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COMPARATIVE STUDY OF SOLAR IRRADIATION MODELS

Leonardo J. Geovo Coronado
Universidade Federal Rio Grande do Sul, Rua Sarmento Leite, 425
ljgeovo@hotmail.com
Justo José Roberts
Universidad Nacional De Mar Del Plata, Av. Juan B. Justo, 4302
jjroberts@fi.mdp.edu.ar

Andrés A. Mendiburu Zevallos
Universidade Federal Rio Grande do Sul, Rua Sarmento Leite, 425
andresmendiburu@ufrgs.br

Abstract. With increasing of installation of solar systems in the world, the knowledge of the incident solar irradiance in tilt surfaces is relevant. In most cases, only the global horizontal irradiance is available. The principal objective of the present article is assessing the performance of different combinations between some of the most used models in the literature, namely the decomposition and transposition models, to determine hourly global irradiance in the tilt surface from the global horizontal irradiance. In order to select the models that have the best performance, a total of 16 Decomposition-Transposition models were evaluated. These 16 compositions were derived from the combination of 4 decomposition models and 4 transposition models. All models were implemented in a computational routine and the results were compared to the values obtained from the software Radiasol 2, at 30º tilt for Porto Alegre – Brazil. The model that showed the best results was Perez model in three different combinations (OH-Pe, Re-Pe and Er-Pe) with a rRMSE between 5.68% - 6.13%, and a rMBE from -2.15% to -2.47%.

Keywords: Decomposition Model, Transposition model, Global tilted irradiance, Global horizontal irradiance and Renewable energy

Nomenclature

I	Global horizontal Irradiance (W/m^2)
$I_{b,n}$	Direct normal irradiance (W/m^2)
I_d	Diffuse horizontal irradiance (W/m^2)
I_b	Direct horizontal irradiance (W/m^2)
I_T	Global tilted irradiance (W/m^2)
$I_{T,b}$	Beam radiation on tilted surface (W/m^2)
$I_{T,d}$	Diffused radiation on tilted surface (W/m^2)
$I_{T,r}$	Ground reflected radiation on tilted surface (W/m^2)
I_o	Extraterrestrial horizontal irradiance (W/m^2)
$I_{o,n}$	Extraterrestrial direct beam irradiance
R_b	Beam radiation conversion factor
k_t	Clearness index
k_d	Diffuse fraction
k_n	Direct transmittance
$k_{n,c}$	Clear-sky direct transmittance
f_{xx}	Brightness coefficients
f_k	Correction factor from Klucher
p	Local air pressure (Pa)
Δk_n	Deviation from clear-sky direct transmittance
$I_{T,d,iso}$	Isotropic diffuse component on inclined surface (W/m^2)
$I_{T,d,cs}$	Circumsolar component on inclined surface (W/m^2)
$I_{T,d,hb}$	Horizon brightening component on inclined surface (W/m^2)

y_i	Predict (calculated) value
x_i	Observed measures
$\bar{x}$	Measured mean value
N	Number of observations

Greek letters

β	Surface tilt angle (degree)
θ_z	zenith angle (degree)
α_s	Solar altitude angle (degree)
θ	Angle of incidence (degree)
ε	Clearness parameter
ρ_g	Ground reflectance albedo
Δ	Brightness parameter

Abbreviations

|	
RMSE	Root mean square error
rRMSE	Relative root mean square error
MBE	Mean bias error
rMBE	Relative mean bias error
R^2	R squared
AM	Air mass

1. INTRODUCTION

It is known that there is a necessity to find new environmentally friendly energy sources, in this sense, the renewable energies became more relevant for energetic applications. The solar energy is one of the energy sources which usage is growing very fast (Jakhrani et al., 2013). Therefore, the solar irradiation data is necessary for different applications like: photovoltaic and thermal systems, in different areas like agriculture and thermal comfort (Lee et al., 2017).

In order to implement a solar energy-based system, it is a prerequisite to obtain solar radiation database for the zone of interest. However, the available data of solar irradiation are limited to a few locations or to short time periods (Jamil and Akhtar, 2017). The solar irradiation data are provided principally by satellites and local weather stations, normally they measure the global horizontal irradiation (I), the direct normal irradiance ($I_{b,n}$) and the diffuse horizontal irradiance (I_d) are rarely measured on this way. Actually, I_d and $I_{b,n}$ are measured mostly by research institutions, due to the high cost involved with the necessary equipment (Jamil and Akhtar, 2017).

Generally, the solar collectors present an angle of inclination (β) in relation to the horizontal plane to increase the solar irradiation received throughout the year (Le Roux, 2016). By combining two models it is possible to determine the global tilt irradiance (I_T). from the global horizontal irradiance (I) and direct normal irradiance ($I_{b,n}$) or diffuse horizontal irradiance (I_d) (Notton et al., 2006). The decomposition models used the global horizontal irradiance to provide the components $I_{b,n}$ and I_d, these methods can be implemented once I it's known (Yang, 2016). Some of the methods found in the literature are those by Liu and Jordan (1960), Orgill and Hollands (1977) Erbs et al. (1982), Skartveit and Olseth (1987), Reindl et al. (1990), Ineichen et al. (1992); Klucher (1979) Maxwell (1987). The transposition models use the global horizontal irradiance and the direct normal irradiance or diffuse horizontal irradiance to establish the global tilt irradiance with slope β as shown in Fig. 1 (Mahachi and Rix, 2016). The transposition models can be classified in two.

(i)   Isotropic models, these models take the intensity of the diffuse irradiation in the uniform sky throughout the dome of the sky and that reflection on the ground is diffuse (Stanciu et al., 2016). One of the first isotropic models was proposed by Hottel and Woertz (1942), where they assumed that the combination of diffuse and ground-reflected radiation is isotropic.. An improvement on this model was proposed by Liu & Jordan (1960), they considered three components in order to determine the irradiance on the tilted surface, namely, beam ($I_{T,b}$), isotropic diffuse ($I_{T,d,iso}$) and solar radiation diffusely reflected from the ground ($I_{T,r}$).

(ii)   Anisotropic models, these models adopt the equations for the determination of $I_{T,b}$ and $I_{T,r}$ used by (Liu & Jordan, 1960), furthermore, they the calculation of the diffuse sky component by taking into account the effects of circumsolar radiation ($I_{T,d,cs}$) and of the horizon brightening ($I_{T,d,hb}$) radiation (Duffie & Beckman, 2006) (Kalogirou, 2014).

Figure 1. Method for determining the irradiance on the tilted surface from global horizontal irradiance
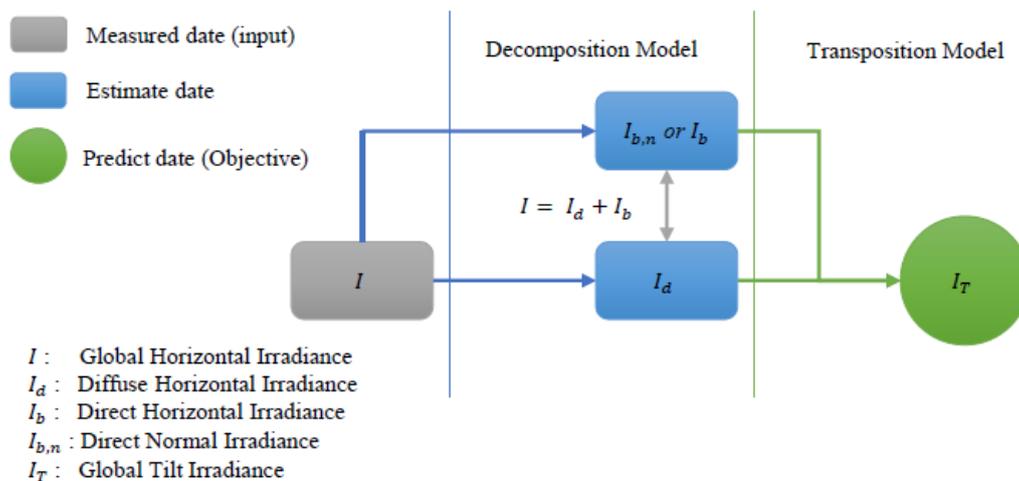
Several works assessed the performance of the different isotropic and anisotropic models for a variety of weather conditions at different regions of the world. The research presented by Mahachi and Rix(2016) used data of I and I_T, measured in intervals of 30 minutes in a solar photovoltaic plant (PV) in South Africa, in order to validate different combination of decomposition-transposition models that estimate global tilt irradiance from measures of global horizontal irradiance. A total of 7 decomposition models and 7 transposition models were evaluated. It was observed that all transposition models underestimate the global tilt irradiance for winter at the reference site. The combination Perez-

DIRINT and Perez-Louche showed the best results when compared to the measured values. Jakhrani et al. (2013) compared 4 models ((Liu and Jordan, 1960), (Reindl et al., 1990b)(Duffie and Beckman, 2006) and (Klucher, 1979)). They found that the model by Klucher (1979) showed the best performance among the examined models. Portolan dos Santos and Rüther (2014) used data obtained by the Solar and Wind Energy Resource Assessment (SWERA) to analyze the global horizontal irradiance in the capital cities of Brazil and through the use the software Radiasol. The obtained I and I_T for a certain tilt angle were compared against 4 models. The models by Perez et al. (1990)and Klucher (1979) showed the best results. Souza and Escobedo (2013) analyzed 20 models including isotropic and anisotropic types. The models that presented better results were those developed by Badescu (2002) and Koronakis (1986) for the isotropic models and for those developed by (Reindl et al., 1990b) (Klucher, 1979) (Perez et al., 1990) and (Hay, 1979) for anisotropic models. According to Roberts et al. (2016) the comparison among combinations of 4 decomposition and 4 transposition models showed that the best performance was obtained for DISC-LJ, DISC-Ko, DIRINT-Ko and DIRINT-HDKR models.

In the order to get a realist behavior of the global tilted irradiance, it is necessary to perform a computational simulation. However, it is unavoidable to have some uncertainty related to the suppositions made by the models. Therefore, it is important to identify and quantify the error sources of these models.

The objective of this research is to assess different possible combination among four decomposition and four transposition models, these models showed good accuracy in different climates around the world and they will be assessed with data for Porto Alegre city in Brazil. The sixteen combinations of decomposition-transposition models were computational implemented in Matlab® for evaluation of their performance to determine the hourly global tilted irradiance. The models will be compared with data obtained from software Radiasol 2.1 for a tilt angle of 30º by using the following statistical indicators: Mean Bias Error (MBE), Relative Bias Mean Bias Error (rMBE), Root Mean Square Error (RMSE), Relative Root Mean Square Error (rRMSE) and R-Squared (R^2).

2. METHODOLOGY

The present work consists of three main steps: (i) determination of the diffuse horizontal irradiance and direct normal irradiance from global horizontal irradiance provided by Solar and Wind Energy Resource assessment (SWERA), through the decomposition models. (ii) determination of global tilted irradiance by means of transposition models using data of I_d and $I_{b,n}$ obtained from the decomposition models. (iii) evaluation of 16 combinations of decomposition-transposition models and comparison with the results obtained by the software Radiasol 2 at a tilt angle of 30º. However, no combination of decomposition-transposition models is widely accepted as a standard for converting I to I_T (Roberts et al., 2016). In the sections that follow, the theory and concepts regarding the decomposition and transposition models and their implementation will be developed.

2.1 Measured Data and validation

The measured data of solar irradiation selected for this work comprises data of one-hour periods. The global horizontal irradiance data were obtained from ("Solar and Wind Energy Resource Assessment (SWERA) | Open Energy Information," 2018). The measures were performed for more than 10 years over the national territory of Brazil.

The validation process will be performed by comparison with the results obtained from the software Radiasol 2. This software was developed by researchers from the Universidad Federal Rio Grande Do Sul The software uses the global horizontal irradiance data provided by SWERA for Porto Alegre city (Latitude -30..02 and Longitude -51.22) and it used the decomposition model developed by Collares-Pereira and Rabl (1979) to determinate the diffuse and direct horizontal irradiance, furthermore, in order to calculate the global tilted irradiance for different tilt angles from I_d and I_b, it is used the model by Perez et al. (1987) (Krenzinger and Carvalho, 2010).

The recorded data of solar irradiation are generally taken at one-hour intervals and the uncertainties may be significative mainly near to sunset and sunrise. This is related to the value obtained for the cosine and the mask effect of the surrounding mountains that introduce errors in these zones (Notton et al., 2006)(De Miguel et al., 2001). Therefore, a quality control test is performed to exclude some data that present high uncertainty.

De Miguel et al., (2001) and Notton et al., (2006) proposed the use of the quality control criteria shown in Eq. (1). The data that does not comply with the conditions shown in Eq. (23) will not be taken into account for the calculations and validation.

$$\begin{cases} 0 \leq I_d \leq (1.1 \times I) \\ 0 \leq I \leq (1.1 \times I_o) \\ 0 \leq I_d \leq (0.8 \times I_o) \\ 0 \leq I_b \leq I_o \\ \alpha_s < 5° \end{cases}$$

(1)

The accuracy of the different combinations of the models will be assessed and compared to the values obtained from the software Radiosol 2 in terms of statistical indicators that have been widely adopted in the literature (Roberts et al., 2016) (Al-Rawahi et al. , 2016) (Demain, Journée, & Bertrand, 2013). These statistical indicators are presented below. The y_i, represent the calculate values, the x_i represent the measured values and the $\bar{x}$ represent the mean values of the measurements.

The Root mean square error (RMSE) allows to determine the short-term performance of the correlation, providing a term by term comparison between the predicted and measured values. The smaller the value of RMSE the better the performance of the model (Roberts et al., 2016) (Demain et al., 2013). The RMSE and its relative form (rRMSE) are calculated by the expressions given in Eq. (2).

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(y_i-x_i)^2}{N}}, \quad rRMSE = \frac{\sqrt{\frac{\sum_{i=1}^{N}(y_i-x_i)^2}{N}}}{\bar{x}} \tag{2}$$

The Mean bias error (MBE) provide information on the performance of the models over a long-term period. A positive value of MBE indicates that the model tends to overestimate the actual value. A negative value of MBE indicated that there is a underestimation of the calculated value (Salari and Javaran, 2018). The MBE equation and its relative form (rMBE) are presented in Eq. (3).

$$MBE = \frac{\sum_{i=1}^{N}(y_i - x_i)}{N}, \quad rMBE = \frac{\sum_{i=1}^{N}(y_i - x_i)}{N * \bar{x}} \tag{3}$$

The R-squared (R^2) coefficient represents the fraction of the variability that is accounted for by the model when it is compared to a data set (Roberts et al., 2016).

$$R^2 = 1 - \frac{\sum_{i=1}^{N}(y_i - x_i)^2}{\sum_{i=1}^{N}(x_i - \bar{x})^2} \tag{4}$$

2.2 Decomposition models

The decomposition models studied in the present paper are shown in the Tab. 1. The input variables necessary for each model and the sites from which the original validation data were obtained are also shown on Table 1.

Table 1. Decomposition models implemented.

Models	Input Variable	Test Site	Abbreviature
(Erbs et al., 1982)	I, k_t	USA	Er
(Orgill & Hollands, 1977)	I, k_t	Canada	OH
(Maxwell, 1987)	I, k_t, p, θ_z	USA	DISC
(Reindl et al., 1990a)	I, k_t, α_s	USA and Europa	Re

The decomposition models can be empirical models such as Erbs, OH and Re, which are based in correlations relating the clearness index ($k_t = I/I_o$) or direct beam transmittance ($k_n = I_{b,n}/I_{o,n}$) to the diffuse fraction ($k_d = I_d/I$), where I_o and $I_{o,n}$ are extraterrestrial irradiance and extraterrestrial normal irradiance respectively. The DISC model is considered as a quasi-physical model; therefore, it uses physical principles together with empirical correlation.

2.2.1 Erbs model (Er)

The model developed by Erbs et al. (1982) used the direct normal and global irradiance data from 5 weather stations located at USA. They proposed correlations between k_T and k_d as shown in Eq. (5).

$$k_d = \begin{cases} 1.0 - 0.09\,k_T, & k_T < 0.22 \\ 0.9611 - 0.1604\,k_T + 4.388\,k_T{}^2 - 16.638\,k_T{}^3 + 12.336\,k_T{}^4, & 0.22 < k_T \le 0.80 \\ 0.165, & k_T > 0.80 \end{cases} \tag{5}$$

2.2.2 Orgill and Hollands models (OH)

This model was based in measurements carried out at Toronto in Canada. Orgill and Hollands (1977) relate the diffuse fraction and the clearness index through the correlations shown in Eq. (6).

$$k_d = \begin{cases} 1.0 - 0.09\ k_T, & k_T < 0.35 \\ 1.577 - 0.184\ k_T & 0.35 < k_T \leq 0.75 \\ 0.177 & k_T > 0.75 \end{cases} \tag{6}$$

2.2.3 Reindl model (Re)

In the model developed by Reindl et al. (1990a) the diffuse fraction k_T is estimated from global horizontal irradiance recorded in 5 sites located in USA and Europe, with latitudes between 28° and 60° in the north hemisphere. They developed two different models, in the article only the second model will be considered and it is denoted by Re. This model estimates the diffuse fraction k_d in terms of the clearness index k_T and the solar altitude angle α_s, as given in Eq. (7).

$$k_d = \begin{cases} 1.020 - 0.254\ k_T + 0.0123\ \sin(\alpha_s) & 0 \leq k_T \leq 0.30 \\ 1.400 - 1.749\ k_T + 0.177\ \sin(\alpha_s) & 0.3 < k_T < 0.78 \\ 0.486\ k_T - 0.182\ \sin(\alpha_s) & k_T \geq 0.78 \end{cases} \tag{7}$$

2.2.4 Maxwell model (DISC)

Maxwell (1987) proposed a model called DISC (Direct insolation Simulation Code) that combines physical principles with correlations for different conditions. The model determines $I_{b,n}$ by using I. It also is known as. The model determines first the direct transmittance of clear sky ($k_{n,c}$) as a function of air mass (AM).

$$k_{n,c} = 0.866 - 0.122(AM) + 0.0121(AM)^2 - 0.000653(AM)^3 + 0.000014(AM)^4 \tag{8}$$

Where the air mass is calculated with the Eq. (9) where θ_z the zenith angle and p is the local air pressure. Kn is determined by Eq. (10).

$$AM = [\cos(\theta_z) + 0.15 * (93.885 - \theta_z)^{-1.253}]^{-1} * \frac{p}{1013.25} \tag{9}$$

$$k_n = k_{n,c} - \Delta k_n \tag{10}$$

Where Δk_n can be determinate by means of the Eq. (11).

$$\Delta k_n = a + b * \exp(c * AM) \tag{11}$$

The coefficients a, b and c are functions of k_T as shown in the Eqs. (12) and (13).

$$\begin{cases} a = 0.512 - 1.56.77\ k_t + 2.286\ k_t{}^2 + 2.222\ k_t{}^3 \\ b = 0.37 - 0.962\ k_t & k_t \leq 0.6 \\ c = -0.28 + 0.932\ k_t - 2.048k_t{}^2 \end{cases} \tag{12}$$

$$\begin{cases} a = -5.74 + 21.77k_t - 27.49k_t{}^2 + 11.56k_t{}^3 \\ b = 41.40 - 118.50k_t + 66.05k_t{}^2 + 31.09k_t{}^3 & k_t > 0.6 \\ c = -47.01 + 184.2k_t - 222.0k_t{}^2 \end{cases} \tag{13}$$

The determination of $I_{b,n}$ is made by using Eq. (14)

$$I_{b,n} = I_{o,n} * K_n \tag{14}$$

2.3 Transposition models

These models generally convert the global horizontal irradiance into global tilted irradiance. where I_T, is the sum of three components, namely, the diffuse radiation ($I_{T,d}$), the beam radiation ($I_{T,b}$) and ground-reflective radiation ($I_{T,r}$) as given in Eq. (15) (Duffie & Beckman, 2006).

$$I_T = I_{T,b} + I_{T,d} + I_{T,r} \tag{15}$$

The beam irradiation on the tilted surface ($I_{T,b}$) can be determined in a simple form through the geometric relation by considering the incidence angle θ, as shown in Eq. (16).

$$I_{T,b} = I_{b,n}\, cos(\theta) \tag{16}$$

Ground-reflected irradiation ($I_{T,r}$) can be determinate by means of isotropic models through simple algorithms as given by Eq. (17). Where β, is the slope regarding the horizontal plane and ρ_g diffuse reflectance from surrounding.

$$I_{T,r} = I\,\rho_g\left(\frac{1 - \cos(\beta)}{2}\right) \tag{17}$$

The diffuse component $I_{T,d}$ can be defined as the fraction of the total irradiation received from the sun that is scattering for the atmosphere. This is distributed over the whole sky dome and is a function of extremely unpredictable conditions like cloudiness and atmospheric clearness (Jakhrani et al., 2013). The diffuse component can be divided into three diffuse irradiations: (i) The isotropic diffuse irradiation ($I_{T,d,iso}$), which represents part of the uniform diffuse irradiance received on the surface over the whole sky dome. (ii) The circumsolar diffuse irradiance ($I_{T,d,cs}$), that is the result of the scattering of beam solar irradiation and is concentrated in the section of the sky around the sun. (iii) The horizon brightening diffuse irradiation ($I_{T,d,hb}$), which is the result of the incident irradiation that crosses most of the air mass due to its concentration near to horizon (Widen, 2009) (Duffie & Beckman, 2006). The diffuse component is the sum of the isotropic, circumsolar and horizon brightening components as shown in Eq. (18).

$$I_{T,d} = I_{T,d,iso} + I_{T,d,cs} + I_{T,d,hb} \tag{18}$$

Due to its definition, the diffuse irradiation does not need an angle of incidence on the horizontal plane. Therefore, different models were proposed to determine the global tilted irradiation from data measured on the horizontal surface. These models can be classified in isotropic and anisotropic models (Kalogirou, 2014). The Table 2 presents the transposition models that will be considered in this study. Two isotropic models Ko (Koronakis, 1986) and Ba (Badescu, 2002) and two anisotropic models Kl (Klucher, 1979) and Pe (Perez et al., 1990). These models were selected because they are widely cited in the literature.

Table 2. Transposition models implemented.

Model	Input Variable	Type	Abbreviation
(Koronakis, 1986)	I_d, β	Isotropic	Ko
(Badescu, 2002)	I_d, β	Isotropic	Ba
(Klucher, 1979)	I, I_d, β, θ_z, θ	Anisotropic	Kl
(Perez et al., 1990)	I_o, I_d, k_t, $I_{b,n}$, θ_z, θ, AM	Anisotropic	Pe

2.3.1   Koronakis model (Ko)

In their work Koronakis (1986), proposed a modification to the model developed by Liu and Jordan (1960). It was assumed that the south of the sky is responsible for 63% of the diffuse flux. The result of that modification is shown in Eq. (19).

$$I_T = I_b R_b + I_d\left(\frac{2 + \cos\beta}{3}\right) + I\,\rho_g\left(\frac{1 - \cos\beta}{2}\right) \tag{19}$$

2.3.2 Badescu model (Ba)

Badescu (2002) developed a model that uses the zenith and azimuth angles to describe the position of the sun in the sky. Therefore, the global tilted irradiance is expressed as shown in Eq. (20).

$$I_T = I_b R_b + I_d \left(\frac{3 + \cos 2\beta}{4}\right) + I \rho_g \left(\frac{1 - \cos \beta}{2}\right) \tag{20}$$

2.3.3 Klucher model (Kl)

Klucher (1979), found that isotropic models present good results for cloudy sky conditions. However, they underestimate the irradiation under clear sky and partly cloudy sky conditions. That inaccuracy is related to the increasing intensity near to horizon and the circumsolar fraction. In order to improve the calculations a modification of the model by Temps and Coulson (1977) was proposed. A correction factor $f_k = 1 - \left(\frac{I_d}{I}\right)^2$ was added. That factor estimates the effect of the clouds on the irradiation (Klucher, 1979), as shown in Eq. (21).

$$I_T = I_b R_b + I_d \left(\frac{1 + \cos \beta}{2}\right)(1 + f_k \cos^2\theta \cos^3\theta_z)\left(1 + f_k \sin^3\left(\frac{\beta}{2}\right)\right) + I \rho_g \left(\frac{1 - \cos \beta}{2}\right) \tag{21}$$

2.3.4 Perez et al. model (Pe)

Perez et al. (1990) based their model in a detailed analysis of the three diffuse components. The tilted diffuse irradiation is given by Eq. (22).

$$I_{T,d} = I_d \left[(1 - F_1)\left(\frac{1 + \cos \beta}{2}\right) + F_1 \frac{a}{b} + F_2 \sin \beta\right] \tag{22}$$

Where a and b, are terms that explain the angle of incidence of the circumsolar radiation cone and on the inclined and horizontal surfaces, they are given by $a = \max(0, \cos \theta)$ and $b = \max(\cos 85, \cos \theta_z)$, F_1 and F_2 are the coefficients for the circumsolar and the horizon brightening fractions, respectively. They are given in Eqs. (23) and (24) as functions of three parameters that describe the condition of the sky, namely, the zenith angle θ_z, the clearness ε and the brightness Δ.

$$F_1 = \max\left[0, \left(f_{11} + f_{12}\Delta + \frac{\pi\theta_z}{180} f_{13}\right)\right] \tag{23}$$

$$F_2 = \left(f_{21} + f_{22}\Delta + \frac{\pi\theta_z}{180} f_{23}\right) \tag{24}$$

Where ε, is the clearness parameter and it is calculated by Eq. (25). Where I_d, is the diffuse horizontal irradiation, $I_{b,n}$ is the direct normal irradiance. The brightness parameter Δ can be determinate like show the Eq. (26). Where AM, is the air mass and $I_{o,n}$ is the extraterrestrial normal irradiance. The brightness coefficient (f_{xx}) are dependently of clearness coefficient ε, and can be find in (Perez et al., 1990).

$$\varepsilon = \frac{\frac{I_d + I_{b,n}}{I_d} + 5.535 * 10^{-6} \theta_z^3}{1 + 5.535 * 10^{-6} \theta_z^3} \tag{25}$$

$$\Delta = AM \frac{I_d}{I_{o,n}} \tag{26}$$

3. RESULT

In the present section the accuracy of the models is assessed by comparison of the calculated values from the combinations of different decomposition-transposition models with the results provided by the software Radiasol 2. All the models were implemented in the computational language Matlab®.

3.1 Comparison between the software results and the models estimates

In this section the results obtained from the combinations of the four decomposition models with the four transposition models will be compared with the results obtained by Radiasol 2 software. The models were presented in sections 2.2 and 2.3 and they generate 16 combinations in total. The input data were obtained from the global horizontal irradiance provided by SWERA for Porto Alegre city. The values of the statistical estimators for combined irradiance models are show in the Table 3.

Table 3. Statistical analysis of the predict global tilted irradiance models (decomposition model + transposition model)

Model	RMSE(W/m2)	rRMSE(%)	MBE(W/m2)	rMBE(%)	R^2	Order	N
Er-Ba	50,871	11,63	-38,607	-8,83	0,9925	9	3721
Er-Ko	35,194	8,05	-22,228	-5,08	0,9964	5	3721
Er-Kl	139,497	31,9	-102,365	-23,41	0,9434	13	3721
Er-Pe	**26,799**	**6,13**	**-9,915-**	**-2,27**	**0,9979**	**3**	3721
OH-Ba	52,049	11,89	-39,819	-9,10	0,9920	12	3781
OH-Ko	36,172	8,26	-22,963	-5,25	0,9961	8	3781
OH-Kl	142,30	32,51	-104,610	-23,90	0,9399	16	3781
OH-Pe	**26,490**	**6,05**	**-10,810**	**-2,47**	**0,9979**	**2**	3781
Re-Ba	53,731	11,46	-42,441	-9,05	0,9930	11	3512
Re-Ko	36,813	7,85	-24,373	-5,20	0,9967	7	3512
Re-Kl	144,452	30,81	-105,764	-22,56	0,9497	14	3512
Re-Pe	**26,609**	**5,68**	**-10,067**	**-2,15**	**0,9983**	**1**	3512
DISC-Ba	57,386	11,29	-45,986	-9,05	0,9942	10	2993
DISC-Ko	38,645	7,6	-26,068	-5,13	0,9974	6	2993
DISC-Kl	148,883	29,29	-105,266	-20,71	0,9612	15	2993
DISC-Pe	30,832	6,07	-12,720	-2,50	0,9983	4	2993

In terms of RMSE the error range of the models is from 26.490 W/m^2 (6.05% rRMSE) for the OH-Pe model to 148.883 W/m^2 (29.29% rRMSE) for the DISC-Kl model. While the MBE ranges from -9.915 w/m2 (-2.27% rMBE) for the Er-Pe model to -105.765 W/m^2 (-22.56% rMBE) for the DISC-Kl model. All results obtained for MBE of the different models are negative which implies that the combined irradiance models underestimate the values provided by the software. All models represent the variability with an accuracy of more than 99% with respect to the values obtained by the Radiasol 2.1 software, except for the combined irradiance models that used the Kl transposition model. The combinations that include the K1 transposition model present the worst performance. The R^2 ranged from 0.9399 for OH-Kl to 0.9983 presented by the Re-Pe and DISC-Pe models. Therefore, the models that present the best performance are Re-Pe, OH-Pe and Er-Pe models.

Figure 2 presents the results of RMSE and MBE (Figure 2a) and their relative counterparts rRMSE and rMBE (Figure 2b) obtained in the present study for the different model combinations. Further statistical analysis of the results obtained by the different models implemented in this work are presented in Figure 3 and Table 4.
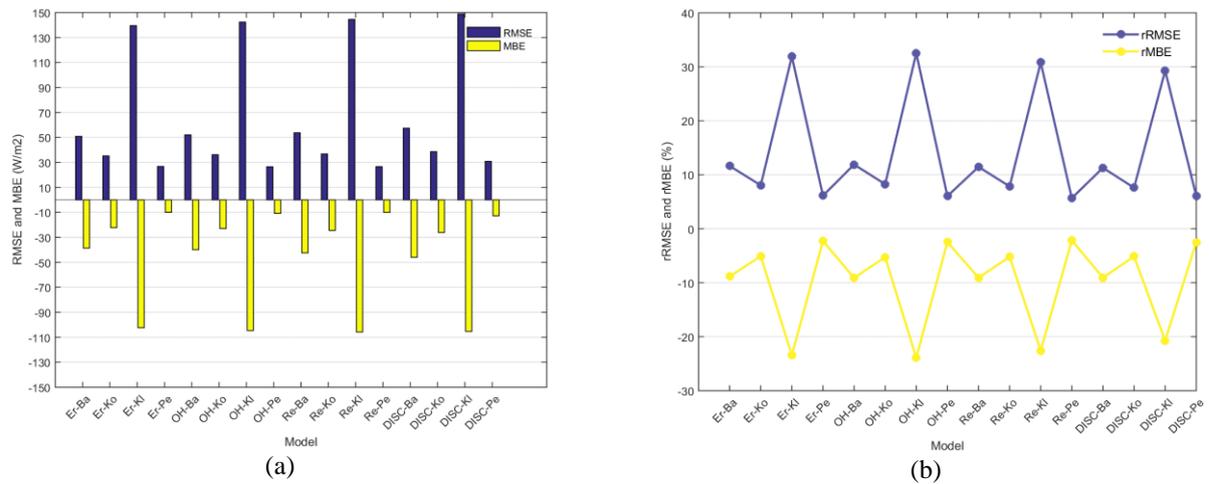
Figure 2. Comparative graph of the different statistical estimators obtained for the model combinations a) RMSE and MBE, b) rRMSE and rMBE

Table 4. Results for the combined irradiation model according to the literature

Referent	Decomposition models	Transposition models	City	β(Deg)	rMBE(%)	rRSME(%)
(Yang et al., 2013)	------	Badescu	Singapore	18.3	-----	10.13
(Demain et al., 2013)	------	Badescu	Brussels, Belgium	50.8	3.10	10.27
(Notton, Poggi, et al., 2006)	DISC	Koronakis	Ajaccio	45.0	-5.88	9.99
(Roberts et al., 2016)	OH	Koronakis	Magdeburg, Germany.	45.0	−0.19	21.24
(Roberts et al., 2016)	DISC	Koronakis	Magdeburg, Germany.	45.0	1.39	16.06
(Gueymard, 2009)	Reindl	Klucher	Golden, USA	40.0	-1.30	10.00
(Li, et al., 2017)	-----	Klucher	Beijing	90.0	15.79	14.38
(Utrillas et al., 1991)	-----	Klucher	Valencia, Spain	90.0	-7.60	11.10
(Gueymard, 2009)	DISC	Klucher	Golden, USA	40.0	-0.20	9.40
(Notton, Poggi, et al., 2006)	DISC	Klucher	Ajaccio	45.0	-2.33	8.11
(Gueymard, 2009)	Erbs	Perez	Golden, USA	40.0	-1.60	10.4
(Notton, Poggi, et al., 2006)	DISC	Perez	Ajaccio	45.0	-0.60	9.94
(Roberts et al., 2016)	OH	Perez	Magdeburg, Germany.	45.0	3.82	20.34
(Utrillas et al., 1991)	-----	Perez	Valencia, Spain	90.0	-2.40	9.00
(Gueymard, 2009)	DISC	Perez	Golden, USA	40.0	-0.50	9.80
(Li, et al., 2017)	-----	Perez	Beijing	90.0	7.48	23.60
(Gueymard, 2009)	Reindl	Perez	Golden, USA	40.0	-2.20	9.90
This Work	Reindl	Perez	Porto Alegre	30.0	-2.15	5.68
This Work	OH	Perez	Porto Alegre	30.0	-2.47	6.05
This Work	Er	Perez	Porto Alegre	30.0	-2.27	6.13

The graphs depicted on Figure 2 show similar behaviors among the transposition models, when they are used with different decomposition models. The statistical estimators depend more on the transposition model used than on the decomposition model. The isotropic models (Ba and Ko) generally tend to underestimate the irradiance (MBE < 0) because they neglect the diffuse circumsolar irradiance and the diffuse horizon irradiation. On the other hand, the anisotropic models (Kl and Pe) tend to overestimate the irradiance (MBE > 0). The results obtained in the present article show that all models underestimate the data provided by the software.

The RMSE is a remarkably interesting parameter for comparison, which shows the adequacy of the model. The models (Re-Pe, OH-Pe, Er-Pe and DISC-Pe) show good results with rRMSE below 7%. the Ko model in different combinations (Re-Ko, OH-Ko, Er-Ko and DISC-Ko) also presents good rRMSE between 7% and 9%.

A literature review was performed in order to compare the results obtained in the present study with those obtained by other authors. The information regarding the performance of different models available in the literature is presented in Table 4. According to the information provided on that Table, the combination DISC-Ko tested for Ajaccio by Notton et al. (2006) underestimates the irradiance presenting a rMBE of -5.88% and a rRMSE of 9,989%. These results are similar to those obtained in the present work for Porto Alegre, for instance, in the present work it was obtained a rMBE of -5.13% and a rRMSE of 7.6%.
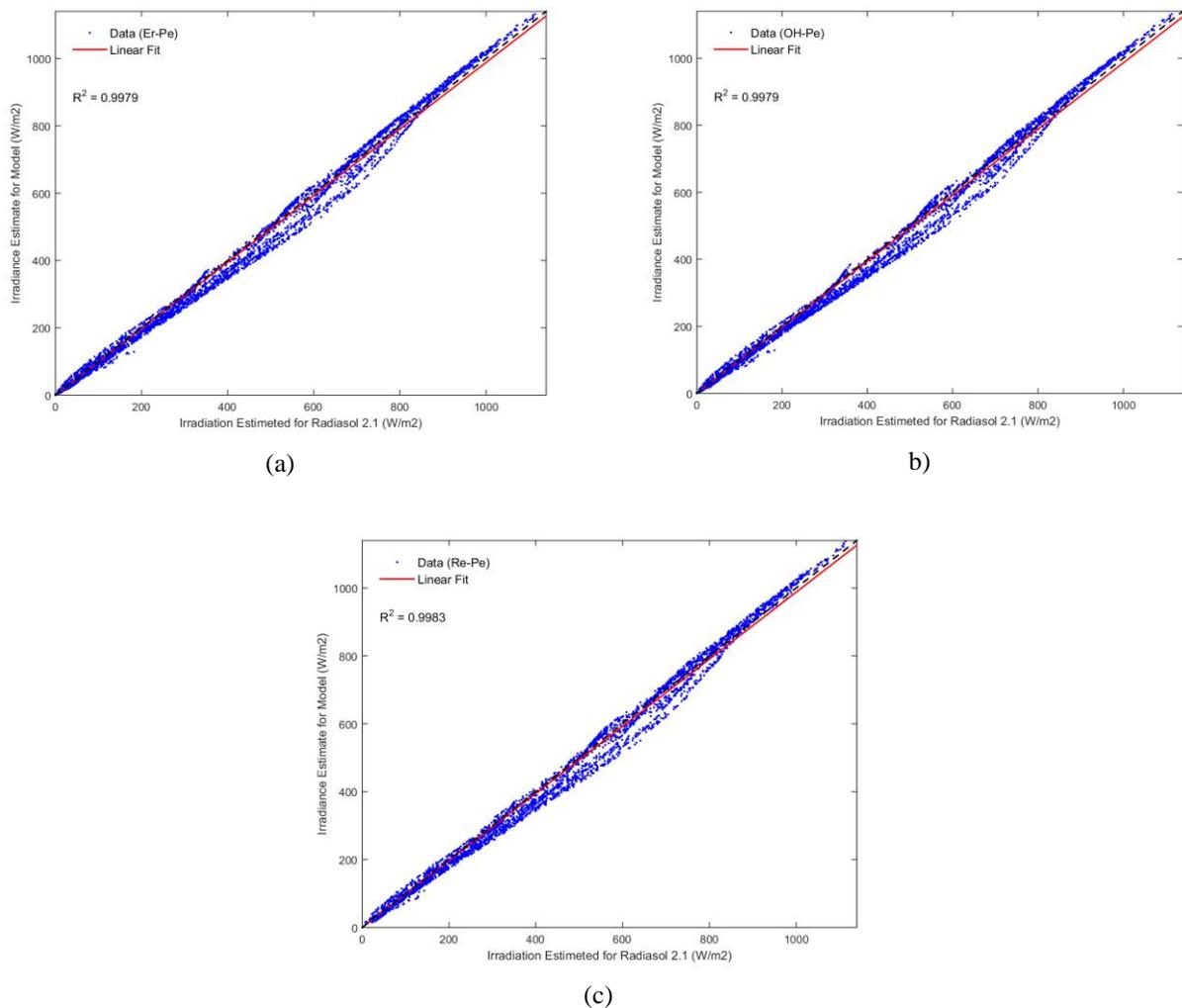

(a)

(b)

(c)

Figure 3. Estimated values for irradiance on an inclined surface by the Radiacol 2.1 software and the values predicted by the 3-best decomposition-transposition models: a) Er-Pe, b) OH-Pe and c) Re-Pe

The Pe model has been widely studied, as shown in see Tab. 4. The variation between the results obtained by different authors does not allow to determine whether the transposition model overestimates or underestimates the solar irradiance, since as can be observed the values of MBE are positive or negative depending on the city that was considered. Concerning to results of RMSE values obtained in this work, they show the similar magnitude than the results presented in the cited literature. The results obtained at tilt angles of 90 degrees are higher than those obtained for lower tilt angles.

The results of the Kl model in its different combinations with the decomposition models are very different from those presented in the literature as observed in table 4. On the other hand, for the models Ba and Ko the results obtained in the present work have similar accuracy than those presented by other authors.

Figure 3 compares the hourly irradiance obtained by the Radiasol 2 software with the irradiance calculated by the models that presented the best accuracy in this work. The irradiance was calculated on a surface with a tilt angle of 30 degrees. The red line represents the best linear fit of the data, while the dashed line represents the same values obtained by the software.

As can be observed in Fig. 3, the results obtained in this work indicate a good performance when compared to the software's results. The data estimated by the decomposition-transposition models clearly show a very good fit with the data estimated by Radiasol 2 software. A squared correlation coefficient R^2 of 0.9979 was obtained for Er-Pe and OH-Pe models and a R^2 of 0.9983 was obtained for Re-Pe model. It is important to point out that the models used by Radiasol 2 software for decomposition was developed by Collares-Pereira and Rabl (1979) and the model used for transposition was developed by Perez et al. (1987). The decomposition models employed by Radiosol 2 are similar to those developed by Erbs et al. (1982), Orgill and Hollands (1977) and Reindl et al. (1990a). Since the model developed by Maxwell (1987) combines physical principles, it present the higher deviations when compared to the software results. The transposition model implemented in this work uses brightness coefficients which are not used in the models implemented in Radiasol 2.

4. CONCLUTION

Sixteen combinations of decomposition-transposition models were tested to determine the solar irradiance on a tilted surface from global horizontal irradiance. The main objective of the present work was to evaluate the performance of the different combinations of some of the most cited models to determine global hourly irradiance on an inclined surface to choose models that have good accuracy. The 3 best combinations among them were identified.

The three combinations of decomposition-transposition models that appear to be the most accurate are the Er-Pe, OH-Pe and Re-Pe models. They have an rRMSE between 5.68% and 6.13% and an rMBE between -2.15% to -2.47%. Therefore, presenting similar accuracy than those models presented in the literature.

Future studies involving the evaluation of potential applications of solar energy systems in Porto Alegre can use these three models since they have shown accurate results.

5. ACKNOWLEDGEMENTS

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