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Empirical Models for the Evaluation of Global Solar Radiation for the Site of Abeche in the Province of Ouaddaï, in Chad

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Abstract

The global sustainability plan for future development relies on solar radiation which is the main source of renewable energy. Thus, this work studies the performance of six models to estimate global solar radiation on a horizontal surface for the Abeche site in Chad. The data used in this work were collected at the General Directorate of National Meteorology of Chad. The reliability and accuracy of different models for estimating global solar radiation were validated by statistical indicators to identify the most accurate model. The results show that among all the models, the Sabbagh model has the best performance in estimating the global solar radiation. The average is 6.354 kWh/m^2 with an average of −3.704%. This model is validated against NASA data which is widely used.

Keywords

Empirical Models, Statistical Indicators, Solar Radiation, Abeche

1. Introduction

Due to increasing population, increasing consumption of fossil fuels and economic activities as well as contamination from air pollution, unstable oil prices and greenhouse gas emissions greenhouse, interest in solar energy continues to grow [1] [2] [3]. The first step in assessing the availability of solar energy is knowledge of solar radiation data [4] [5] [6] [7]. For a variety of solar energy applications, solar radiation is also the basic input [8] [9] [10]. Estimation of solar radiation Due to maintenance, calibration and high cost of measuring equipment, various models of solar radiation are proposed [11] [12]. In an attempt to develop models for estimating global solar radiation, many studies have been conducted including information on the day of the year [13], the use of a machine learning algorithm [14] [15], meteorological parameters [16] and geographical information [17]. Sammy *et al.* [18] 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 [19] conducted the 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.* [20] 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 agreement between the estimated values and the NASA values. Manisha *et al.* [21] for the evaluation of global solar radiation in the Baramati region used empirical models. Thus, the regression constants of the proposed and developed model were estimated and the performance analysis was evaluated. Sheikh Mujabar *et al.* [22] for the industrial city of Jubail estimated the global solar radiation using empirical models. The results obtained show that the estimation of the statistical error of the developed models reveals that the measured and estimated values give similar results and seem exponentially high. In Chad, only 8% of the population has access to electricity, with a significant gap between rural (1%) and urban (20%) areas. Chad is one of the countries with the lowest electricity access rates in the world. Paradoxical situation despite the natural resources available to the country, namely oil and renewable energies. Apart from the 1 MW wind power plant (composed of 4 wind turbines) in Amdjarass, a city located in the East of the country, electricity is now only supplied by generators, which regularly break down. Oil, which is used to run the groups, is a non-renewable, an expensive, and very polluting energy source. This situation hinders the socio-economic development of the country and affects the quality of life of the population [23]. The objective of this work is to study the performance of six models to estimate the solar radiation of the city of Abeche in the province of Ouaddaï in Chad (Lat. 13˚51˚N and long. 20˚51˚E). Thus, the following points can be considered as contributions of the current study: Estimation of the solar radiation potential of Abeche; Performance evaluation of one of the best models based on meteorological data; Evaluation and comparison of the performances of the six models. The work will be structured in an introduction, material and method, results and discussions and we will end with a conclusion.

2. Methodology

In this section, we will present the different methods of estimating the global solar radiation.

2.1. Estimation of the Solar Radiation

The extraterrestrial radiation on a horizontal plane is evaluated according to the following relation [24]:

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

where δ and ω_s are given by [25]:

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

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

where I_{sc}: solar constant (W/m^2); ω_s sunset hour angle (˚C); φ latitude of the location (˚) and δ solar declination (˚).

2.2. Modeling of Global Solar Radiation Using the Angstrom-Prescott Model

The most practical correlation for assessing global solar radiation and the most commonly used is given by the relation [26] [27]:

$$\frac{H}{H_0} = a + b\left(\frac{S}{S_0} \right) \quad (4)$$

Thus, by Equations (5), (6) and (7), the correlation parameters can be defined as:

$$a = -0.110 + 0.235 \cos\varphi + 0.323\left(\frac{S}{S_0} \right) \quad (5)$$

$$b = 1.449 - 0.553 \cos\varphi - 0.694\left(\frac{S}{S_0} \right) \quad (6)$$

Thus, the duration of sunshine is given by [28]:

$$S_0 = \frac{2}{15} \cos^{-1}\left(-\tan\varphi \tan\delta \right) \quad (7)$$

where S_0 monthly average day length (h); S monthly average daily hours of bright sunshine (h) and a, b regression coefficients.

2.3. Modeling of Global Solar Radiation Using the Allen Model

The global solar irradiation is estimated by this model using several parameters namely T_M, T_m, K_r as well as atmospheric pressures [29].

$$\frac{H}{H_0} = K_r \left(T_M - T_m \right)^{0.5} \quad (8)$$

where K_r is defined as:

$$K_r = K_{ra}\left(\frac{P}{P_0}\right)^{0.5} \tag{9}$$

where according to Lunde [30], $K_{ra} = 0.17$ and the pressures $\frac{P}{P_0}$ is defined as:

$$\frac{P}{P_0} = \exp\left(-0.0001184h\right) \tag{10}$$

where h is altitude, varies from site to site; T_M maximum temperature and T_m minimum temperature.

2.4. Modeling of Global Solar Radiation Using the Sabbagh Model

This model estimates global solar radiation by taking into account parameters such as relative humidity, sunshine duration, maximum temperature and geographical location [31].

$$H = 1.530K * \exp\varphi\left(\frac{S}{S_0} - \frac{RH^{1/3}}{100} - \frac{1}{T_{\max}}\right) \tag{11}$$

with

$$K = 100\left(nT_{\max} + \psi_{ij}\cos\left(\varphi\right)\right) \tag{12}$$

$$n = \frac{1}{1 + 0.1\varphi} \tag{13}$$

2.5. Modeling of Global Solar Radiation Using the Hargreaves Model

Global solar radiation is estimated by this model using parameters such as minimum temperature, maximum temperature as well as extraterrestrial irradiation [32].

$$\frac{H}{H_0} = a\left(T_{\max} - T_{\min}\right)^{0.5} \tag{14}$$

2.6. Modeling of Global Solar Radiation Using the Annandale Model

This model uses parameters such as maximum and minimum temperature to estimate global solar radiation [33].

$$\frac{H}{H_0} = a\left(1 + 2.7\times10^{-5}Z\right)\left(T_{\max} - T_{\min}\right)^{0.5} \tag{15}$$

2.7. Modeling of Global Solar Radiation Using the A.A.A Sayigh Model

The global solar radiation is estimated by the Sayigh model using parameters such as RH, $T_{\max}$, DI and φ [34].

$$G_H = 11.6KN \exp\left(\varphi\left(\frac{DI}{T_m}\right) - \left(\frac{RH}{15}\right) - \left(\frac{1}{T_{max}}\right)\right) \quad (16)$$

3. Comparison Techniques of Used Model and Their Validation

To evaluate different performance of solar radiation models in this study, 10 quantitative statistical indicators were used. It's about:

3.1. RRMSE: Relative Root Mean Square Error

This indicator is estimated by taking the ratio of the RMSE as well as the average value of the data measured. The accuracy of the model according to [35], is poor if RRMSE < 43%; mean if 20% < RRMSE < 30%; good if 10% < RMSE < 20% and excellent RMSE < 10%.

$$\text{RRMSE} = \frac{\sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\bar{H}_{i,m} - \bar{H}_{i,c}\right)^2}}{\sum_{i=1}^{n}\bar{H}_{i,m}} \times 100 \quad (17)$$

3.2. t-Stat: t-Statistics

For a more comprehensive evaluation of models estimating solar radiation, this indicator proposed by Stone [36] can be used in conjunction with RMSE and MBE [37] [38] [39] [40] [41].

$$\text{t-stat} = \sqrt{\frac{(n-1)\text{MBE}^2}{\text{RMSE}^2 - \text{MBE}^2}} \quad (18)$$

3.3. RMSE: Root Mean Square Error

To compare the forecast errors of different models, the RMSE is a frequently used measure. The model is better when the value of RMSE is low.

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\bar{H}_{i,m} - \bar{H}_{i,c}\right)^2} \quad (19)$$

3.4. U_{95}: 95% Uncertainty

In order to show more information about the model deviation, this indicator is used after Behar *et al.* [40] and Gueymard [39]. Thus, the 95% confidence uncertainty is given by:

$$U_{95} = 1.96\left(\text{SD}^2 + \text{RMSE}^2\right)^{1/2} \quad (20)$$

where SD is the standard deviation of the difference between the measured and calculated data and 1.96 is the coverage factor corresponding to the 95% confidence level.

3.5. MBE: Mean Bias Error

While values of MBE closest to zero are desirable, this indicator therefore expresses the tendency of the model to overestimate (positive value) and to underestimate (negative value) the global radiation.

When the model shows underestimated and overestimated values at the same time, this test does not show the correct performance, which is the drawback; because the values of underestimation and overestimation cancel each other out.

$$\text{MBE} = \frac{1}{n}\sum_{i=1}^{n}\left(\bar{H}_{i,m} - \bar{H}_{i,c}\right) \tag{21}$$

3.6. MAE: Mean Absolute Error

The MAE is the ratio of the sum of the absolute values divided by the number of observations.

To measure how close, the estimated values are to the measured values, this quantity is often used in statistics. In inter-comparisons of mean model performance error and dimensioned evaluations, the authors pointed out some advantages of MAE over root mean square error (RMSE) [42].

$$\text{MAE} = \frac{1}{n}\sum_{i=1}^{n}\left|\bar{H}_{i,m} - \bar{H}_{i,c}\right| \tag{22}$$

3.7. MARE: Mean Absolute Relative Error

MARE is known as Mean Absolute Percentage Error (MAPE) when expressed as a percentage. Between measured and estimated solar radiation, this indicator is expressed as an average absolute value.

$$\text{MARE} = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{\bar{H}_{i,m} - \bar{H}_{i,c}}{\bar{H}_{i,m}}\right| \tag{23}$$

3.8. erMAX: Maximum Absolute Relative Error

$$\text{erMAX} = \max\left(\left|\frac{\bar{H}_{i,m} - \bar{H}_{i,c}}{\bar{H}_{i,m}}\right|\right) \tag{24}$$

3.9. RMSRE: Relative Root Mean Square Error

$$\text{RMSRE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\frac{\bar{H}_{i,m} - \bar{H}_{i,c}}{\bar{H}_{i,m}}\right)^2} \tag{25}$$

3.10. R^2: Coefficient of Determination

To estimate the performance of models, this indicator is often used in statistics. Thus, the models are efficient when the coefficient of determination is close to 1.

$$\text{R}^2 = 1 - \frac{\sum_{i=1}^{n}\left(\bar{H}_{i,m} - \bar{H}_{i,c}\right)^2}{\sum_{i=1}^{n}\left(\bar{H}_{i,m} - \bar{H}_{m,avg}\right)^2} \tag{26}$$

The relative error in percentage (e) of the global solar radiation values can be estimated by the following equation:

$$e = \left|\left(H_m - H_{es}\right)/H_m\right| \times 100$$

4. Results and Discussions

4.1. Different Models for Estimating Global Solar Radiation

Table 1 presents the different values of the methods used to estimate the global solar irradiation for the Abeche site. The values vary from 5.081 kWh/m^2 in April to 5.832 kWh/m^2 in August using the Angstrom-P model. Using Allen's model, they vary from 4.86 in August to 6.396 kWh/m^2 in February. As for the Sabbagh model, the variation is between 5.189 in August to 7.606 in April. For the Hargreaves model, they vary from 4.574 in August to 6.020 in February. Using the Annandale model, they vary from 1.353 in August to 1.366 in December. As for the Sayigh method, the variation is from 0.049 in August to 2.672 in February.

Thus, for the six models used, the minimum irradiation values are 0.049 kWh/m^2 using the Sayigh model and the maximum value is 7.606 kWh/m^2 using the Sabbagh method.

4.2. Statistical Indicators for Empirical Models Employed in the Research

Table 2 presents the values calculated by all the statistical indicators used in this work.

The most accurate model is identified by comparing its statistical errors with those of other models with the largest R^2 value. 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, MBE are respectively 0.706, 2.866, −0.214 kWh/m^2, 0.324, −0.037, 0.735%, 0.115, 7.337 kWh/m^2, 0.542 kWh/m^2 and 0.037 kWh/m^2. Allen's model ranked second, with R^2 equal to 0.219, followed by Angstrom-Prescott model equal to 0.164, Hargreaves model −0.129, Annandale model and Sayigh model.

Figure 1 below presents the histogram of the different model values estimating the global solar irradiation for the Abeche site. It shows that the model whose value is close to that measured (NASA) is the Sabbagh model, this model is the most suitable.

Table 3 presents the difference between the satellite values (NASA) with the values estimated by the six models. Thus, the Sabbagh model presents the minimum average value of −3.704% while the maximum average value of 80.725% is recorded by the Sayigh model. This allows us to deduce that from the monthly averages, the Sabbagh model is the most appropriate. Proceeding to the monthly minimum values, it is the Angstrom-Prescott model which presents the lowest monthly minimum value of −8.750 and the highest minimum value of 73.731 by the Annandale model. As for the maximum monthly values, it is the Sabbagh model which has the lowest maximum value of 11.451 and the highest maximum monthly value of 99.164 by the Sayigh model.

Table 1. Values of models used to estimate global solar irradiance.

Months	Angs-P	Allen	Sabbagh	Hargreaves	Annandale	Sayigh
January	5.69	6.107	5.943	5.748	1.364	1.657
February	5.491	6.396	6.624	6.020	1.354	2.350
March	5.175	6.125	7.276	5.765	1.365	2.672
April	5.081	5.978	7.606	5.627	1.359	2.199
May	5.637	5.499	7.01	5.176	1.359	1.113
June	5.783	5.086	6.094	4.787	1.351	0.428
July	5.738	5.168	5.568	4.864	1.356	0.117
August	5.832	4.86	5.189	4.574	1.353	0.049
September	5.788	5.501	5.871	5.177	1.355	0.116
October	5.575	5.942	6.631	5.593	1.363	0.701
November	5.752	5.996	6.327	5.644	1.359	1.445
December	5.655	6.303	6.11	5.932	1.366	1.498
Average	5.6	5.747	6.354	5.409	1.359	1.195

Table 2. Statistical indicators.

Methods	R^2	t-Stat	MAE	RMSRE	MARE	RRMSE	erMAX	U_{95}	RMSE	MBE
Angs-P	0.164	3.295	0.540	0.466	0.078	1.241	0.281	15.407	0.914	−0.078
Allen	0.219	2.084	0.393	0.490	−0.055	1.199	6.224	10.884	0.884	−0.055
Sabbagh	0.706	2.866	−0.214	0.324	−0.037	0.735	0.115	7.337	0.542	0.037
Hargreaves	−0.129	4.075	0.731	0.572	0.110	1.442	0.275	21.737	1.063	−0.110
Annandale	−22.185	48.968	4.781	2.692	−0.777	6.535	6.878	152.545	4.815	−0.777
Sayigh	−24.234	20.889	4.945	2.837	0.807	6.818	0.992	158.527	5.023	−0.807

Table 3. Estimated errors.

Months	Hargr.	Anna.	Sayigh	Ang-P	Allen	Sabbagh
January	−4.130	75.290	69.982	−3.080	−10.634	−7.663
February	4.747	78.576	62.816	13.117	−1.203	−4.810
March	15.962	80.102	61.050	24.563	10.714	−6.064
April	20.410	80.778	68.897	28.133	15.446	−7.581
May	24.217	80.102	83.704	17.467	19.488	−2.635
June	27.470	79.530	93.515	12.379	22.939	7.667
July	18.389	77.248	98.037	3.725	13.289	6.577
August	21.945	76.911	99.164	0.478	17.065	11.451
September	13.138	77.265	98.054	2.886	7.701	1.493
October	5.364	76.937	88.139	5.668	−0.541	−12.200
November	−0.966	75.689	74.150	−2.898	−7.263	−13.184
December	−14.077	73.731	71.192	−8.750	−21.212	−17.500
Average	11.039	77.680	80.725	7.807	5.482	−3.704

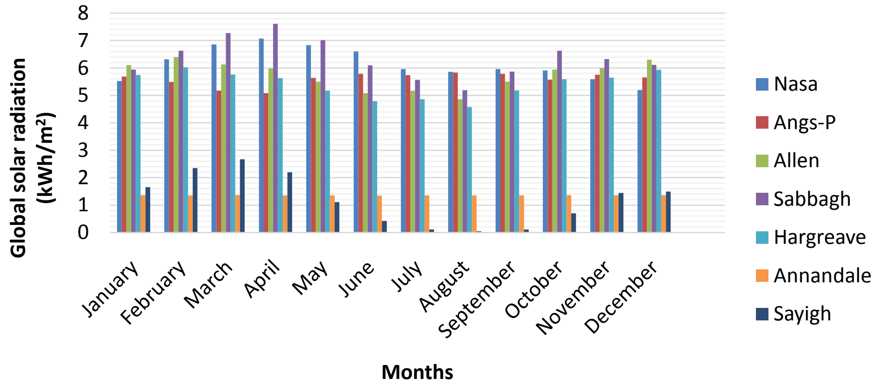

Figure 1. Representation of global solar irradiation by the different models.

5. Conclusion

Using meteorological data for 26 years for the Abeche site and the performance of six empirical models, the global solar radiation is estimated on a horizontal surface. To evaluate and validate the performance of the models, statistical indicators are used. According to the results obtained in this study, the models used estimate the global solar radiation on a horizontal surface. The most precise estimates are provided by the Sabbagh model with excellent values and the highest precision for the statistical indicators (R^2 = 0.706; t-Stat = 2.866; MAE = −0.214 kWh/m^2; RMSRE = 0.324; MARE = −0.037; RRMSE = 0.735%; erMAX = 0.115; U_{95} = 7.337 kWh/m^2; RMSE = 0.542 kWh/m^2; MBE = 0.037 kWh/m^2). Unlike the other five models, the Sabbagh model has an acceptable error value, err = −3.704% showing the better performance. The next work will be the subject of optimal sizing and technical-economic analysis of a photovoltaic system.

Conflicts of Interest

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

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