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Empirical Models for Estimating Global Solar Radiation at the Site of the 7MW Photovoltaic Solar Power Plant in Malbaza (Niger)

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Abstract To increase energy production, the State of Niger has built a 7MW photovoltaic solar power plant connected ongrid of the Nigerien electricity company in the department of Malbaza, Region of Tahoua (13° 58'3.54" North and 5°31'11.95" East). In order to find a model for estimating global solar radiation on the site of this plant, we studied seven (7) estimation models developed by the researchers and proposed a new model for the site. These eight models were established using the duration of sunshine, the global radiation and the meteorological parameters (normalized air temperature, relative humidity and wind speed) recorded for one year (2019) on the site and applying a regression by the method of least squares. The accuracy of the established models was tested using statistical indicators: Mean Absolute Bias Error (MABE), Root Mean Square Error (RMSE), Mean Bias Error (MBE), and Mean Percentage Error (MPE). The study showed that the Newland linear-logarithmic model established for the site presents the best statistical indicators with a multiple correlation coefficient of 0.636. But the new established model which takes into account temperature, humidity and wind speed has the largest multiple correlation coefficient (0.722) with good error precision.

Keywords Empirical models, regression, Malbaza, clarity index, solar fraction, meteorological parameters, wind

1. Introduction

In a rapidly changing global energy context marked by a decrease in conventional fossil energy resources and greenhouse gas emissions in constant growth, the use of renewable energies remains among the essential solutions allowing to limit the effects of the activity human on global warming.

Of all the renewable energies, solar energy is of particular interest for Africa, since it has a significant solar deposit.

However, the amount of solar radiation reaching the Earth's surface varies considerably depending on varying atmospheric conditions as well as the changing position of the Sun during the day. Precise data on global solar radiation is necessary at different stages of the design, simulation and performance evaluation of any project involving solar energy [1].

This article consists of establishing methods for estimating solar radiation for the site of the 7MW photovoltaic solar power plant in Malbaza using the lightness index, the fraction of sunshine and the meteorological data (temperature, humidity) recorded on the site for a year.

We will first review the literature on solar radiation estimation models, then present the materials and method used to establish the site's solar radiation estimation models, and finally present the results and discuss them.

2. Literature Review

The estimation of global solar radiation from the duration of sunshine was studied for the first time by Angstrom in 1924 [2-3]. The Angstrôm-Prescott equation has been widely used by several authors in studies related to the evaluation of solar radiation, since its development by Prescott in 1940 [2, 4]. Thus:

EO Falayi et al [5] used the Angstrom equation to establish other multilinear regression models between global solar radiation and meteorological parameters (clarity index, average daily temperature, maximum daily temperature ratio and (relative humidity and relative sunshine duration) recorded for the city of Iseyin (Nigeria) for five years (1995 to 1999). The study showed that there is a model which gives satisfactory statistical values.

K. Gairaa and S. Benkaciali [6] proposed models of linear regressions of the index of clarity determined by the method of least squares written according to the fraction of sunshine for a horizontal plane and some inclined planes (15 °, 30 °, 45 °) of southern orientations as well as those giving the diffuse fraction according to the fraction of sunshine and the index of clarity for a horizontal plane. To establish these models, they used data from direct, diffuse and global illuminations received on a horizontal plane. These data were measured during 2005 by a radiometric station using a three-dimensional tracking system, installed at the Ghardaïa Applied Renewable Energy Research Unit. The results found were in good agreement with the measurements and the statistical values (relative errors and correlation coefficients) were satisfactory.

Shaqur Rehman [7] used the monthly average values of the global solar radiation and the duration of sunshine in forty-one (41) places in Saudi Arabia to develop an empirical correlation allowing to estimate the global solar radiation in places where it is not measured. He then compared the model found with other models developed under geographic and varied weather conditions. The study found that the correlation found produced the best estimates of solar radiation.

Chegaar and Guechi [8] (2009) estimated the global solar radiation on a horizontal surface, using the meteorological parameters collected, for different stations in Algeria (Algiers, Oran, Bechar, Tamanrasset). They applied the equation of Swartman and Ogunlade (1967) which expresses global solar radiation as a function of the fraction of sunshine and relative humidity. The results found showed that the agreement between the values calculated for the study places is remarkable.

Michael S. Okundamiya et al [9] evaluated the performance of six models of solar radiation. The objective was to determine the most accurate model for estimating global solar radiation on a horizontal surface in Nigeria. They used meteorological data from three cities in Nigeria (Abuja, Benin City and Sokoto) recorded for Twenty-two (22) years. This study revealed that the estimation results of the models considered are statistically significant at the 95% confidence level, but their precision varies from place to place. However, the multivariable regression relation deduced between the sunshine rate, the air temperature fraction, the maximum air temperature and the cloudiness is more efficient than the other relations.

Besharat, Dehghan and Faghih [10]: have developed several models for calculating the average monthly global solar radiation on a horizontal surface using geographic and meteorological data from the city of Yazd (in Iran). The developed models were then evaluated and compared on the basis of statistical error indices and the most precise model was chosen in each category. The results revealed that all the proposed correlations have a good estimate of the monthly global solar radiation on a horizontal surface in the city. However, they showed that the sun-based model of El-Metwally (2005), which gives a no-linear relationship between the lightness index and the sunshine fraction, predicts the monthly global solar radiation with a higher great precision.

3. Materials and Methods

3.1. Location of the Malbaza photovoltaic solar power plant site

Located at a latitude of 130 58’3.54 "North and a longitude 5031’11.95" East, the photovoltaic solar power plant is located in the department of Malbaza (Tahoua region), about 455 km from Niamey, capital of Niger. The elevation of the location is 325 meters and there is no significant difference in the leveling of the ground across

the area. Overall, the region is flat with a gentle slope. It is a 7MW photovoltaic solar power plant connected to the public power grid.
The study site covers an area of 11 ha and is located 1.4 km from the connection station.
The location of the plant is as defined in Figure 1 below.

Figure 1: Location of the Malbaza power plant

3.2. Materials

The plant site has a measuring station composed of:
• two pyrarometers: one for measuring the global radiation on the inclined plane of the modules and the other for measuring the global radiation on the horizontal plane.
• Two thermometers for measuring ambient and module temperatures;
• A hygrometer for measuring humidity;
• A heliometer for measuring wind speed;
• A rain gauge for measuring rainfall.
• An automatic heliograph which automatically measures the duration of sunshine.

The photos of the measuring station and the two pyranometers are shown in Figures 2 and 3 below.

Figure 2: Photo of the measuring station

Figure 3: photo of the two pyranometers

These measuring devices make it possible to measure all metrological parameters on the site of the plant from the control room. All of these parameters (electrical and metrological) are recorded by SCADA (Supervisory Control and Data Acquisition) and are accessible from the server in the control room. The different parameters found are summarized in the following table:

Table 1: The metrological parameters of the site for 2019

	Average exposure time per day on site (in hours)	**Temperature (°C)**	**Maximum temperature (°C)**	**Humidity (%)**	**Wind speed (m/s)**	**Global solar radiation of the site (MJ/m^2/jour)**
January	11.194	26.93	32.11	11.42	3.93	20.399
February	11.458	28.30	33.40	10.65	4.38	22.372
March	11.774	34.49	39.33	8.88	4.12	19.290
April	12.159	37.72	42.54	10.94	3.25	22.238
may	12.424	35.79	40.65	38.29	3.61	19.328
June	12.443	33.10	37.49	49.98	3.19	22.864
July	12.382	30.82	34.63	58.87	3.05	20.991
August	12.075	28.70	32.11	69.59	2.64	18.201
September	11.815	31.28	35.53	61.41	1.77	21.751
October	11.458	31.79	36.47	50.54	2.22	20.246
November	11.259	33.44	38.28	16.02	2.77	21.233
December	11.117	27.70	32.55	14.01	4.66	19.971

3.3. Methodology

The method consists first of all in applying the different models on the site using the methodological data obtained from SCADA. A comparison is then made based on statistical criteria such as MBE, MAE, MPE, and RMSE.

3.3.1. Presentation of basic models

The models studied are as follows:

3.3.1.1. The Angstrom-Prescott model:

The solar irradiation and the duration of sunshine depend on the combined effects of astronomical and meteorological events.

The linear regression model used to correlate clarity index ($\overline{G}/\overline{G_0}$) and the sunshine fraction ($\overline{S}/\overline{S_0}$) is given by the following Angstrom-Prescott formula [2] [5] [6] [9] [11] [15]:

$$\frac{\overline{G}}{\overline{G_0}} = a + b.\left(\frac{\overline{S}}{\overline{S_0}}\right) \quad (1)$$

With:

- $\overline{G}$: the average monthly value of the daily radiation measured on the site (in MJ /m^2/Day);
- $\overline{G_0}$:The average monthly value of the daily extraterrestrial radiation measured on the horizontal plane (in MJ /m^2/Day), the daily extraterrestrial radiation being calculated by the equation [15]:

$$G_0 = \frac{24}{\pi} I_0.(1 + 0.033\cos\frac{360.n}{365}).(\cos\varphi\cos\delta\sin\omega + \frac{2\pi}{360}.\omega.\sin\varphi\sin\delta) \quad (2)$$

Where :

- I_0 : The solar constant, it is worth 1367W.m^{-2};
- n the number of the day of the year from January 1;
- φ : The latitude of the place;
- δ : The solar declination calculated by [5] [15]:

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

- ω : The hour angle given by [5] [6] [15]:

$$\omega = \cos^{-1}[\cos(-\tan\varphi \tan\delta)] \quad (4)$$

- $\overline{S}$: the monthly average duration of sunshine or duration of the day measured on the site (in hours);
- $\overline{S_0}$: The monthly average of the maximum possible number of sunshine during the day (in hours).

  The maximum daily sunshine duration (S0) is calculated by the equation [5] [6] [15]:

$$S_0 = \frac{2}{15}.\omega$$

- a and b represent empirical constants determining the climatic state of the region studied. They are determined by the method of least squares.

3.3.1.2. Logarithmic model of Ampratwum and Dorvlo

Ampratwum et al expressed the clarity index as a function of the sunshine fraction by the following equation (6) [2] [14]:

$$\frac{\overline{G}}{\overline{G_0}} = a + b.\log\left(\frac{\overline{S}}{\overline{S_0}}\right) \quad (6)$$

3.3.1.3. Elagib and Mansell exponential model

Elagib and Mansell expressed the index of clarity as a function of the fraction of sunshine by the following formula (7) [2] [18]:

$$\frac{\overline{G}}{\overline{G_0}} = a + b.\exp\left(\frac{\overline{S}}{\overline{S_0}}\right) \quad (7)$$

3.3.1.4. Newland logarithmic linear model

Newland established a linear logarithmic model of the form [2] [14]:

$$\frac{\overline{G}}{\overline{G_0}} = a + b.\left(\frac{\overline{S}}{\overline{S_0}}\right) + c.\log(\frac{\overline{S}}{\overline{S_0}}) \quad (8)$$

3.3.1.5. Swartman and Ogunlade model

Swartman and Ogunlade (1967) expressed the clarity index as a function of the fraction of sunshine and the relative humidity by equation (9) following [2] [9] [11] [15] [17] :

$$\frac{\overline{G}}{\overline{G_0}} = a + b.\left(\frac{\overline{S}}{\overline{S_0}}\right) + c.R \quad (9)$$

With

• R: the monthly average relative humidity (%).

• a, b and c: are the parameters of this model which will be determined by the method of least squares using the meteorological data of the site.

3.3.1.6. Regression models used by Falayi E. O et al

Falayi and Al expressed a model (model 1) of the clarity index as a function of the fraction of sunshine and of the average air temperature normalized by the following equation (10) [5] [17]:

$$\frac{\overline{G}}{\overline{G_0}} = a + b.\left(\frac{\overline{S}}{\overline{S_0}}\right) + c.T_n \qquad (10)$$

With

• a, b, c: are the parameters of this model which will be determined by the method of least squares

• and (T_n) the monthly average of the normalized air temperature (T / T_{max}).

3.3.1.7. Another model from Falayi E. O et al:

Falayi and Al again expressed another model (model 2) of the clarity index as a function of the fraction of sunshine, the average normalized air temperature and the average relative humidity by equation (11) below [5] [17]:

$$\frac{\overline{G}}{\overline{G_0}} = a + b.\left(\frac{\overline{S}}{\overline{S_0}}\right) + c.T_n + d.R \qquad (11)$$

• a, b, c, d: are the parameters of this model which will be determined by the method of least squares.

• Tn, R: being respectively, the monthly average of the normalized air temperature and the average relative humidity of the air.

3.3.1.8. Proposed model for estimating solar radiation at theMalbaza solar power plant site :

From the Falayi model (equation 11), we introduce the wind speed as a fourth parameter to estimate the solar radiance at the Malbaza solar power plant site. The proposed equation is of the form:

$$\frac{\overline{G}}{\overline{G_0}} = a + b.\left(\frac{\overline{S}}{\overline{S_0}}\right) + c.T_n + d.R + d.V \qquad (12)$$

With V the average monthly wind speed (m / s) measured on the site.

3.3.2. Models evaluation methods

To compare the results of the different models, we evaluated the following static parameters for each model:

- Mean Bias Error (MBE): it gives information on the tendency of the model to overestimate the observed values (MBE> 0) or to underestimate them (MBE <0). It is calculated by the following formula [2] [5] [7]:

$$MBE = \frac{\sum_{i=1}^{n}(\overline{G}_{ic} - \overline{G}_{im})}{n} \qquad (13)$$

With:

- $\overline{G}_{ic}$: the monthly average of the global radiation calculated from the model;
- $\overline{G}_{im}$: the monthly average of the global radiation measured on the site;
- n : the number of months in the year (n = 12).

- Mean Absolute Bias Error (MABE): it corresponds to the average of the absolute relative errors. The closer this value is to zero, the lower the model's average error. It is calculated by the following formula [2] [5] [7] [15]:

$$\text{MABE} = \frac{\sum_{i=1}^{n}\left|(\overline{G}_{ic} - \overline{G}_{im})\right|}{n} \tag{14}$$

- Root Mean Square Error (RMSE): it represents the average error made in absolute value between the measured values and those estimated by the model, the lower this error the more the values simulated by the model are close to the measured values. It is calculated by the following formula[2] [5] [7] 15]:

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(\overline{G}_{ic} - \overline{G}_{im})^2}{n}} \tag{15}$$

- Mean Percentage Error (MPE): this is the average of the error made between the values measured and those estimated by the model. It is calculated by the following formula [2] [5] [7] [15]:

$$\text{MPE}(\%) = \frac{\sum_{i=1}^{n}\left(\frac{\overline{G}_{ic} - \overline{G}_{im}}{\overline{G}_{im}} x100\right)}{n} \tag{16}$$

- The coefficient of determination or multiple correlation coefficient R^2: it is the strength of the linear relationship between the predicted load values and those actually observed. It represents the proportion of the total variance of the quantity to be estimated which can be taken into account by the estimation variables. The closer the coefficient is to one (1), the stronger the correlation between the predicted and observed values. R^2 is calculated using the following equation [15]:

$$R^2 = \frac{\frac{1}{n}\sum_{i=1}^{n}(\overline{G}_{ic} - \overline{G}_{ic\_an}).(\overline{G}_{im} - \overline{G}_{im\_an})}{\sqrt{\left[\sum_{i=1}^{n}(\overline{G}_{ic} - \overline{G}_{ic\_an})^2\right].\left[\sum_{i=1}^{n}(\overline{G}_{im} - \overline{G}_{im\_an})^2\right]}} \tag{17}$$

With:

- $\overline{G}_{ic\_an}$: The average annual solar radiation calculated;
- $\overline{G}_{im\_an}$: The average annual solar radiation measured on the site.

4. Results and Discussions

4.1. Results

The results of calculations of the parameters of the different models are summarized in the following table:

Table 2: Parameters calculated for the plant site

	G/G0	S/S0	Tn
January 2019	0.68	0.993	0.839
February 2019	0.68	0.992	0.847
March 2019	0.53	0.988	0.877
April 2019	0.58	0.987	0.887
May 2019	0.50	0.982	0.880
June 2019	0.60	0.971	0.883
July 2019	0.55	0.972	0.890

August 2019	0.48	0.970	0.894
September 2019	0.59	0.979	0.880
October 2019	0.60	0.982	0.872
November 2019	0.69	0.993	0.874
December 2019	0.69	0.994	0.851

The estimation of the different models as well as the statistical evaluation indicators are grouped in Table 3. The coefficients of the different models are determined by applying a regression by the method of least squares.

Table 2: Solar radiation estimation models on the site and statistical indicator

N°	**Models**	**Models for empirical estimation of radiation on site**	**Statistics Parameter**				
			MBE	**MPE(%)**	**MABE**	**RMSE**	**R^2**
1	Angstrom-Prescott	$\frac{G}{G_0}=5.94(\frac{S}{S_0})-5.244$	1.7924	9.05	2.7396	0.1551	0.52
2	Ampratwum et Dorvlo	$\frac{G}{G_0}=5.824.\log(\frac{S}{S_0})+0.6954$	1.8033	9.1	2.7435	0.1553	0.518
3	Elagiba et Mansel	$\frac{G}{G_0}=2.228\exp(\frac{S}{S_0})-5.3599$	1.7754	8.96	2.7325	0.1547	0.521
4	Newland	$\frac{G}{G_0}=873.88(\frac{S}{S_0})-852.32\log(\frac{S}{S_0})-873.079$	1.662	8.43	2.6996	0.16	0.636
5	SwartmanetOgunlade	$\frac{G}{G_0}=8.7344(\frac{S}{S_0})+0.001161.H-8.031$	1.802	9.11	2.7769	0.158	0.545
6	Falayi E O et Al (modèle 1)	$\frac{G}{G_0}=2.4484(\frac{S}{S_0})-2.25998.T_n+0.1433$	1.8062	9.09	2.7626	0.1627	0.643
7	Falayi E O et Al (modèle 2)	$\frac{G}{G_0}=4.1565.(\frac{S}{S_0})-2.136.T_n+0.0006224.H-1.6459$	1.811	9.13	2.7991	0.1611	0.65
8	Proposed model for the site	$\frac{G}{G_0}=-0.8258(\frac{S}{S_0})-3.45.T_n-0.001616.H-0.04305.V+4.618$	1.811	9.01	2.6669	0.1601	0.722

By drawing the comparison diagram of the different models, we have the following figure:

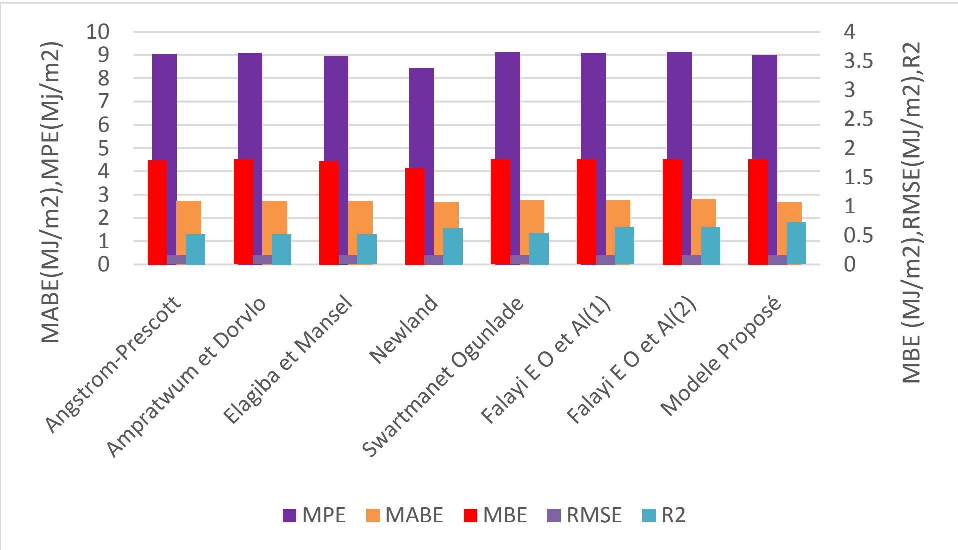

Figure 4: Diagram comparing the different models

4.2. Discussions

Note that the eight solar radiation estimation models on the Malbaza solar power plant site have acceptable statistical parameters:

- The MBE is between 1.662MJ/m^2 and 1.811MJ/m^2;
- The MPE is between 8.43% and 9.13%;
- The MABE is between 2.6669MJ/m^2 and 2.7769MJ/m^2;
- The multiple correlation coefficient R^2 is between 0.52 and 0.722.

We also note that:

- The Newland logarithmic linear model presents the best values of MBE (1.662 MJ/m^2), MPE (8.43%), MABE (2.6996 MJ/m^2) and RMSE (0.16 MJ/m^2). Its multiple correlation coefficient R^2 which is 0.636 is among the best. However, the model does not take into account very important meteorological parameters such as temperature and humidity;
- The Angstrom-Prescott, Ampratwum and Dorvlo, Elagiba and Mansel, and Swartmanet Ogunlade models present high statistical indicators with low correlation coefficients compared to the other models, in addition they do not take into account all weather parameters;
- Model 1 of Falayi E.O presents weak statistical indicators compared to model 2 of Falayi with a coefficient of multiple correlation lower than this one;
- The proposed model has the highest MBE (1.811Mj / m^2). But its MPE (9.01%) and its MABE are lower than those found by the Angstrom-Prescott and Falayi models. It also has the best multiple correlation coefficient (0.772) with an RMSE (2.6669MJ / m^2) lower than that of Falayi models and it takes into account the duration of sunshine, temperature, humidity and wind speed.

Conclusion

There are several empirical methods for estimating global solar radiation using the sunshine fraction and meteorological parameters. The eight solar radiation estimation models studied present acceptable statistical indicators (MBE, MPE, MEBA, RMSE and R^2). Among these models, the Newland linear-logarithmic model gave the highest error precision with a multiple correlation coefficient of 0.636. The study also showed that the new model which takes into account meteorological parameters (normalized air temperature, humidity and wind speed) can be used to estimate daily values of global solar radiation with good accuracy and a coefficient of highest multiple correlation.

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