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# Comparison of Different Models to Estimate Global Solar Irradiation in the Sudanese Zone of Chad

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**Abstract**

Sustainable future development relies on solar radiation, which is the main source of renewable energy. Thus, in this article, the monthly average global solar irradiation of four sites in the Sudanian zone region of Chad is estimated using different empirical models. The data used in this study were collected at the General Directorate of Meteorology of Chad. The reliability and accuracy of six models estimating global solar radiation were validated and compared by statistical indicators identifying the most accurate model. The results obtained show that the Allen model has the best performance for the Moundou site (5.760 kWh/m²/d, $R^2$=0.843), the Angstrom Prescott model for the Sarh sites (5.658 kWh/m²/d, $R^2$=0.805) and Pala (5.793 kWh/m²/d, $R^2$=0.889), the Sabbagh model for the Bongor site (5.657 kWh/m²/d, $R^2$=0.888). These models are validated against NASA data. The results show that the Sudanian zone of Chad has good solar potential and is therefore suitable for possible exploitation.

**Keywords:** renewable energy, empirical models, statistical indicators, solar radiation, Sudanese zone

## I. INTRODUCTION

As an indicator of the level of development, the increase in energy demand day by day and the decrease in fossil fuels increase the importance of renewable energy sources. The main source of all direct or indirect energy sources, which has the greatest energy potential among all known renewable energy sources such as solar, wind, biomass, and geothermal, is the sun. Solar energy is one of the most important energy sources that can be obtained directly from the sun. Meteorological observations made in order to determine the solar energy potential in a particular region require significant economic investments and qualified manpower. It is not always possible to measure solar radiation data, which is of great importance in the design of solar energy systems, for every region. Therefore, it is important to develop new models to predict solar radiation values. Since solar radiation values depend on many geographical or meteorological parameters, it is possible to obtain various models [1]–[3]. In this study, the predictability of solar radiation with the models available in the literature has been demonstrated.

A lot of studies have been conducted to develop models to predict global solar radiation, including day-of-year information [4], the use of a machine learning algorithm [5], [6], meteorological parameters [7], and geographic information [8]. Sammy et al. [9] focused their study on the evaluation of global solar radiation at Al-baha and the comparison of empirical models. The results obtained showed that it is during the summer that the maximum values of solar energy occur, unlike the months of autumn and winter where the lowest values occur. Bamigbola and Atolagbe [10] conducted a study on the prediction of global radiation using empirical models depending on location and season on the African continent. The results obtained show that the dominant localization factor is the altitude component. When estimating global solar radiation for any practical application, the new models present optimal performance compared to existing models and constitute suitable and predictive tools. Tegenu et al. [11] made a comparative evaluation of insolation-based models and Artificial Neural Networks for the prediction of Labibela's daily global solar radiation. The results obtained show a good

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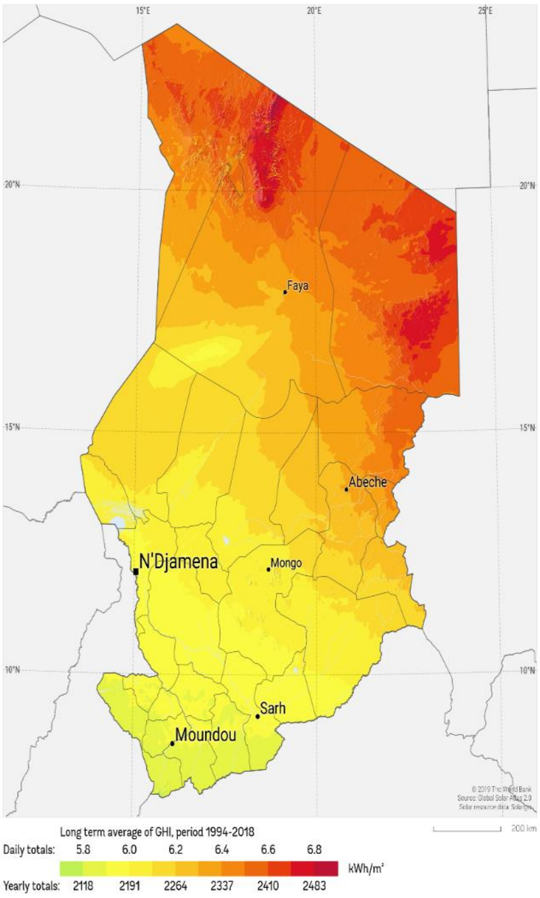


Figure 1. The considered sites' Global Horizontal Irradiation in Chad [14].

agreement between the estimated values and the NASA values. State of Central Africa located in the heart of the African continent, Chad is a vast territory of 1,284,000 km² with a population estimated at 11,175,915 inhabitants in the RGPH2 of 2009. The climate is characterized by high average temperatures and strong thermal amplitudes, a prevailing North-East wind regime, low average relative humidity, and high evaporation [12]. Knowledge of global radiation can be acquired by three methods using measurements (pyranometer for measuring global and diffuse; pyrheliometer for measuring direct), mathematical models based on meteorological data, and satellite images [13]. The objective of this study is to study the performance of six models to estimate global solar radiation for each of the sites in the Sudanian zone of Chad. Figure 1 displays the sites considered in this study. Thus, the following points can be considered as contributions of the current study:

- Estimation of the solar radiation potential of four cities.
- Performance evaluation of one of the best models based on meteorological data.
- Evaluation and comparison of the performances of the six models.

The realistic variation data of the solar radiation (kW/m$^2$) for simulations are shown in Figure 2. Meteorological and global solar radiation data provided by NASA of 2021. Vast of 1,284,000 km$^2$, Chad in central Africa at an average altitude of 200 meters above the sea extends between 7˚ and 24˚ of north latitude and between 14˚ and 24˚ of longitude east.

A numerical approach is adopted to measure solar radiation loss due to atmospheric conditions. Physically clear and sunny conditions are characterized by a parameter known as the cloudiness index, which has a value ranging from 0 to 1. A high value relates to clear sunny conditions and low values indicate cloudy conditions. The cloudiness index is obtained by calculating the ratio between total solar radiation and extraterrestrial radiation ($H_0$). Solar radiation is different around the country depending on weather conditions, direction, different types of days, and latitude. For the case study, the four different cities (Moundou 16.4˚E, 8.3˚N, Pala 14.55˚E, 9.22˚N, Sarh 18.23˚E, 9.9˚N, and Bongor 15.22˚E, 10.16˚N) in Chad are chosen. Figure 2 shows the daily average solar radiation, ambient temperature, and clearness index data in the chosen districts. It can be noticed that the daily average solar radiation ranges from 4.7 to 6.8 kWh/m²/day, while the annual average of solar radiation is 5.8 kWh/m²/day. The clearness index ranges from 0.47 to 0.71, while the average daily clearness index is 0.60.

There are many studies in the literature similar to the subject of this study. However, there are several aspects that distinguish this study from other studies, which were carried out to estimate the measured global solar radiation for Chad and to compare it with common irradiance models: Models developed based on different parameters affecting global solar radiation values were examined and six different models were compared. Studies in the literature are generally given as separate studies and have not been compared with other models. It is also thought that this study will contribute to the literature as it has regional importance in terms of obtaining information about Chad for solar energy investors and can offer a solution to Africa's electrical energy problem. The main reason for this study is to reduce the error rate by finding the closest values to the data of the current examined region in the healthy measurement of solar radiation. For this purpose, many different methods were examined, and the main aim was to achieve statistical compatibility.

The organization of this article is designed as follows. In Chapter 2, the material and method used in the study are mentioned, and in Chapter 3, comparison of the used methods is explained. In Chapter 4, the results are given and finally, in Chapter 5, the results are discussed.

## II. METHODOLOGY

In this section, the data set used in the study is explained and the methods used are examined in detail. As can be understood from the studies in the literature [15]–[18], meteorological parameters such as sunshine duration and air temperature have a strong effect on solar radiation. Different test methods are used to compare the solar radiation calculated from the models in the literature with the measured values and to test the accuracy. In this study, six different models (see Table 1)

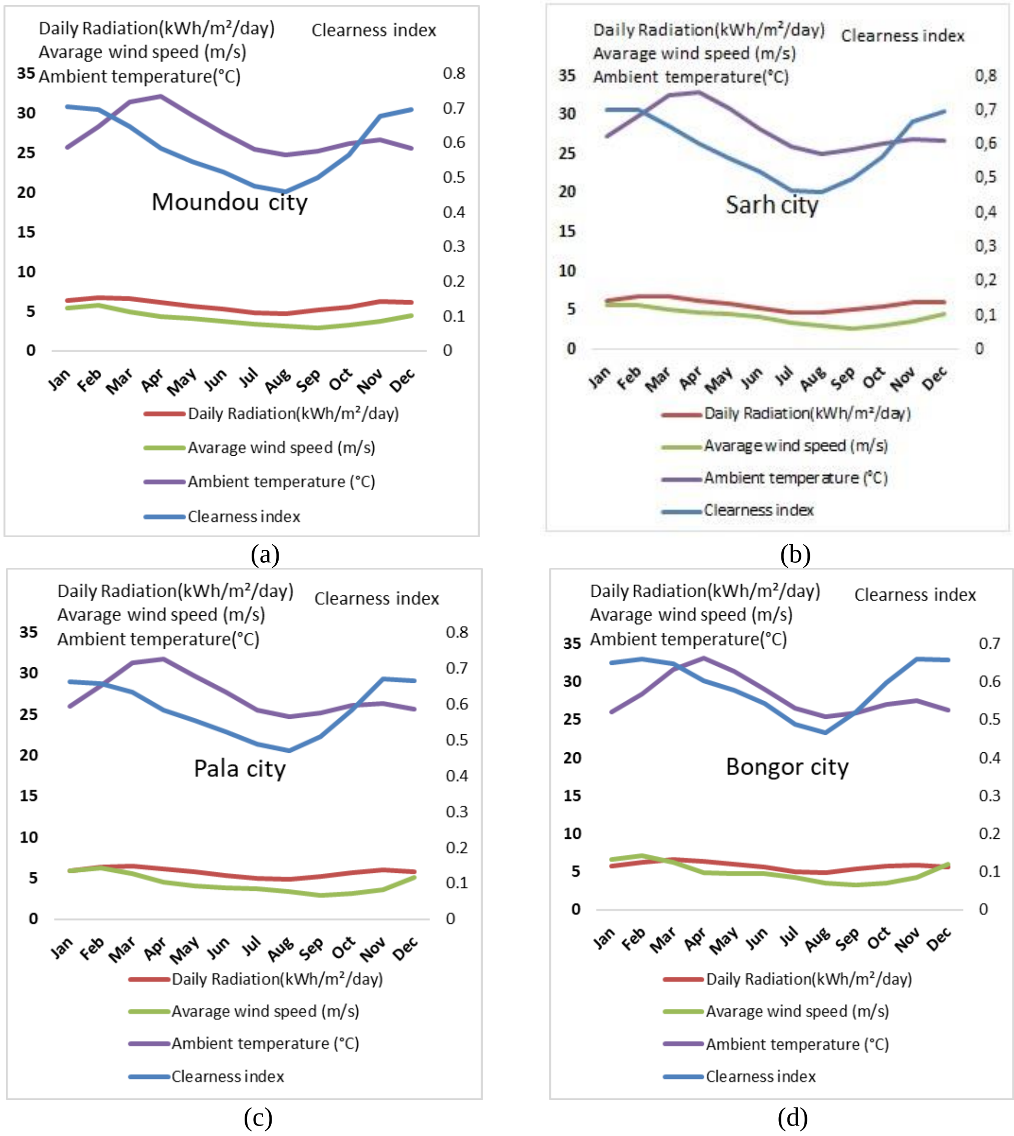


Figure 2. Climate summary of selected zones; (a) Moundou city; (b) Sarh city; (c) Pala city; (d) Bongor city.

in the literature were examined in order to determine the monthly average daily global solar radiation on the horizontal plane, considering the climatic characteristics and topographic structure of the Sudanian region. The extraterrestrial radiation on a horizontal plane is

TABLE 1
LIST OF MODELS USED FOR THE DETERMINATION OF GLOBAL SOLAR RADIATION

| Model | Symbol | Required Parameters | Relation |
|---|---|---|---|
| A.A.A.Sayigh [22] | M1 | DI, K, N, $T_{max}$, RH, $T_m$ | $G_H = 11.6\ KN \exp\left(\varphi\left(\frac{DI}{T_m}\right) - \left(\frac{RH}{15}\right) - \left(\frac{1}{T_{max}}\right)\right)$ |
| Hargreaves [23] | M2 | $T_{max}$, $T_{min}$, $K_r$, $H_0$ | $\frac{H}{H_0} = K_r(T_{max} - T_{min})^{0.5}$ |
| Allen [24] | M3 | $\alpha$, $T_M$, $T_m$, $H_0$ | $\frac{H}{H_0} = \alpha(T_M - T_m)^{0.5}$ |
| Sabbagh [25] | M4 | K, S, $S_0$, RH, $T_{max}$ | $H = 1.530K * \exp\varphi\left(\frac{S}{S_0} - \frac{RH^{1/3}}{100} - \frac{1}{T_{max}}\right)$ |
| Annandal [26] | M5 | Z, a, $H_0$, $T_{max}$, $T_{min}$ | $\frac{H}{H_0} = a(1 + 2.7 * 10^{-5}Z)(T_{max} - T_{min})^{0.5}$ |
| Angstrom-P [27] | M6 | S, $S_0$, $H_0$, a, b | $\frac{H}{H_0} = a + b\left(\frac{S}{S_0}\right)$ |

evaluated according to the following relation (1) [19], [20].

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

where $I_{sc}$ is the solar constant (1367 W/m²), δ and $\omega_s$ are given by (2) and (3), respectively [21].

$$\omega_s = \cos^{-1}(-\tan\varphi\tan\delta) \quad (2)$$

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

where $\omega_s$ is sunset hour angle (°C); φ is latitude of the location (°), δ is solar declination (°), and $D_n$ denotes the number of days of the year starting from January 1. Table 1 presents the different models used in this study to estimate the global solar irradiation for the four sites in the Sudanian zone of Chad.

## III. Comparison

To evaluate the different performances of solar radiation models in this study, 11 quantitative statistical indicators were used. Thus, Table 2 presents these indicators with the different parameters as well as the relationships.

In the literature, different test methods are used to compare the solar radiation calculated from the models with the measured values and to test the accuracy. In this study, 11 different statistical error methods such as Relative Root Mean Squared Error (RRMSE [%]), t-statistic, Root Mean Square Error (RMSE [kWh/m²]), Expanded uncertainty at 95% ($U_{95}$[kWh/m²]), Mean Bias Error (MBE [kWh/m²]), Mean Absolute Error (MAE [kWh/m²]), Mean Absolute Relative Error (MARE), Maximum Absolute Relative Error (erMAX), Root Mean Square Relative Errors (RMSRE [%]), Correlation Coefficient ($R^2$), the Relative Percentage Error ($e$) were used to evaluate different models. These quantitative indicators are briefly summarized in Table 2.

Where, $n$ is total number of observations, $H_{i.m}$ , $H_{i.c}$, and $H_{m.avg}$ show the i.th measured, calculated, and average solar radiation values from the models, respectively. For better data modeling results, statistical error parameters should be close to zero, but $R^2$ should be close to 1. The MBE indicates that the model's solar radiation tends to be very low or very high, while the closer it is to zero, the higher the performance indicator. The $R^2$ indicator is a statistical method often used to predict the performance of models. It varies between 0 and 1, and when this value approaches 1, it means that the dependence between model predictions and measurement values is strong. The lower the RMSE value, the better the predictive ability of a model in terms of its absolute bias. MARE displays the percentage value

TABLE 2
LIST OF STATISTICAL INDICATORS

| No. | Indicators | Required Parameters | Relation |
|---|---|---|---|
| 1 | RRMSE [28] | $\bar{H}_{i,m}$, $\bar{H}_{i,c}$, n | $RRMSE = \frac{\sqrt{\frac{1}{n}\sum_{i=1}^{n}(\bar{H}_{i,m}-\bar{H}_{i,c})^2}}{\sum_{i=1}^{n}\bar{H}_{i,m}} X100$ |
| 2 | t − stat [29] | MBE, RMSE, n | $t-stat = \sqrt{\frac{(n-1)MBE^2}{RMSE^2 - MBE^2}}$ |
| 3 | RMSE [30] | $\bar{H}_{i,m}$ , $\bar{H}_{i,c}$, n | $RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\bar{H}_{i,m}-\bar{H}_{i,c})^2}$ |
| 4 | $U_{95}$ [31] | SD, RMSE | $U_{95} = 1.96(SD^2 + RMSE^2)^{1/2}$ |
| 5 | MBE [32] | $\bar{H}_{i,m}$, $\bar{H}_{i,c}$, n | $MBE = \frac{1}{n}\sum_{i=1}^{n}(\bar{H}_{i,m}-\bar{H}_{i,c})$ |
| 6 | MAE [29] | $\bar{H}_{i,m}$, $\bar{H}_{i,c}$, n | $MAE = \frac{1}{n}\sum_{i=1}^{n}\lvert\bar{H}_{i,m}-\bar{H}_{i,c}\rvert$ |
| 7 | MARE [33] | $\bar{H}_{i,m}$, $\bar{H}_{i,c}$, n | $MARE = \frac{1}{n}\sum_{i=1}^{n}\left\lvert\frac{\bar{H}_{i,m}-\bar{H}_{i,c}}{\bar{H}_{i,m}}\right\rvert$ |
| 8 | erMAX [30] | $\bar{H}_{i,m}$, $\bar{H}_{i,c}$, max | $erMAX = \max\left(\left\lvert\frac{\bar{H}_{i,m}-\bar{H}_{i,c}}{\bar{H}_{i,m}}\right\rvert\right)$ |
| 9 | RMSRE [33] | $\bar{H}_{i,m}$, $\bar{H}_{i,c}$, n | $RMSRE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\frac{\bar{H}_{i,m}-\bar{H}_{i,c}}{\bar{H}_{i,m}}\right)^2}$ |
| 10 | RRMSE [28] | $\bar{H}_{i,m}$, $\bar{H}_{i,c}$, n, $\bar{H}_{m,avg}$ | $R^2 = 1 - \frac{\sum_{i=1}^{n}(\bar{H}_{i,m}-\bar{H}_{i,c})^2}{\sum_{i=1}^{n}(\bar{H}_{i,m}-\bar{H}_{m,avg})^2}$ |
| 11 | t − stat [29] | $H_m$, $H_{es}$ | $e = \lvert\{(H_m - H_{es})/H_m\}\rvert \times 100$ |

of the deviations between the measured and calculated values.

Due to the high difference in air temperature, some methods have been developed in literature [7], [23], [34] for the estimation of solar radiation (*H*). However, the accuracy of these estimates needs to be tested using different methods for different regions.

## IV. Results and Discussions

### A. Different Models for Estimating Global Solar Radiation

Table 3 presents the monthly global irradiation values obtained by the six models for Moundou in Southern Chad. Allen's model is the most efficient. According to the results obtained, we find that for the Moundou site, the calculated annual average of global radiation is 5.760 kWh/m$^2$/d. In addition, it varies on average from 4.031 kWh/m$^2$/d (August) to 7.066 kWh/m$^2$/d (December). It follows from the results obtained that the Moundou site could be the most suitable for the exploitation of photovoltaics because of the significant solar potential.

The six models' results for Sarh city in southern Chad are shown in Table 4 as monthly global irradiation values. The Angstrom-Prescott model is the most efficient. According to the results obtained, we find that for the Sarh site, the calculated annual average of global radiation is 5.658 kWh/m$^2$/d. In addition, it varies on average daily from 5.136 kWh/m$^2$ (July) to 6.026 kWh/m$^2$ (December). It follows from the results obtained that the Sarh site could be the most suitable for the exploitation of photovoltaics because of the significant solar potential.

The results for monthly global irradiation for Pala city in southern Chad are shown in Table 5. The Angstrom-Prescott model is the most efficient. From the results obtained, we find that for the Pala site, the calculated annual average of global radiation is 5.793 kWh/m$^2$/d. In addition, it varies on average from 5.374 kWh/m$^2$/d (July and August) to 6.123 kWh/m$^2$/d (November). It follows from the results obtained that the Pala site could be the most suitable for the exploitation of photovoltaics because of the significant solar potential.

Table 6 presents the values of the monthly global irradiation obtained by the six models for Bongor in southern Chad. Sabbagh's model is the most appropriate.

TABLE 3
VALUES OF MODELS USED TO ESTIMATE GLOBAL SOLAR IRRADIANCE FOR MOUNDOU CITY

| Months | Sayigh | Hargreave | Allen | Sabbagh | Annandale | Angs-P |
|---|---|---|---|---|---|---|
| January | 0.664 | 6.392 | 6.791 | 5.525 | 1.45 | 6.182 |
| February | 1.183 | 6.151 | 6.535 | 6.029 | 1.439 | 6.112 |
| March | 0.857 | 6.086 | 6.466 | 6.307 | 1.448 | 6.077 |
| April | 0.281 | 5.552 | 5.899 | 6.049 | 1.441 | 5.88 |
| May | 0.097 | 5.125 | 5.445 | 5.498 | 1.441 | 5.894 |
| June | 0.048 | 4.558 | 4.843 | 4.977 | 1.434 | 5.715 |
| July | 0.029 | 4.394 | 4.668 | 4.691 | 1.436 | 5.376 |
| August | 0.023 | 4.048 | 4.301 | 4.509 | 1.434 | 5.376 |
| September | 0.028 | 4.558 | 4.843 | 4.733 | 1.434 | 5.653 |
| October | 0.045 | 5.255 | 5.583 | 5.113 | 1.442 | 5.963 |
| November | 0.146 | 6.288 | 6.681 | 5.597 | 1.446 | 6.174 |
| December | 0.318 | 6.65 | 7.066 | 5.493 | 1.452 | 6.155 |
| **Average** | 0.310 | 5.421 | 5.760 | 5.377 | 1.441 | 5.880 |

TABLE 4
VALUES OF MODELS USED TO ESTIMATE GLOBAL SOLAR IRRADIANCE FOR SARH CITY

| Months | Sayigh | Hargreave | Allen | Sabbagh | Annandale | Angs-P |
|---|---|---|---|---|---|---|
| January | 6.886 | 6.489 | 6.894 | 5.565 | 1.436 | 6.009 |
| February | 9.927 | 6.372 | 6.77 | 6.147 | 1.425 | 5.948 |
| March | 6.473 | 5.649 | 6.002 | 6.006 | 1.431 | 5.81 |
| April | 2.608 | 5.122 | 5.442 | 5.83 | 1.424 | 5.713 |
| May | 1.124 | 5.048 | 5.363 | 5.613 | 1.427 | 5.783 |
| June | 0.534 | 4.695 | 4.989 | 4.988 | 1.421 | 5.374 |
| July | 0.289 | 4.564 | 4.849 | 4.721 | 1.424 | 5.136 |
| August | 0.246 | 4.466 | 4.745 | 4.638 | 1.423 | 5.223 |
| September | 0.293 | 4.742 | 5.038 | 4.771 | 1.422 | 5.211 |
| October | 0.451 | 5.048 | 5.363 | 5.071 | 1.427 | 5.666 |
| November | 1.336 | 6.086 | 6.466 | 5.583 | 1.43 | 5.994 |
| December | 3.643 | 6.674 | 7.091 | 5.683 | 1.437 | 6.026 |
| **Average** | 2.818 | 5.413 | 5.751 | 5.385 | 1.427 | 5.658 |

TABLE 5
VALUES OF MODELS USED TO ESTIMATE GLOBAL SOLAR IRRADIANCE FOR PALA CITY

| Months | Sayigh | Hargreave | Allen | Sabbagh | Annandale | Angs-P |
|---|---|---|---|---|---|---|
| January | 1.024 | 6.012 | 6.388 | 5.326 | 1.435 | 6.071 |
| February | 1.504 | 5.725 | 6.083 | 5.583 | 1.422 | 6.027 |
| March | 1.325 | 5.807 | 6.17 | 6.163 | 1.433 | 5.872 |
| April | 0.402 | 5.151 | 5.473 | 6.005 | 1.425 | 5.756 |
| May | 0.142 | 4.856 | 5.16 | 5.592 | 1.427 | 5.77 |
| June | 0.06 | 4.867 | 5.17 | 4.948 | 1.423 | 5.671 |
| July | 0.033 | 4.379 | 4.653 | 4.532 | 1.423 | 5.374 |
| August | 0.026 | 4.303 | 4.572 | 4.489 | 1.423 | 5.374 |
| September | 0.31 | 4.588 | 4.875 | 4.643 | 1.421 | 5.4 |
| October | 0.07 | 5.1 | 5.418 | 5.137 | 1.428 | 5.977 |
| November | 0.369 | 6.07 | 6.449 | 5.671 | 1.432 | 6.123 |
| December | 0.773 | 5.976 | 6.349 | 5.329 | 1.435 | 6.095 |
| **Average** | 0.503 | 5.236 | 5.563 | 5.285 | 1.427 | 5.793 |

TABLE 6
VALUES OF MODELS USED TO ESTIMATE GLOBAL SOLAR IRRADIANCE FOR BONGOR CITY

| Months | Sayigh | Hargreave | Allen | Sabbagh | Annandale | Angs-P |
|---|---|---|---|---|---|---|
| January | 1.598 | 6.558 | 6.968 | 5.413 | 1.413 | 6.001 |
| February | 2.676 | 6.19 | 6.577 | 6.023 | 1.399 | 5.961 |
| March | 4.971 | 6.27 | 6.661 | 6.495 | 1.411 | 6.014 |
| April | 3.208 | 6.392 | 6.791 | 6.691 | 1.408 | 5.996 |
| May | 4.17 | 5.843 | 6.208 | 6.268 | 1.409 | 5.85 |
| June | 5.763 | 6.728 | 7.148 | 6.12 | 1.41 | 5.92 |
| July | 0.296 | 3.968 | 4.216 | 4.711 | 1.398 | 5.422 |
| August | 0.21 | 4.276 | 4.543 | 4.456 | 1.4 | 5.003 |
| September | 0.21 | 4.77 | 5.068 | 4.941 | 1.399 | 5.723 |
| October | 0.806 | 4.953 | 5.262 | 5.399 | 1.404 | 6.053 |
| November | 3.49 | 6.387 | 6.785 | 5.935 | 1.408 | 6.06 |
| December | 6.051 | 6.39 | 6.79 | 5.426 | 1.412 | 6.059 |
| **Average** | 2.787 | 5.727 | 6.085 | 5.657 | 1.406 | 5.839 |

According to the results obtained, we find that for the Bongor site, the calculated annual average of global radiation is 5.657 kWh/m$^2$/d. In addition, it varies on average from 4.456 kWh/m$^2$/d (August) to 6.691 kWh/m$^2$/d (April). The findings suggest that, given its significant solar potential, the Bongor site might be the feasible location for photovoltaics.

## B. Statistical Indicators for Empirical Models Employed in The Research

Table 7 presents the values calculated by all the statistical indicators used in this study for the Moundou site. According to the results obtained, the most accurate model is identified by comparing its statistical errors with those of the other models with the largest value of $R^2$. The best performance is obtained by the Allen model and its statistical errors, $R^2$, t-Stat, MAE, RMSRE, MARE, RRMSE, erMAX, $U_{95}$, RMSE, and MBE are respectively 0.843; 0.564; 0.027 kWh/m$^2$; 0.236; -0.008; 0.538; 5.782; 1.827 kWh/m$^2$; 0.396 kWh/m$^2$; and 0.008 kWh/m$^2$. The Angstrom-Prescott model ranked second, with $R^2$ equal to 0.810, followed by the Sabbagh model, Hargreaves model, Annandale model, and Sayigh model.

Table 8 presents the values calculated by all the statistical indicators used in this study for the Sarh site. According to the results obtained, the most accurate model is identified by comparing its statistical errors with those of the other models with the largest value of $R^2$. The best performance is obtained by the Angstrom-Prescott model and its statistical errors, $R^2$, t-Stat, MAE, RMSRE, MARE, RRMSE, erMAX, $U_{95}$, RMSE, and MBE are respectively 0.805; 2.777; 0.146 kWh/m$^2$; 0.246; 0.018; 0.599; 0.137; 3,567 kWh/m$^2$; 0.442 kWh/m$^2$; and 0.018 kWh/m$^2$. The Sabbagh model ranked second, with $R^2$ equal to 0.781, followed by the Allen model 0.738, Hargreaves model, Sayigh model and Annandale model.

The values estimated by each of the statistical indicators utilized in this study for the Pala location are shown in Table 9. The most accurate model is determined by comparing its statistical errors to those of the other

TABLE 7
STATISTICAL INDICATORS FOR MOUNDOU CITY

| Methods | $R^2$ | t-Stat | MAE | RMSRE | MARE | RRMSE | erMAX | $U_{95}$ | RMSE | MBE |
|---|---|---|---|---|---|---|---|---|---|---|
| Angs-P | 0.810 | 1.707 | -0.093 | 0.275 | -0.025 | 0.591 | 0.095 | 4.885 | 0.435 | -0.025 |
| Allen | 0.843 | 0.564 | 0.027 | 0.236 | -0.008 | 0.538 | 5.782 | 1.827 | 0.396 | 0.008 |
| Sabbagh | 0.774 | 23.623 | 0.410 | 0.269 | 0.069 | 0.645 | 0.134 | 13.541 | 0.475 | 0.069 |
| Hargreaves | 0.739 | 9.515 | 0.365 | 0.320 | 0.067 | 0.693 | 0.146 | 13.119 | 0.511 | 0.067 |
| Annandale | -18.314 | 33.284 | 4.345 | 2.592 | -0.748 | 5.965 | 6.537 | 148.784 | 4.395 | 0.748 |
| Sayigh | -29.164 | 107.390 | 5.477 | 3.302 | 0.952 | 7.454 | 0.995 | 186.841 | 5.492 | 0.952 |

TABLE 8
STATISTICAL INDICATORS FOR SARH CITY

| Methods | $R^2$ | t-Stat | MAE | RMSRE | MARE | RRMSE | erMAX | $U_{95}$ | RMSE | MBE |
|---|---|---|---|---|---|---|---|---|---|---|
| Angs-P | 0.805 | 2.777 | 0.146 | 0.246 | 0.018 | 0.599 | 0.137 | 3.567 | 0.442 | 0.018 |
| Allen | 0.738 | 0.671 | 0.052 | 0.286 | -0.009 | 0.694 | 5.838 | 1.991 | 0.511 | 0.009 |
| Sabbagh | 0.781 | 31.961 | 0.419 | 0.263 | 0.069 | 0.635 | 0.117 | 13.645 | 0.468 | 0.069 |
| Hargreaves | 0.615 | 5.565 | 0.390 | 0.354 | 0.067 | 0.842 | 0.191 | 13.198 | 0.621 | 0.067 |
| Annandale | -18.590 | 33.012 | 4.376 | 2.603 | -0.751 | 6.007 | 6.549 | 147.401 | 4.426 | 0.751 |
| Sayigh | -14.624 | 1.476 | 2.986 | 2.514 | 0.559 | 5.365 | 0.949 | 109.764 | 3.953 | 0.559 |

TABLE 9
STATISTICAL INDICATORS FOR PALA CITY

| Methods | $R^2$ | t-Stat | MAE | RMSRE | MARE | RRMSE | erMAX | $U_{95}$ | RMSE | MBE |
|---|---|---|---|---|---|---|---|---|---|---|
| Angs-P | 0.889 | 1.846 | -0.060 | 0.204 | -0.015 | 0.453 | 0.098 | 2.978 | 0.334 | -0.015 |
| Allen | 0.826 | 3.850 | 0.169 | 0.250 | -0.031 | 0.567 | 5.562 | 6.080 | 0.418 | 0.031 |
| Sabbagh | 0.771 | 51.666 | 0.448 | 0.292 | 0.079 | 0.650 | 0.118 | 15.472 | 0.479 | 0.079 |
| Hargreaves | 0.627 | 12.958 | 0.496 | 0.371 | 0.088 | 0.829 | 0.162 | 17.238 | 0.611 | 0.088 |
| Annandale | -17.779 | 58.686 | 4.305 | 2.596 | -0.749 | 5.881 | 6.290 | 147.076 | 4.333 | 0.749 |
| Sayigh | -26.4634 | 147.552 | 5.229 | 3.190 | 0.917 | 7.113 | 0.995 | 180.102 | 5.241 | 0.917 |

models with the biggest value of $R^2$, according to the findings. The best performance is obtained by the Angstrom-Prescott model and its statistical errors, $R^2$, t-Stat, MAE, RMSRE, MARE, RRMSE, erMAX, $U_{95}$, RMSE and MBE are respectively 0.889; 1.846; -0.060 kWh/m$^2$; 0.204; -0.015; 0.453; 0.098 kWh/m$^2$; 2.978 kWh/m$^2$; 0.334 kWh/m$^2$; and -0.015 kWh/m$^2$. Allen's model ranked second, with $R^2$ equal to 0.826, followed by Sabbagh's model 0.771, Hargreaves model, Annandale model and Sayigh model.

The values derived for the Bongor site from each statistical indicator utilized in this investigation are shown in Table 10. The most accurate model is determined, in accordance with the results, by contrasting its statistical errors with those of the other models with the highest value of $R^2$. The best performance is obtained by the Sabbagh model and its statistical errors, $R^2$, t Stat, MAE, RMSRE, MARE, RRMSE, erMAX, $U_{95}$, RMSE and MBE are respectively 0.888; 3.769; 0.113 kWh/m$^2$; 0.209; 0.022; 0.454; 0.085; 4,289 kWh/m$^2$; 0.334 kWh/m$^2$; and -0.022 kWh/m$^2$. The Angstrom-Prescott model ranked second, with $R^2$ equal to 0.887, followed by the Allen model 0.379, Hargreaves model 0.546, Annandale model, and Sayigh model.

Results of statistical analysis of different sunshine radiation models are given in Table 7-10. Although $R^2$ ranges from 0 to 1, it could be seen that models [26] Angstrom-P [27] have negative $R^2$, which is possible due to the computational definition of the coefficient of determination. The fact that these values are negative,

TABLE 10
STATISTICAL INDICATORS BONGOR CITY

| Methods | $R^2$ | t-Stat | MAE | RMSRE | MARE | RRMSE | erMAX | $U_{95}$ | RMSE | MBE |
|---|---|---|---|---|---|---|---|---|---|---|
| Angs-P | 0.887 | 2.116 | -0.069 | 0.199 | -0.016 | 0.457 | 0.092 | 3.186 | 0.337 | -0.016 |
| Allen | 0.379 | 2.008 | -0.316 | 0.486 | 0.052 | 1.069 | 5.614 | 10.220 | 0.788 | -0.052 |
| Sabbagh | 0.888 | 3.769 | 0.113 | 0.209 | 0.022 | 0.454 | 0.085 | 4.289 | 0.334 | -0.022 |
| Hargreaves | 0.546 | 0.309 | 0.042 | 0.427 | 0.010 | 0.914 | 0.213 | 2.407 | 0.673 | 0.010 |
| Annandale | -18.283 | 58.982 | 4.363 | 2.615 | -0.754 | 5.960 | 6.407 | 148.127 | 4.391 | 0.754 |
| Sayigh | -11.326 | 2.879 | 2.982 | 2.212 | 0.531 | 4.765 | 0.961 | 104.335 | 3.511 | 0.531 |

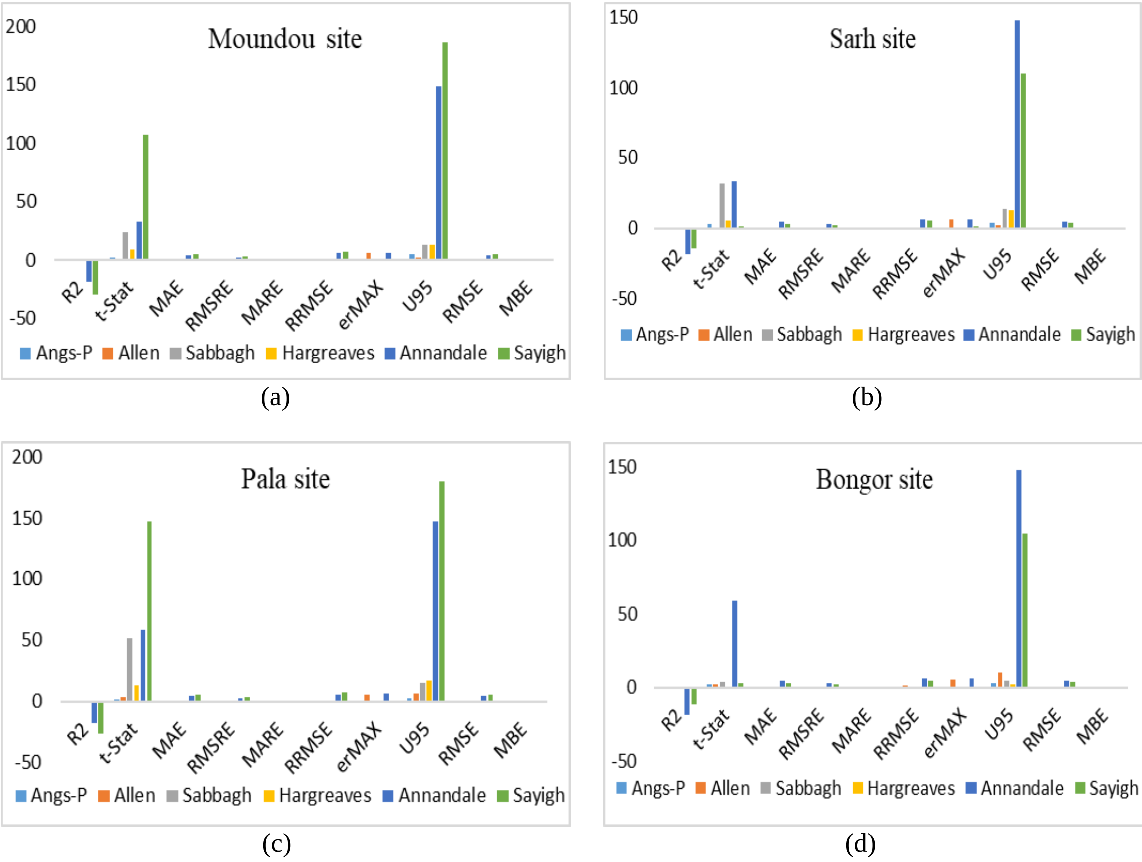


Figure 3. Ranking based on the global performance index for various methods, (a) Moundou site; (b) Sarh site; (c) Pala site; (d) Bongor site.

however, it suggests that the relevant models do not forecast well, or fit worse than a horizontal line. This is also visible from other statistical indicators for these models which are disproportionately high. By far, the worst statistical indicators are shown by model Annandale [26] Angstrom-P [27]. Since the authors in the original study [26], [27] did not evaluate that model, it is impossible to determine whether such bad performance is only on a global scale. Figure 3 shows ranking based on the global performance index for various methods.

## V. Conclusions

In this study, a comparison of different models for estimating global solar radiation for different regions of Chad is made. To achieve the objective, six models including Sayigh, Hargreaves, Allen, Sabbagh, Annandale, and Angstrom-Prescott are considered. To evaluate and validate the performance of the models, statistical indicators are used. The best performance is obtained by the Allen model and its statistical errors, $R^2$, t-Stat, MAE, RMSRE, MARE, RRMSE, erMAX, $U_{95}$, RMSE, and MBE are respectively 0.843; 0.564; 0.027 kWh/m$^2$; 0.236; -0.008; 0.538; 5.782; 1.827 kWh/m$^2$; 0.396 kWh/m$^2$; and 0.008 kWh/m$^2$ for Moundou. The best performance is obtained by the Angstrom-Prescott model and its statistical errors, $R^2$, t-Stat, MAE, RMSRE, MARE, RRMSE, erMAX, $U_{95}$, RMSE, and MBE are respectively 0.805; 2.777; 0.146 kWh/m$^2$; 0.246; 0.018; 0.599; 0.137; 3,567 kWh/m$^2$; 0.442 kWh/m$^2$; and 0.018 kWh/m$^2$ for Sarh. The best performance is obtained by the Angstrom-Prescott model and its statistical errors, $R^2$, t-Stat, MAE, RMSRE, MARE, RRMSE, erMAX, $U_{95}$, RMSE, and MBE are respectively 0.889; 1.846; -0.060 kWh/m$^2$; 0.204; -0.015; 0.453; 0.098 kWh/m$^2$; 2.978 kWh/m$^2$; 0.334 kWh/m$^2$; and -0.015 kWh/m$^2$ for Pala. The best performance is obtained by the Sabbagh model and its statistical errors, $R^2$, t-Stat, MAE, RMSRE, MARE, RRMSE, erMAX, $U_{95}$, RMSE and MBE are respectively 0.888; 3.769; 0.113 kWh/m$^2$; 0.209; 0.022; 0.454; 0.085; 4.289 kWh/m$^2$; 0.334 kWh/m$^2$ and -0.022 kWh/m$^2$ for Bongor. Ten statistical indicators were used to compare the models. The Angstrom-Prescott model is adaptable based on the results for the Sarh and Pala sites. The Allen model for the city of Moundou and Sabbagh for the Bongor site. The future study will be the subject of optimal sizing and technical-economic analysis of a photovoltaic system for each of the sites.

## Declarations

### Conflict of Interest

The authors have declared that no competing interests exist.

### CRediT Authorship Contribution

Marcel Hamda Souloukngа: Conceptualization, Methodology, Software, Writing-Original draft preparation; Hasan Huseyin Coban: Conceptualization, Supervision, Software, Writing-Original draft preparation, writing—review and editing; Ruben Zieba Falama: Visualization, Investigation; Kwefeu Mbakop: Investigation, Data curation; Noel Djongyang: Supervision, Funding Acquisition.

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