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ESTIMATION OF ANNUAL SOLAR RADIATION ON A TILTED SURFACE AS A FUNCTION OF THE SLOPE ANGLE

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Abstract. *The total annual energy received in a tilted surface can present significant differences, the slope angle playing an important role. This paper performed an analysis of the influence of the surface slope on the annual energy received. It was developed a model to determine the annual solar radiation incident on a surface located in Belo Horizonte, in the southern hemisphere. The slope of the surface was varied every 5 °, for different levels of clearness index. The results indicated that the values obtained for the total annual energy, the total energy in the summer and the total energy in winter are in good agreement with literature data.*

Keywords: *Solar radiation, Tilt angle, Annual energy.*

1. INTRODUCTION

The world population has been significantly increasing over the last decades. Since the human quality of life is strongly related to the consumption of energy, the energy demand has been multiplied and can no longer be satisfied by usual energy technologies. Renewable sources are required to complement traditional energy sources. Nowadays, there is a higher penetration of renewable resources in the energy portfolios of several communities, mainly wind and solar energy. For a particular location, the design and performance evaluation of solar technologies depend on reliable input data of solar radiation. For many developing countries, solar radiation measurements are not easily available, making of paramount importance the development of methods to estimate the solar radiation (El-Sebaii et al, 2010).

In practical applications, it is essential to calculate the daily beam radiation on a tilted surface, and the widely used correlation for estimating daily beam radiation on a tilted surface is the one suggested by Liu and Jordan (Yang et al, 2012). Determination of monthly and annual solar radiation on tilted surfaces is also of fundamental importance on the design of solar applications. Several papers have been developed on the measurement and estimation of solar radiation in the world. Jiménez (1981) examined fluctuations of the daily solar radiation during 3 years at Bellaterra, within the metropolitan area of Barcelona. Akrawi et al (1988) determined monthly averages of hourly irradiances on tilted flat surfaces, based on experimental data for Baghdad. The authors also evaluated the total annual irradiation for several inclinations. Optimum slopes corresponding to a maximum incident energy were determined for each month of the year. Ahmad and Husain (1986) evaluated annual and monthly averages of solar radiation for Karachi, based on 25 years of experimental data for a tilted surface.

Solar collectors need to be tilted at the correct angle to maximize the performance of the system (Shariah et al, 2002). Since solar radiation varies with geographic latitude, season and time of a day due to the various sun positions under the unpredictable weather conditions (Li et al, 2008), the optimum tilt angle depends on the same parameters. Several papers have been developed on the determination of the optimum tilt angle of solar collectors.

Yakup and Malik (2001) evaluated the tilt angle for the maximum total radiation in a solar collector in Brunei Darussalam. The results showed that changing the tilt angle 12 times a year maintains approximately the total amount of solar radiation near the maximum value found by changing the tilt angle daily to its optimum value. The authors also concluded that this procedure promotes a yearly gain in solar radiation of 5% more than the case of a solar collector fixed on a horizontal surface. Skeiker (2009) adopted the same procedure for a solar collector in Syria, and found similar results. The main difference was the yearly gain over a fixed solar collector, of about 30%. Shariah et al (2002) studied the optimum inclination angles for a thermosyphon solar water heater installed in northern and southern parts of Jordan. The annual solar fraction of the system was used as an indicator. The results showed that the optimum tilt angle is about the latitude + (0 to 10°) for the northern region and the absolute value of latitude + (0 to 20°) for the southern region. Gunerhan and Hepbasli (2007) determined the optimum tilt angle of solar collectors for building applications in Turkey. The authors concluded that the best orientation for solar collectors in Turkey is due south and they recommended that the solar collector should be mounted at the monthly average tilt angle and the slope adjusted once a month. Duffie and Beckman (2006) developed a mathematical model for the estimation of the average solar radiation on various orientations on an annual basis, for fixed conditions. The authors assumed a latitude of 45°N, an azimuth angle of 0°, and a ground reflectance of 0.2. Although the clearness index is strongly affected by the location (Ahwide, Spena and El-Kafrawy, 2013), Duffie and Beckman assumed a fixed value of 0.5. The results showed that the maximum energy is obtained for a tilted angle equal to the absolute value of the location latitude. The maximum is broad and the changes in annual total energy are less than 5% for slopes of 20° more or less than the optimum. However, it is not always desired to collect the maximum energy throughout the year. In some cases, it is preferable to maximize the energy collected in a specific season, like in the winter, with lower levels of solar radiation. Duffie and Beckman (2006) showed that the slope corresponding to the maximum estimated total winter energy is approximately 15° more than the absolute value of the latitude. Moreover, for maximum summer availability, the slope should be approximately 10 to 15° less than the absolute value of latitude. The slopes are not critical; deviations of 15° result in reduction of the order of 5%.

In this paper, it is evaluated the energy received by a tilted surface in Belo Horizonte, Brazil (latitude of 19.93°S), for various tilt angles. It is intended to determine the maximum solar radiation during the summer, winter and throughout the year.

2. METHODOLOGY

The energy received by a tilted surface depend on several parameters. For a given solar collector, the most important are the hour and day of the year, the location latitude, the clearness index and the tilt angle. In this paper, it is estimated the total energy received in a tilted surface, based on the model described by Duffie and Beckman (2006). The average solar radiation received by a surface on a daily basis is equal to the sum of the beam solar radiation (first term of Eq. 1), the diffuse solar radiation (second term) and the reflected solar radiation from the surroundings (third term):

$$H_T = R_b\,(H - H_d) + H_d\left(\frac{1 + \cos\beta}{2}\right) + H\rho_g\left(\frac{1 - \cos\beta}{2}\right) \tag{1}$$

H and H_d represent, respectively, the total and diffuse components of the daily solar radiation on a horizontal surface. The total solar energy (Eq. 2) is determined as a function of the clearness index - K_T and the extraterrestrial radiation on a horizontal surface - H_0.

$$H = K_T H_0 \tag{2}$$

The extraterrestrial radiation on a horizontal surface is given by Eq. 3:

$$H_0 = \frac{24 \times 3600\, G_{sc}}{\pi}\left(1 + 0.033\cos\frac{360n}{365}\right)\left(\cos\phi\cos\delta\sin\omega_s + \frac{\pi\omega_s}{180}\sin\phi\sin\delta\right) \tag{3}$$

G_{sc} is the solar constant (assumed as 1367 W/m^2), n is the day of the year, ϕ is the location latitude, δ is the declination (Eq. 4), and ω_s is the sunset hour angle (Eq. 5).

$$\delta = 23.45\sin\left(360\frac{284 + n}{365}\right) \tag{4}$$

$$\cos\omega_s = -\frac{\sin\phi\sin\delta}{\cos\phi\cos\delta} = -\frac{\tan\phi}{\tan\delta} \tag{5}$$

The diffuse component of the solar radiation on a horizontal surface H_d is obtained using Erbs et al (1982) correlations (Eq. 6 and Eq. 7):

$$\text{If } \omega_s \le 81.4°,\ \frac{H_d}{H} = \begin{cases} 1.0 - 0.2727K_T + 2.4495K_T^2 - 11.9514K_T^3 + 9.3879K_T^4 & for\ K_T < 0.715 \\ 0{,}143 & for\ K_T \ge 0.715 \end{cases} \tag{6}$$

$$\text{If } \omega_s > 81.4°,\ \frac{H_d}{H} = \begin{cases} 1.0 + 0.2832K_T - 2.5557K_T^2 + 0.8448K_T^3 & for\ K_T < 0.722 \\ 0{,}175 & for\ K_T \ge 0.722 \end{cases} \tag{7}$$

R_b is the ratio between the average daily beam radiation on the tilted surface to that on a horizontal surface (Eq. 8).

$$R_b = \frac{\cos(\emptyset+\beta)\cos\delta\sin\omega_s' + \left(\frac{\pi}{180}\right)\omega_s'\sin(\emptyset+\beta)\sin\delta}{\cos\emptyset\cos\delta\sin\omega_s + \left(\frac{\pi}{180}\right)\omega_s\sin\emptyset\sin\delta} \tag{8}$$

β is the tilt angle and ω_s' is the sunset hour angle for the tilted surface for the mean day of the month (Eq. 9):

$$\omega_s' = min\begin{bmatrix}\cos^{-1}(-\tan\emptyset\tan\delta)\\ \cos^{-1}(-\tan(\emptyset+\beta)\tan\delta)\end{bmatrix} \tag{9}$$

The previous analysis is performed for each day of the year. To determine the annual energy, the corresponding values of each day of the year were added.

The calculations were performed for a surface positioned in the city of Belo Horizonte, Brazil, with latitude of 19.93°S. An azimuth angle of 180° was used, as indicated for locations in the southern hemisphere. The surface slope angle was varied between 0° and 90°, with increments of 5°.

The clearness index is the ratio of the radiation incident on a horizontal surface and the extraterrestrial radiation, i.e., it represents a measure of the maximum radiation incident on a surface. This parameter is random and may vary from year to year for a given location. Different ways to estimate the clearness index are available (Woyte et al, 2007; Ahwide et al, 2013; Hassan, 2014) and its efficiency to a generic location is debatable. In the present work three different methodologies are proposed: in the first situation, the standard year data provided by INMET (National Institute of Meteorology) were used to determine the daily incident radiation on a horizontal surface. Then, the daily extraterrestrial radiation was calculated. The ratio of these values has provided a daily value for K_T. In a second situation, a similar procedure was used, but the monthly radiation and extraterrestrial radiation were used. Finally, in a third situation, it was determined an average value of K_T for the full year. This approach was adopted because it resembles the procedure established by Duffie and Beckman (2006), which adopted a constant value of K_T throughout the year. The authors adopted the average value of 0.50, considered by them a typical value for many temperate climates. In this study, as the results were obtained for a specific location, it was decided to calculate an average value that best represents the radiation at this location. In all simulations for clearness index, the INMET data were used, which defines a standard year to various locations, including Belo Horizonte. The standard year (TMY - Typical Meteorological Year) consists on the collection and analysis of meteorological data on a long term period.

3. RESULTS AND DISCUSSION

The results were obtained for the city of Belo Horizonte (Brazil), with latitude of 19.93°S, considering an azimuthal angle of surface of 180° and the clearness index chosen as the monthly index of the standard year. Table 1 shows the tabulated values of annual total energy and the composition of this energy for each season due to the slope of the collector.

Table 1. Annual total and by season energy (GJ/m^2)

	0°	5°	10°	15°	20°	25°	30°	35°	40°	45°	50°	55°	60°	65°	70°	75°	80°	85°	90°
H total	6,88	7,26	7,75	7,80	7,44	7,26	7,54	7,87	7,73	7,23	6,96	7,14	7,31	6,99	6,36	6,04	6,15	6,20	3,71
H summer	1,84	1,84	1,84	1,82	1,79	1,76	1,73	1,70	1,66	1,61	1,56	1,52	1,47	1,42	1,35	1,29	1,25	1,21	0,77
H autumn	1,55	1,70	1,90	1,94	1,84	1,80	1,93	2,08	2,05	1,90	1,84	1,94	2,03	1,95	1,75	1,67	1,74	1,78	1,03
H winter	1,67	1,89	2,18	2,22	2,04	1,97	2,16	2,38	2,35	2,11	2,01	2,17	2,33	2,21	1,92	1,80	1,93	2,02	1,15
H spring	1,82	1,83	1,84	1,82	1,78	1,74	1,72	1,71	1,67	1,60	1,55	1,51	1,48	1,42	1,34	1,28	1,24	1,20	0,77

Figures 1, 2 and 3 were obtained with the data presented in Table 1. Figure 1 represents the data for each 5°, Fig. 2, for each 15° and Fig. 3, for each 30°.

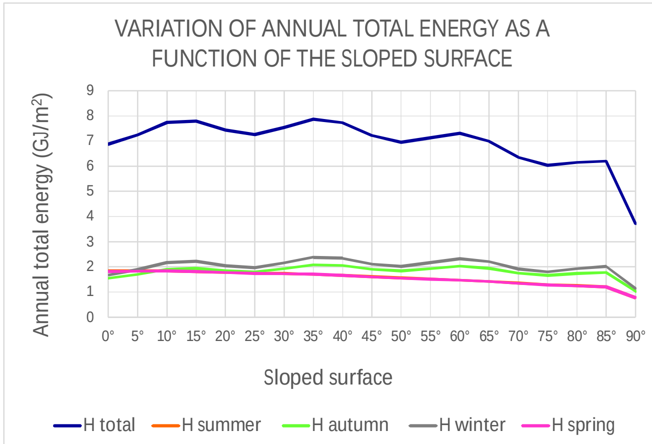

Figure 1. Annual total energy and of the four seasons for sloped surface ranging from 0° to 90° in increments of 5°

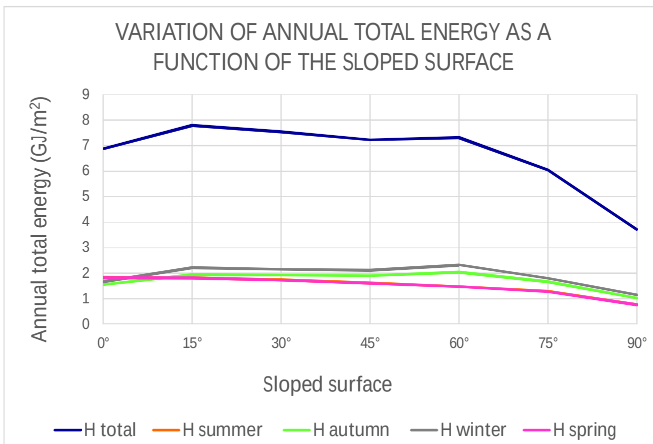

Figure 2. Annual total energy and of the four seasons for sloped surface ranging from 0° to 90° in increments of 15°

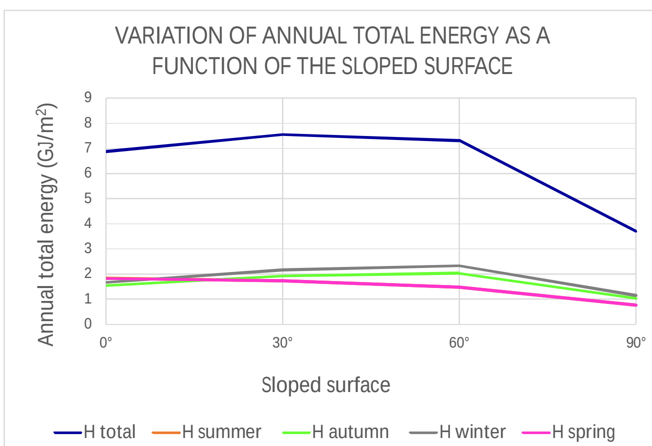

Figure 3. Annual total energy and of the four seasons for sloped surface ranging from 0° to 90° in increments of 30°

When the increment of the slope angle is 5° (Fig. 1), it can be seen that the curves do not present homogeneous arcs as the curves presented by Duffie and Beckman (2006). However, as the increment increase (Fig. 2 and 3), the profiles of the curves resemble the curves presented by the authors. Thus, the calculations and analyzes for this paper were performed to an interval of 5°, but the curves were plotted for an interval of 30°, in order to facilitate visual comparison with the curves presented in literature.

It can be seen that the energy received in summer and spring are very similar, and lower than the energy received during winter and autumn.

Results presented below were obtained for Belo Horizonte, using an azimuthal surface angle of 180° and a tilt angle varying from 0° to 90°. Only the results for summer and winter were shown. The clearness index was assumed as:

Condition 1: A daily value, based on INMET data for Belo Horizonte;

Condition 2: A monthly value, based on INMET data for Belo Horizonte;

Condition 3: A constant value, $K_T = 0.56$, assumed as the average value for the TMY for Belo Horizonte;

Condition 4: A constant value, $K_T = 0.56$, assumed as the average value for the TMY for Belo Horizonte. However, the calculations were performed for a location with latitude of 45°S. This condition was assumed to approximate the parameters used by Duffie and Beckman (2006).

Table 2 summarizes the results for condition 1, and Fig. 4 presents these results in a graphic form.

Table 2. Annual total, summer and winter energy (GJ/m²) to ϕ = -19.93°, γ = 180° due to the surface tilt, whereas K_T = daily index

	0°	5°	10°	15°	20°	25°	30°	35°	40°	45°	50°	55°	60°	65°	70°	75°	80°	85°	90°
H total	6,89	7,39	8,08	8,12	7,56	7,27	7,69	8,19	7,99	7,27	6,90	7,23	7,55	7,14	6,28	5,88	6,15	6,34	3,71
H summer	1,84	1,87	1,92	1,90	1,80	1,74	1,75	1,77	1,71	1,59	1,51	1,51	1,50	1,42	1,29	1,21	1,21	1,20	0,73
H winter	1,68	1,93	2,26	2,31	2,09	2,00	2,22	2,49	2,44	2,16	2,05	2,24	2,43	2,29	1,95	1,82	1,98	2,09	1,19

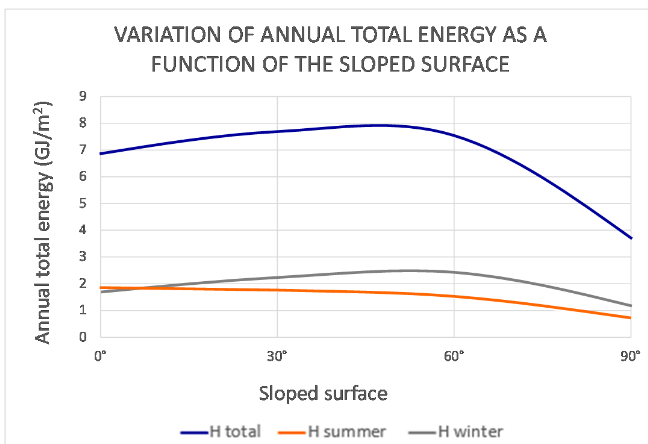

Figure 4. Annual total, summer and winter energy to ϕ = -19.93°, γ = 180° due to the surface tilt, whereas K_T = daily index

Table 3 summarizes the results for condition 2, and Fig. 5 presents these results in a graphic form.

Table 3. Annual total, summer and winter energy (GJ/m²) to ϕ = -19.93°, γ = 180° due to the surface tilt, whereas K_T = monthly index of the standard year

	0°	5°	10°	15°	20°	25°	30°	35°	40°	45°	50°	55°	60°	65°	70°	75°	80°	85°	90°
H total	6,88	7,26	7,75	7,80	7,44	7,26	7,54	7,87	7,73	7,23	6,96	7,14	7,31	6,99	6,36	6,04	6,15	6,20	3,71
H summer	1,84	1,84	1,84	1,82	1,79	1,76	1,73	1,70	1,66	1,61	1,56	1,52	1,47	1,42	1,35	1,29	1,25	1,21	0,77
H winter	1,67	1,89	2,18	2,22	2,04	1,97	2,16	2,38	2,35	2,11	2,01	2,17	2,33	2,21	1,92	1,80	1,93	2,02	1,15

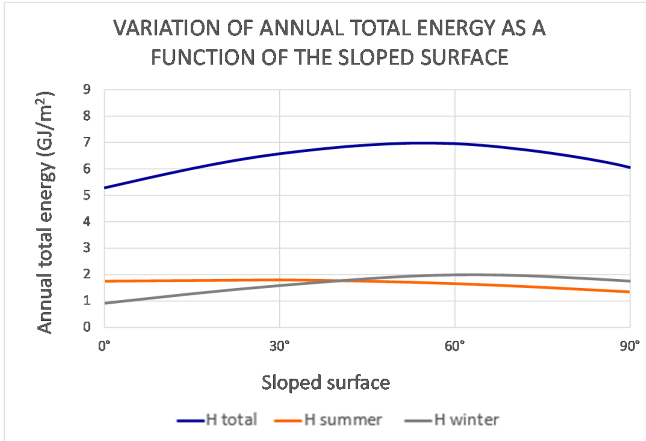

Figure 5. Annual total, summer and winter energy to ϕ = -19.93°, γ = 180° due to the surface tilt, whereas K_T = monthly index of the standard year

Table 4 summarizes the results for condition 3, and Fig. 6 presents these results in a graphic form.

Table 4. Annual total, summer and winter energy (GJ/m²) to ϕ = -19.93°, γ = 180° due to the surface tilt, whereas K_T = 0.56

	0°	5°	10°	15°	20°	25°	30°	35°	40°	45°	50°	55°	60°	65°	70°	75°	80°	85°	90°
H total	6,99	7,33	7,77	7,78	7,38	7,16	7,40	7,70	7,52	6,98	6,68	6,84	6,99	6,65	6,01	5,68	5,79	5,85	3,51
H summer	2,03	2,09	2,18	2,15	2,00	1,91	1,94	2,00	1,92	1,75	1,64	1,66	1,69	1,58	1,39	1,29	1,32	1,33	0,80
H winter	1,49	1,60	1,74	1,78	1,72	1,70	1,79	1,88	1,87	1,77	1,73	1,79	1,84	1,77	1,64	1,57	1,60	1,61	0,96

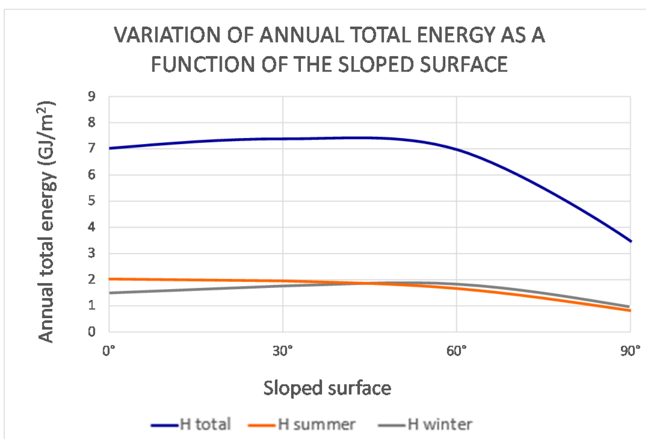

Figure 6. Annual total, summer and winter energy to ϕ = -19.93°, γ = 180° due to the surface tilt, whereas K_T = 0.56

Table 5 summarizes the results for condition 4, and Fig. 7 presents these results in a graphic form.

Table 5. Annual total, summer and winter energy (GJ/m²) to ϕ = -45°, γ = 180° due to the surface tilt, whereas K_T = 0.56

	0°	5°	10°	15°	20°	25°	30°	35°	40°	45°	50°	55°	60°	65°	70°	75°	80°	85°	90°
H total	4,91	5,05	5,17	5,27	5,37	5,44	5,50	5,53	5,55	5,56	5,54	5,50	5,44	5,37	5,28	5,17	5,05	4,91	4,76
H summer	1,73	1,74	1,74	1,75	1,76	1,76	1,75	1,73	1,71	1,70	1,68	1,64	1,60	1,56	1,53	1,48	1,43	1,37	1,33
H winter	0,74	0,80	0,86	0,91	0,94	0,98	1,02	1,06	1,08	1,10	1,11	1,13	1,14	1,14	1,13	1,12	1,11	1,10	1,07

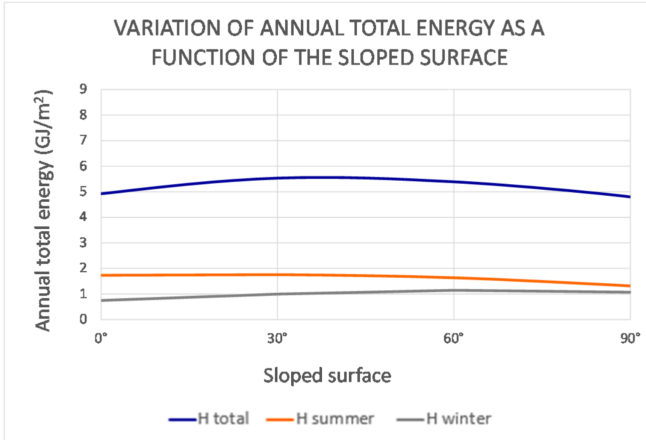

Figure 7. Annual total, summer and winter energy to ϕ = -45°, γ = 180° due to the surface tilt, whereas K_T = 0.56

Table 6 presents the slope angles for the maximum energy received in the surface. The expected maximum energy represents the optimum angles suggested from literature (Duffie and Bekman, 2006). The obtained maximum energy represents the values obtained from the model presented in this paper.

Table 6. Summary of the results obtained as a function of the collector surface slope

ϕ	Expected maximum energy			K_T	Obtained maximum energy		
	Total $\beta \cong \lvert\phi\rvert$	Summer $\beta \cong \lvert\phi\rvert$ - 15° to $\lvert\phi\rvert$ - 10°	Winter $\beta \cong \lvert\phi\rvert$ + 10° to $\lvert\phi\rvert$ + 15°		Total	Summer	Winter
-19,93°	≅ 20°	≅ 5 to 10°	≅ 30 to 35°	Daily	35°	10°	35°
				Monthly	35°	0°	35°
				Annual	15°	10°	35°
-45°	≅ 45°	≅ 30 to 35°	≅ 55 to 60°	Annual	45°	25°	60°

The main results can be expressed as:

- The adopted K_T influences directly on the results obtained.
- For the city of Belo Horizonte (latitude 19.93°S), the maximum range is broad. Furthermore, the variations of annual total energy are lower than 10% when evaluated slopes of approximately 20° from the optimal situation. For a latitude of 45°S, the maximum range is also broad and the variations of annual total energy are lower than 5% for slopes of approximately 20° from the optimal situation, as stated by Duffie and Beckman (2006).
- The maximum total energy obtained for the latitude of 19.93°S did not match the expected slope of the surface, i.e., $\beta=\lvert\phi\rvert$. However, analyzing the data of Tables 2, 3 and 4 it can be seen that the optimal values did not vary significantly in a range of approximately 20° from the optimal situation. For the latitude of 45°, the maximum energy was obtained for $\beta=\phi$, as predicted by Duffie and Beckman (2006).
- For the maximum summer energy received in Belo Horizonte, it was observed that conditions 1 and 3 matched the expected results from literature. For condition 2 (a monthly value for the clearness index), the maximum energy was obtained for a slope angle of 0°. However, analyzing the data from Tab. 3 it is seen that the change in energy in the tilted surface between 0 and 15° has nearly the same order of magnitude. For the latitude of 45°S, the maximum energy in the summer confirmed Duffie and Beckman (2006) statement, in which the maximum total energy is obtained for $\lvert\phi\rvert - 15°$.
- The maximum energy expected for winter, for the latitudes of 19.93°S and 45 °S, matched the statement that the maximum occurs when the tilt angle is approximately $\lvert\phi\rvert + 15°$.

4. CONCLUSIONS

In this paper, it was performed an analysis of the energy absorbed by a flat surface in Belo Horizonte, as a function of the slope angle. The results were compared to literature data, for the total energy absorbed during one year, and for the seasons. It was also evaluated the influence of the clearness index on the results. A daily, a monthly and a constant value were evaluated.

The annual terrestrial radiation received or received annual total energy is maximum when the slope surface of the collector is $\beta = \lvert\phi\rvert$, the maximum winter energy is maximum for $\beta = \lvert\phi\rvert + 15°$ and the maximum summer energy is maximum for $\beta = |\phi| - 15°$, corroborating the expected from literature. The influence of the clearness index is significant on the analysis.

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