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DEVELOPMENT OF SOFTWARE TO ESTIMATE THE SOLAR RADIATION ON FIXED SLOPED SURFACES

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Abstract. *Solar simulations provide a method for the study of solar energy systems. The use of these simulations allows control over the variables of the process, reducing the dependence on the local climate. It also makes possible to repeat several experiments under similar conditions, and tests under uncommon conditions. The development of these simulations requires a long-term (e.g. 20 years) meteorological data or data obtained from a reduced database and a set of empirical models. The majority of data available is given for the radiation on a horizontal plane. However, most applications use inclined surfaces for the absorption of radiation. For the appropriate use of this data for the simulation of radiation several correlations were developed to estimate the radiation on a tilted surface based on the radiation on a horizontal surface. Most correlations, however, have been developed using data from temperate climates and present discrepancies when used in tropical climates. In this work, it was developed a software to estimate the hourly radiation received by a inclined surface for the city of Belo Horizonte, Brazil. A meteorological data for the period of 2000 to 2009 was used. For the calculation of the radiation on a tilted surface correlations for tropical climate found in the literature were used. The verification of the software was made using cumulative radiation for 3-hour periods for the years of 2010 and 2012. The software generates a list with values of hourly and daily radiation for every day of the year for the desired surface orientation.*

Keywords: *Solar simulation, Sloped surface, solar radiation*

1. INTRODUCTION

The use of renewable sources for the generation of energy has presented a considerable growth on the past years. According to REN21 (2012), the average growth rate of global installed capacities for most renewable sources far exceeds those of fossil fuels, which usually present a growth rate of 3-5%. Amongst this sources wind and solar energies are the ones that present the highest rates of growth. In the period of 2006 to 2011 solar photovoltaic energy has showed a 58% increase in installed capacity, wind energy had a 26% increase and solar hot water/heating has shown an average 17% growth as can be seen in Fig. 1:

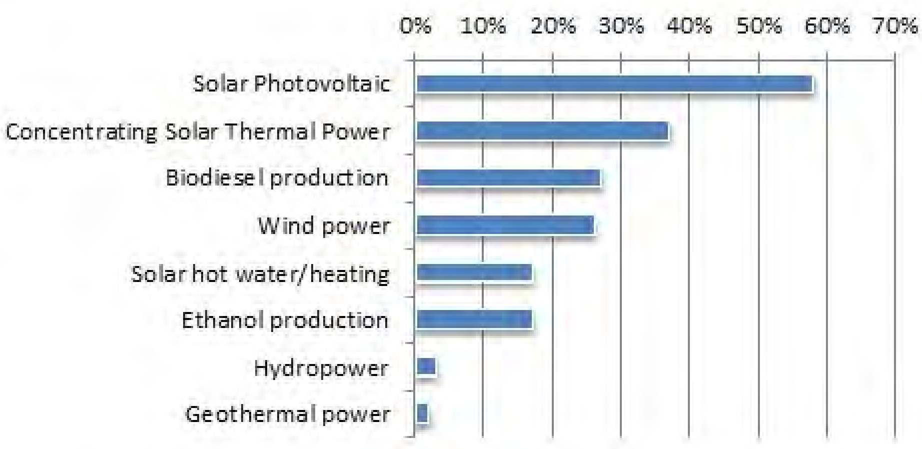

Figure 1. Average Annual Growth of Renewable Energy Capacity and Biofuels Production, 2006 - 2011. Adapted from REN21 (2012).

The use of solar simulations provide a way of reproducing some of the main conditions under which a solar collector operates and allows the study of solar energy systems in a controlled indoor environment reducing the influence of the climate variability in the analysis, allowing the test of different systems under the same circumstances and in a reduced

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amount of time. It also allows the study of the system for different locations and climates without the need of relocating the equipment. In order to develop this simulations for a particular region, past meteorological data must be used for an adequate estimation of the radiation in this region.

In this work, a software was developed in MATLAB for the estimation of radiation on a tilted surface for a region located at the southern hemisphere. The development of the software consisted in the selection of the most adequate correlations available in the literature for the calculation of the tilted and diffuse radiation on a city in South America. The software was tested comparing the obtained results with data from solar energy resource maps produced as part of the Solar and Wind Energy Resource Assessment(SWERA) project. In Brazil this project was coordinated by the Brazilian Institute for Space Research (INPE).

2. METEOROLOGICAL DATA

In order to simulate the global radiation received by a tilted surface a sequence of steps must be taken. The first step is the calculation of the hourly I_o and daily H_o extraterrestrial radiation, since their values are used as a reference for the maximum theoretical radiation received by a horizontal surface. Equations presented by Duffie and Beckman (2006) were used in the development of a software to calculate this parameters as a function of the geometry of the system, the day of the year n and hour angle ω (depends on the location and the local time). The second step consists in gathering and adapting the experimental data for the region and the solar collector configuration to be studied. The dataset size needed to perform a simulation depends on the type of study to be developed. If system dynamics under certain loads is the main purpose of the study, then a dataset of a few weeks is adequate for the simulation, given that it represents the range of conditions of interest (Duffie and Beckman, 2006). If the dataset is to be used for design purposes, a dataset of a full year is suggested. Duffie and Beckman (2006) presented two studies that proposed the adequate selection of an yearly dataset based on experimental measurements. The first study was developed by Klein *et al.* (1976) in which the concept of design year was developed and applied for data from 8 years. A design year, as proposed by Klein *et al.* (1976), is obtained by selecting among a set of months (e.g. Januarys) in the entire dataset the month with mean radiation closest to the mean for the entire period for each month of the year. The second study was developed by Hall *et al.* (1978) in which a set of Typical Meteorological Year (TMY) data was developed for 26 stations in the U.S. and additional locations based on 23 years of data. In this work 3 typical years for the global horizontal radiation were used in order to verify the best option to perform the simulation. The first dataset was obtained used by the software METEONORM and it was generated based on 17 years of data for the monthly total radiation. The second was obtained from the SWERA project, that generated the yearly values of mean monthly radiation as a function of the climate (temperature, relative humidity, cloud properties, etc) and the location. The design year concept presented by Klein *et al.* (1976) was used for the generation of the third dataset based on data for the city of Belo Horizonte. It was obtained from INPE , measured with the data collection platform (PCD) ID = 32513 located at Belo Horizonte, which consisted of mean ambient temperature, in degrees Celsius, and relative humidity, in %, measured every 3 hours and accumulated solar radiation in a horizontal surface, in MJ/m^2, with partial daily values every 3 hours (integrated value for the last 3 hour interval) for the period of 2000 to 2012. In order to obtain the daily radiation H, the radiation values were summed for each day. Days with missing data were marked as invalid through assignment of a negative value of radiation.

The values for the hourly radiation I were then obtained using the equations for the ratio of hourly radiation over daily radiation $r_T = I/H$ proposed by Collares-Pereira and Rabl (1979), based on the curves generated by Liu and Jordan(1960):

$$r_t = \frac{I}{H} = \frac{\pi}{24}(a + b\cos\omega)\frac{(\cos\omega - \cos\omega_s)}{(\sin\omega_s + \frac{\pi\omega_s}{180}\cos\omega_s)} \quad (1)$$

where ω is the hour angle for the hour in question (the midpoint of the hour for which the calculations are made), ω_s is the sunset hour angle and a and b are given by the following equations:

$$a = 0.409 + 0.5016\sin(\omega_s - 60) \quad (2)$$

and,

$$b = 0.6609 - 0.4767\sin(\omega_s - 60) \quad (3)$$

In many cases the available data for solar radiation is given for a horizontal surface. In order to obtain the equivalent radiation for a surface with a different geometric orientation it is necessary to adapt the experimental data. This process can be divided in two main phases. First the decomposition of the radiation I into its diffuse I_d and beam I_b components,

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and the second phase is the calculation of the total radiation on a tilted surface I_T based on a model for treatment of the direction from which the surface receives each of this components.

3. DIFFUSE AND BEAM FRACTIONS OF HORIZONTAL RADIATION

Several models have been developed to estimate the fractions of the global radiation I, based on data for different locations. The usual approach is to correlate the fraction of hourly horizontal radiation that is diffuse $k_d = I_d/I$ to the hourly clearness index $k_T = I/I_o$. Polynomial models are one of the most common type of models used for this purpose. They are usually presented in the form of Eq. (4):

$$k_d = \begin{cases} a_1 + a_2 k_T & \text{,first region of } k_T \\ a_3 + a_4 k_T + a_5 k_T^2 + a_6 k_T^3 + a_7 k_T^4 & \text{,second region of } k_T \\ a_8 & \text{,third region of } k_T \end{cases} \tag{4}$$

The a_i coefficients for some polynomial models are displayed in Tab. 1, and the respective regions of k_T in Tab. 2:

Table 1. Coefficients of polynomial models for k_d, adapted from Torres *et al.* (2009) and Karakoti *et al.* (2011).

Models and Locations	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8
First order models								
Lam and Li (1996) Hong Kong	0.977	0	1.237	-1.361	0	0	0	0.273
Orgill and Holland (1977) Toronto	1	-0.249	1.557	-1.84	0	0	0	0.177
Reindl *et al.* (1990) Several sites	1.02	-0.248	1.557	-1.84	0	0	0	0.177
Second order models								
Hawlader (1984) Singapore	0.915	0	1.135	-0.9422	-0.3878	0	0	0.18
Third order models								
Miguel *et al.* (2001) North Mediterranean	0.995	-0.081	0.724	2.738	-8.32	4.96	0	0.19
Karatasou *et al.* (2003) Athens	0	0	0.9995	-0.05	-2.4156	1.4926	0	0.78
Jacovides *et al.* (2006) Cyprus	0.987	0	0.94	0.937	-5.01	3.32	0	0.177
Fourth order models								
Erbs *et al.* (1982) USA	1	-0.09	0.951	-0.1640	4.388	-16.638	12.336	0.165
Oliveira *et al.* (2002) Sao Paulo	1	0	0.97	0.8	-3.0	-3.1	5.2	0.17

Boland *et al.* (2007) proposed a logistic function with general validity, also correlating k_d to k_T:

$$k_d = \frac{1}{1 + e^{(-5.00 + 8.60 k_t)}} \tag{5}$$

Another logistic model was proposed by Ridley *et al.* (2009), tested for locations both on southern and on northern hemisphere, but they included other parameters, known as the Boland-Ridley-Lauret(BRL) model. In this model, the additional parameters are the daily clearness index K_T, the solar altitude α_s, the apparent solar time AST and a variable to account for variability called persistence, obtained from the following equation :

$$\psi = \begin{cases} \frac{k_{t-1} + k_{t+1}}{2} & \text{sunrise} < t < \text{sunset} \\ k_{t+1} & t = \text{sunrise} \\ k_{t-1} & t = \text{sunset} \end{cases} \tag{6}$$

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Table 2. Region of k_T for the diffuse radiation models.

Models and Locations	Second region of k_T
First order models	
Lam and Li (1996) Hong Kong	$0.15 < k_T \leq 0.7$
Orgill and Holland (1977) Toronto	$0.35 < k_T \leq 0.75$
Reindl *et al.* (1990) Several sites	$0.3 < k_T \leq 0.78$
Second order models	
Hawlader (1984) Singapore	$0.225 < k_T \leq 0.775$
Third order models	
Miguel *et al.* (2001) North Mediterranean	$0.21 < k_T \leq 0.76$
Karatasou *et al.* (2003) Athens	$0 < k_T \leq 0.78$
Jacovides *et al.* (2006) Cyprus	$0.1 < k_T \leq 0.8$
Fourth order models	
Erbs *et al.* (1982) USA	$0.22 < k_T \leq 0.8$
Oliveira *et al.* (2002) Sao Paulo	$0.17 < k_T \leq 0.75$

The BRL model is given by Eq. (7):

$$k_d = \frac{1}{1 + e^{-5.38+6.63k_T+0.006AST-0.007\alpha_s+1.75K_T+1.31\psi}} \quad (7)$$

4. DIRECTION OF SOLAR RADIATION

In order to be able to calculate the radiation received by a sloped surface, the directions from which both components, beam and diffuse, of solar radiation are received by the surface must be known. The theory behind the calculation of the angle of incidence of the beam radiation θ is well-established. For its calculation an equation obtained from Duffie and Beckman (2006) that correlates θ as a function of the geometry of the system, the day n and the hour angle ω was used. The problem of diffuse radiation direction is more complex since the diffuse fraction doesn't have a single direction but a distribution over the sky dome. The distribution of diffuse radiation over the sky hemisphere is dependent on the presence of clouds and atmospheric clarity (Duffie and Beckman, 2006). According to Perez *et al.* (1988), one of the potential causes of computational errors is in the treatment of the sky diffuse component of the solar radiation. Perez *et al.* (1988) proposed a description of the sky dome that considered the two most consistent anisotropic effects in the atmosphere, forward scattering and retroscaterring near the horizon, resulting in the division of the diffuse radiation in three components, isotropic diffuse, circumsolar diffuse (caused by the forward scattering) and horizontal diffuse (due to horizontal brightening). This components are illustrated in Fig. 2:

According to Duffie and Beckman (2006) the angular distribution of the diffuse radiation is, to some extent, a function of ground reflectance ρ_g. Due to the complexity in the calculation of the radiation received from this reflected radiation in all its details, as it would require the estimation of reflected radiation from each element in the surrounding(trees, buildings, etc),it is a common practice to model the reflected radiation as coming from a horizontal, diffusely reflecting ground with reflectance ρ. An usual value used for this reflectance for ground with no snow cover is $\rho = 0.2$. The radiation received by a tilted surface can then be represented by the following equation(Duffie and Beckman, 2006):

$$I_T = I_{T,b} + I_{T,d,iso} + I_{T,d,cs} + I_{T,d,hz} + I_{T,refl} \quad (8)$$

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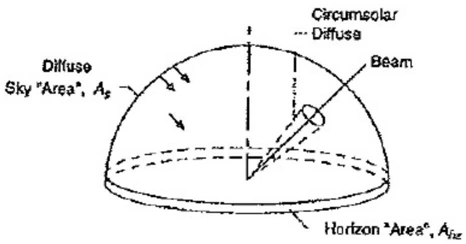

Figure 2. Components of diffuse radiation (Duffie and Beckman, 2006)

In this equation the subscripts b, d, iso, cs, hz, refl represent, respectively, beam, diffuse, isotropic, circumsolar, horizon and ground reflected.

Many models have been developed to calculate I_T for a tilted surface based on Eq. (8), differing mostly on the way that the reflected and the diffuse radiations are treated. Liu and Jordan (1963) have proposed a isotropic sky model that considered the diffuse and the ground reflected radiation were assumed to be isotropic and the circumsolar and the horizon components were considered to be zero. Duffie and Beckman (2006) presents two sky models that takes into account the anisotropy of diffuse radiation: the HDKR model, developed by Hay and Davies (1980) and later improved by Klucher (1979) and Reindl *et al.* (1990), and a model developed by Perez *et al.* (1990), both considering circumsolar and horizon diffuse radiations. According to Duffie and Beckman (2006) both models result in higher and more accurate values of radiation. Although the Perez *et al.* (1990) model agrees better with experimental data, the HDKR model is considerably simpler and shall, therefore, be used in this work. The HDKR model is represented by Eq. (9):

$$I_T = (I_b + I_d A_t) R_b + I_d (1 - A_i) \left(\frac{1 + \cos \beta}{2} \right) \left[1 + f \sin^3 \left(\frac{\beta}{2} \right) \right] + I \rho_g \left(\frac{1 - \cos \beta}{2} \right) \tag{9}$$

where β is the inclination of the surface, A_t is an anisotropy index, which determines the fraction of the horizontal diffuse radiation to be treated as forward scattered, and f is a correction factor for the model to take into account horizon brightening and cloudiness. They are given by the following equations:

$$A_t = \frac{I_b}{I_o} \tag{10}$$

and

$$f = \sqrt{\frac{I_b}{I}} \tag{11}$$

In order to choose the model to be used in the estimation of the components of global radiation, data for a latitude tilted surface given by SWERA for Belo Horizonte ($\phi = 19.888^o$ S and $lon_{loc} = 43.826^o$ O) were used as reference. The statistical parameters used to study the data were the percentage error (PE) and the root mean square error (RMSE).

5. METHODOLOGY

The development of the software consisted in three steps. The first step is the selection of the best data to represent the annual radiation for the region being studied. The second step is the selection of the diffuse radiation model to be used in the calculations. And the third step is the selection of a model for the calculation of the tilted radiation.

For the first step a algorithm was implemented in MATLAB for the generation of the design year following the methodology presented by Klein *et al.* (1976). This algorithm has two outputs, a matrix with the daily values and a matrix with the monthly mean values of radiation and temperature of the design year. The selection of the annual data consisted in the comparison of the second output with the data obtained from METEONORM and SWERA. Then the a initial version of the main MATLAB script for the calculation of the tilted radiation was developed using the traditional theory presented by Duffie and Beckman (2006). For the selection of the diffuse model a variation of this initial version was made which performed the calculation of the diffuse and beam radiation components by each of the models presented in section 2. As cited in section 3, the HDKR model was chosen for the calculation of the tilted radiation as it is simpler and is also a suggested model for a azimuth angle $\gamma = 180^o$ for the southern hemisphere(Duffie and Beckman, 2006). Figure 3 shows a simplified flowchart of the final software:

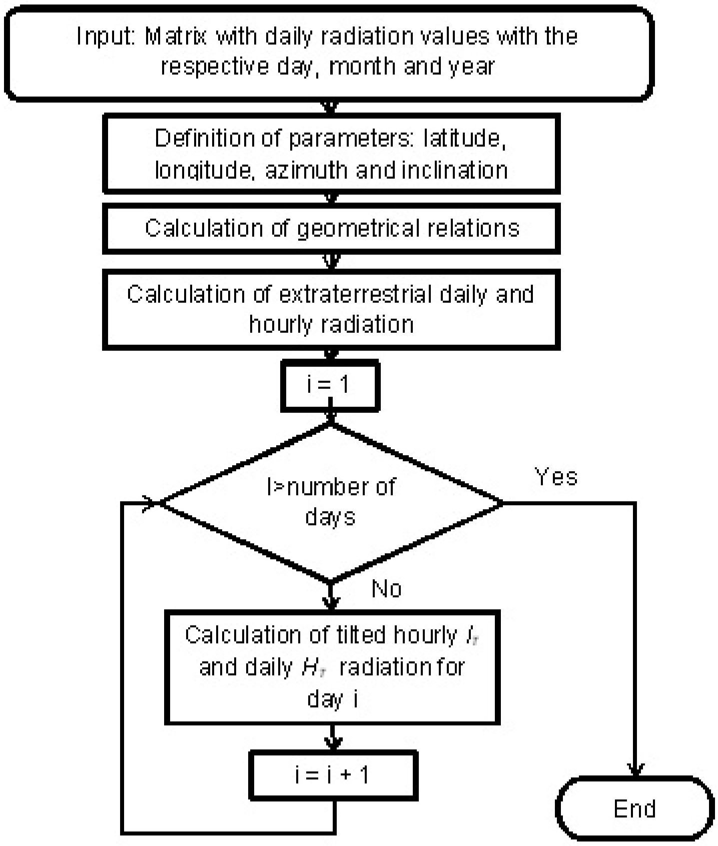

Figure 3.

6. RESULTS

The data obtained from INPE-CPTEC was for the period of 2000 to 2012. In order to test the methodologies for typical years selection, the original dataset was divided in two. The first from 2000 to 2009, and the second set from 2010 to 2012. The first part was used to generate a design year as proposed by Klein *et al.* (1976), and the data from 2010 to 2012 was used as a test set. The mean monthly radiation values for the generated design year and the values obtained from METEONORM and the SWERA database were then compared to the experimental values for the entire dataset. Figure 4 shows the results for some years in the dataset used for generation of the design year and for the test set.

A initial analysis of Fig (4) shows that the SWERA data present higher values of radiation whereas the data from METEONORM and the design year have more conservative values. The study of the results was made through the comparison of the RMSE values for the data used for the generation of the design year and for the test set. The obtained values are shown in Tab. 3. As can be seen the design year have a smaller value of RMSE for almost every year in the dataset and, although the SWERA data tends to have a more accurate result for years with high radiation values, it have a worse result over the year. The design year and the TMY obtained from METEONORM have a similar behaviour along the year, but the design year, being based in a more recent database, present higher and more accurate values of radiation. In order to evaluate the validity of the software to calculate the radiation on a tilted surface, the data obtained for horizontal surfaces by the design year was used in MATLAB. Since there were no measured data for the diffuse radiation for the city of Belo Horizonte. In the second step of the development of the software the monthly mean global radiation from the SWERA data was used as input for the software and the results of I_T were used for the selection of the diffuse radiation models through the comparison with the I_T values also given by the SWERA project. Figure 5 shows the radiation obtained through each of the models presented in section 3 and the values given by SWERA for a latitude tilted surface over the year. As can be seen from Fig. 5 all models follow the trend of the reference values and differ slightly between themselves, being the maximum mean PE of 4.15 % for the Boland *et al.* (2007) model and the minimum of 3.06 % for the model developed by Oliveira *et al.* (2002) for the city of Sao Paulo. Figure 5 also shows that the diffuse radiation models work better between the months of October and January, when the mean PE for all models is about 1.70 %, which are also the months with higher H, whereas in the period from April to August the mean PE is 5.5 %.

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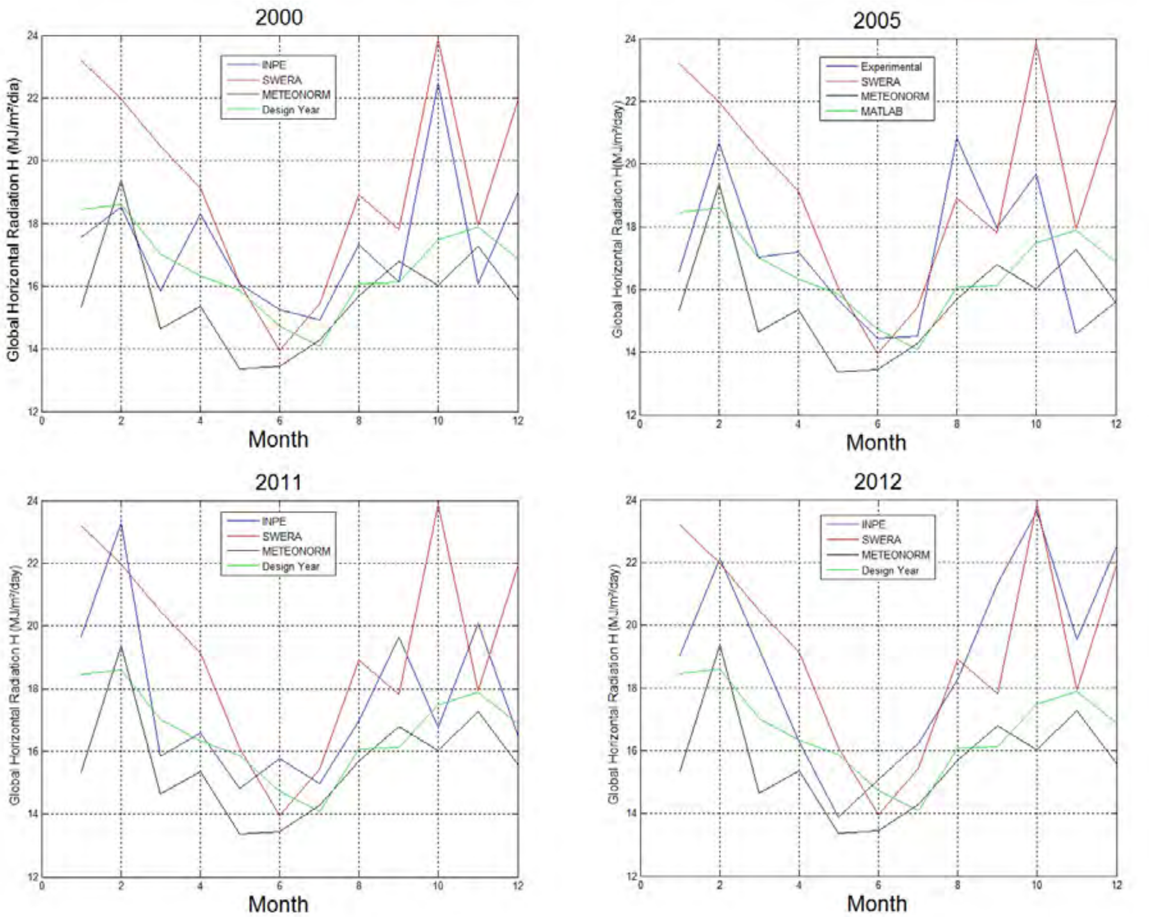

Figure 4. Global Horizontal Radiation values for design year data, 2000 and 2003, and from the test set, 2011 and 2012

Table 3. RMSE values for each year.

Year	SWERA	METEONORM	DESIGN YEAR
2000	2.588	2.559	1.789
2001	2.680	2.151	1.402
2002	10.649	8.755	8.678
2003	3.071	2.314	2.024
2004	3.360	3.145	2.576
2005	3.223	2.273	2.004
2006	5.181	4.385	4.018
2007	3.128	4.138	3.473
2008	5.626	3.507	3.949
2009	3.588	2.036	1.449
2010	2.756	2.239	1.667
2011	3.275	2.218	1.890
2012	1.956	3.810	3.174

The better results were selected and the values of the selected models were plotted in a Estimated value X Reference value graph, shown in Fig. 6.

As expected the selected polynomial models were all from climates either similar or close to the climate of Belo Horizonte, tropical savanna climate (Aw) bordering humid subtropical climate (Cwa) by the Koppen climate classification. Figure 6 also shows that, in this case, the polynomial correlations present values closer to the observed values than the BRL logistic function for most mean radiation values, even though it has a general validity (Boland *et al.*, 2007). The obtained values of RMSE for the selected models are shown in Tab. 4.

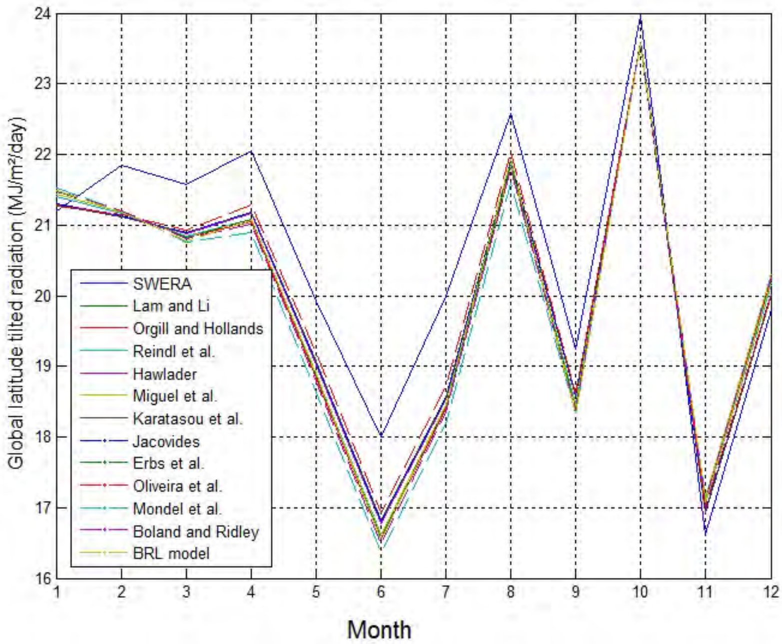

Figure 5. Global latitude tilted radiation values

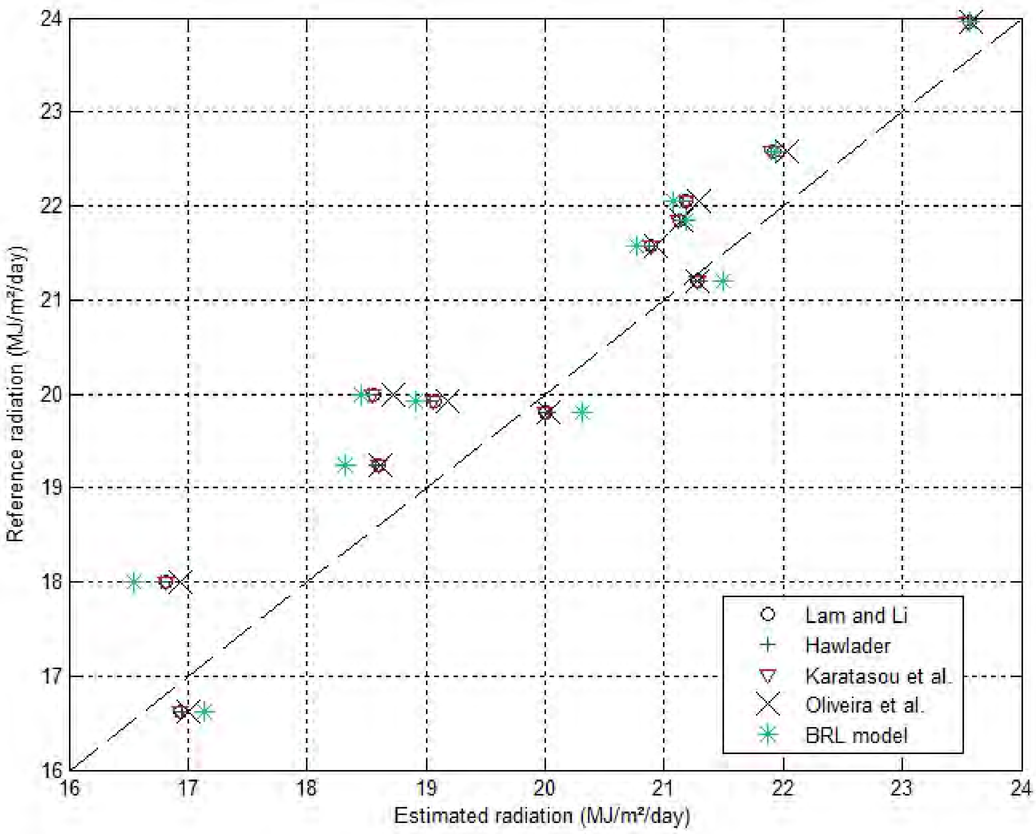

Figure 6. Estimated tilted radiation X Estimated tilted radiation

As can be seen from Tab. 4, the polynomial model developed by Oliveira *et al.* (2002) presented the smallest RMSE between the analyzed models. Therefore this model was chosen for the use in the software for the calculations for the city of Belo Horizonte. As a final step the software was used to generate values of horizontal and tilted radiation and the

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Table 4. RMSE of selected models

Model	RMSE
Lam and Li (1996)	0.7681
Hawlader (1984)	0.7910
Karatasou *et al.* (2003)	0.7734
Oliveira *et al.* (2002)	0.6983
Boland *et al.* (2007)	0.8955

generated H values compared to the available data for the year of 2013, which consisted in the months from January to May. The comparison of the monthly mean values led to a mean PE of -1.79%, indicating that the estimated are slightly higher than the observed values. And the RMSE of 2.297.

7. CONCLUSION

The use of solar simulations allows a fast and controlled way of analysing a solar energy system. In this work a software was developed in MATLAB for the estimation of the solar radiation on a tilted surface based on data for horizontal surfaces. Initially the typical year for the region was chosen based on comparisons of the available datasets with experimental data obtained from INPE. The next step was the selection of the more suitable model for the estimation of the diffuse and direct fractions of the solar global radiation. The criteria for this last step was based on statistical analysis of the calculated values with data from radiation on a latitude tilted surface as given by the SWERA project. The developed software obtained is capable of calculating the hourly radiation received by a surface in a defined geometric orientation based on models chosen on the literature allowing the generation of reliable values for solar radiation for several geometrical configurations of surfaces.

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9. Responsibility notice

The authors are the only responsible for the printed material included in this paper