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Estimation of Global Solar Radiation in Rwanda Using Empirical Models

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Abstract: Understanding solar radiation data is essential for modeling solar energy systems. The purpose of the present study was to estimate global solar radiation on horizontal surface using sunshine-based models. Angström-type polynomials of first and second order have been developed from long term records of monthly mean daily sunshine hour values and measured daily global solar radiation on horizontal surface at Kigali, Rwanda. Coefficients of those polynomials were derived using least square regression analysis. These coefficients were then used for the estimation of solar radiation in other places of Rwanda where measures of solar radiation do not exist but sunshine records are available.

Key words: Solar model, Angström, solar energy system, Rwanda

INTRODUCTION

While Rwanda has adequate solar energy potential to support its energy demand, it is therefore important to harness that resource in view to find solution to energy shortage and environmental degradation the country is being faced to. Solar energy is now considered to be the most effective and economic alternative resource (Scheer and Ketley, 2002). In developing countries, such as Rwanda, interest in solar energy applications has been growing in providing electricity and water supply in rural areas. Understanding solar radiation data is essential for modeling solar energy systems. Solar radiation is used directly to produce electricity for photovoltaic (PV) systems and solar thermal systems. Therefore, precise knowledge of historical global solar radiation at a location of study is required for the design and estimation of the performance of any solar energy system.

In Rwanda, quite few stations have been measuring the daily solar radiation on a consistent basis. Geostationary satellites give estimates of incident radiation on large regions (1° by 1° or larger grid-cells) but their non-precise historical databases have limited applications for local studies (Kustas *et al*., 1994; Pinker *et al*.,1995). In the absence and shortage of reliable solar radiation data, hence, it is necessary to approximate solar radiation by the use of empirical model in order to estimate and predict global solar radiation. These models use historical meteorological data of the location under study. Empirical models are classified in three categories: sunshine-based models, temperature-based models and cloud-based models (Firoz and Intikhab, 2004; Myers, 2005; Yang *et al*., 2006; Muneer *et al*., 2007; Nguyen and Pryor, 1997; Thornton and Running, 1999; Ridha and Ammar, 2008; Myers, 2003). Recently some studies on modeling solar radiation have been done in Rwanda (Bashahu and Nkundabatware, 1994; Museruka and Mutabazi, 2007), but yet comparative studies on techniques used and results are still needed.

In this study, Angström-type polynomials of first and second order have been developed for approximating the global solar radiation in Rwanda from a long term records of monthly mean daily sunshine hour values and measured daily global solar radiation on horizontal surface at Kigali

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International Airport Station, Rwanda. Correlation coefficients obtained from the least square regression were then used to estimate solar radiation at locations where only sunshine records were available.

MATERIALS AND METHODS

Data

In Rwanda, recorded global solar radiation data on horizontal surface were obtained for only one station located at the International Airport of Kigali (Lat: 01° 58S, Lon: 030° 08E, Alt: 1.490 m). The remaining primary surface weather stations are recording daily temperature, pressure, relative humidity, precipitation, wind speed and direction and sunshine duration. While the secondary stations (not mentioned in the present study) are recording temperature, pressure, relative humidity and precipitation. Data were provided by the Department of Meteorology in the Ministry of Infrastructure (Rwanda). Table 1 presents the locations of stations and the period of observation for which global solar radiation R_G and sunshine duration S were measured.

Description of the Model for the Estimation of Solar Radiation

The global solar radiation reaching the earth's surface is made up of two components, direct and diffuse. Direct radiation is the part which travels unobstructed through space and the atmosphere to the surface and diffused radiation is the part scattered by atmospheric components such as gases molecnles, aerosols, dust and clouds.

At the top of the atmosphere, extra-terrestrial solar radiation, also known as Angot radiation (Wh/m^2/day) can be calcnlated using the following expression:

$$R_0 = I_0 \frac{24}{\pi} (1 + 0.033\cos(\frac{2\pi}{365} J) \cos\phi \cos\delta \sin\omega_s + \frac{2\pi}{360} \omega_s \sin\phi \sin\delta) \quad (1)$$

Global solar radiation reaching the Earth's surface can be estimated by empirical models when measured data are available. The simplest model commonly used to estimate average daily solar radiation on horizontal surface is the well-known Angström equation (Ångström, 1924; Chidiezie, 2008):

$$\frac{\overline{R_G}}{\overline{R_0}} = \alpha_1 + \alpha_2 (\frac{\overline{S}}{S_0}) \quad (2)$$

Angström had suggested values of 0.2 and 0.5 for empirical coefficients α_1 and α_2, respectively. In the present study, Angström model was compared to a second degree polynomial function of monthly average daily sunshine hours of the form:

$$\frac{\overline{R_G}}{\overline{R_0}} = \alpha_3 + \alpha_4 (\frac{\overline{S}}{S_0}) + \alpha_5 (\frac{\overline{S}}{S_0})^2 \quad (3)$$

Table 1: Location of stations and period of observations of global solar radiation and daily sunshine duration

Station	Altitude (m)	Latitude (S)	Longitude (E)	R_G	S
Kigali	1,490	01° 58'	30° 08'	1984-87	1971-now
Butare	1,760	02° 36'	29° 44'	-	1988-93
Kamembe	1,591	02° 28'	28° 55'	-	1988-99
Gisenyi	1,554	01° 40'	29° 15'	-	1986-93
Gikongoro	1,930	02° 29'	29° 34'	-	1990-99
Kibungo	1,680	02° 10'	30° 32'	-	1990-92

RESULTS AND DISCUSSION

Linear and polynomial least square regression techniques were developed based on Eq. 1, 2 and 3 and observed global solar radiation at Kigali International Airport station. The computed values for the coefficients of regression are $\alpha_1 = 0.2416$, $\alpha_2 = 0.6411$, $\alpha_3 = 0.0696$, $\alpha_4 = 1.3261$, $\alpha_5 = -0.06674$. The linear Angström equation is then given by:

$$\frac{\overline{R}_G}{\overline{R}_0} = 0.2416 + 0.6411\left(\frac{\overline{S}}{\overline{S}_0}\right) \tag{4}$$

And the second degree polynomial function is given by:

$$\frac{\overline{R}_G}{\overline{R}_0} = 0.0696 + 1.3261\left(\frac{\overline{S}}{\overline{S}_0}\right) - 0.6674\left(\frac{\overline{S}}{\overline{S}_0}\right)^2 \tag{5}$$

Values of $\overline{R}_G$ (4) and $\overline{R}_G$ (5) corresponding to the estimated global solar radiation, respectively with Eq. 4 and 5 are presented in Table 2 and are compared to the measured values $\overline{R}_{Gobs}$. The deviations between the estimated and measured values given by R^2 (%), RMSE (%) and MBE (%) are presented in Table 3. The poor correlation observed in Fig. 1, 2 and Table 2, during the rainy season period (November to April) is probably due to large differences in the characteristics of the sky during this period. Nevertheless, the two models are slightly in good agreement with the observed data and hence they can simply be applied to estimate monthly average daily global radiation from monthly average daily sunshine hours, which are available in primary stations across the country. The results in Table 4 give an annual solar radiation value of 5,269 Wh/m^2/day for Rwanda while the commonly given value in literature or web site is 5.15 k Wh/m^2/day. The monthly value obtained by Museruka and Mutabazi (2007) using a non linear Meteorological Radiation Models (MRM) with satellite data was varying between about 4.3 and 5.2 k Wh/m^2/day. In the present study in Table 3, the minimum value for the station of Kigali (R_G(4) = 4942 Wh/m^2/day, R_G (5) = 4960 Wh/m^2/day) occurs in May, while the maximum value (R_G(4) = 5721 Wh/m^2/day, R_G (5) = 5738 Wh/m^2/day).

Table 2: Comparison between the observed global solar radiation R_{Gobs} and estimation of global solar radiation from equations (4) R_G (4) and (5) R_G (5) at the station of Kigali

Month	R_{Gobs}	R_G(4)	R_G (5)	RE (4)	RE (5)
Jan.	5211	5311	5315	-1.91	-2.00
Feb.	5156	5473	5483	-6.15	-6.34
Mar.	5339	5336	5326	0.06	0.25
April	5067	5055	5043	0.24	0.47
May	5267	4942	4960	6.16	5.82
June	5461	5472	5469	-0.20	-0.14
Jul.	5664	5680	5652	-0.28	0.21
Aug.	5722	5721	5738	0.02	-0.27
Sep.	5544	5525	5557	0.35	-0.23
Oct.	5367	5447	5457	-1.49	-1.67
Nov.	5042	5114	5079	-1.43	-0.75
Dec.	5356	5161	5151	3.63	3.81
Annual	5350	5353	5352	-0.06	-0.05

Table 3: Values of R^2, RMSE (%), MBE (%)

Model	R^2	RMSE (%)	MBE (%)
Linear	0.8893	2.78	-0.062
Polynomial	0.8911	2.77	-0.054

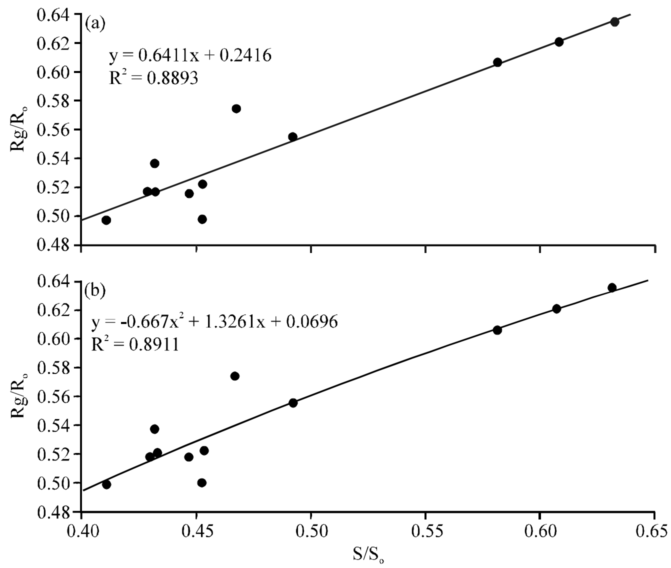

Fig. 1: Least square linear regression and polynomial regression between R_G/R_0 and S/S_0 (a) Linear regression and (b) Polynomial regression

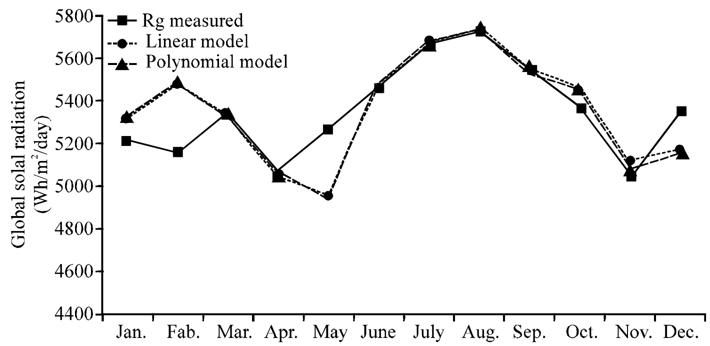

Fig. 2: Comparison of Global solar radiation and estimates of global solar radiation from Eq. 4 and 5 at International Airport station of Kigali

Table 4: Annual values of the ratio S/S_0, extraterrestrial solar radiation R_0, estimate of Global solar radiation R_G in Rwanda and the ratio R_G/R_0

Station	Annual S/S_0	Annual R_0 (Wh/m²/day)	Annual R_G (Wh/m²/day)	Annual R_G/R_0
Kigali	0.477	10098	5335	0.53
Butare	0.502	10164	5488	0.54
Kamembe	0.414	10150	4937	0.49
Gisenyi	0.454	10067	5196	0.52
Gikongoro	0.507	10152	5529	0.54
Kibnngo	0.446	10119	5131	0.51
Average	0.466	10125	5269	0.52

Rwanda, being a small country but with difference in terrain at different locations, the computed coefficients α_1, α_2, α_3, α_4 and α_5 obtained by least square regression techniques have been used to estimate global solar radiation at places where there is no equipment to measure that quantity but sunshine duration has been measured. Estimated Global solar radiation for the five studied sites is shown in Fig. 3. Figure 4 shows the monthly average of estimated global solar radiation on the sites of Rwanda.

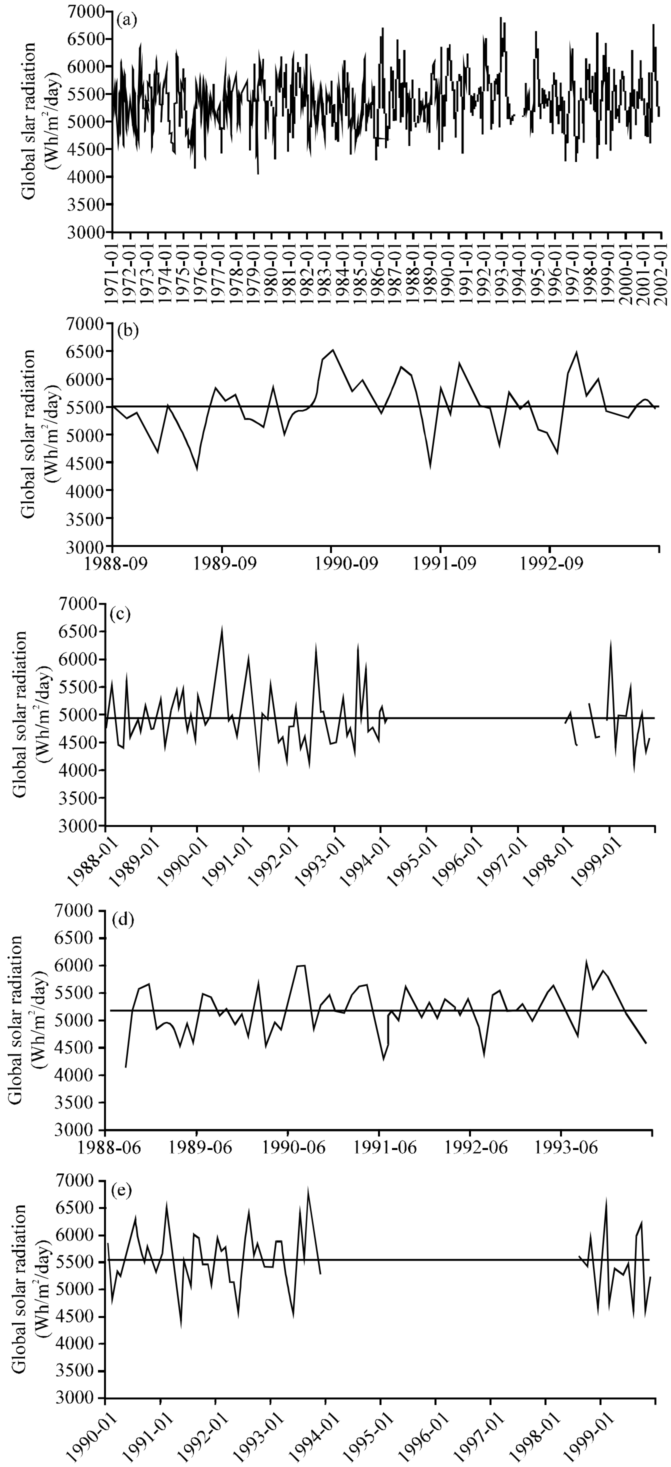

Fig. 3: Estimated global solar radiation for the five studied sites. (a) Kigali, (b) Butare, (c) Kamembe, (d) Gisenyi and (e) Gikongoro

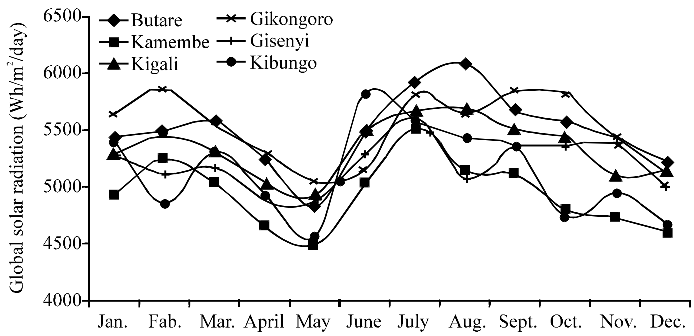

Fig. 4: Monthly average of estimated global solar radiation on the sites of Rwanda

CONCLUSION

The empirical Angström-type linear model and a second degree polynomial model both based on sunshine duration have been studied in this work. The two models were compared with the data collected on the site of Kigali International Airport station. From the comparison of the results of these models it was observed that the estimated were in good agreement with the observed data and the two models were slightly similar. This has led to choose one of the two models to be applied for all stations of Rwanda where measures of sunshine duration exist but facilities of recording global solar data do not exist. The estimated data can further be used in the design and estimation of performance of solar systems in Rwanda.

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NOMENCLATURE

Astronomical Quantities and Solar Quantities

$\delta = (23.5\frac{\pi}{180})\sin(2\pi(284 + J)/365)$: Solar declination (radian)

$J = 1, 365$, Julian day

$\phi = (\frac{2\pi}{360}) \times$ Latitude: Latitude at the place (radian)

$\omega_s = \arccos(-\tan\phi\tan\delta)$: Sunset hour angle (radian)

$\pi = 4.0 \times \arctan(1.0)$

$I_0 = 1367$ W m^{-2}: Solar Constant

R_0: Extra terrestrial solar radiation (Wh/m²/day)

$\overline{R}_0$: Monthly average daily extra terrestrial solar radiation (Wh/m²/day)

R_G: Daily global solar radiation on horizontal surface (Wh/m²/day)

$\overline{R}_G$: Monthly average daily global solar radiation on horizontal surface (Wh/m²/day)

$S_0 = \frac{2}{15}\omega_s\frac{180}{\pi}$ Day length

$\bar{S}_0 = \frac{2}{15}\omega_s\frac{180}{\pi}$: Monthly average day length

S: Daily sunshine hours

$\bar{S}$: Monthly average daily aunshine hours

Statistics Quantities

α_1, α_2, α_3, α_4, α_5,: Coefficients of regressions

$Qmes_i$: Measured quantity

$Qest_i$: Estimated quantity

$\overline{Qest}_i = \frac{1}{N-1}\sum_{i=1}^{N} Qest_i$: mean of $Qmes_i$, i = 1, N

$\overline{Qmes} = \frac{1}{N-1}\sum_{i=1}^{N} Qmes_i$: mean of $Qest_i$, i = 1, N

$R = \frac{\sum(Qmes_i - \overline{Qmes})(Qest_i - \overline{Qest})}{\sqrt{\sum(Qmes_i - \overline{Qmes})^2 \sum Qest_i - \overline{Qest})^2}}$: Correlation coefficient between $Qmes_i$ and $Qest_i$ quantities

R^2: Coefficient of determination

$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(Qmes_i - Qest_i)^2}{N}}$: Root mean square error

$RRMSE = \frac{RMSE}{\overline{Qmes}}$: Relative root mean square error

N: Number of observations

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