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Estimation of Global Solar Radiation Using Three Simple Methods

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Abstract

The purpose of this paper is to evaluate the linear regression methods (Linear model, Quadratic model and Cubic model), which were previously used by researchers commonly, for the estimation of monthly and annual average global solar radiation from locations namely Troyes-Barberey city in France. Comparative studies between the global solar radiations estimated from the three models and the measured values show that all models used in the present paper give very good results, and that the linear model gives better estimate of solar components where the errors between the measured values and those calculated are negligible.

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Keywords: global solar radiation; modeling; meteorological parameters; solar energy systems.

1. Introduction:

Solar radiation is the most evenly distributed energy resource on earth and the most abundant. The amount of energy released by the sun (captured by earth) during one hour may be sufficient to cover the world's energy needs for one year. Part of this radiation can be used directly to produce heat (solar thermal) or electricity called photovoltaic solar energy. This mode of production does not require network distribution, because it can generate electricity and can be consumed in places such as villages, detached houses (one third of the world's population lacks access to electricity), water pumping, refuges...

The sun discharges continuously an enormous amount of energy radiant in the solar system. Earth intercepts a small portion of this energy radiated into space. An average of 1367 watts per square meter

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reaches the edge outside of the terrestrial atmosphere (for an average distance Earth sun 150 million kilometers), this quantity is called the solar constant. The energy received by earth's surface depends on the thickness of the atmospheric crossing. It is the function of air mass. Some countries such as France have conducted studies to have measurements to encourage generating electricity from solar energy.

Therefore, for the design and development of various solar energy systems, the estimation of solar radiation is considered as the most important parameter. However, the availability of the required data is very scarce and often not readily accessible. In this study, three different models are employed to estimate the daily global solar radiation for the Troyes station, using the relative duration of sunshine.

The main objective of the present study is to estimate the daily global solar radiation with measured daily sunshine duration data and to find the most suitable model for global radiation estimation at TROYES-BARBEREY, France.

Nomenclature

Hg	The daily global solar radiation on a horizontal surface.
H0	The daily value of the extraterrestrial radiation.
S	The sunshine duration.
S0	The maximum possible sunshine duration
a,b,c,d	Empirical coefficients
φ	The latitude
η	The hour angle
δ	The solar declination
α	angle solar
β	The solar azimuth.
J	Julian day
Sc	Supplied value used by the World Radiation Center $1367 w/m^2$
τ^M	The transmissivity coefficient
M	The length of the route with the solar azimuth
P/P_0	The correction factor related to atmospheric pressure
R_{dir}	Direct radiation
R_{diff}	Diffuse radiation
R_{ref}	Reflected radiation
Sh	A binary value of shadowing

r	The reflectance of the ground surface.
R_{tot}	The global radiation
K_c	The cloud attenuation factor
R_{totc}	The global radiation solar with cloudy sky
N	The cloudiness in octas

2. Models used

Many models to estimate global solar radiation have been found in the literature [1],[2],[3],[4].The models used in the present paper to estimate the daily global solar radiation from the measured duration of sunshine hours are as follows[5].

Linear model [4]:

$$\frac{H_g}{H_0} = a_1 + b_1\left(\frac{S}{S_0}\right) \quad (1)$$

Quadratic model [6]:

$$\frac{H_g}{H_0} = a_2 + b_2\left(\frac{S}{S_0}\right) + c_2\left(\frac{S}{S_0}\right)^2 \quad (2)$$

Cubic model [7]:

$$\frac{H_g}{H_0} = a_3 + b_3\left(\frac{S}{S_0}\right) + c_3\left(\frac{S}{S_0}\right)^2 + d_3\left(\frac{S}{S_0}\right)^3 \quad (3)$$

The parameters a_i, b_i , c_i and d_i can be obtained by the regression method.

3. Methods

Shortwave radiation covers the 0.28-5 µm range of the spectrum. They can be separated into three components [8], [9], [10], direct radiation from the sun, which is generally the greatest, diffused sky radiation, which is diffused by the atmosphere and depends on its composition and terrain- reflected radiation, which is the part of the direct or diffused radiation scattered by the ground. This component is a function of the ground cover, and can be large for snow-covered areas because of high albedo.

The amount of global radiation is obtained by summation of the direct, diffused and terrain- reflected components at the earth's surface. They are determined by three groups of factors: geometric relations between the sun and the earth's surface, atmospheric attenuation and topographic factors [9], [11].

Geometric relations between the sun and the earth's surface are characterized by the earth's geometry, revolution, and rotation that can be calculated with astronomic formulas. Atmospheric attenuation is due to gases, solid and liquid particles. Extraterrestrial solar radiation is attenuated according to the thickness of the atmosphere, and calculated according to altitude. It can be determined with a good level of precision. Topographic factors induce strong variations on a local scale, due to surface orientation and surface inclination, which modify the angle of incidence of insolation [9]. Attenuation by clouds is considered separately. It can provide from different sources of data [12]. We used empirical equations based on the nebulosity measured for each hour ground meteorological stations.

The elevation of the sun above the horizon for a location is defined by the solar altitude given by [9].

$$\sin(\alpha) = \sin(\varphi)\sin(\delta) + \cos(\varphi)\cos(\eta)\cos(\delta) \quad (4)$$

Where φ is the latitude, η is the hour angle and δ is the solar declination. This declination angle δ is the angle at solar noon between the sun and the equator, referenced as north positive. It can be approximated for a specific Julian day J given by this [13],[14].

$$\delta = 23.45 * \sin(360(284 + J)/365) \quad (5)$$

To calculate the Julian day for D M A where D is the day of month, M is the month and A is the year

$$J1 = Ent((M*275)/9) \quad (6)$$

$$J2 = Ent((M*9)/12) \quad (7)$$

$$K = 1 + Ent((A - 4 * Ent(A/4) + 2)/3) \quad (8)$$

K=2 for a common year and K=1 for a bissextile. The rank of the day is giving by

$$J = J1 - J2 * K + D - 30 \quad (9)$$

In general, the azimuth angle varies with the latitude and time of year and the equation to calculate the azimuth is given by [15]:

4. Characteristics of solar flux

Solar flux is a function of the solar constant Sc (supplied value used by the World Radiation Center, $1367 w/m^2$), and the day of the year (J) [16]:

$$Rout = Sc * (1 + 0.034 * \cos(360J)/365) \quad (10)$$

The transmissivity coefficient τ^M represents the fraction of incident radiation on the surface of the atmosphere reaching the ground along a vertical path. A value τ = 0.6 have been chosen [9]. M is the length of the route with the solar azimuth. In mountain areas, it is necessary to use a correction factor related to atmospheric pressure P/P_0, which depends on the altitude. The formula used is [16]:

$$M = M_0\left(\frac{P}{P_0}\right) \quad (11)$$

Where M_0 being calculated using the following formula:

$$M_0 = \left(\sqrt{1229 + (614 * \sin(\alpha))^2}\right) - 614 * \sin(\alpha) \qquad (12)$$

5. Calculation of global radiation

The hourly calculation of global radiation is obtained by the sum of the direct components R_{dir}, diffused R_{diff} and reflected R_{ref} with:

$$R_{dir} = Sh * R_{out} * \tau^{M} \cos(i) \qquad (13)$$

Where *Sh* is calculated for each hour of the day and each integer value of angle solar α and solar azimuth β.
Modeling diffuse radiation is complex because irradiation is anisotropic, particularly under cloudy conditions. We assumed that diffuse radiation is isotropic [17] and the isotropic model in [18] was used to calculate the reflected radiation. This model takes into account the solar angle and transmissivity of the atmosphere in clear sky conditions:

$$R_{diff} = R_{out} * (0.271 - 0.294 * \tau^{M}) * \sin(\alpha) \qquad (14)$$

The diffused radiation is calculated from the formula [9]

$$R_{ref} = r * S_c (0.271 + 0.294 * \tau^{M}) * \sin(\alpha) \sin^2(\chi / 2) \qquad (15)$$

The summation of the three components gives global radiation R_{tot} for each hour of calculation(w/m^2):

$$R_{tot} = R_{dir} + R_{diff} + R_{ref} \qquad (16)$$

Cloudy conditions [12],[19] and [20]are calculated using the cloud attenuation factor K_c defined by Kasten and Czeplak[21]. This equation requires only the measured values in octas, each octa representing a 1/8 of visible sky. The radiation solar with cloudy sky R_{totc} is then calculated:

$$R_{totc} = R_{tot} * K_c \qquad (17)$$

Where $K_c = (1 - 0.75(N/8)^{3.4})$ *(18)*

Global radiation can be calculated for periods ranging from one day to one year, by summing the values daily during the reporting period.

6. Comparison techniques

There are numerous works in literature, which deal with the assessment and comparison of daily solar radiation estimation models. The most popular statistical parameters are the Mean Bias Error (MBE), the Mean Percentage Error (MPE) and The Root Mean Square Error (RMSE) [22].

6.1. The mean bias error:

$$MBE = (1/n)\sum_{1}^{n}\left(H_{i,g} - H_{i,0}\right) \tag{19}$$

6.2. The mean Percentage Error:

$$MPE(\%) = (1/n)\sum_{1}^{n}\left(\left(H_{i,g} - H_{i,0}\right)/H_{i,0}\right)*100 \tag{20}$$

6.3. The Root Mean Square Error:

$$RMSE = \sqrt{(1/n)\sum_{1}^{n}\left(H_{i,g} - H_{i,0}\right)^2} \tag{21}$$

6.4. Statistic test:

As defined by Student [23] in one of the tests for mean values, the random variable t with n−1 degree of freedom may be written here as follows:

$$t = sqrt\left((n-1)*(MBE)^2/(RMSE)^2 - (MBE)^2)\right) \tag{22}$$

The smaller the value of t the better is the performance

7. Results

We will treat an example in the north of France, which is cloudier. Meteorological data measured in the following locality: Méteo France ground station of the Troyes-Barbery (latitude: 48°19’24”N, longitude 4°01’12”E, 112m altitude) is used in this work. Field measurements were made from the 1 January 2009 at 00: 00 until the 31 December 2011 at 23: 00 in the Troyes- Barberey. Nebulosity was measured at hourly intervals (number of sunny minutes per hour) by Méteo-France.

The nebulosity measured was used to construct the cloud attenuation factor, which was then integrated to obtain the average total amount of monthly energy received. The figure 1 shows the radiation calculated from measurements of nebulosity every month for the last 3 years and their average.

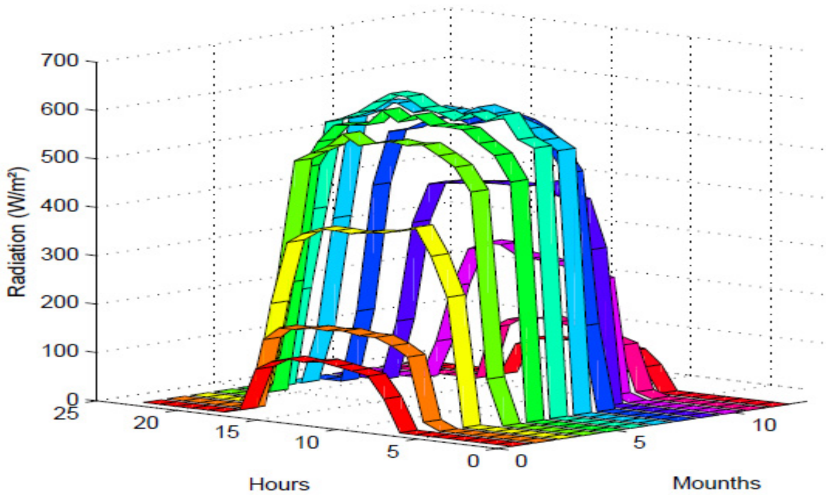

Fig. 1: Measured monthly average daily global radiation

In this study, the accuracy among the three models was determined using the data measured at Troyes-BARBEREY city in FRANCE in the period of 2009, 2010 and 2011.By using the data, the regression constants a, b, c et d are given for these models in table 2:

Table 1: The regression coefficient for Troyes, in the period 2009-2011

Model type	a	b	c	d
Linear	0.491	0.2634	-	-
Quadratic	0.4338	0.2327	0.1659	-
Cubic	0.4002	0.2147	0.1530	1196

It’s evident that the Angstrom coefficients a, b, c and d are subjected to a large variability according to type of model.

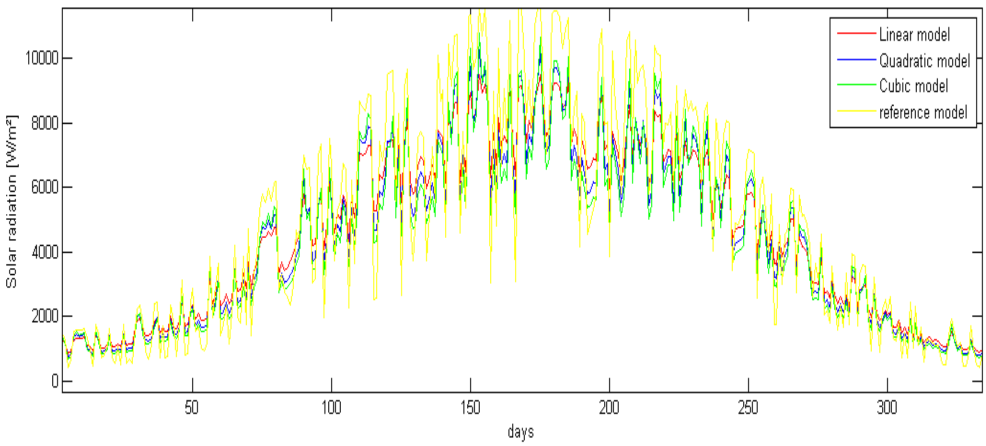

Fig. 2: Comparison of the estimated value of daily global solar radiation from various models with the measured data

The measured (reference) and calculated values of the daily global radiation using the three models for the Troyes-BARBEREY are illustrated in Figure 2. As can be seen from this figure, agreement between the values obtained from the three models and the measured data are good for all the days of the years. Figure 3, Figure 4 and Figure 5 prove this agreement where the most of points in this figures have the measured value almost equal to the calculated value.

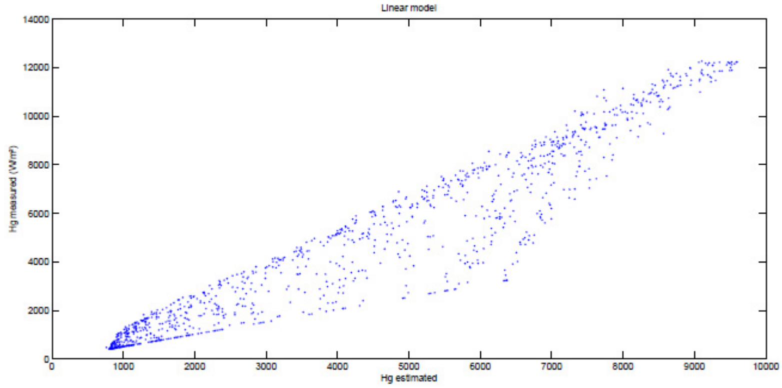

Fig. 3: The measured and predicted values calculated by the linear model

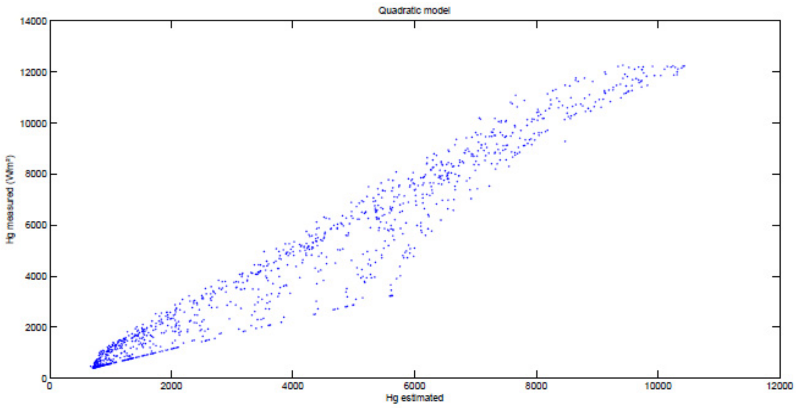

Fig. 4: The measured and predicted values calculated by the quadratic model

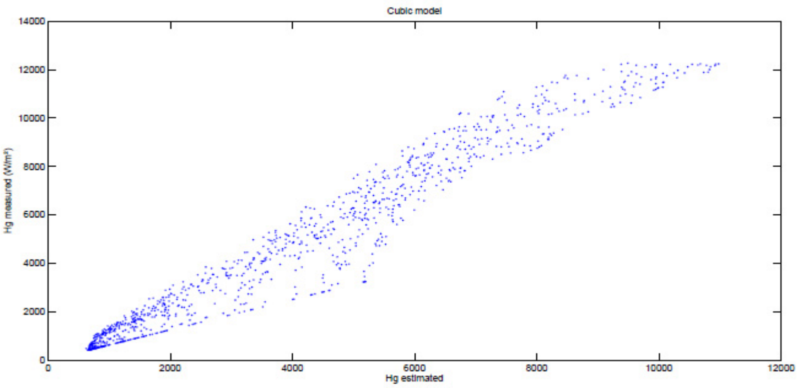

Fig. 5: The measured and predicted values calculated by the cubic model

The performance of the models was evaluated on the basis of the following statistical error tests: mean bias error, mean percentage error and root mean square error. These tests are the ones that are applied most commonly in comparing the models of solar radiations

Table 2: Validation of the models under different statistical tests

Statistical parameters	Linear model	Quadratic model	Cubic model
MBE	-1.6003	-2.0655	-2.4907
MPE	0.117021	0.03981	-0.012818
RMSE	4.8607	4.4275	4.5492
t	0.076	0.1347	0.1719

According to the statistical parameters, MBE, MPE and RMSE, used to determinate the statistical test t, it can be seen that the estimated values of daily global radiation are in a favourable agreement with the measured values for all the models. However, the linear model has better performance than the two other models caused of the statistical test value, so this test prove that this model can be recommended.

8. Conclusion

In this work, the modeling of the solar radiation using three approaches is presented. These models can be used as a reference level for the first category of procedures. It can be seen from the results that the three models give good estimated results of the global solar radiation for TROYES-BARBEREY. The most favorable estimated results are given by the linear model. It can also be concluded from this study that using the methods of global solar radiation estimation is a suitable tool with the advantage that the meteorological data can be estimated easily.

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References

[1] B. Nguyen and . T.L.Pryor, “, “The relationship between global solar radiation and sunshine duration in vietnam,” Renewable Energy, vol. 11, pp. 47–60, 1997.

[2] Y. J.Zhou and G.Yan, “General formula for estimation of monthly average daily global solar radiation in china,” Energy Conversion & Management, vol. 46, pp. 257–268, 2005.

[3] F. E. C. Ertekin a, “Spatio-temporal modeling of global solar radiation dynamics as a function of sunshine duration for turkey,” Agricultural and Forest Meteorology, vol. 145, p.36–47, 2007.

[4] Angstrom. A, “Solar and terrestrial radiation,” Quarterly Journal of Royal Meteorological Society,, vol. 50, pp. , 121–125, 1924.

[5] C. E. Hakan Okyay Menges and M. H. Sonmete, “Evaluation of global solar radiation models for konya, turkey,” Energy Conversion and Management, vol. 47, pp. 3149–3173,, 2006.

[6] E. A. Akinoglu B.G., “Construction of a quadratic model using modified angstrom coefficients to estimate global solar radiation,” Solar Energy, vol. 45, p. 85–92, 1990.

[7] S. T.D.M.A, “Estimation of global radiation for sri lanka,”Solar Energy, vol. 47, p. 333–337, 1991.

[8] R. Dubayah and M. Paul, “Topographic solar radiation models for gis,” International Journal of Geographical Information Systems, vol. 9, no. 4, pp. 405–419, 1995.

[9] D. Gates, “Biophysical ecology springer-verlag,” New York, p. 611, 1980.

[10] C. Piedallu and J. Gégout, “Multiscale computation of solar radiation for predictive vegetation modelling,” Annals of forest science, vol. 64, no. 8, pp. 899–909, 2007.

[11] P. Rich, W. Hetrick, and S. Saving, “Modeling topographic influences on solar radiation : a manual for the solarflux model,” Los Alamos National Lab., NM (United States), Tech. Rep., 1995.

[12] R. Dubayah and S. Loechel, “Modeling topographic solar radiation using goes data,” Journal of Applied Meteorology, vol. 36, no. 2, pp. 141–154, 1997.

[13] P. Cooper, “The absorption of radiation in solar stills,” Solar Energy, vol. 12, no. 3, pp. 333–346, 1969.

[14] A. M’Raoui, S. Mouhous, A. Malek, and B. Benyoucef, “Etude statistique du rayonnement solaire à alger,” Revue des Energies Renouvelables, vol. 14, no. 4, pp. 637–648, 2011.

[15] T. Oke, Boundary layer climates. Psychology Press, 1988.

[16] F. Kreith and J. Kreider, “Principles of solar engineering,” 1978.

[17] L. Kumar, K. ANDREW, and E. Knowles, “Modelling topographic variation in solar radiation in a gis environment,” International Journal of Geographical Information Science, vol. 11, no. 5, pp. 475–497, 1997.

[18] B. Liu and R. Jordan, “The interrelationship and characteristic distribution of direct, diffuse and total solar radiation,” Solar Energy, vol. 4, no. 3, pp. 1–19, 1960.

[19] V. Badescu, “Verification of some very simple clear and cloudy sky models to evaluate global solar irradiance,” Solar Energy, vol. 61, no. 4, pp. 251–264, 1998.

[20] J. Hofierka and M. Suri, “The solar radiation model for open source gis : implementation and applications,” in Manuscript submitted to the International GRASS users conference in Trento, Italy, 2002.

[21] F. Kasten and G. Czeplak, “Solar and terrestrial radiation dependent on the amount and type of cloud,” Solar energy, vol. 24, no. 2, pp. 177–189, 1980.

[22] A.M Muzathik “Daily global radiations estimate based on sunchine hours”,International Journal of Mechanical and Materials Engeneering, vol.6No.1, 75-80, 2011.

[23] B. P.R, Data reduction and error analysis for the physical sciences, N. Y. McGraw Hill Book Co., Ed. first ed, 1969.