2	5.9	22.1	36.5	14.4	6.0
February	12.3	37.8	25.5	6.6	25.5	38.2	12.7	6.7
March	16.0	39.2	23.2	7.1	29.0	40.5	11.5	7.1
April	19.4	40.6	21.2	7.1	31.3	41.8	10.5	7.0
May	19.3	42.0	22.7	6.7	28.9	40.9	12.0	6.4
June	18.5	39.9	21.4	6.3	26.3	39.4	13.1	6.0
July	18.3	37.0	18.7	5.8	24.9	38.9	14.0	5.5
August	19.1	37.0	17.9	5.7	24.5	36.5	12.0	5.4
September	18.0	36.4	18.4	5.8	26.3	36.2	9.9	5.8
October	18.3	37.3	19.0	5.7	27.0	36.9	9.9	6.4
November	14.1	37.9	23.8	6.2	26.7	37.4	10.7	6.6
December	11.7	36.0	24.3	5.8	26.6	38.2	11.6	5.9

Table 1c: Long term Average of metrological data for Sokoto and Yelwa-Yawuri

Months	Sokoto				Yelwa-Yawuri			
	Ground Ambient Temperature (°C)			Ground Insolations (kWH/m ² /day)	Ground Ambient Temperature (°C)			Ground Insolations (kWH/m ² /day)
	Min	Max	Δ T		Min	Max	Δ T	
January	17.14	33.26	16.1	5.8	16.8	43.7	26.9	9.6
February	19.85	35.86	16.0	6.4	18.0	46.5	28.5	10.3
March	23.45	39.72	16.3	6.8	21.6	50.7	29.1	10.7
April	27.19	41.43	14.2	6.8	24.5	50.7	26.2	10.6
May	27.40	39.67	12.3	6.2	25.0	44.6	19.6	9.8
June	25.59	36.39	10.8	6.0	23.7	37.6	13.9	9.2
July	23.83	32.65	8.8	5.3	22.9	32.9	10.0	8.6
August	22.93	31.03	8.1	5.3	22.5	32.5	10.0	8.5
September	26.26	32.56	6.3	5.6	22.3	34.4	12.1	8.7
October	22.94	35.58	12.6	5.9	21.7	42.4	20.7	9.3
November	20.44	36.82	16.4	5.9	19.5	46.3	26.8	9.9
December	17.72	33.89	16.2	5.6	17.3	43.3	26.0	9.6

The constants *a* and *b* were derived and the plot of the details of the variables used are presented in Tables 2 and subsequently used for estimating location insolation levels.

Table 2: Summary of Derived Empirical Constants of Location.

S/n	Locations	Empirical Constants	
		a	B
1	Kaduna	0.373	0.223
2	Kano	0.373	0.223
3	Katsina	0.277	0.201
4	Gusau	0.624	0.022
5	Sokoto	0.546	0.085
6	Yelwa-Yawuri	0.654	0.195

Based on the empirical constants derived as summarized in Table 2 for each location, it was noted that the values for Kano conform to $a= 0.326$, $b= 0.292$ as given by Ogolo [12] for wet seasons. Thus, Equations (1) was used for the prediction of insolation levels of the six (6) locations. The results are presented in Table 3.

Table 3: Estimated Insolation Levels of Locations kWh/m²/day

Month	Kaduna	Kano	Katsina	Gusau	Sokoto	Yelwa- Yawuri
January	5.6526	6.1375	6.2940	5.6189	5.6552	9.6993
February	5.9034	6.4328	6.6961	6.0981	6.0895	10.4407
March	6.2731	7.1101	6.7456	6.5488	6.6876	11.4407
April	6.3158	6.3624	5.9987	6.0765	6.0753	10.3434
May	6.4830	6.5972	6.7811	6.8114	6.6734	10.0788
June	6.4105	6.0223	6.4480	6.7515	6.5008	9.0091
July	6.4163	5.7927	6.0300	6.7756	6.3640	8.4130
August	6.0827	5.7629	5.9615	6.7628	6.3271	8.4940
September	6.4418	5.7888	5.9566	6.5747	6.0335	8.7177
October	5.5704	6.0523	5.7263	6.1559	4.7021	9.6175
November	5.9929	6.2872	6.1616	5.6529	5.7748	9.8379
December	5.0494	5.7488	5.8275	5.3925	5.4809	9.3021

Thus, as the correlation between the measured values against estimated values validate, the model validation was achieved through the values as presented in Table 4.

Table 4: Model Validation Indicators

S/No	State	R ²	RMSE	CRM
1	Kaduna	0.6797	0.7233	0.4919
2	Kano	0.6210	0.2374	-0.105
3	Katsina	0.6045	0.5242	2.527
4	Gusau	0.9046	0.9038	3.1196
5	Sokoto	0.9969	0.7655	0.2642
6	Yelwa-Yawuri	0.3583	3.6320	43.2942

It can be noticed from Table 4 that the model estimation is an accurate means of the observation based on the high percentages of the coefficient of determination (R^2) except in the case of Yelwa-Yawuri in Kebbi state. The values of RMSE show low and high precisions depending on the locations as features of temperature based model and the predicted insolation values when compared directly with ground measurement are adequate.

Consequently, there is over estimation in the case of insolation data for three location Katsina, Gusau and more in the case of Yelwa-Yawuri in Kebbi state as confirmed by coefficient of residual mass (CRM) being high up to 43.2942. Perhaps, the over estimations based on the empirical constant a and b were attributed to the model type and the high temperature conditions but when the estimated insolation levels were compared with that measured are within the acceptable levels. The monthly insolation values are also in conformity with what Ojosu [17] measured and presented as the average monthly average radiation level range in Nigeria during both the Harmattan and hot seasons.

The derived and validated empirical constants values are in conformity with postulations of Ogolo [12]. It is also interesting to note that, even the highest estimation value does not greatly over estimate the monthly average global solar radiation based on the validations and comparison with the ground measured values. The prediction ability of the model behaves as postulated by Ogolo [12] that it is more suitable in the Midland and Coastal areas of Nigeria than in the Sahelian being our study area.

4.0 Conclusion

Any minimum value taken for the design and application of solar system would be sufficient within the study area, except where specificity and exact precision are required. Generally, the least monthly average insolation value estimated based on the derived constants are adequate and does not significantly vary monthly as described by Abdulsalam *et al.*, [7] and can be used for the whole year. Thus, the derived and validated empirical constants values and estimated insolation data are therefore recommended for similar climatic conditions in the design and application of solar energy system, energy efficient buildings, weather forecasting and agricultural system.

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