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# ANALYSIS OF THEORETICAL MODELS OF THE GLOBAL SOLAR RADIATION WITH DATA COLLECTED IN BRASÍLIA - DF

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***Abstract.*** *The purpose of this paper is to analyze the theoretical models for estimating solar radiation, including that of Liu and Jordan (1960) for an isotropic sky, and of Klucher (1979), Hay-Davies (1980) and Reindl et al. (1990), which take into account anisotropic radiation, using data collected from the National Organization System of Environmental Data (SONDA) in 2014. The methodology is based on a mathematical modeling with the theoretical models of solar radiation developed in the MATLAB® R2016a software, in relation to the acquired data. It created a set of comparative data about solar radiation on vertical and tilted surfaces, technical observations on global, direct normal and diffuse radiation throughout 2014, and results for the definitions of a clear sky and a cloudy sky through the distribution of global and incidental radiation (Kt), with the distribution of diffuse radiation divided by the global (Kd). The comparison of the theoretical models presented satisfactory and visible results for the Reindl model, such as the anisotropic behavior characterized most precisely the estimate of global solar radiation in Brasilia - DF.*

***Keywords:*** *solar radiation, theoretical models, diffuse radiation*

## 1. INTRODUCTION

The development of a society is intrinsically linked with its capacity to harness energy and the frenetic search for new energy technologies seeks to supply the future demands of society. Solar energy is used widely, and in order to reach the maximum efficiency of the system it is necessary to understand the factors that influence the quantity of heat transferred. As such, a transfer of heat occurs when there is a differential in temperature and ceases when the medium reaches a thermal equilibrium. In this case the thermic solar radiation is a transfer of heat emitted from the sun.

For a detailed study it's necessary to know the incidence of solar radiation over a surface, which depends on various factors. Solar radiation varies in relation to the position of the the sun, which means it depends on the latitude, the time of the day, the solar declination due to the Earth's rotation and the translation of the Earth in that year (MASTERS, 2004).

The measurement is taken via stations of solar radiometry. However, due to the high cost of the implementation of radiometric stations, there are very few of them for the monitoring and acquisition of data. Owing to the necessity of this data, numerous models were developed to estimate direct and diffuse global irradiation in a determined region (LOUTZENHISER, 2007). The objective of this study is to estimate and compare the solar irradiation in some theoretical models as Liu & Jordan, 1960; Klucher, 1979, Hay-Davies, 1980 and Reindl et al,1990.

## 2. SOLAR IRRADIATION

Solar irradiation which occurs in the stratosphere is called total solar irradiation and has the approximate value of G=1373 W/m² (ÇENGEL; GHAJAR, 2012).

Solar irradiation can be divided into Direct Normal Irradiance (DNI) and Diffuse Horizontal Irradiance (DHI). DNI is that which reaches the Earth's surface without being absorbed or dispersed. DHI is that which reaches the surface uniformly in all directions. Global Horizontal Irradiation (GHI) is arrived at through Equation (1), as the sum of diffuse and direct energy.

$$GHI = DHI + DNI.\cos\theta \tag{1}$$

However, a solar energy system normally isn't installed horizontally, but at an angle to increase the intercepted radiation and reduce the loss to reflection. A tilted surface is calculated through Equation (2), which is the sum of direct irradiation ($G_{Bt}$), diffuse irradiation ($G_{Dt}$) and solar irradiation reflected from the soil ($G_{Gt}$):

$$G_t = G_{Bt} + G_{Dt} + G_{Gt} \tag{2}$$

Equation (3) represents the direct solar irradiation above a tilted surface, which depends on the direct horizontal solar irradiation and, as evident in Eq. (4), the factor of inclination.

$$G_{Bt}=G_B\,.R_B \tag{3}$$

$$R_B=\frac{\cos(\phi\pm\beta).\cos\delta.\cos\omega+\sin(\phi\pm\beta).\sin\delta}{\cos\phi.\cos\delta.\cos\omega+\sin\phi.\sin\delta} \tag{4}$$

The development of theoretical models allows estimating the diffuse solar irradiation. Comparing the diverse models is of great importance to determinate the correct dimensioning of a photovoltaic system. Below there are some theoretical models to objectively determine an estimate of solar irradiation on a tilted surface.

### 2.1 Isotropic sky model

The isotropic sky model was developed by Hottel and Woertz (1942) and perfected by Liu and Jordan (1960) (Duffie & Beckman, 1980). The model in Equation (5) and Equation (6) is simple and assumes that the diffuse irradiation is uniformly distributed in all directions of the celestial dome.

$$R_d=\frac{(1+\cos\beta)}{2} \tag{5}$$

$$G_t = R_B.G_B + G_D.R_d+(G_B+G_D)\rho_G\left[\frac{1-\cos(\beta)}{2}\right] \tag{6}$$

### 2.2 Klucher Model

The Klucher model (1979) offers good results for cloudy skies, while being less efficient reading radiation when the sky is clear and partly cloudy. The model developed for solar radiation is described in Eq. (7) e Eq. (8), for flat, tilted surfaces.

$$G_t = R_B.G_B + G_D.R_d.\left[1+F'.\sin^3\left(\frac{\beta}{2}\right)\right]\left[1+F'.\cos^2(\beta).\sin^3(\phi)\right]+(G_B+G_D)\rho_G\left[\frac{1-\cos(\beta)}{2}\right] \tag{7}$$

$$F'=1-\left(\frac{G_D}{G_D+G_B}\right)^2 \tag{8}$$

### 2.3 Hay-Davies Model

The Hay-Davies model was developed in 1980 and divides the sky diffuse radiation into isotropic and circumsolar components. The anisotropy index is defined in Eq. (9), and represents the transmittance of direct radiation through the atmosphere. The global radiation in Eq. (10) is then calculated.

$$A=\frac{G_{Bn}}{G} \tag{9}$$

$$G_t = R_B.(G_B+G_D.A) + G_D.R_d.(1-A)+(G_B+G_D)\rho_G\left[\frac{1-\cos(\beta)}{2}\right] \tag{10}$$

### 2.4 Reindl Model

The Reindl sky diffuse radiation model was proposed in 1990. This model expands on the model of Hay-Davies and represents the circumsolar contribution to diffuse irradiance and the diffuse isotropic irradiance corrected by horizon brightening. Eq. (11) describes how total irradiance is calculated on an tilted surface.

$$G_t = R_B.(G_B+G_D.A) + G_D.R_d.(1-A).\left[1+\sqrt{\frac{G_B}{G_B+G_D}}.\sin^3\left(\frac{\beta}{2}\right)\right]+(G_B+G_D)\rho_G\left[\frac{1-\cos(\beta)}{2}\right] \tag{11}$$

## 3. DATABASE

The database used comes from the National System of Organization for Environmental Data (SONDA), with data collected from January to December 2014 at the station in Brasilia, DF (15° 36' 03" S, 47° 42' 47" O, 1023 m). It is a tropical climate at over 1000 meters of elevation, characteristic of high plains and sierras with a well-defined season of precipitation, which begins in October and extends into March. The dry season occurs throughout the rest of the ye ar, from April to September (SONDA, 2017).

## 4. RESULTS AND DISCUSSION

The methodology used is an analysis of data acquired from a database of the National System of Environmental Data (SONDA) and data calculated through theoretical models of radiation. The theoretical models of radiation were initially calculated, with the purpose of analyzing the characteristics of the studied region. The SONDA data are then used to compare the results with the data calculated by the models and measured data.

Normally estimate models for solar radiation on horizontal and tilted surfaces can be found in the literature. The model of radiation for horizontal surfaces was based on clear sky radiation work by Hottel (1976), which uses a transmittance model for direct normal and diffuse radiation depending intrinsically on the zenith angle. This can be determined through the elements that characterize the trajectory of solar rays, which are defined respectively by the local geographic coordinates, the solar time, the solar declination and the zenith angle (SCOLAR, 2003). Normally the solar panels are not installed horizontally, but at an angle which increases the intercepted radiation and reduces the losses due to reflection and to the cosine (KALOGIROU, 2016). To maximize the total daily radiation projected on a tilted surface in Brazil, the surface normally faces the equator and the best angle of inclination is the same as the latitude. Figure (1) shows the daily radiation on a tilted and horizontal surface. On a tilted surface in relation to a horizontal surface, there is an increase in radiation at the minimum point of the graphic during the winter, and a reduction of radiation during the summer.

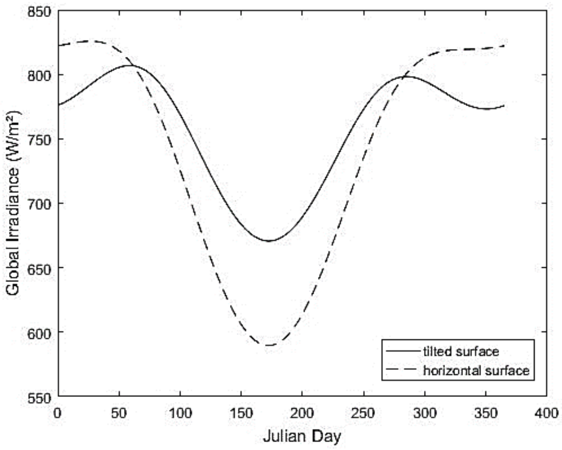


Figure 1. Daily solar radiation on tilted and horizontal surfaces based on clear sky radiation model

Figure (2) shows a comparison of the average monthly levels of global, direct normal and diffuse radiation with data calculated by the clear sky model and data measured by the SONDA. From this, it is possible to make meteorological observations such as determine when there is the period of highest diffuse radiation, such as between November and March which is when there are more rain clouds in the sky, or between May and October when there is more direct radiation because of the clear sky. That is, in technical terms it shows a variation of solar energy incidence on the Earth, related to the annual movement of the earth around the sun, which has its winter and summer solstice on the 21st of June and December, respectively, and its equinox of Autumn and Spring on the 21st of March and September, respectively. In these periods there is a transition with a greater and lesser solar incidence because of the translation and rotation of the earth. Another factor is the declination of the earth on its axis, which inclines at 23.45 degrees and is an angular distance in relation to the north of the equator and the rays of the sun. On the solstice the represented declination is 23.45 degrees and on the equinox it is 0 degrees (KALOGIROU, 2016).

A flat tilted surface receives direct radiation, diffuse radiation and solar radiation reflected by the soil. The direct solar radiation on a tilted surface can be determined by the product of the direct solar radiation on horizontal surfaces with an inclination factor of radiation. Liu and Jordan (1960) developed a model for clear skies on tilted surfaces, while Klucher (1979), Hay-Davies (1980) and Reindl et al. (1990) developed theoretical models which estimate the anisotropy of diffuse irradiation, differentiating isotropic, circumsolar and horizontal diffusion. And the radiation reflected by the soil is characterized as direct and diffuse radiation on horizontal surfaces, and also by the albedo of the soil. According to Silva et al. (2016), the maximum albedo in an urban area in Brazil's Federal District is 0.195.

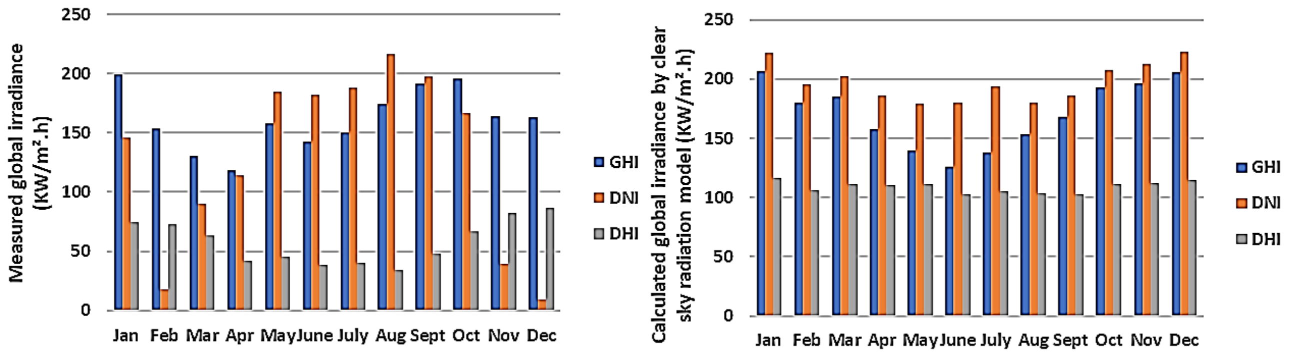


Figure 2. Measure of global irradiance in 2014 and calculation of global irradiance by clear sky radiation model

The radiation for tilted surfaces discussed by Liu and Jordan is a model for isotropic sky - that is, the diffuse radiation is uniformly distributed in all directions of the celestial dome. It is a model of simple methodology presenting good results principally for cloudy skies, inasmuch as on days with clear skies the diffuse radiation has an anisotropic behavior and for a calculation of diffuse radiation is highly important to consider isotropic and anisotropic results.

Klucher observed the moment in which the intensity of irradiance increases close to the horizon, which is more intense than the zenith (horizontal brightening) and the brightening of the sky close to the sun (circumsolar). Therefore, the amount of diffuse radiation concluded by Liu and Jordan is modified to include anisotropic behavior. The Klucher model applies a clarity index to adjust the variation between clear and cloudy skies. When the sky is cloudy the clarity index becomes 0, and skews towards the isotropic sky model of Liu and Jordan.

The Ray-Davies model considers itself an anisotropic index, although such an index does not consider the clarity of the horizon. The diffuse radiation is composed of a component coming from the solar disc (circumsolar) and the rest of the celestial dome (isotropic). When the sky is cloudy the anisotropic index skews towards 0 and the diffuse radiation is considered isotropic.

By the fact that the Ray-Davies model didn't consider the horizontal clarity, Reindl et al. propose an irradiance model that analyzes the horizontal brightening as well as the circumsolar of the Klucher model together with the same anisotropic index from Ray-Davies. In a cloudy sky, the anisotropic component skews towards 0 and the model becomes isotropic. Figure (3) shows the variation of daily global radiation in Brasilia between the theoretical models over the year. The variation is larger in autumn and winter, which coincides approximately to the Julian days 100 to 250, when there is a higher frequency of clear sky, as is represented on the minimum point of the graph.

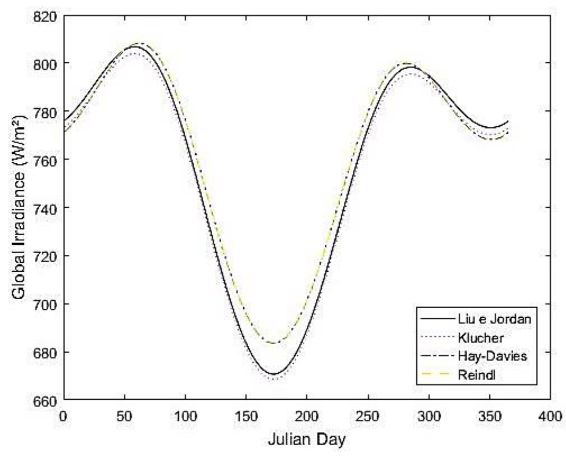


Figure 3. Daily global radiation according to the theoretical models

The clarity index is a factor for analysis. Figure (4) shows through theoretical models a daily distribution of global radiation divided by extraterrestrial radiation (Kt) with a variation between 0 and 0.9, or that is, portraying the variation of the density of the clouds in the atmosphere, along with the daily distribution of the diffuse radiation divided by global radiation (Kd), corresponding from 0 to 1, and the incidence of diffuse radiation on the surface of the earth, which varies a percentage from global radiation. The distribution of global radiation in function of the clarity index (Kt) represents the intervals of clarity. That is, from 0 to 0.1 presents diffuse radiation and the sky is classified as cloudy; from 0.1 to 0.5 is an alternation between direct and diffuse radiation with the sky partly cloudy; and above 0.5 it is direct radiation with a clear sky and diffuse minimum with tendency to global radiation.

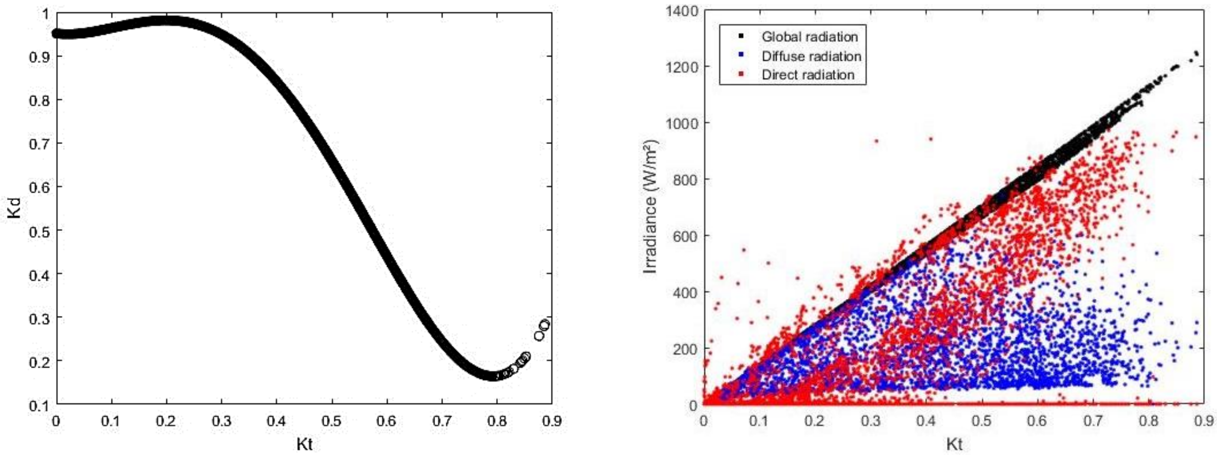


Figure 4. Distribution of global radiation divided by extraterrestrial radiation (Kt) with a distribution of the diffuse radiation divided by global radiation (Kd) and Irradiance with Kt

Figure (5) presents the relation between measured and estimated values of global radiation incidence on horizontal surfaces by the models of Liu and Jordan (1960), Klucher (1979), Hay-Davies (1980) and Reindl et al. (1990). Note that the model by Reindl et al. presents the best fit with correlation coefficient of 0.9644, when closer to 1 the better. That is, when the points are closest to the line, the better the approximation.

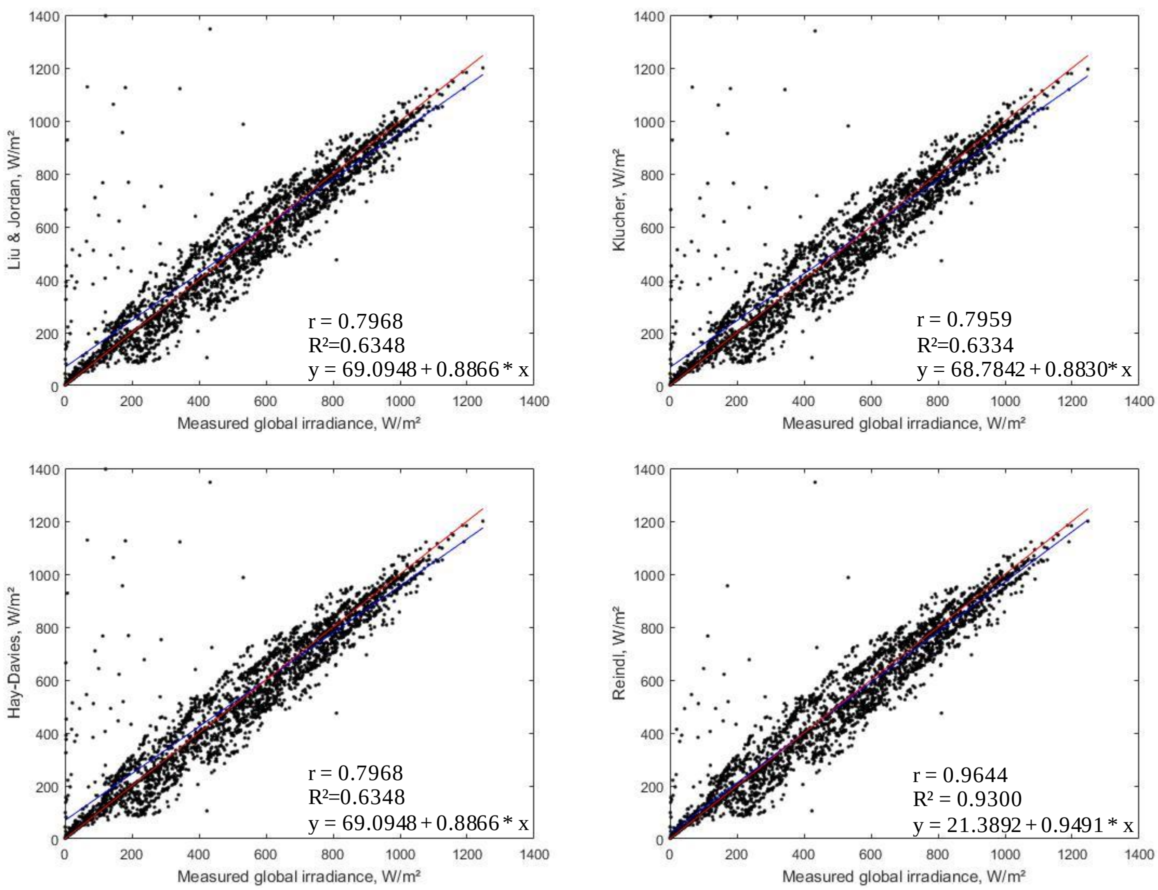


Figure 5. Relation between the measured and estimated values of global radiation incidence on horizontal surfaces as measured by the models of Liu and Jordan (1960), Klucher (1979), Hay-Davies (1980) and Reindl et al. (1990)

Belúcio (2014) describes a practical rule for interpreting the size of a correlation coefficient between the variables. The correlation coefficient is considered to be very weak if $\pm$ 0.00 ≤ | r | ≤ $\pm$ 0.19, weak if $\pm$ 0.20 ≤ | r | ≤ $\pm$ 0.39, moderate if $\pm$ 0.40 ≤ | r | ≤ $\pm$ 0.69, strong if $\pm$ 0.70 ≤ | r | ≤ $\pm$ 0.89 and very strong if $\pm$ 0.90 ≤ | r | ≤ $\pm$ 1.00. Table (1) shows the correlation coefficient, the coefficient of determination and size interpretation of a correlation coefficient of theoretical models.

Table 1. Correlation coefficient, coefficient of determination and size interpretation of a correlation coefficient

| Theoretical models | Correlation coefficient (r) | Coefficient of determination ($R^2$) | Interpretation |
|---|---|---|---|
| Liu and Jordan | 0.7968 | 0.6348 | Strong correlation |
| Klucher | 0.7959 | 0.6334 | Strong correlation |
| Hay-Davies | 0.7968 | 0.6348 | Strong correlation |
| Reindl et al. | 0.9644 | 0.9300 | Very Strong correlation |

It is possible to analyze through the Reindl Model that in the linear regression of the data obtained by the model on the measured data only 93% of the model variation would be explained by the linear regression method, that is, this coefficient of determination ($R^2$) indicates how the Reindl Model was able to explain the measured data. However, the analysis should not only cover $R^2$, since another extremely important factor can be caused by the quality of the measured data or the model could not represent the variability of the data measured in the analyzed period.

Table 2. Correlation coefficient, coefficient of determination and the size interpretation of a monthly correlation coefficient of the Reindl et al.

| Month | Correlation coefficient (r) | Coefficient of determination ($R^2$) | Interpretation |
|---|---|---|---|
| January | 0.9759 | 0.9524 | Very strong correlation |
| February | 0.7056 | 0.4979 | Strong correlation |
| March | 0.9695 | 0.9399 | Very strong correlation |
| April | 0.9599 | 0.9215 | Very strong correlation |
| May | 0.9548 | 0.9116 | Very strong correlation |
| June | 0.9633 | 0.9280 | Very strong correlation |
| July | 0.9740 | 0.9486 | Very strong correlation |
| August | 0.9763 | 0.9531 | Very strong correlation |
| September | 0.9815 | 0.9633 | Very strong correlation |
| October | 0.9888 | 0.9776 | Very strong correlation |
| November | 0.9340 | 0.8723 | Very strong correlation |
| December | 0.3489 | 0.1217 | Weak correlation |

Table (2) is a monthly analysis of the correlation coefficient of the Reindl et al. It verifies in detail if a monthly evaluation of the measured and estimated values, such analyzes establish months with weak correlation the very strong correlation. The quality of the data can be verified as excellent in most months and worse in December, this result may comprise the rainy period, which makes it difficult to analyze and collect the data in the SONDA.

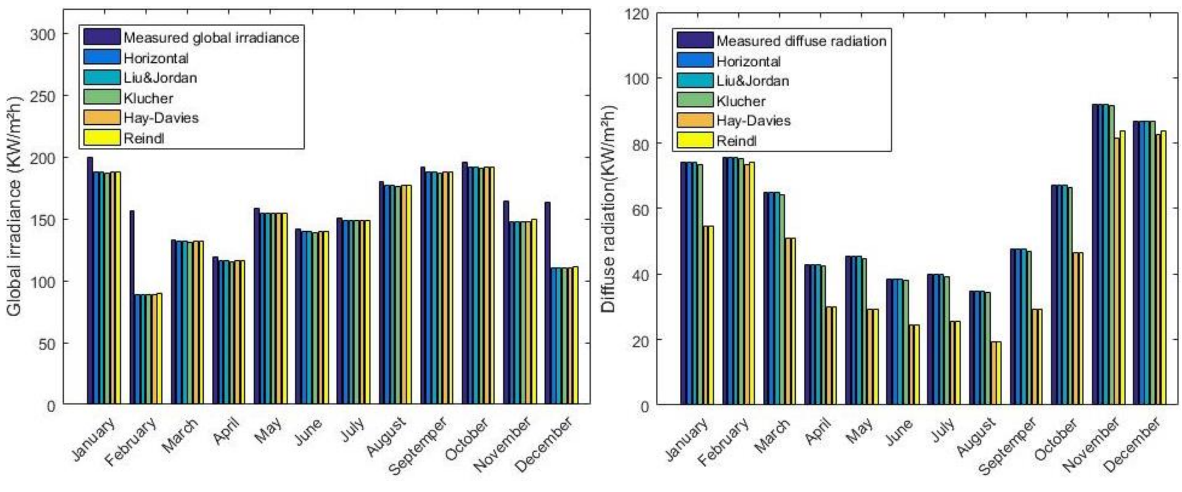


Figure 6. Global radiation and diffuse radiation during the months of the year

Figure (6) shows a comparison of the values measured and estimated by the theoretical models, that is, the different variations of the global radiation and diffuse radiation of the models during the months of the year. An irregularity is observed in the summer due to data losses during the rainy season in the global irradiance. In diffuse radiation, each theoretical model has its particularity Liu and Jordan is described by a simple and isotropic model, Klucher, Hay-Davies and Reindl is delineated by corrections that provides an anisotropic adjustment in the diffuse radiation. In Brasília, the adjustment made by Hay-Davies and Reindl et al. allows a maximum energy capture by direct radiation and consequently decreases diffuse radiation, since it considers other variations in its equations.

## 5. CONCLUSIONS

This work presents a brief review of literature estimating solar global radiation on horizontal and vertical surfaces. On the vertical surfaces there were considered the theoretical models of the Liu and Jordan (1960) for isotropic sky and anisotropic by Klucher (1979), Hay-Davies (1980) and Reindl et al. (1990). The specific database was used for derivation of the National Organization System of Environmental Data (SONDA, 2017), from the year 2014, with data about global, direct normal and diffuse radiation. The reviews were determined through modeling using the software MATLAB® R2016a. The method used for the analyses of the data was a correlation through the linear regression of the values measured by the SONDA with the values estimated by the theoretical models. The quality of the data during the year is mainly affected as the weather presents many clouds, which makes difficult the data collection.

However, the relation between the measured and estimated results presented a satisfying correlation, as it allowed one to visualize the best model for global radiation incidence on tilted surfaces in Brasilia. It is worth pointing out that the modeling is in its development phase and the data discovered are initial results. Therefore, to estimate solar radiation and verify reliable results, new analyses of the implemented models, as well as validation through solarmetric stations for tilted surfaces and analysis of the coefficient of correlation, will be done by the MATLAB software.

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