



Estimating Global Horizontal Irradiance in Nigeria: An Empirical Modelling Perspective

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ABSTRACT

Accurate Global Horizontal Irradiance (GHI) data is key to designing optimal solar PV systems. Limited by the availability and high cost of traditional pyranometers in developing countries like Nigeria, this study proposes a cost-effective alternative using the Ångström-Prescott model and readily available sunshine data from the Nigerian Meteorological Agency. Empirical models for GHI estimation were developed for 37 selected locations across Nigeria. The country was divided into three regions, and estimates were then compared with NASA data using statistical metrics like R^2 , MBE, and RMSE to evaluate model performance. The results indicate that Sokoto, Ibi, and Abakaliki have the highest GHI values of 5.86 kWh/m²/day, 4.90 kWh/m²/day, and 4.76 kWh/m²/day, respectively. Conversely, the lowest GHI values were observed in Jos, Ilorin, and Benin City, with values of 4.84 kWh/m²/day, 4.71 kWh/m²/day, and 4.37 kWh/m²/day for regions 1, 2, and 3, respectively. Statistical tests revealed underestimation in the Gusau and Abuja models, slight overestimation in Sokoto, and the lowest accuracy in Jos. R^2 values ranged from 0.706 to 0.985, indicating strong correlations and high accuracy in most regions. By leveraging readily available sunshine data, this cost-effective method allows accurate GHI estimation, driving improved solar PV systems in Nigeria and similar contexts.

1. Introduction

Solar energy has emerged as one of the most promising sustainable resources, capable of bridging the energy demand gap while mitigating climate change problems. Its availability and accessibility in

virtually every region of the world have made it a dependable energy source. For reliable evaluation, planning, and deployment of a solar energy system, a good knowledge of the global horizontal irradiance (GHI) data, otherwise called global solar radiation (GSR) data, is of paramount importance [1]. While

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electricity generation tops the list of applications of solar radiation data, other fields such as meteorology, agriculture, water resources management, and forestry also find it useful [2]. Hence, accurate data is necessary for efficient use, system design, sizing, and performance [3].

Ground measurements at a specified location have been described as the most reliable source of GHI data. To achieve this, a pyranometer is the tool of choice, stationed at the location where long-term measurement data will be collected. However, this tool is relatively expensive when compared to the equipment cost of other meteorological parameters (ambient temperature, cloud cover, relative humidity, and sunshine duration), and it requires a specialist to operate and maintain [4]. Therefore, there is a need to strike a balance between accurate data acquisition and cost. To address this, several alternative approaches have been developed by designers of solar energy systems and researchers for policymakers to make informed choices. These approaches involve developing empirical models to estimate solar radiation using readily available meteorological parameters such as sunshine, clouds, temperature, relative humidity, precipitation, and a combination of two or more parameters [5-7]. The foremost among the available is the Ångström-Prezcott (A-P) empirical model for estimating the Global Solar Radiation (GSR) of a specific location using collected data based on sunshine hours [8-10].

In the literature, several derivative empirical models have been proposed from the groundbreaking Ångström-Prezcott (A-P) models to forecast global solar radiation based on sunshine hours [1]. Asilevi et al., [11] analyzed the amount of global solar irradiation (GSI) in Ghana using the A-P model and data based on sunshine duration from 22 stations in Ghana. The estimated GSI in the country indicates that there is great potential for utilizing solar energy in the region for different purposes. A similar work by Liu et al., [12] assessed and compared the performance of the A-P model and eight predictive models for estimating daily global solar radiation in different regions of China. Using data from 105 radiation stations across seven geographic zones, results indicated that altitude was a key factor influencing the A-P model parameters, and all models showed acceptable accuracy across the country but varied in performance among regions. In addition, the performance of the models developed supports their application for estimating daily GSI in locations without measured data and in other similar climates.

The temperature-based empirical model was first proposed by Hargreaves & Samani [13]. This original model was based on the difference between the minimum and maximum temperatures. The advantage of a temperature-based model over other models lies in its independence from global solar radiation input [14]. Over the years, several studies have predicted solar radiation levels based on modified versions of the original model. Ghazouani et al., [15] examined the performance of temperature-based solar radiation models to estimate global solar radiation in Arar City, KSA. The model demonstrated high performance across different validation datasets, indicating its potential for solar radiation estimation for the region and other locations with similar conditions. Jamil et al., [16] presented a model based on monthly average daily ambient temperature extremes for India. Results showed that the models provided good estimates for sites with varying climate characteristics within India.

Other less prominent parameters for solar radiation data prediction have also been reported, including cloud cover, humidity, and precipitation [1, 17]. Ahamed et al., [18] provided a wide-ranging review of cloud cover-based solar radiation models for hourly global solar radiation estimates. Most of these models are based on the A-P model and are used for estimating monthly average daily total solar radiation. Yakoubi et al., [19] described new correlation models between clearness index, cloud cover, and other meteorological parameters to estimate the monthly average daily global solar radiation. The models show good prediction levels for the affected location and can be useful for designing and assessing solar energy applications in similar climatic conditions. This supports the idea that a hybrid approach enhances the performance of the different parameter-based models and provides superior accuracy. However, model accuracy is better at sites with clear skies and scattered clouds [20]. To enhance the performance of the different parameter-based models, a hybrid approach has been demonstrated to provide superior accuracy [21].

In Nigeria, most of the meteorological stations lack the pyranometer instrument used to measure global solar radiation [22]. Consequently, several studies have employed different meteorological parameters for solar radiation prediction, such as sunshine-based approaches [23], temperature-based approaches [24], and a combination of multiple parameter-based approaches [25]. Some studies focused on a single/selected location within the country [26, 27], while others examined either the

northern [28] or the southern region [29, 30]. A review of the existing literature revealed that no previous study included locations in every state of Nigeria. To address this gap, this study developed an empirical model based on the Ångström-Preusscott sunshine-based model, covering 37 locations across Nigeria. Using realistic sunshine hour data obtained from the Nigerian Meteorological Agency (NiMet), the developed models were employed to estimate GHI values for the selected locations. The accuracy of these estimated values was validated using statistical indicators.

Overall, the research novelty in this study is the comprehensive empirical model developed for GSR estimation across all regions of Nigeria, addressing the lack of a nationwide model in previous research. It also enhances a broader understanding of solar energy potential in Nigeria. Specifically, the key contributions of this study can be summarized as follows:

- Developed a comprehensive coverage of solar radiation estimates for 37 locations in Nigeria.
- It provides valuable information for promoting solar energy projects, supporting sustainable energy access, and addressing energy challenges faced by the country.
- It promotes solar energy use, which also supports environmental preservation efforts, contributing to a broader understanding of sustainable energy solutions in Nigeria.
- The research holds significance for policymakers, energy planners, and investors in Nigeria.

2. Materials and Methods

2.1 The Study Areas

Nigeria has a wide network of meteorological stations, with approximately 54 stations routinely measuring various climatic parameters, including sunshine hours, temperature, rainfall, atmospheric pressure, and humidity. This study selected one station from each of the 37 states for data collection. Sunshine hour data for each selected station was obtained from the Nigerian Meteorological Agency (NiMet). Figure 1 shows the distribution of NiMet stations across the country. The geographical details of the selected stations are also shown in Table 1.

2.2 Data Collection

Daily sunshine hour data for the 37 selected locations was collected from NiMet. Monthly data for each location was calculated by averaging the daily sunshine hour data using Microsoft Excel [31]. Additionally, meteorological solar radiation data for the 37 selected locations was obtained from NASA for the validation developed model.

2.3 Analytical technique for processing data

The sunshine hour data was analyzed using technical approaches, specifically a combination of an empirical model and statistical indicators. The Ångström-Preusscott (A-P) linear regression model, widely recognized for its accuracy, was adopted for developing empirical models for the 37 selected locations. The A-P model has been extensively used by researchers for global solar radiation estimation and is reported to have yielded the best correlation on a single-variable basis, making it one of the most widely accepted models worldwide for estimating global solar radiation [32-34]. The model as given by Pelkowski,[10] as:

$$H = H_0 \left(a + b \frac{S}{S_0} \right) \quad (1)$$

Where H is the monthly average daily global solar radiation falling on a particular location, H_0 is the monthly average daily extra-terrestrial radiation, S is the average daily number of observed sunshine hours, and S_0 is the monthly mean value of day length at a particular location. "a" and "b" are the climatologically determined regression constants, which are given by Ikotoni et al., [35] as follows:

$$a = 0.10 + 0.24 \left(\frac{S_{avg}}{S_{0avg}} \right) \quad (2)$$

$$b = 0.38 + 0.08 \left(\frac{S_{avg}}{S_{0avg}} \right) \quad (3)$$

The length of the astronomical day (in hours) is obtained by using (4) Kumari & Toshniwal, [7];

$$S_0 = \frac{2}{15} \omega_s \quad (4)$$

The monthly average daily extra-terrestrial radiation H_0 is given thus by Kumari & Toshniwal, [7];

$$H_0 = \frac{24}{\pi} G_{sc} [d_r] [A + B] \quad (5)$$

where G_{sc} is the Solar constant given as 1367 W/m^2 . d_r , A and B are given by Kumari & Toshniwal, [7] as;

$$d_r = 1 + 0.033 \cos\left(\frac{360J}{365}\right) \tag{6}$$

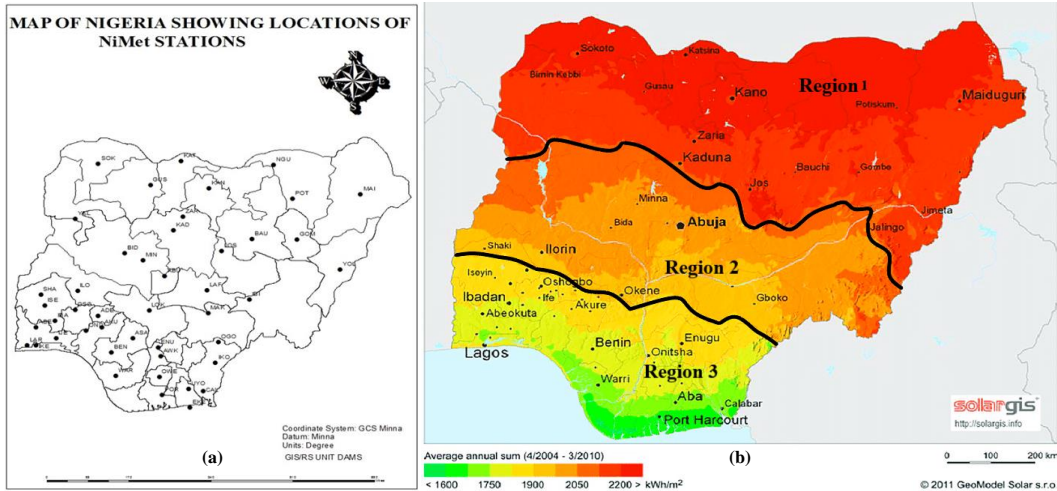


Figure 1. Map of Nigeria showing (a) locations of NiMet stations [36]; (b) regional distribution of solar irradiance [37]

$$A = \left(\frac{2\pi\omega_s}{360}\right) \sin \varphi \sin \delta \tag{7}$$

$$B = \cos \varphi \cos \delta \sin \omega_s \tag{8}$$

Where φ is the latitude of the different locations and the sunset hour angle given in Kumari & Toshniwal, [7] as;

$$\omega_s = \cos^{-1}[-\tan \delta \tan \varphi] \tag{9}$$

The solar declination angle δ can be obtained from the (10) and given by Kumari & Toshniwal, [38];

$$\delta = 23.45 \sin\left[\frac{360(J + 284)}{365}\right] \tag{10}$$

The Julian day (J) represents the number of the day in the year, ranging from 1 (January 1) to 365 or 366 (December 31). In most cases, researchers assume that J can be approximated as the middle of the month, counting from the beginning of the year. Table 2 provides the recommended values of J for each month of the year. This study adopts the approach of considering the middle of the month. For instance, $J = 15$ for January, $J = 31 + 14 = 45$ for February, and so on. [39].

2.4 Model Validation and Statistical Analysis

Validating the accuracy of the estimated data value obtained from the empirical model derived against the measured data from the satellite is determined based on the analysis of different statistical indicators, which include the coefficient of determi-

nation (R^2), mean bias error (MBE), and root mean square error (RMSE). Expressed as given in (11)–(13), MBE and RMSE are known as common error terms, mostly used in comparing models for better data modeling [38]. For better data modeling, these error indicators should be closer to zero, while R^2 should approach unity as closely as possible. MBE determines the average error in the estimation; the metric is expressed as given in (11), A positive MBE indicates that the model overestimates the calculated value of the global solar radiation as compared to the observed value, and a negative MBE indicates that the model underestimates the calculated value of the global solar radiation when compared with the measured or observed value. Lower values of MBE indicate a strong correlation between the estimated and observed values. MBE is expressed by Sen, [40] as:

$$MBE = \frac{1}{n} \sum_{i=1}^n (H_{est.} - H_{obs.}) \tag{11}$$

The root mean square error (RMSE) compares the estimated and observed datasets and measures the statistical variability of the estimation accuracy, which can be expressed as (12). The RMSE gives information on the short-term performance of the regression models, whereas the MBE gives information on the long-term performance of the regression models. Low RMSE values indicate the best-suited solar energy models. RMSE is expressed in equation (12) by Sen, [40] as:

Table 1. Geographical Locations of selected stations in Nigeria

S/No.	Station	Latitude (°N)	Longitude (°E)	Region
1	Bauchi	10.5	10	1
2	Dutse	11.69	9.34	1
3	Gombe	10.25	11.17	1
4	Maiduguri	11.84	13.15	1
5	Potiskum	11.71	11.08	1
6	Yola	9.21	12.48	1
7	Jos	9.92	8.9	1
8	Kaduna	10.52	7.44	1
9	Kano	11.99	8.53	1
10	Katsina	12.25	7.5	1
11	Gusau	12.17	6.66	1
12	Sokoto	13.06	5.24	1
13	Yelwa	10.83	4.74	1
14	Abuja	9.06	7.49	2
15	Ibi	8.18	9.75	2
16	Ilorin	8.5	4.55	2
17	Lafia	8.48	8.52	2
18	Lokoja	7.8	6.74	2
19	Makurdi	7.73	8.54	2
20	Minna	9.62	6.55	2
21	Umuahia	5.53	7.49	3
22	Uyo	5.03	7.92	3
23	Awka	6.21	7.07	3
24	Yenagoa	4.93	6.27	3
25	Calabar	4.98	8.34	3
26	Asaba	6.19	6.73	3
27	Abakaliki	6.32	8.11	3
28	Benin City	6.33	5.62	3
29	Ado Ekiti	7.62	5.22	3
30	Enugu	6.45	7.5	3
31	Owerri	5.49	7.03	3
32	Ikeja	6.6	3.35	3
33	Abeokuta	7.15	3.35	3
34	Akure	7.25	5.19	3
35	Oshogbo	7.78	4.55	3
36	Ibadan	7.38	3.9	3
37	Port-Harcourt	4.77	7.02	3

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (H_{est.} - H_{obs.})^2} \tag{12}$$

The coefficient of determination (R^2), also known as the squared correlation coefficient, is a statistical measure of the strength of the relationship between the estimated and observed values of global solar irradiation (GSI). It determines the performance of a model in terms of its suitability. Ideally, a model is considered perfect if $R^2 = 1$. This implies that the estimated values match perfectly with the observed values. R^2 is given by Sen, [40] as:

$$R^2 = 1 - \frac{\sum_{i=1}^n (H_{est.} - H_{obs.})^2}{\sum_{i=1}^n (H_{obs.} - \overline{H_{obs.}})^2} \tag{13}$$

Where $H_{est.}$ is the estimated global solar radiation on the horizontal surface, $H_{obs.}$ is the observed global solar radiation, $\overline{H_{obs.}}$ is the average value of observed global solar radiation and n is the number of observations.

3. Results and Discussion

The regression constants, also referred to as the empirical constants 'a' and 'b', were derived for all 37 selected locations as presented in Table 3. These derived regression constants were used to develop the empirical models used for estimating the monthly mean daily global horizontal irradiance (GHI) for each of the selected locations. The 37 empirical models developed are presented in Table 4. The developed models in Table 4 were used to estimate the annual horizontal global solar radiation for the 37 selected locations across the states in Nigeria. The respective annual estimated horizontal global solar radiation ($H_{est.}$) is being compared with observed values ($H_{obs.}$) given by the National Aeronautics and Space Administration (NASA) data using statistical error indices, which indicate the performance accuracy of the model. The results of MBE, RMSE, and R^2 for each of the selected locations are given in Table 5. MBE values indicate the systematic bias in estimated global solar radiation, with positive values

Table 2. Recommended values of J for each month of the year

Month	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
J	15	45	74	105	135	166	196	237	258	288	319	349

Table 3. Monthly mean daily sunshine hour, empirical constants and estimated global horizontal irradiance for the 37 selected locations

Station	S	S_0	S/S_0	H	H_0	H/H_0	a	b
Abuja	6.96	11.99	0.58	4.81	9.89	0.49	0.24	0.43
Bauchi	8.13	11.99	0.68	5.48	9.84	0.56	0.26	0.43
Dutse	8.24	11.99	0.69	5.52	9.80	0.57	0.27	0.44
Gombe	8.07	11.99	0.67	5.44	9.84	0.56	0.26	0.43
Gusau	8.29	11.99	0.69	5.53	9.78	0.57	0.27	0.44
Ibi	7.11	11.99	0.60	4.91	9.90	0.50	0.24	0.43
Ilorin	6.80	11.99	0.57	4.71	9.90	0.48	0.24	0.43
Jos	7.04	11.99	0.59	4.84	9.86	0.49	0.24	0.43
Kaduna	7.69	11.99	0.64	5.21	9.84	0.53	0.25	0.43
Kano	8.21	11.99	0.69	5.49	9.79	0.56	0.26	0.43
Katsina	8.34	11.99	0.70	5.55	9.76	0.57	0.27	0.44
Lafia	6.98	11.99	0.58	4.82	9.90	0.49	0.24	0.43
Lokoja	6.91	11.99	0.58	4.80	9.91	0.49	0.24	0.43
Maiduguri	8.57	11.99	0.72	5.68	9.76	0.59	0.27	0.44
Makurdi	6.92	11.99	0.58	4.80	9.92	0.49	0.24	0.43
Minna	7.02	11.99	0.59	4.83	9.86	0.49	0.24	0.43
Potiskum	8.30	11.99	0.70	5.55	9.80	0.57	0.27	0.44
Sokoto	8.58	11.99	0.72	5.68	9.74	0.59	0.27	0.44
Yelwa	7.72	11.99	0.65	5.22	9.83	0.53	0.26	0.43
Yola	7.81	11.99	0.65	5.31	9.88	0.54	0.26	0.43
Umuahia	6.44	12.00	0.54	4.54	9.96	0.46	0.23	0.42
Uyo	6.15	12.00	0.51	4.38	9.97	0.44	0.22	0.42
Awka	6.44	11.99	0.54	4.54	9.95	0.46	0.23	0.42
Yenagoa	5.87	12.00	0.49	4.22	9.98	0.42	0.22	0.42
Calabar	6.13	12.00	0.51	4.37	9.97	0.44	0.22	0.42
Asaba	6.21	11.99	0.52	4.40	9.95	0.44	0.22	0.42
Abakaliki	6.83	11.99	0.57	4.76	9.95	0.48	0.24	0.43
Benin City	6.16	11.99	0.51	4.37	9.95	0.44	0.22	0.42
Ado Ekiti	6.67	11.99	0.56	4.66	9.92	0.47	0.23	0.42
Enugu	6.43	11.99	0.54	4.53	9.95	0.46	0.23	0.42
Owerri	6.63	12.00	0.55	4.66	9.97	0.47	0.23	0.42
Ikeja	6.19	11.99	0.52	4.39	9.94	0.44	0.22	0.42
Abeokuta	6.30	11.99	0.53	4.44	9.93	0.45	0.23	0.42
Akure	6.567	11.99	0.55	4.60	9.93	0.46	0.23	0.42
Oshogbo	6.41	11.99	0.54	4.50	9.92	0.45	0.23	0.42
Ibadan	6.29	11.99	0.53	4.45	9.93	0.45	0.23	0.42
Port-Harcourt	5.87	12.00	0.49	4.22	9.98	0.42	0.22	0.42

indicating overestimation (e.g., Abuja, Umuahia, Yenagoa, Calabar, and Port Harcourt) and negative values (e.g., Yola, Bauchi, Maiduguri, and Gusau) indicating underestimation. Locations, where MBE values are close to zero (e.g., Lokoja, Lafia, and Oshogbo), show relatively unbiased estimations.

In addition to the MBE results, most locations exhibit negative MBE values, suggesting that the developed model tends to slightly underestimate the amount of solar radiation in these regions. RMSE values quantify the overall magnitude of errors in the estimation, with smaller values indicating higher

accuracy and precision. Lower RMSE values (e.g., Owerri, Lokoja, and Dutse) indicate more accurate estimations, while higher values (e.g., Jos, Abuja, and Yola) suggest larger discrepancies between estimated and observed values. R^2 values measure the goodness of fit between estimated and observed values, with higher R^2 values (e.g., Umuahia, Yola, Potiskum, and Sokoto) indicating better agreement and lower values (e.g., Minna, Jos, and Asaba) indicating lesser model performance. Moreover, the

Table 4. Empirical models developed for the 37 selected locations in Nigeria.

Selected locations	Empirical model developed	Selected locations	Empirical model developed
Abuja	$H = H_o \left(0.240 + 0.427 \frac{S}{S_0} \right)$	Gusau	$H = H_o \left(0.266 + 0.435 \frac{S}{S_0} \right)$
Yola	$H = H_o \left(0.257 + 0.432 \frac{S}{S_0} \right)$	Umuahia	$H = H_o \left(0.229 + 0.423 \frac{S}{S_0} \right)$
Bauchi	$H = H_o \left(0.264 + 0.435 \frac{S}{S_0} \right)$	Uyo	$H = H_o \left(0.223 + 0.421 \frac{S}{S_0} \right)$
Makurdi	$H = H_o \left(0.239 + 0.426 \frac{S}{S_0} \right)$	Awka	$H = H_o \left(0.229 + 0.423 \frac{S}{S_0} \right)$
Maiduguri	$H = H_o \left(0.270 + 0.438 \frac{S}{S_0} \right)$	Yenagoa	$H = H_o \left(0.218 + 0.419 \frac{S}{S_0} \right)$
Gombe	$H = H_o \left(0.262 + 0.434 \frac{S}{S_0} \right)$	Calabar	$H = H_o \left(0.223 + 0.421 \frac{S}{S_0} \right)$
Dutse	$H = H_o \left(0.266 + 0.435 \frac{S}{S_0} \right)$	Asaba	$H = H_o \left(0.226 + 0.422 \frac{S}{S_0} \right)$
Kaduna	$H = H_o \left(0.254 + 0.431 \frac{S}{S_0} \right)$	Abakaliki	$H = H_o \left(0.234 + 0.425 \frac{S}{S_0} \right)$
Kano	$H = H_o \left(0.254 + 0.435 \frac{S}{S_0} \right)$	Benin City	$H = H_o \left(0.223 + 0.421 \frac{S}{S_0} \right)$
Katsina	$H = H_o \left(0.267 + 0.436 \frac{S}{S_0} \right)$	Ado Ekiti	$H = H_o \left(0.234 + 0.425 \frac{S}{S_0} \right)$
Yelwa	$H = H_o \left(0.255 + 0.432 \frac{S}{S_0} \right)$	Enugu	$H = H_o \left(0.229 + 0.423 \frac{S}{S_0} \right)$
Lokoja	$H = H_o \left(0.239 + 0.426 \frac{S}{S_0} \right)$	Owerri	$H = H_o \left(0.233 + 0.424 \frac{S}{S_0} \right)$
Ilorin	$H = H_o \left(0.236 + 0.425 \frac{S}{S_0} \right)$	Ikeja	$H = H_o \left(0.224 + 0.421 \frac{S}{S_0} \right)$
Lafia	$H = H_o \left(0.240 + 0.427 \frac{S}{S_0} \right)$	Abeokuta	$H = H_o \left(0.226 + 0.422 \frac{S}{S_0} \right)$
Minna	$H = H_o \left(0.241 + 0.427 \frac{S}{S_0} \right)$	Akure	$H = H_o \left(0.232 + 0.424 \frac{S}{S_0} \right)$
Jos	$H = H_o \left(0.241 + 0.427 \frac{S}{S_0} \right)$	Oshogbo	$H = H_o \left(0.228 + 0.423 \frac{S}{S_0} \right)$
Sokoto	$H = H_o \left(0.278 + 0.439 \frac{S}{S_0} \right)$	Ibadan	$H = H_o \left(0.226 + 0.422 \frac{S}{S_0} \right)$
Ibi	$H = H_o \left(0.243 + 0.428 \frac{S}{S_0} \right)$	Port-Harcourt	$H = H_o \left(0.218 + 0.419 \frac{S}{S_0} \right)$
Potiskum	$H = H_o \left(0.267 + 0.436 \frac{S}{S_0} \right)$		

Table 5. The estimated global solar radiations and the statistical error indices of the developed model for the 37 selected locations

Selected Locations	Statistical Error Indicators		
	MBE	RMSE	R ²
Abuja	0.313011	0.591233	0.761
Yola	-0.32475	0.560388	0.957
Bauchi	-0.29961	0.481607	0.913
Makurdi	-0.22621	0.441295	0.749
Maiduguri	-0.1911	0.427895	0.857
Gombe	-0.3086	0.464822	0.746
Dutse	-0.28791	0.396544	0.82
Kaduna	-0.30008	0.54383	0.723
Kano	-0.30018	0.417275	0.803
Katsina	-0.34401	0.440395	0.904
Yelwa	-0.27476	0.434743	0.818
Lokoja	-0.00856	0.392985	0.756
Ilorin	-0.31118	0.495054	0.766
Lafia	-0.27687	0.536422	0.749
Minna	-0.29656	0.545564	0.71
Jos	-0.32542	0.612646	0.706
Sokoto	-0.31694	0.39778	0.955
Ibi	-0.27236	0.556293	0.851
Potiskum	-0.32707	0.493103	0.879
Gusau	-0.359	0.467393	0.93
Umuahia	0.025925	0.435985	0.985
Uyo	-0.13451	0.398784	0.758
Awka	-0.19538	0.444317	0.882
Yenagoa	0.048491	0.478284	0.829
Calabar	0.093182	0.51424	0.825
Asaba	-0.12556	0.448459	0.848
Abakaliki	-0.10918	0.511721	0.898
Benin City	-0.00642	0.494713	0.819
Ado Ekiti	-0.03847	0.47112	0.964
Enugu	-0.20544	0.420932	0.817
Owerri	-0.0384	0.398954	0.838
Ikeja	-0.13782	0.4844	0.76
Abeokuta	-0.19948	0.471455	0.77
Akure	-0.10014	0.43435	0.805
Oshogbo	-0.08822	0.495026	0.95
Ibadan	-0.2014	0.468	0.762

lowest R² value is 0.71, suggesting that there is a strong linear relationship between observed and estimated values for all the selected locations, indicating the high reliability of the developed models.

Based on the regional classification of the selected locations shown in Figure 1, a comparative plot of the NASA satellite (observed) and estimated global horizontal irradiance (GHI) for the 37 locations is illustrated in Figures 2, 3, and 4. Figure 2 shows that there are months where overestimation and underestimation were recorded in region 1, as well as months where there was an alignment between the estimated and observed GHI values during the year. It is clear from Figure 2 that the deviation between the estimated and observed values using the developed models is very small in all the selected locations. GHI in this region varied between 4 kWh/m²/day and 7 kWh/m²/day. In region 2 (Figure 3), this value ranged between 3.8 kWh/m²/day and 6.1 kWh/m²/day. Also, the average difference between estimated and observed values is less than 0.5 kWh/m²/day in places like Abuja, Lokoja, and Ilorin, indicating the suitability of the model for accurate predictions in these areas. Other locations, such as Makurdi, Lafia, and Minna, demonstrate a more exceptional agreement with an average difference of less than 0.1 kWh/m²/day. Additionally, the months of November to April, which coincide with the dry season, exhibit better accuracy when compared with the months of May to October, which is the wet season. The reason adduced for this may be due to the prevailing cloud cover, which characterizes the wet season. Compared with regions 1 and 2, region 3 is largely characterized by low GHI values with predicted values as low as 3 kWh/m²/day in locations such as Calabar, Port-Harcourt, and Yenagoa as shown in Figure 4. Some disparities exist between the estimated and observed values, which range from less than 0.1 kWh/m²/day in locations such as Abakaliki, Ado-Ekiti, Benin City, and Akure to a maximum of 0.5 kWh/m²/day for most locations such as Enugu, Umuahia, Uyo, Awka, Yenagoa, Port-Harcourt, and Owerri.

Figures 5, 6, and 7 illustrate the regional monthly average of estimated and observed GHI for the selected sites across the three regions. While Figure 5 indicates that the regional estimated and observed monthly average is 5.42 and 5.73 kWh/m²/day respectively, the estimated values are generally lower than the observed values, except for the month of October. Nonetheless the difference in regional

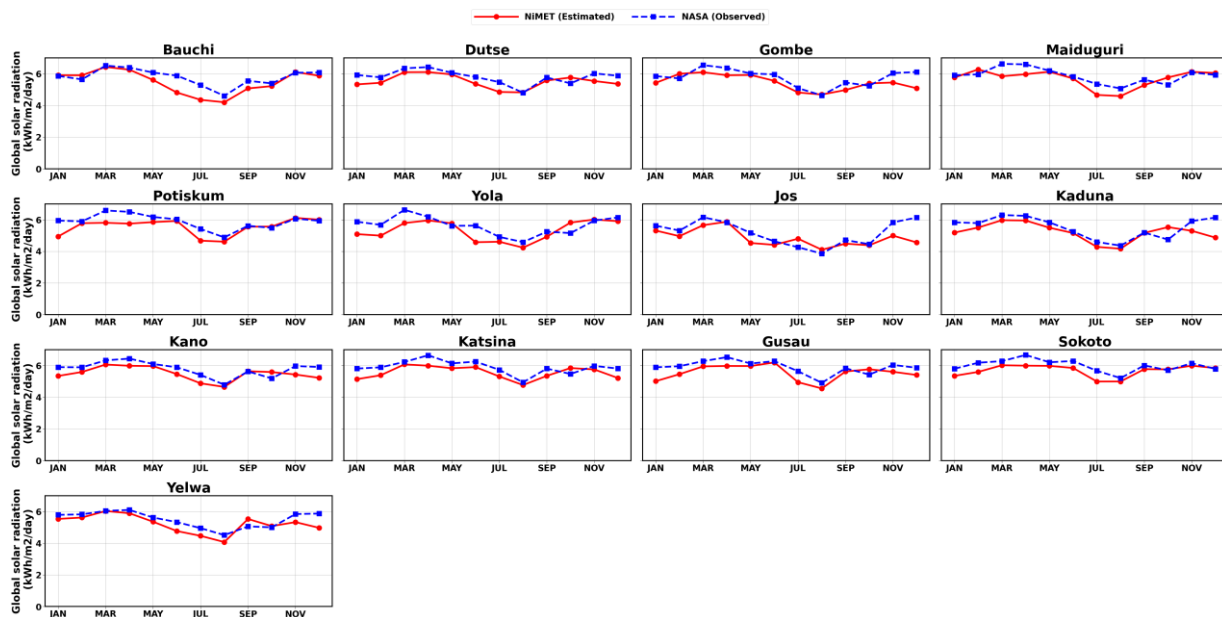


Figure 2. Comparison between the observed and the estimated global horizontal radiation for the 13 locations in region 1.

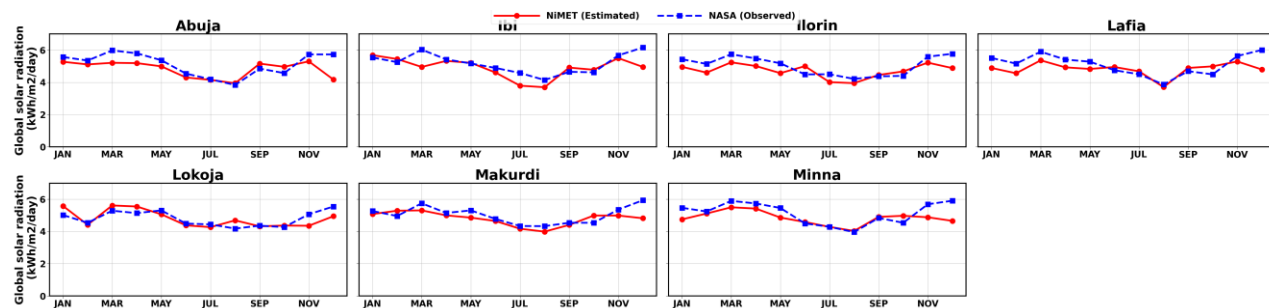


Figure 3. Comparison between the observed and the estimated global horizontal radiation for the 7 locations in region 2.

estimated and observed value is greatest in December. This is also similar to the case in region 2 as shown in figure 6. The region also exhibited a slightly lower regional monthly average. An estimated regional average GHI of 4.81 kWh/m²/day is recorded, while the observed value is 4.84 kWh/m²/day. The result from region 3 closely follows that of region 2 with a regional estimated average GHI of 4.47 and an observed GHI of 4.67. Just like the region 1 and 2, the month of December displayed the greatest difference. Figure 8 illustrates a comparison between the estimated maximum and minimum annual average GHI values across regions. Sokoto, Ibi, and Abakaliki recorded the highest annual average GHI levels, measuring 5.86 kWh/m²/day, 4.90 kWh/m²/day, and 4.76 kWh/m²/day for regions 1, 2,

and 3, respectively. In contrast, the lowest annual average GHI values for regions 1, 2, and 3 were observed in Jos, Ilorin, and Benin City, with values of 4.84 kWh/m²/day, 4.71 kWh/m²/day, and 4.37 kWh/m²/day, respectively. Overall, estimated values are in alignment with NASA's observed values in all regions.

4. Conclusions

The primary objective of this study was to develop empirical models using the Ångström-Prescott sunshine-based model for estimating the global horizontal irradiance (GHI) at various locations across

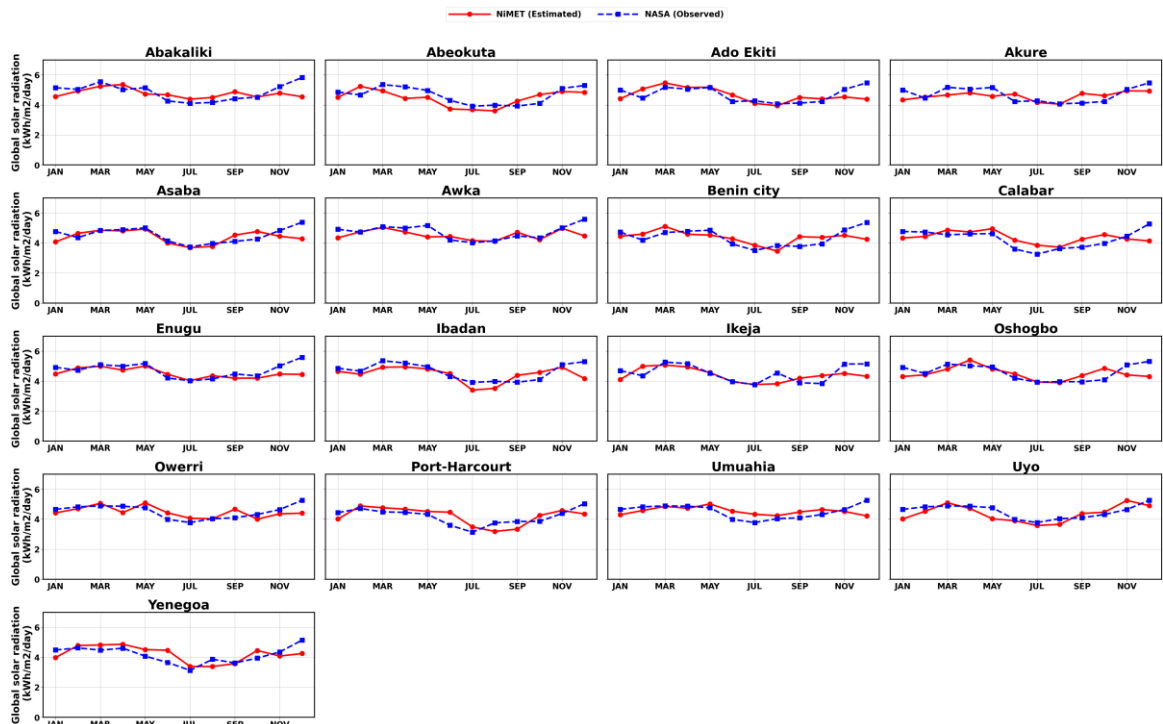


Figure 4. Comparison between the observed and the estimated global horizontal radiation for the 17 locations in region 3.

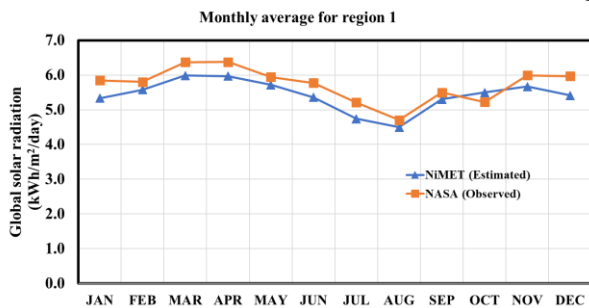


Figure 5. Regional average for each month in region 1.

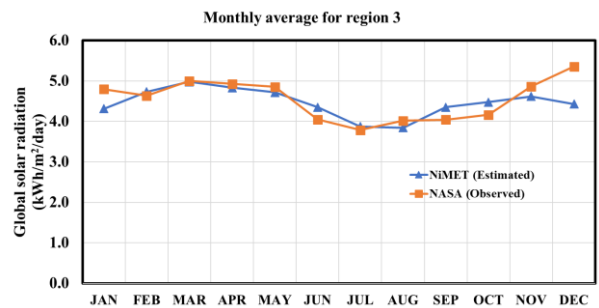


Figure 7. Regional average for each month in region 3.

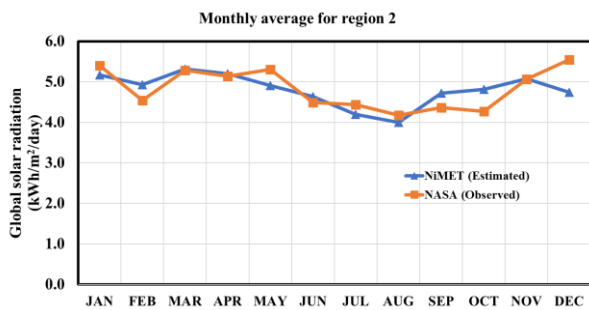


Figure 6. Regional average for each month in region 2.

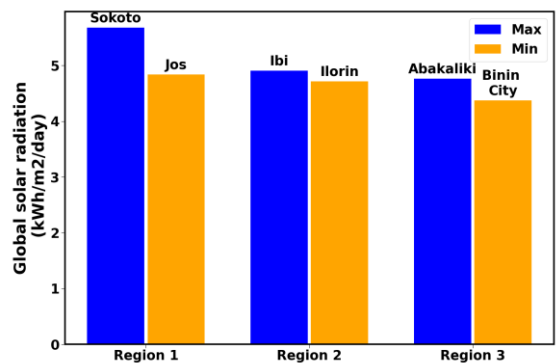


Figure 8. Estimated maximum and minimum global horizontal radiation for each region.

Nigeria. A total of 37 models were developed for specific locations, representing at least one state in Nigeria across three regions. The results were evaluated using statistical indicators such as mean bias error (MBE), root mean square error (RMSE), and coefficient of determination (R^2). A small deviation between the estimated and NASA satellite-observed values for all selected locations was observed, indicating the effectiveness of the developed models. The MBE values vary from -0.359 in Gusau (the highest underestimation) to 0.313 in Abuja (the highest overestimation). The RMSE values vary between 0.396 and 0.612. Sokoto has the lowest RMSE, indicating the highest accuracy, while Jos has the highest RMSE, indicating the lowest accuracy. The R^2 values in this study range from 0.706 to 0.985. 62% of the locations considered in this study have R^2 values above 0.8, which suggests that the model fits the data quite well. The result further shows that in regions 1,2 and 3, Sokoto, Ibi and Abakaliki have the highest estimated GHI value of 5.86 kWh/m²/day, 4.90 kWh/m²/day and 4.78 kWh/m²/day respectively while Jos, Ilorin and Benin City have the lowest estimated GHI value of 4.84 kWh/m²/day, 4.71 kWh/m²/day and 4.37 kWh/m²/day respectively.

On the whole, the statistical analysis indicates that the developed model is effective in estimating global solar radiation for the chosen locations in Nigeria. However, certain locations have higher errors than others, which could be due to local weather patterns, topography, or other factors specific to each site. The findings of this study are expected to benefit researchers, solar engineers, and installers by enhancing their understanding of GHI estimation and its practical application in the field. Additionally, these empirical models can be used to assess the performance of solar systems under real operating conditions, comparing them to the results obtained from the models. Furthermore, the research emphasizes the significance of consistently monitoring and refining solar radiation models to enhance their precision and usefulness in practical situations.

While the results presented in this study may be limited by the lack of consideration for some local factors such as cloud cover or pollution, overall, this study contributes to the advancement of knowledge and practical utilization of GHI estimation, supporting the development and implementation of solar energy systems in Nigeria. Future directions are anticipated from this study to determine the electric energy potential that can be harnessed or

generated from each location, which could be integrated into the existing grid system to improve the energy security of Nigeria.

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Nomenclature

AP	Ångström-Prescott
a	Climatologically determined regression constant
b	Climatologically determined regression constant
G_{sc}	Global constant (1367 W/m ²)
GSR	Global solar radiation (kWh/m ² /day)
GHI	Global horizontal irradiance (kWh/m ² /day)
H	Monthly average daily global solar radiation (kWh/m ² /day)
$H_{est.}$	Estimated horizontal global solar radiation (kWh/m ² /day)
$H_{obs.}$	Observed horizontal global solar radiation (kWh/m ² /day)
$\overline{H_{obs}}$	Mean observed global horizontal irradiance (kWh/m ² /day)
H_o	Monthly average daily extra-terrestrial radiation (kWh/m ² /day)
J	Julian day
$MABE$	Mean absolute bias error
MBE	Mean bias error
$NASA$	National aeronautics and space administration
$NiMet$	Nigerian meteorological agency
N	Numbers of observations
PV	Photovoltaic
$RMSE$	Root mean square error
R^2	Coefficient of determination
S	Average daily number of observed sunshine hours
S_{avg}	Average daily sunshine hours (hours)
S_o	Astronomical day length (hours)
S_{oavg}	Average monthly day length (hours)
ω_s	sunset hour angle
δ	solar declination
φ	latitude (⁰ N)

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