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Estimation of Solar Radiation Incident on Horizontal and Tilted Surfaces For 7 Colombian Zones

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Abstract: ***This paper discusses a procedure that was adopted for the development of a linear regression model for estimating solar radiation on horizontal surfaces for 7 Colombian zones. The correlations, the simulated global solar radiation on tilted surface and the simulated diffuse solar radiation on a horizontal surface for each zone are shown. The values of sunshine-hours and the solar radiation were taken from January 2012 to January 2013. The solar radiation values obtained were compared with the measured values. The obtained mean absolute percentage error was below 5%. The results of the global solar radiation show that the areas of greatest solar potential are Tibú> Baranoa> ICP> GRB> Morichal> Castilla> Guamues and the months of the year with the highest solar radiation are June, July and August.***

KeyWords: solar energy, solar radiation, Angstrom constants, empirical models.

INTRODUCTION

Renewable energy sources are strongly dependent on the microclimate, weather conditions and climatological phenomena. For this reason any application requires an assessment of the resource. This evaluation comprises the determination of the amount of available energy to be used in an application (Usually this is done from on-site measurements).

Solar systems use different components of solar radiation, so that assessment may require different measurement systems. Similarly, the level of detail with which should be known each component can be very different from one application to another (solar photovoltaic or solar thermal).

The assess of the solar potential of Colombia was made mainly using information from IDEAM's meteorological stations. This information is processed to be transformed from meteorological information to energy information. Although this has been a breakthrough in the estimation of energy resources, experts recommend site measurement before sizing a solar or wind project.

Considering the above, Ecopetrol had made the measurement of meteorological variables required for wind or solar projects in 13 zones (where it has operational processes). These zones are: Alisales, Ayacucho, Araguaney Apiay Baranoa, Castilla, GRB, Guamues, Herveo, ICP, Morichal, Manizales and Tibú. This paper only provides the results for zones that showed usable solar potential..

Theorical Considerations

Extraterrestrial Radiation on a Horizontal Surface

The solar extraterrestrial radiation (KWh/m^2) is given by equation 1 [1]:

$$\overline{H_O} = I_{sc}\frac{24}{\pi}\left[1 + 0.033\cos\frac{360n}{365}\right]\left[\frac{\pi\omega_S}{180}\sin\phi\sin\delta + \cos\phi\cos\delta\cos\omega_s\right] \quad (1)$$

Where: I_{Sc} is the solar constant with a value of 1.367 w/m^2, δ is the declination angle, ϕ is the latitude of the location, n is the Julian day number and ω_s is the sunset hour angle.

The Julian day number, n, is calculated using the formula presented in [2] and the declination angle is given by following equation [3]:

$$\delta = 23.45\sin\left[\frac{360}{365}(n + 284)\right] \quad (2)$$

The sunset hour angle can be calculated by:

$$\varpi_s = \arccos(-tan\phi \cdot tan\delta) \quad (3)$$

ESTIMATION OF MONTHLY GLOBAL RADIATION ON A HORIZONTAL SURFACE

There are many methods, which have been devised to predict the amount of solar radiation reaching the Earth's surface at a given location. The method used in this paper is the one developed by Angstrom [4]:

$$\frac{\overline{H}}{\overline{H_0}} = a + b\frac{n_d}{N_m} \quad (4)$$

where: a y b are empirical constants, n_d is the monthly average daily hours of bright sunshine and N_m is the monthly average of the maximum possible daily hours of bright sunshine. Nm is given by equation 5 [1].

$$N_m = \left[\frac{2}{15}\right]\varpi_s \qquad (5)$$

ESTIMATION OF MONTHLY AVERAGE DAILY RADIATION ON A TILTED SURFACE

The monthly average daily radiation is calculated using the equation 6 [5]:

$$\overline{H_\beta} = \bar{H}\left[1-\frac{\overline{H_d}}{\bar{H}}\right]\bar{R}_b + \bar{H}_d\left[\frac{1+\cos\beta}{2}\right] + \bar{H}\rho_r\left[\frac{1-\cos\beta}{2}\right] \qquad (6)$$

Where: $\bar{H}_d$ is the diffuse component of total global radiation, $\bar{R}_b$ is the monthly average daily geometric factor, β is the slope of the surface and ρ_r is the surrounding diffuse reflectance for the total solar radiation taking from [1].

The geometric factor ($\bar{R}_b$) is calculated from equation 7:

$$\bar{R}_b = \frac{\cos(\phi-\beta)\cos\delta\sin\omega_m + \left(\pi/_{180}\right)\omega_m\sin(\phi-\beta)\sin\delta}{\cos\phi\cos\delta\sin\omega_m + \left(\pi/_{180}\right)\omega_m\sin\phi\sin\delta} \qquad (7)$$

where w_m is the effective surface sunset hour angle and corresponds to the smaller value from:

$$\omega_m = \cos^{-1}(-\tan\phi\tan\delta)$$

(8)

$$\omega_m = \cos^{-1}(-\tan(\phi-\beta)\tan\delta)$$

METHODOLOGY

PROCEDURE FOR THE CALCULATION OF MONTHLY AVERAGE DAILY RADIATION ON HORIZONTAL SURFACE

The monthly average global solar radiation was calculated using data from 7 meteorological stations (Table 1) over the period between January 2012 and January 2013.

Table 1. Location of the 7 meteorological stations

STATION NAME	STATE	LATITUDE (SOUTH)		LONGTUDE (WEST)		ALTITUDE (m)
Castilla	Meta	4°	4'	73°	22'	467
GRB	Santander	7°	4'	73°	51'	81
Guamues	Putumayo	0°	38'	77°	02'	300
ICP	Santander	7°	00'	73°	03'	959
Morichal	Casanare	5°	16'	72°	17'	350
Tibú	Norte de santander	8°	30'	72°	36'	75
Baranoa	Atlántico	10°	51'	74°	54'	50

The calculation of the solar radiation extraterrestrial horizontal surface was calculated using the equation (1). The declination angle (δ) and the sunset hour angle (ω_s), were calculated using equations (2) and (3). For known the value of sunset hour angle, N_m is obtained from equation (5). Then with assumed monthly average daily hours of bright sunshine (n_d), the n_d / N_m ratio is calculated. The regression coefficients "a" and "b" were obtained from a graphical plot of H/Ho and n_d/N_m, with "a" as intercept on the H/Ho axis and "b" as the gradient.

To evaluate the developed model for each zone, three error statistics were used, namely, the mean absolute percentage error (MAPE), mean bias error (MBE) and root mean square error (RMSE). The MAPE is an indicator of accuracy in which it usually expresses accuracy as a percentage, MBE is an indicator for the average deviation of the predicted values from the measured data and RMSE provides information on the short-term performance of the models and is a measure of the variation of the predicted values around the measured data [5]:

$$MBE = \frac{1}{n}\sum_{i=1}^{n} H_{pi} - H_i \qquad (8) \qquad (9)$$

$$MAPE = \frac{1}{n}\sum_{i=1}^{n}\frac{H-H_p}{H} \qquad (10)$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(H_{pi}-H_i)^2} \qquad (11)$$

Where: H is the real value, Hp is the predicted value and n is the number of fitted points.

PROCEDURE FOR THE CALCULATION OF MONTHLY AVERAGE DAILY RADIATION ON TILTED SURFACES

The first step to calculate the average monthly solar radiation on tilted surface is to calculate R_b using equation (7) and the relationship H_d/H from the measured data, or using any of the correlations presented in [6]. In this work, the two methods for H_d/H ratio calculation were used. The equation used (equation 12) applies for ω_s>81.4° and $0.3 \leq H/H_o \leq 0.8$. To evaluate the results, the values of MAPE%, MBE and RMSE were calculated (equations 9 - 11).

$$\frac{\overline{H_d}}{\overline{H}} = 1.311 - 3.022\frac{\overline{H}}{\overline{H_o}} + 3.43\left[\frac{\overline{H}}{\overline{H_o}}\right]^2 - 1.82\left[\frac{\overline{H}}{\overline{H_o}}\right]^3 \quad (12)$$

For known R_b and H_d/H ratio, monthly average daily radiation on tilted surface was calculated. The tilted angle (β) is considered as equal to the latitude of respective places.

RESULTS AND DISCUSSION

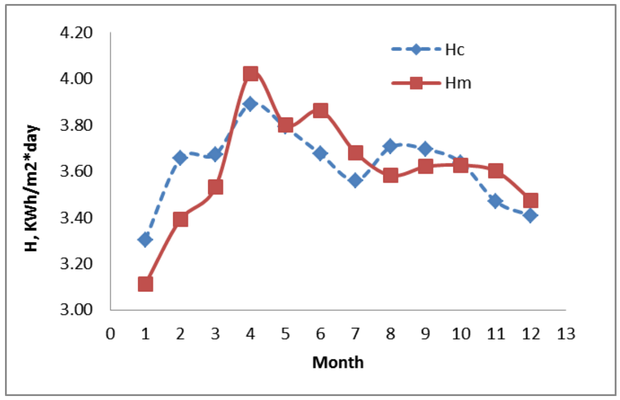
DETERMINATION OF THE ANGSTROM CONSTANTS

Values of regression constants, along with the correlation coefficients (R^2) and the values of the MPE, MAPE and RMSE for the 7 zones are summarized in Table 2.

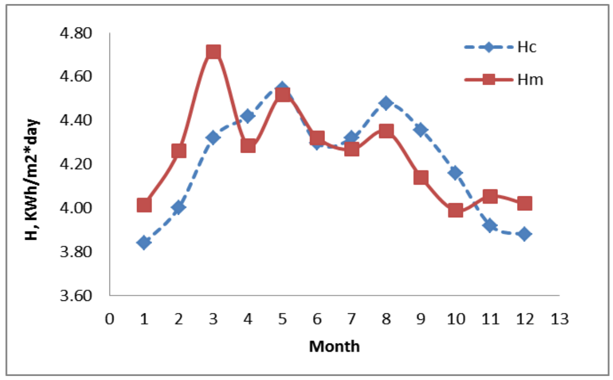
Table 2. Regression constants and the corresponding values of MAPE, MBE and RMSE.

STATION NAME	a	b	R^2	MAPE, %	MBE	RMSE
Castilla	0.2281	0.2397	0.90	3.42	0.01	0.14
GRB	0.2877	0.2032	0.88	3.62	-0.03	0.18
Guamues	0.1099	0.6795	0.93	3.03	0.07	0.12
ICP	0.171	0.5209	0.93	4.06	-0.06	0.21
Morichal	0.1939	0.3983	0.89	2.66	0.01	0.13
Tibú	0.1332	0.5177	0.92	3.66	0.05	0.20
Baranoa	0.2203	0.3353	0.97	2.04	0.00	0.09

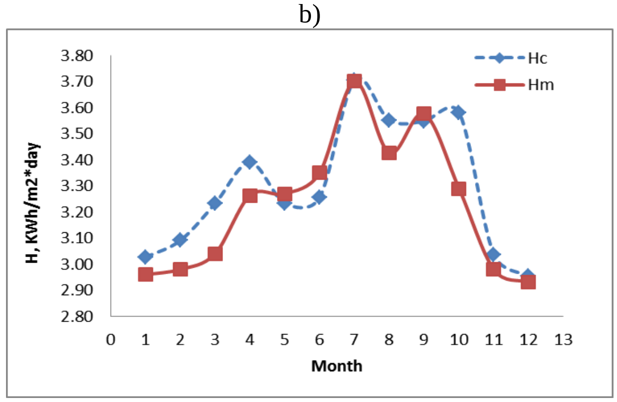
Results presented show that regression coefficients are higher than 0.89. That means there is a good fitting between the clearness index (H/Ho) and the relative possible number of sunshine hours (n/N) for all the analyzed zones. Figure 1 shows the comparison between observed and predicted values of monthly average daily global solar radiation (H).



a)



b)



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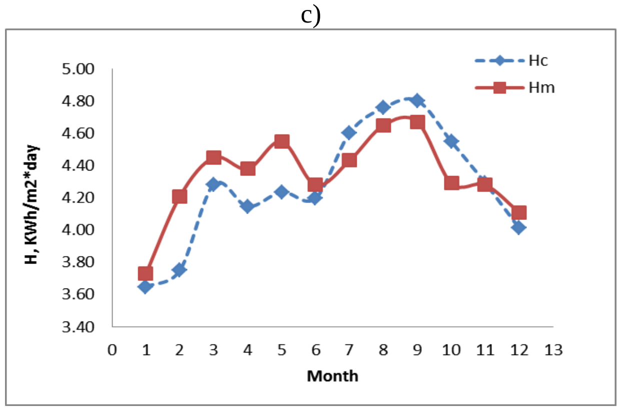

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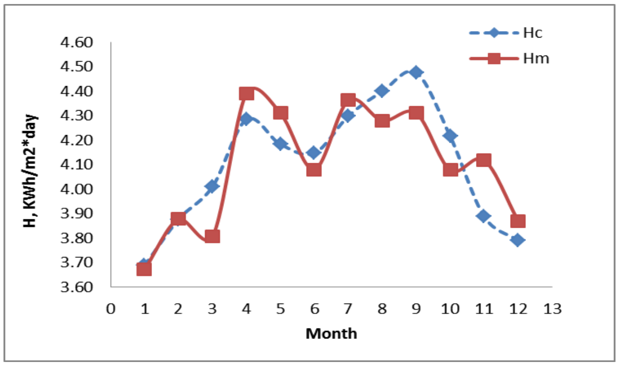

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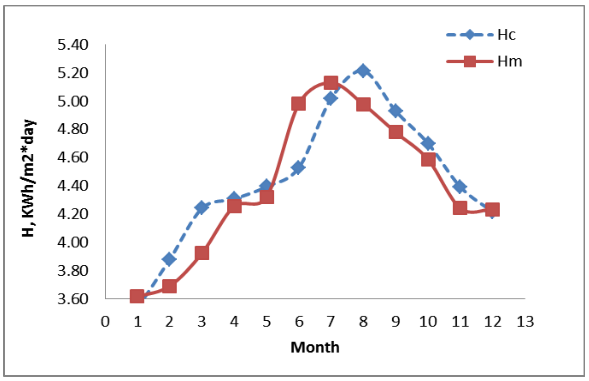

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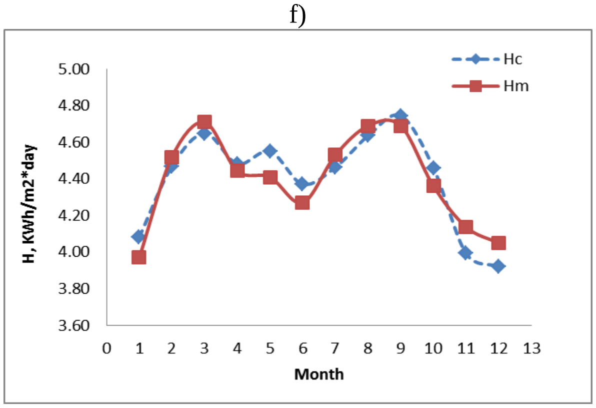

g)

Figure 1. Comparison between observed (Hm) and predicted (Hc) values of H a) Castilla; b) GRB; c) Guamues; d) ICP; e) Morichal; f) Tibú y g) Baranoa.

The results show that in case of not having measured values of global solar radiation on a horizontal surface, could be used the Angstrom equations obtained in this study.

ESTIMATION OF THE MONTHLY AVERAGE DAILY GLOBAL SOLAR RADIACÓN ON TILTED SURFACE

The first step to calculate the global solar radiation on tilted surface is to calculate the ratio Hd/H. Table 3 shows the values of MAPE, MBE and RMSE obtained from calculated data using equation (12). As it is noted, there is a good approximation of the calculated data; it means that this correlation can be used to calculate the ratio H_d / H, if there are not any measured data of diffuse solar radiation.

Table 3. Values of MAPE, MBE and RMSE for H_d/H ratio.

STATION	MAPE, %	MBE	RMSE
Castilla	4.82	0.01	0.03
GRB	4.21	0.01	0.03
Guamues	4.18	-0.02	0.03
ICP	4.64	0.00	0.02
Morichal	3.54	0.00	0.02
Tibú	4.64	-0.02	0.03
Baranoa	4.09	0.00	0.02

Table 4 presents the values of global solar radiation and monthly average diffuse radiation on a horizontal surface for the 7 analyzed areas.

Table 4. Monthly global and diffuse radiation for the 7 zones.

	Castilla		GRB		Guamues		ICP		Morichal		Tibú		Baranoa	
	H	H_d	H	H_d	H	H_d	H	H_d	H	H_d	H	H_d	H	H_d
Mes 1	3.11	2.15	4.01	2.14	2.96	2.32	3.73	1.95	3.67	2.16	3.61	2.09	3.97	1.98
Mes 2	3.39	2.21	4.26	2.22	2.98	2.30	4.21	2.10	3.88	2.24	3.69	2.05	4.52	2.15
Mes 3	3.53	2.27	4.71	2.07	3.04	2.31	4.45	2.12	3.81	2.10	3.92	2.08	4.71	2.08
Mes 4	4.02	2.21	4.29	2.25	3.26	2.28	4.38	2.18	4.39	2.23	4.26	2.10	4.44	2.05
Mes 5	3.80	2.24	4.52	2.12	3.27	2.24	4.55	2.13	4.31	2.15	4.32	2.05	4.41	2.09
Mes 6	3.86	2.16	4.32	2.20	3.35	2.22	4.28	2.16	4.08	2.21	4.98	2.10	4.27	2.11
Mes 7	3.68	2.19	4.27	2.18	3.70	2.26	4.43	2.06	4.36	2.17	5.13	2.08	4.53	2.09
Mes 8	3.58	2.24	4.35	2.12	3.43	2.29	4.65	2.02	4.28	2.09	4.98	2.10	4.69	2.10
Mes 9	3.62	2.20	4.14	2.15	3.58	2.27	4.67	2.02	4.31	2.15	4.78	2.20	4.69	2.10
Mes 10	3.63	2.18	3.99	2.17	3.29	2.24	4.29	2.12	4.08	2.17	4.59	2.25	4.36	2.17
Mes 11	3.60	2.18	4.05	2.12	2.98	2.28	4.28	2.25	4.12	2.12	4.24	2.10	4.14	2.18
Mes 12	3.48	2.15	4.02	2.24	2.93	2.23	4.11	2.27	3.87	2.24	4.23	2.10	4.05	2.25

Table 5 presents the results of global solar radiation on tilted surface. It is noted that between June and August, global solar radiation increases in most areas. The areas with the greatest potential are Tibu> Baranoa> ICP> GRB> Morichal> Castilla> Guamues.

Table 5. Monthly average daily solar radiation on tilted surface.

	Castilla	GRB	Guamues	ICP	Morichal	Tibú	Baranoa
Mes 1	3.11	4.01	2.96	3.73	3.67	3.61	3.97
Mes 2	3.39	4.26	2.98	4.21	3.88	3.69	4.52
Mes 3	3.53	4.71	3.04	4.45	3.81	3.92	4.71
Mes 4	4.02	4.29	3.26	4.38	4.39	4.26	4.44
Mes 5	3.80	4.52	3.27	4.55	4.31	4.32	4.41
Mes 6	3.86	4.32	3.35	4.28	4.08	4.98	4.27
Mes 7	3.68	4.27	3.70	4.43	4.36	5.13	4.53
Mes 8	3.58	4.35	3.43	4.65	4.28	4.98	4.69
Mes 9	3.62	4.14	3.58	4.67	4.31	4.78	4.69
Mes 10	3.63	3.99	3.29	4.29	4.08	4.59	4.36
Mes 11	3.60	4.05	2.98	4.28	4.12	4.24	4.14
Mes 12	3.48	4.02	2.93	4.11	3.87	4.23	4.05

CONCLUSIONS

The study established that the linear model proposed by Angstrom can be applied to the data of the 7 analyzed areas of Colombia. This is of great importance since it is not always possible to have measured data for sizing solar processes. Likewise, it is concluded that the model developed by Erbs et al and presented in [6] applies well for the calculation of diffuse solar radiation on a horizontal surface in the analyzed areas.

From the measured data it was established that global solar radiation in most of the analyzed areas, increases between June and August months. It was also determined that the areas with the greatest potential are Tibú> Baranoa> ICP> GRB> Morichal> Castilla> Guamues.

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