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Proposal of Models for Global Solar Radiation Estimation in Burkina Faso

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Abstract

The solar data used to size installations for energy needs are most often oversized. The data used are either old or suffer from the effects of climate change or from data extrapolated to a whole region. For a country with a strong sunshine all year round, it is good to compare the many models that exist to find the most suitable for the country. The distribution of solar radiation on a territory is not uniform; it depends on several geographical, meteorological and astrological parameters. In addition, solar radiation data is often not available due to the high cost of measuring equipment. To address this issue, we propose models based on easily measurable meteorological data. In this study, models are proposed for annual estimation, for estimation during the rainy season and the dry season for the localities of Dori in the North, Ouagadougou in the Center, and Bobo-Dioulasso in the South of Burkina-Faso. Regression models based on insolation duration and hybrid models for estimating global solar radiation on a horizontal surface in these localities have been proposed. The results obtained are satisfactory, with a coefficient of determination between "0.84 - 0.99" and a statistical t-test between "0 - 0.09", showing that over 90% of solar radiation variability is explained by these models.

Keywords

Insolation, Regression, Global Solar Radiation, Hybrid, Solar Declination

1. Introduction

Local global solar radiation is a required input for most models that simulate crop growth, for estimating evapotranspiration, for architectural design, and for solar energy systems. The design of a solar energy conversion system requires accurate knowledge of the availability of global solar radiation at the site of interest. Since the amount of global solar radiation reaching the Earth's surface depends on weather conditions, a study of solar radiation under local climate conditions is essential [1]. For sites where measured values are not available, solar irradiance can be estimated using an empirical model. Various methods have been explored by many researchers to estimate solar radiation from other available weather data. The input parameters include astronomical factors (solar constant, Earth-Sun distance, solar declination, and hour angle); geographical factors (latitude, longitude, and altitude); geometric factors (surface azimuth, surface tilt angle, solar altitude, solar azimuth); physical factors (albedo, scattering by air molecules, water vapor content, scattering by dust and other atmospheric constituents); and meteorological factors (atmospheric pressure, cloudiness, temperature, sunshine duration, air temperature, soil temperature, relative humidity, evaporation, precipitation, number of rainy days, total precipitable water, etc.) [1]-[3]. Nowadays, renewable energies hold a prominent place in the global energy mix, especially in that of many African countries [4]. A country with an average solar irradiation duration of 3000 h/year, Burkina-Faso paradoxically knows an important energy deficiency [5]. The design and control of a photovoltaic (PV) installation require prior knowledge of certain parameters particularly the solar potential in the site which is predicted by models. In this article, insulation-based models and hybrid models are proposed for estimating solar potential. The models are validated seasonally (year-round, dry season and rainy season).

2. Materials and Methods

Several models for estimating global solar radiation on the horizontal plane have been developed. The first authors were Angstrom in 1924 [6] and Angstrom-Prescott in 1940 [7]. Depending on the availability of meteorological data, several models are developed based only on duration of insolation, relative humidity, temperature, precipitation, Cloud Cover or hybrid parameters. In this paper, we are interested in the first group which is based on the duration of insolation. Sunshine duration is commonly used a parameter in the estimation of global solar radiation [8]. The modified model of Angstrom proposed by Prescott is of the form in formula (1) [6] [7].

$$\frac{\bar{H}_m}{\bar{H}_0} = a + b \times \left(\frac{\bar{S}}{\bar{S}_0} \right) \tag{1}$$

Until today, the proposed models are either linear, polynomial (up to order 3), logarithmic and exponential. In this article, we validated models for estimating solar potential in Burkina Faso for three localities chosen according to the climatic zones:

- Dori for the Sahelian zone in the North,
- Ouagadougou for the Sudano-Sahelian zone in the center,
- Bobo-Dioulasso for the Sudano-Guinean zone in the South.

Measured by the National Meteorological Agency of Burkina Faso (ANAM/BF) from 1976 to 2001, the meteorological data are: the average horizontal global solar radiation, the average daily duration of sunshine, the average daily maximum and minimum temperatures, relative humidity, and wind speed.

The objective of this work is to propose regression models for the prediction of solar radiation in Burkina Faso from meteorological data, tested by their performance indicators such as Root Mean Square Error (RMSE), Mean Error Mean (MBE), Mean Percent Error (MPE), and Statistical Test t. These performances will make it possible to determine the best model for the studied localities and other localities having the same geographical and climatic indices.

Based on the Angstrom model, relative humidity (H_r), sunshine duration (S_t), maximum temperature (T_{max}), extraterrestrial radiation (H_0), the sine of the solar declination ($\sin\delta$), the ratio of maximum to minimum temperature (θ), and wind speed (V) are used for model validation. The proposed models are of the following form:

$$\frac{\bar{H}_m}{\bar{H}_0} = a + b\times\left(\frac{\bar{S}}{\bar{S}_0}\right) + c\left(\frac{\bar{S}}{\bar{S}_0}\right)^2 + \cdots \tag{2}$$

$$\bar{H}_m = a + b\times\left(\frac{\bar{S}}{\bar{S}_0}\right) + c\times\left(\frac{\bar{S}}{\bar{S}_0}\right)^2 + \cdots \tag{3}$$

$$\bar{H}_{cal} = a + b\times Y_1 + c\times Y_2 + d\times Y_3 + e\times Y_4 + f\times Y_5 + g\times Y_6 \tag{4}$$

where the Y_i are the variables of the study, which are : $Y_1 = \bar{H}_r$, $Y_2 = \left(\frac{\bar{S}}{\bar{S}_0}\right) = S_t$, $Y_3 = \bar{T}_{max}$, $Y_4 = \bar{H}_0$, $Y_5 = \sin\delta$ and $Y_6 = \left(\frac{\bar{T}_{max}}{\bar{T}_{min}}\right) = \theta$, $\bar{H}_m$ and $\bar{S}$ are respectively the monthly average of the global solar radiation daily (Mj·m^{-2}·day^{-1}) and the average monthly duration of insulation of the localities. The coefficients a, b, c, d … are the correlation parameters.

The day duration S_0 (h) and the average monthly extraterrestrial radiation $\overline{H_0}$ (Mj·m^{-2}·day^{-1}) are calculated using formula (5) [9] and (6) [10]:

$$\bar{H}_0 = \frac{24}{\pi}\times I_{sc}\times\left(1+0.033\cos\left(\frac{360D_n}{365}\right)\right) \times\left(\cos\varphi\cos\delta\sin\omega_s + \frac{\pi\omega_s}{180}\sin\varphi\sin\delta\right) \tag{5}$$

$$S_0 = \frac{2}{15}\omega_s \tag{6}$$

where φ (degree) is the latitude, δ (radian) the sun declination, ω_s (radian) the hour angle are determined by using (7) and (8). J' and D_n are the number of the day in the year and I_{sc} (Mj·m^{-2}·day^{-1}) the solar constant.

$$\omega_s = \cos^{-1}\left(-\tan\varphi\times\tan\delta\right) \tag{7}$$

$$\delta = 0.8 + 23.26\times\sin\left(\frac{2\pi\times J'}{365.24} - 1.395\right) + 0.375\times\sin\left(\frac{4\pi\times J'}{365.24} - 1.47\right) \tag{8}$$

Statistical indicators are used to compare the data calculated $\bar{H}_{ic}$ by the models with those measured $\bar{H}_{im}$. Root mean square error (RMSE), average bias error (MBE), average percentage error (MPE) and statistical test t are calculated by using (8), (9), (10) and (11).

$$\text{RMSE} = \sqrt{\sum_{i=1}^{n} \frac{\left(\bar{H}_{ic} - \bar{H}_{im}\right)^2}{n}} \tag{9}$$

$$\text{MBE} = \sum_{i=1}^{n} \frac{\left(\bar{H}_{ic} - \bar{H}_{im}\right)}{n} \tag{10}$$

$$\text{MPE}(\%) = \frac{1}{n} \times \sum_{i=1}^{n} \frac{\left(\bar{H}_{ic} - \bar{H}_{im}\right)}{\bar{H}_{im}} \times 100 \tag{11}$$

$$t = \sqrt{\frac{(n-1)\text{MBE}^2}{\text{RMSE}^2 - \text{MBE}^2}} \tag{12}$$

In order to avoid redundancy in the use of variables, Pearson's partial correlation coefficients (R_{xy}) between the input variables and solar radiation, as well as between the input variables themselves, are calculated. When the absolute value of R_{xy} given by Equation (13) is close to 1, there is a high degree of linear correlation between the two variables x and y; if $R_{xy} = 0$, there is no linear correlation, but other types of relationships may exist [11]

$$R_{xy} = \left[\sum_{i=1}^{N} (y_i - \bar{y})(x_i - \bar{x})\right] \Big/ \left\{\left[\sum_{i=1}^{N} (y_i - \bar{y})^2\right]\left[\sum_{i=1}^{N} (x_i - \bar{x})^2\right]\right\}^{1/2} \tag{13}$$

x_i and y_i are measured or estimated values, and N is the number of observations. The mean values are calculated using Equation (14).

$$\bar{x} = \frac{1}{N} \sum\nolimits_{i=1}^{N} x_i \tag{14}$$

3. Results

In general, a Pearson correlation coefficient equal to −1 or +1 means that there is a perfect positive (or negative) linear relationship between the variables. For values between −0.5 and 0.5, the relationship between the variables is weak. The calculation of the Pearson coefficient given by formula (8) yields R values between the variables that range from −0.21 to 0.44, allowing us to conclude that the redundancy between variables is weak and therefore all these variables can be used for model validation.

According to the performance indicators, the best models selected for estimating solar radiation over the whole year, for the three locations are given by (15) to (26).

3.1. Annual Estimation Models

Table 1 shows the annual models performances indicators.

Dori:

Located in the heart of the Sahel, Dori (14.035˚N, 0.345˚W) is in the north of

Table 1. Annual models performance indicators.

Model	R	MBE	MPE	RMSE	t
Bobo-Dioulasso					
1	0.97	−0.034	−2.32	1.18	0.09
2	0.99	−0.006	−0.44	0.96	0.02
3	0.91	0.000	0.0024	0.3479	0.000
Dori					
1	0.97	−0.035	−2.04	1.55	0.07
2	0.99	−0.000	−0.02	1.22	0.00
3	0,84	3,0E−16	0,0048	0,5111	0.000
Ouagadougou					
1	0.98	−0.019	−1.27	−1.27	0.05
2	0.99	0.000	0.00	0.74	0.00
3	0.95	0.000	0.0010	0.2639	0.00

the country in Sahelian zone. Precipitation is low with an average of 500 mm/year. They are concentrated in the months of June to September. The locality of Dori has significant potential, with an annual average of 20.61 MJ/m^2. Temperatures are high, with maximums reaching up to 42˚C. After analyzing and the regressions of solar radiation data and insolation duration these models are proposed:

$$\frac{\bar{H}_m}{\bar{H}_0} = 1.862 \times \left(\frac{\bar{S}}{\bar{S}_0}\right) - 1.428 \times \left(\frac{\bar{S}}{\bar{S}_0}\right)^2 \tag{15}$$

$$\bar{H}_m = 62.674 \times \left(\frac{\bar{S}}{\bar{S}_0}\right) - 46.727 \times \left(\frac{\bar{S}}{\bar{S}_0}\right)^2 \tag{16}$$

$$\begin{aligned} \bar{H}_{cal} = & -6.3836 - 9.6223 \times \bar{H}_r - 2.0523 \times \left(\frac{\bar{S}}{\bar{S}_0}\right) - 52.5169 \times \bar{T}_{\max} \\ & + 0.0482 \times \bar{H}_0 - 0.3566 \times \sin\delta + 83.2031 \times \left(\frac{\bar{T}_{\max}}{\bar{T}_{\min}}\right) \end{aligned} \tag{17}$$

Ouagadougou:

Ouagadougou (12,365˚N, 1533˚W) is at the center of Burkina Faso in the Sudano-Sahelian zone. There is an average of 750 mm of rain per year. The rains are concentrated from May to early October. The coefficients of the different correlated models are listed below.

$$\begin{aligned} \frac{\bar{H}_m}{\bar{H}_0} = & -199.630 \times \left(\frac{\bar{S}}{\bar{S}_0}\right) + 1137.517 \times \left(\frac{\bar{S}}{\bar{S}_0}\right)^2 - 2280.751 \times \left(\frac{\bar{S}}{\bar{S}_0}\right)^3 \\ & + 1705.206 \times \left(\frac{\bar{S}}{\bar{S}_0}\right)^4 - 376.068 \times \left(\frac{\bar{S}}{\bar{S}_0}\right)^6 - 18813.822 \times \left(\frac{\bar{S}}{\bar{S}_0}\right)^7 \end{aligned} \tag{18}$$

$$\bar{H}_m = -5108.331\times\left(\frac{\bar{S}}{\bar{S}_0}\right) + 28963.331\times\left(\frac{\bar{S}}{\bar{S}_0}\right)^2 - 57656.945\times\left(\frac{\bar{S}}{\bar{S}_0}\right)^3 + 42779.188\times\left(\frac{\bar{S}}{\bar{S}_0}\right)^4 - 9291.189\times\left(\frac{\bar{S}}{\bar{S}_0}\right)^6 \quad (19)$$

$$\bar{H}_{cal} = -33.1093 - 5.2715\times\bar{H}_r + 1.4376\times\left(\frac{\bar{S}}{\bar{S}_0}\right) - 124.6618\times\left(\frac{\bar{T}_{\max}}{\bar{T}_{\min}}\right)^2 - 0.1474\times\bar{H}_0 + 0.3304\times\sin\delta + 170.2217\times\left(\frac{\bar{T}_{\max}}{\bar{T}_{\min}}\right) \quad (20)$$

Bobo-Dioulasso:

The locality of Bobo-Dioulasso (11.177˚N, 4.297˚W) is one of the cities enjoying good rainfall in Burkina-Faso. Located in the south of the country in the Sudanian zone, the annual rainfall reaches 1000 mm. The rainy season comes a little earlier and starts from April to November.

$$\frac{\bar{H}_m}{\bar{H}_0} = 1.678\times\left(\frac{\bar{S}}{\bar{S}_0}\right) - 1.372\times\left(\frac{\bar{S}}{\bar{S}_0}\right)^2 \quad (21)$$

$$\bar{H}_m = 57.828\times\left(\frac{\bar{S}}{\bar{S}_0}\right) - 46.233\times\left(\frac{\bar{S}}{\bar{S}_0}\right)^2 \quad (22)$$

$$\bar{H}_{cal} = -139.2665 + 496.1371\times\left(\frac{\bar{T}_{\max}}{\bar{T}_{\min}}\right) - 2.1643\times\left(\frac{\bar{S}}{\bar{S}_0}\right)^2 - 0.1460\times\bar{H}_0 - 5.0992\times\bar{H}_r - 369.0948\times\left(\frac{\bar{T}_{\max}}{\bar{T}_{\min}}\right)^2 + 0.2797\times\sin\delta \quad (23)$$

3.2. Models for Rainy Season Estimation

For rainy season, the models proposed for solar radiation estimation are respectively with the performances indicated in Table 2.

Dori:

$$\bar{H}_{cal} = 31.2088 - 0.4042\times\bar{H}_0 - 5.9249\times\left(\frac{\bar{S}}{\bar{S}_0}\right) + 0.2190\times\bar{T}_{\max} \quad (24)$$

Ouagadougou:

$$\bar{H}_{cal} = 18.9109 - 36.9795\times\left(\frac{\bar{T}_{\max}}{\bar{T}_{\min}}\right) + 0.4159\times\bar{T}_{\max} + 0.2938\times\bar{H}_0 \quad (25)$$

Bobo-Dioulasso:

$$\bar{H}_{cal} = 49.4429 + 0.1423\times\bar{T}_{\max} - 54.3506\times\left(\frac{\bar{T}_{\max}}{\bar{T}_{\min}}\right) + 0.0473\times\bar{H}_0 \quad (26)$$

3.3. Models for Dry Season Estimation

Table 3 gives the performances the models proposed for solar radiation estimation in rainy season.

Table 2. Rainy models performances indicators.

Model	R	MBE	MPE	RMSE	t
Bobo-Dioulasso					
1	0.99	0.000	0.0001	0.191	0.09
Dori					
1	0.99	0.000	0.000	0.0554	0.000
Ouagadougou					
1	0.99	0.000	0.002	0.290	0.000

Table 3. Rainy models performance indicators.

Model	R	MBE	MPE	RMSE	t
Bobo-Dioulasso					
1	0.99	0.000	0.0007	0.0859	0.00
Dori					
1	0.96	0.00	−0.008	0.3040	0.00
Ouagadougou					
1	0.99	0.00	0.001	0.104	0.00

Dori:

$$\begin{aligned}\bar{H}_{cal} &= 44.4878 - 66.1823 \times \bar{H}_r + 22.9731 \times \left(\frac{\bar{S}}{\bar{S}_0}\right) \\ &+ 33.7835 \times \left(\frac{\bar{T}_{\max}}{\bar{T}_{\min}}\right) - 0.7750 \times \bar{H}_0 - 10.5995 \times V\end{aligned} \tag{25}$$

Ouagadougou:

$$\begin{aligned}\bar{H}_{cal} &= 11.3256 - 0.0688 \times \bar{H}_0 - 10,4093 \times \bar{H}_r + 0.9866 \times \left(\frac{\bar{S}}{\bar{S}_0}\right) \\ &+ 25.9491 \times \left(\frac{\bar{T}_{\max}}{\bar{T}_{\min}}\right) - 1.5365 \times V\end{aligned} \tag{26}$$

Bobo-Dioulasso:

$$\begin{aligned}\bar{H}_{cal} &= -6.2650 - 0.8915 \times \bar{T}_{\max} + 0.2394 \times \sin\delta \\ &- 0.4632 \times \bar{H}_0 - 1.0621 \times \bar{H}_r + 14.2726 \times \left(\frac{\bar{S}}{\bar{S}_0}\right)\end{aligned} \tag{27}$$

4. Discussion

Figure 1 shows the mean values of the clearness indices (K_T) of the three localities. The K_T values range from 0.43 to 0.65, proving that the atmosphere is full of impurities all year round. The shape of the curves shows a very great variability of the solar potential with a high solar potential available in Dori followed by Ouagadougou and Bobo-Dioulasso. The low values of K_T in December in the three localities can be explained by the fact that in the dry season, the sky is clear. Nevertheless, they are influenced by the dust raised by the winds of the harmattan. The strong K_T values observed at the month of May in Ouagadougou and Dori and at the month of March in Bobo-Dioulasso can be explained by the beginning of rainy seasons and the cloud cover.

The highest K_T is recorded at Dori in the northern part of the country in the Sahelian zone. Rainfall is low and concentrated in the months of June to September with an average of 500 mm/year. The high value of K_T can be explained by the fact that the city is located in the heart of the Sahel. The impact of the aerosols in this part due to the lifting of dust is important.

Figure 2 shows that the sunshine rate varies from 0.45 to 0.82. The average

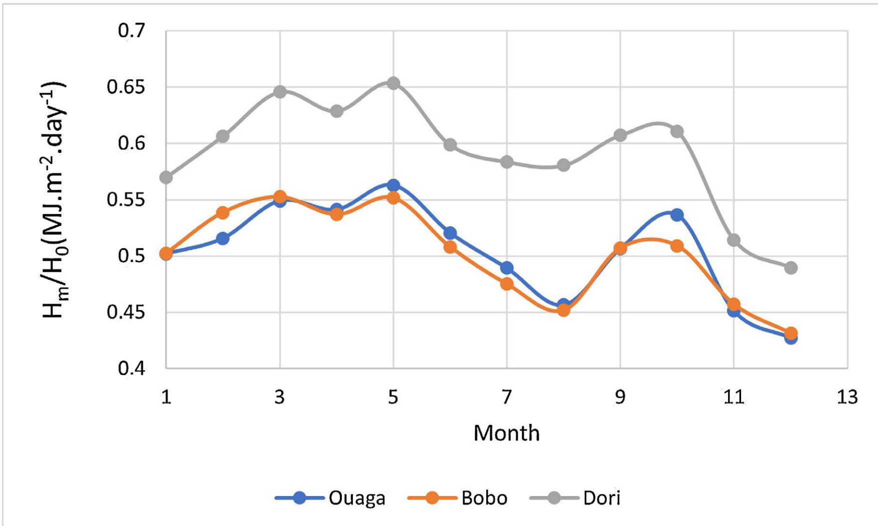

Figure 1. Clearness index of the three localities.

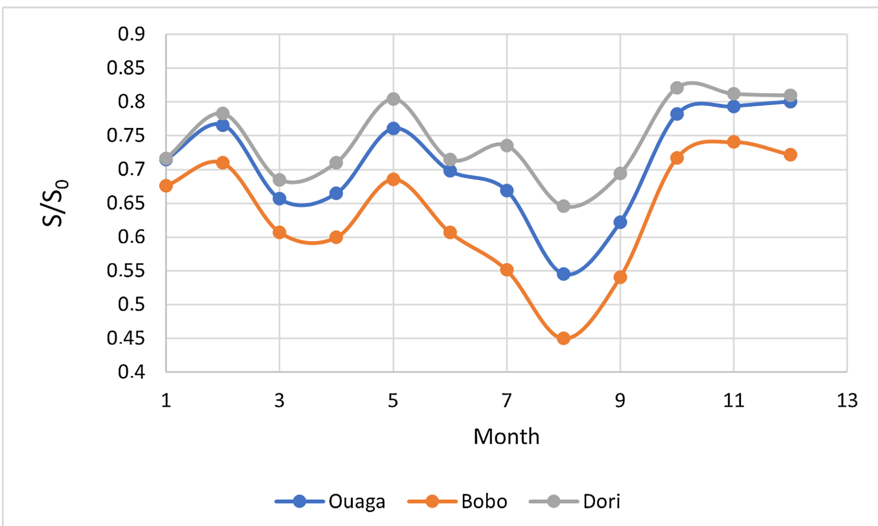

Figure 2. Daily report of the sunshine duration of the three localities.

ratio calculated here is 0.69. It can be noted that localities with high rainfall record the lowest ratios and vice versa. The lowest value of the ratio is recorded in August, the month of heavy rainfall.

The results obtained are satisfactory and must be analyzed taking into account several factors: the geographical location of the locality (proximity or distance from the sea), the measurement period, the horizon, the state of the sky (presence or absence of clouds or dust), the accuracy of the equations used to calculate certain parameters, etc. For hybrid models, depending on the number of variables, we proposed models based on two variables, three variables, four variables, and five variables for estimating irradiation throughout the year, during the rainy season (May-June-July-August and September) and during the dry season (January-February-March-April-October-November and December).

It should be noted that for the locality of Ouagadougou, the insolated proposed models have high polynomial orders. In fact, several models were proposed for each locality, and the models with the best performance were selected and presented in this work.

The value of R ranges 0.84 at 0.99 and indicates a good correlation between the estimated and measured values. The average percentage error (MPE) is acceptable and varies from −2.32% - 0%. The negative sign of MBE shows that models will underestimate global solar radiation and the positive sign shows that models surestimate global solar radiation.

The statistical test (t), which takes in account MBE and RMSE give good values between 0 - 0.09. The adequate models and more accurate for annual estimation for theses localities will be the last two models, which estimate the solar radiation at best.

Our results are comparable to those found in the literature. Several authors have focused on predicting solar radiation [12]. N. N. Gana and D. O. Akpootu used data on the monthly average of daily global solar radiation and measured sunshine duration to propose a model for the town of Kebbi in Nigeria [13]. A correlation coefficient of 97.40% shows a good correlation between the estimated and measured values. It was noted that from January to April, the model underestimates the clarity index in Kebbi, and from August to October, the model overestimates the clarity index.

C. Augustine and M. N. Nnabuchi, using data from the period 1990 to 2007, based their work on Page's model to validate models for four selected locations in the east and south: Owerri, Enugu, Warri, and Uyo. They found regression coefficients a and b equal to 0.278 and 0.331 respectively for the locality of Owerri, 0.336 and 0.247 for the locality of Enugu, 0.29 and 0.42 for the locality of Warri, and 0.290 and 0.253 for the locality of Uyo. The coefficient of determination obtained for the localities of Owerri, Warri, and Uyo is acceptable, at 0.793, 0.795, and 0.793, respectively. For the locality of Enugu, it is equal to 0.382 and shows a low degree of adequacy between the data. The positive mean bias error (MBE) shows that the model overestimates global solar radiation and is equal to 0.219

$MJ \cdot m^{-2} \cdot day^{-1}$ for Owerri and Enugu, 0.219 $MJ \cdot m^{-2} \cdot day^{-1}$ for Warri, and 0.323 $MJ \cdot m^{-2} \cdot day^{-1}$ for Uyo. The RMSE is 2.781 $MJ \cdot m^{-2} \cdot day^{-1}$ for Owerri; 2.761 $MJ \cdot m^{-2} \cdot day^{-1}$ for Enugu and Warri; and 2.157 $MJ \cdot m^{-2} \cdot day^{-1}$ for Uyo. It is high because, according to Iqbal (1983), an RMSE close to zero is desirable. Sani *et al.* proposed and validated models [14]. For the three proposed models (linear, quadratic, and cubic), the coefficients of determination are 0.827, 0.827, and 0.833, respectively. The tests give an MBE of −0.1053 $MJ \cdot m^{-2} \cdot day^{-1}$, 4.01001 $MJ \cdot m^{-2} \cdot day^{-1}$, and 0.06217 $MJ \cdot m^{-2} \cdot day^{-1}$ for each model, respectively. The RMSE is 0.5880 $MJ \cdot m^{-2} \cdot day^{-1}$, 1.32499 $MJ \cdot m^{-2} \cdot day^{-1}$, and 0.57262 $MJ \cdot m^{-2} \cdot day^{-1}$. They concluded on the basis of performance parameters that the linear model based on the modified Angstrom Prescott model is highly recommended for estimating global solar energy in the Kano State region and other regions with similar climatic conditions.

In Burkina Faso, Ousmane Coulibaly [15] used data on daily global solar radiation and sunshine duration to propose models for estimating solar potential in eight locations in Burkina Faso. Based on the modified Angstrom model, they found an average correlation coefficient R of 0.90, which shows a good correlation between the estimated and measured values.

O. T. Kolebaje *et al.* [16], in their hybrid models, found acceptable correlation coefficients of 0.913, 0.876, 0.794, and 0.841 for Port Harcourt, and 0.933, 0.929, 0.764, and 0.879 for Ikeja, showing a good relationship between the calculated and measured values. The calculation of performance indices for model validation led to the conclusion that model 4, which takes all parameters into account, is the most suitable for these locations, with MBE equal to −0.3663 $MJ \cdot m^{-2}$ for Port Harcourt and 0.4126 $MJ \cdot m^{-2} \cdot day^{-1}$ for Ikeja, respectively. Coulibaly *et al.* [10] proposed hybrid models for estimating global solar radiation on the horizontal plane in Burkina Faso. The average correlation coefficient of 0.95 indicates that there is a very good relationship between the measured solar radiation data and the estimated data. The MBE of 0 $MJ \cdot m^{-2} \cdot day^{-1}$ indicates that the models overestimate global solar radiation in all eight locations studied.

The models proposed according to the seasons show that certain variables such as wind speed, temperature ratio, and relative humidity appear in certain dry season models. Indeed, the dry season in Burkina Faso is marked by strong Harmattan winds that carry dust. Studies conducted by Bado *et al.* [17] have shown that aerosol particles, including dust suspensions, significantly influence incident solar radiation.

5. Conclusion

The Angstrom-Prescott models proposed for annual and seasonal estimation of global solar radiation give satisfactory results. More than 95% of the average variation in solar radiation in the horizontal plane is accounted for by these correlations.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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