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World Daily Horizontal Solar Radiation Data Modeling across Togo

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Abstract

The most intriguing renewable energy source in developing nations where solar photovoltaic deposits are plentiful seems to be solar energy. Unfortunately, optimum utilisation of solar installations is hampered by the absence of exact understanding of solar radiation deposit and its restricted data. A working model for daily global horizontal solar radiation is presented in this paper for Togo's five regional capitals: Lomé, Atakpamé, Sokodé, Kara, and Dapaong. The General Directorate of National Meteorology of Togo provided the data for the study, which covered a period of five years. The created model takes into account climatological factors including location latitude, daily relative humidity, daily ratio of sunshine length, and daily mean temperature. It also mixes linear and nonlinear approaches with harmonic and exponential components. Statistical errors of the model were compared to those of two previous models elaborated for Togo and Nigeria. The results showed that the model is more efficient to predict global horizontal solar radiation over the five main cities in Togo. The com-parison of estimated data and measured ones showed a good agreement be- tween them.

Keywords

Horizontal Solar Radiation, Modeling, Non-Linear Regression, Statistical Errors

1. Introduction

Energy access and environmental issues have made research on the development and mastery of renewable energy technologies more than urgent today. Among the various renewable energy technologies, solar photovoltaic appears to be one of the most interesting, particularly in developing countries where access to energy is still relatively low while the solar deposit is abundant. Among other difficulties which often hinder optimal exploitation of solar installations, we can cite that related to the precise knowledge of the deposit. Indeed, the potential of solar applications and the accurate prediction of their performance and behaviour at a given site depend on the precise knowledge of the radiation data at that site. Unfortunately, in some countries, especially in developing ones, solar radiation is not always measured in many parts because of the cost of the entire data collection process [1] [2] [3]. Hence, the need to develop models to estimate, by extrapolation, solar radiation for the locations where there is no measuring equipment installed. In this context, several models using climatic weather parameters have been developed towards the world. Angstrom's model [4] and adjustment given by Prescott [5] afford a correlation between the global horizontal solar radiation and the relative sunshine hours. In Africa, among others, the estimation of the global solar radiation on the horizontal surface have been made with numerous empirical models in many countries such as Egypt [6] [7], Nigeria [8], Sudan [9] and Lesotho [10], where the models were often modified to correlate different geographic and meteorological parameters. In the same way, Ajayi *et al.* [11] focused on a new regression model taking some geographic and meteorological parameters for the whole of Nigeria; consequently, they carry out a good agreement within the measured data and computed results with minimum error. Likewise, Amou *et al.* [12] presented work on the linear and exponential model in order to predict the global horizontal solar radiation of many cities in Togo, thus parameters like relative humidity and mean daily temperature were used. The performance of these empirical models showed that only a few give less than 10% of relative error between simulated and measured values [13] [14]. Amou *et al.* [15], attempt also for forecasting Togo's potential solar radiation maps with the Multilayer Perceptron (MLP) across to artificial neural network (ANN) who depends on three parameters such as latitude, relative humidity and temperature. In view of these previous studies, the statistical errors of which are relatively high, it appears necessary to work on the development of more efficient models in order to be able to generate more precise solar irradiation data for all of Togo. It is in this spirit that this study was undertaken.

In this study, we focused on improving the performance of the nonlinear regression model taking into account parameters such as latitude, number of days, relative humidity, daily mean temperature, and sunshine duration. The model allowed us to establish the available daily solar global horizontal radiation data of many cities in Togo and reach out the best statistical regression factors for validation.

2. Methodology

Study Area

The five regional capitals, which are subject of our study, are presented in **Figure 1**. As can be seen, these cities are distributed over the length of the country and therefore correctly represent the entire climate of the country.

Figure 1. Study cities.

Gathering Weather Data for the Five Main Cities in Togo

Togo is a country located in the northern hemisphere, bordered by the Atlantic Ocean to the south, Burkina Faso to the North, Benin to the East and Ghana to the West. It extends from Lomé to Cinkassé over latitude between 6 and 11 degrees north and a longitude between 1.23 and 0.21 degrees east. For the purposes of this study, we collected data of daily relative humidity, daily mean global solar radiation on horizontal, daily mean temperature and daily sunshine hours along five years (2015-2020), from the General Directorate of National Meteorology of Togo which has a meteorological station in each of the 5 regional capitals concerned by this study, whose geographic coordinates are shown respectively on **Table 1**. The five towns are the most important cities in the country with a high population and most of industries and commercial activities are located in or close to them. These cities have been selected for this study because existing and planned solar plants which are located near them. We were limited to five years back because of the lack of certain data which does not allow to have well-structured and coherent data.

Mathematical Modeling

Among numerous multivariable linear or nonlinear models existing, there are some which give a good accuracy of solar global horizontal radiation dependent to climatic parameters. These methods, often, were limited by the non-availability of measured data all over some regions. Thus, their performances are sometimes

Table 1. Geographic coordinates of the study cities.

City	Longitude (˚)	Latitude (˚)
Lomé	1.23	6.13
Atakpamé	1.11	7.54
Sokodé	1.16	8.98
Kara	1.20	9.48
Dapaong	0.21	10.90

dependent on the locations and the number of geographic parameters considered [11]. The data collected from General Directorate of National Meteorology of Togo are considered over five years for most significant results. In this study, starting from the analysis of the different models of the literature and in particular those developed in Africa such as those of Ajayi *et al.* [11] and Amou *et al.* [12], we developed a model, expressed by Equation (1), which combines linear and nonlinear methods with harmonic and exponential terms to enhance global horizontal solar radiation prediction. The main parameters considered are: location latitude φ, daily relative humidity RH, daily ratio of sunshine duration (n_i/N), daily mean temperature T, and day number in the year n.

$$G_h = a(RH+T)*I_o*\sin(\varphi)+b*I_o*\exp(c*T)*\cos(\varphi) + d*(n_i/N)^2*\cos(\varphi)+e*T^2+f*\cos(\varphi)*\cos(n)+j \quad (1)$$

I_o is the solar constant (1367 W/m^2), n_i is the sunshine duration, N the day length or maximum sunshine duration. The correlation coefficients a, b, c, d, e, f and j are constants calculated for each location considered.

Model Performance and Statistical Errors

Several statistical indicators allow comparing the solar radiation results from theoretical models to measured data. The performance of models and their accuracy in data prediction are often described by parameters like the Root Mean Square Error (RMSE), the Mean Bias Error (MBE), the Mean Percentage Error (MPE) and the Mean Absolute Percentage Error (MAPE) [16] [17] [18]. Their mathematical well-known expressions are given as follow.

$$\text{RMSE} = \sqrt{\left(\sum_{i=1}^{n}(Gm-Gcal)^2\right)/k} \quad (2)$$

$$\text{MBE} = 1/k*\left(\sum_{i=1}^{n}(Gm-Gcal)\right) \quad (3)$$

$$\text{MPE} = 1/K*\left(\sum_{i=1}^{n}\left(\frac{Gm-Gcal}{Gm}\right)*100\right) \quad (4)$$

$$\text{MAPE} = 1/K*\left(\sum_{i=1}^{n}\left|\left(\frac{Gm-Gcal}{Gm}\right)\right|*100\right) \quad (5)$$

where n = number of data points, Gm = mean of all the measured global solar radiation, $Gcal$ = calculated daily global solar radiation. The closer these parameters are to zero, the better the model. The MBE can get negative or positive values, meaning that we have respectively underestimation or overestimation of the calculated solar radiations data compared to those measured. The RMSE is always positive and is best when it is as small as possible. Likewise, the MAPE and MPE are indicators which describe the difference between measured and calculated values [19] [20].

3. Results and Discussion

The correlation coefficients calculated for each of the five main cities in Togo are presented in **Table 2**. These independent constants express the best model approach to real data when nonlinear regression has been done for horizontal solar radiation data.

The statistical errors outcome from the model implemented for each city are shown in **Table 3** and represent the best values of nonlinear regression. From the MBE values, the model gives overestimation for Atakpamé and underestimation for other cities. All RMSE are positives, we get minimum (20.105689 W/m^2) and maximum (25.2459736 W/m^2) deviations in Atakpamé and Dapaong respectively. The MPE and MAPE respectively decrease or increase from Lomé to Dapaong. These results afford to reveal that the model using in Lomé is most performed than others through the MPE and MAPE values. But taking only the RMSE or MBE, it gives us respectively Dapaong and Atakpamé most accurate from the model prediction.

Table 2. Calculated coefficients for the study model.

Model coefficients	Lomé	Atakpamé	Sokodé	Kara	Dapaong
a	−0.0015993	−0.0000353	0.0005096	0.0161266	0.0008064
b	1802830	0.3615234	−0.0947456	−0.1142607	−1.1036759
c	−4.2226325	0.0704849	0.0658425	−0.0021463	−0.0007957
d	−5.3509832	1412.4584850	−507.610323	−447.816994	−4867.783579
e	0.1594232	−1.1641819	−0.7239317	0.1143187	0.1211770
f	0.5945587	1.31671427	0.0000699	0.0000698	0.0000698
j	55.1925940	2.6324906	0.1130813	0.1125114	0.1199275

Table 3. Results of performance of the model for the five cities.

Error terms of the model	Lomé	Atakpamé	Sokodé	Kara	Dapaong
MBE	−0.0001872	0.0011372	−0.0026567	−0.0000508	−0.0000514
RMSE	20.3931769	20.1056890	21.8950090	24.7269509	25.2459736
MPE	−0.9334437	−1.3477398	−1.5249202	−2.2948975	−3.1750512
MAPE	7.7349758	8.4669199	8.5869980	9.9704989	10.5069315

In order to test the performance and accuracy of our model compared to other models in the literature, we compared the statistical parameters of our model with those of Amou *et al.* and Ajayi *et al.* We have targeted these two models because the model of Amou *et al.* is the only model on the prediction of the global solar radiation of Togo known in the literature today; and the model of Ajayi *et al.* meanwhile, is a model that has been applied to the largest country in our sub-region (Nigeria) and above all it has been compared to ten other regional or international models such as: Fagbenle [21], Akpabio *et al.* [22], Udo (Akpabio *et al.*) [22], Akinoglu and Ecevit (Akpabio *et al.* [22]), Ertekin and Yaldiz [23], Akinoglu and Ecevit [24], Yohanna *et al.* [25], Gopinathan [26], Rietveld [27], Glower and McCulloch [28]. **Table 4** presents the results of statistical errors of the different models implemented for each city. From Lomé to Dapaong, we generaly observed that our model parameters values are less than those from both models concerned. The values of MBE, RMSE, MPE, and

Table 4. Results of comparing the model from this study with two other models to determine the model with best fit for the five main cities in Togo.

Error term of model	Locations	Model	Amou *et al.* [15]	Ajayi *et al.* [16]
MBE	Lomé	−0.0001872	0.00070396	−0.00054403
RMSE		20.3931769	21.4905556	20.472645
MPE		−0.93344373	−1.02406335	−0.94080837
MAPE		7.73497583	8.05256909	7.67838959
MBE	Atakpamé	0.00113721	000002.475	0.00099474
RMSE		20.105689	32.7002605	29.4214765
MPE		−1.34773987	−3.11619532	−2.59093116
MAPE		8.4669199	14.0566856	12.4730265
MBE	Sokodé	−0.00265673	0.00545191	0.00010889
RMSE		21.895009	32.2882313	30.0782985
MPE		−1.52492023	−2.72929591	−2.64398625
MAPE		8.58699803	13.1228199	12.1765105
MBE	Kara	−000005.0831	−00000007.3905	−0.0015014
RMSE		24,7269509	34,2080588	32.9304318
MPE		−2.29489755	−3.86642421	−3.66306766
MAPE		9.97049893	14.4054242	13.73233
MBE	Dapaong	−000005.1457	−00000002.2113	−0.00034491
RMSE		25.2459736	36.9080284	36.7547407
MPE		−3.17505127	−5.2197335	−5.23816491
MAPE		10.5069315	15.7789468	15.8406344

MAPE clearly show that the best performance is given by our model followed by Ajayi *et al.* [16] over the five cities. This can be more illustrated with **Figure 2**, even though these values increase from Lomé to Dapaong, our model keeps the best performance to predict global horizontal solar radiation data.

Further to this, **Figures 3-7** shows comparison between estimated data from our model and measured data of daily horizontal solar radiation for the five cities in Togo. It can be seen the proximity of the values predicted by our model and the measured data.

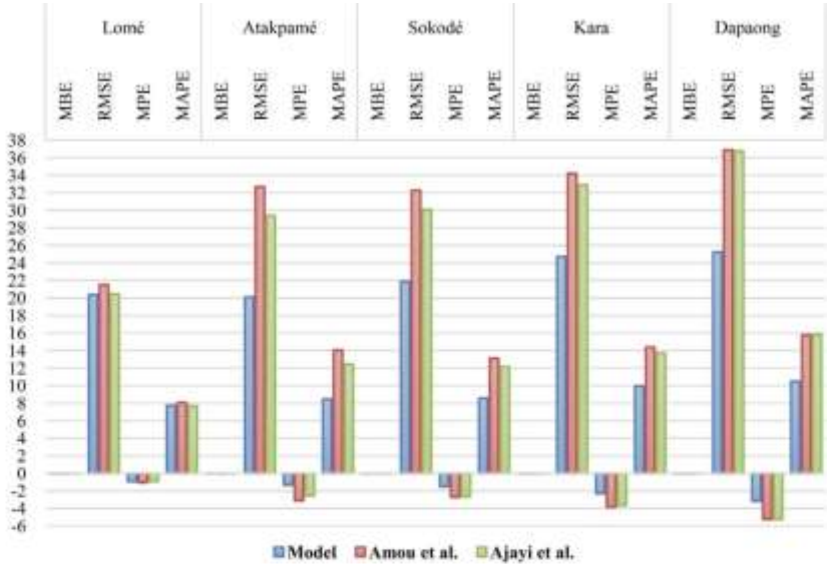

Figure 2. Comparison of statistical errors form our model and two other models for the five main cities in Togo.

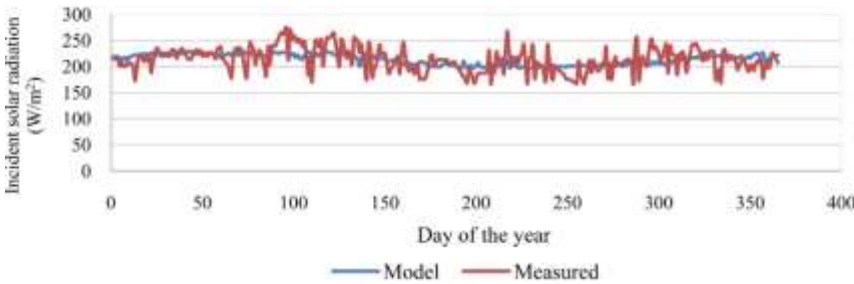

Figure 3. Comparison of estimated and measured data for Lomé.

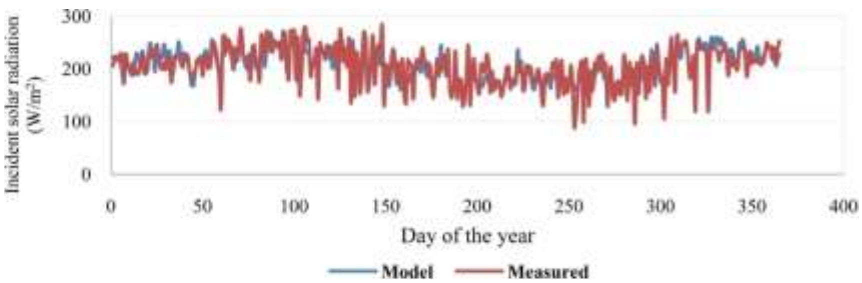

Figure 4. Comparison of estimated and measured data for Atakpamé.

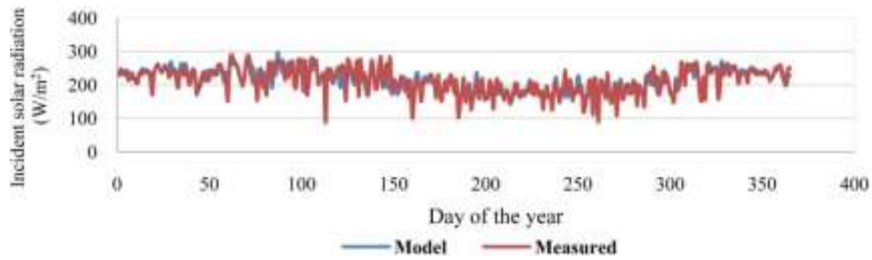

Figure 5. Comparison of estimated and measured data for Sokodé.

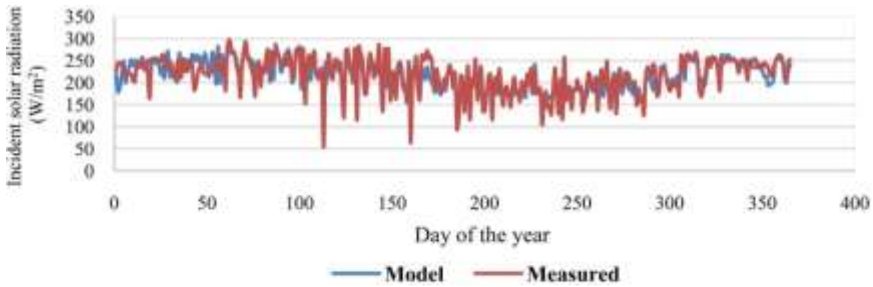

Figure 6. Comparison of estimated and measured data for Kara.

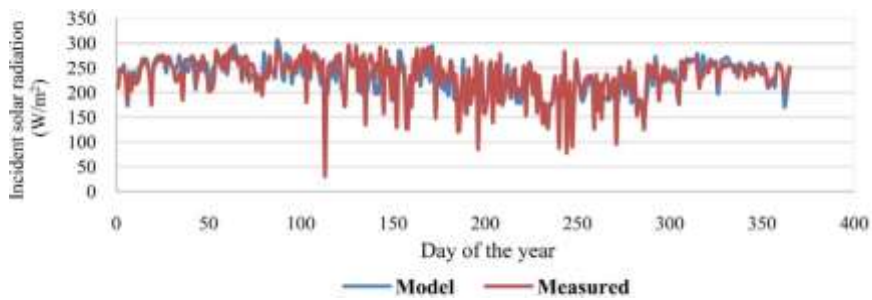

Figure 7. Comparison of estimated and measured data for Dapaong.

4. Conclusions

The availability of solar radiation data necessitates having a solid evaluation of solar potential everywhere in order to manage solar technology and obtain a relevant operational efficiency. Previous research attempted to predict solar data with an acceptable accuracy of no more than 10% of statistical error by linear or nonlinear regressions, taking into consideration climate characteristics, due to the weak distribution of meteorological stations for measuring the daily horizontal sun radiation.In this study, we developed a new model, combining nonlinear and linear models with harmonic and exponential terms to enhance the data prediction in Togo, taking into account parameters like location latitude, daily relative hu- midity, daily ratio of sunshine duration, daily mean temperature and day num- ber in the year. The results revealed that our model is the most efficient, com- pared to the models of Amou *et al.* and Ajayi *et al.*, to predict global horizontalsolar radiation over the five main cities in Togo. Further, this model could be employed for predicting daily global horizontal solar radiation of other similar climatic locations inside or outside of Togo.

Unavailability of observation weather data for a long term to validate the present developed model is a limitation of the work. In the future, the model could be used on larger data, over at least 30 years, in order to evaluate its accuracy over long periods.

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