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Performance comparison of different models for the estimation of global irradiance on inclined surfaces

Validation of the model implemented in PVGIS

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1. Introduction

PVGIS (Photovoltaic Geographical Information System) is a web application, developed by the Institute for Energy and Transport (IET) of the Joint Research Center (JRC) that enables the user to obtain an estimation of the electricity production provided by any PV system.

In order to estimate the PV output, it is necessary to know previously, the global irradiance received by the PV module. This is usually an inclined surface, in order to maximize the solar radiation received, whether by using a fixed inclined mounting position or a sun tracker system. Whatever the mounting configuration, data regarding the global solar radiation received by the PV plane is required. However, this information is not usually available as measured data, being therefore necessary to use estimated values. To that purpose, in the scientific bibliography, there are several models to estimate the global irradiance on tilted surfaces, G_T , using the global irradiance on the horizontal plane, G , and its diffuse and beam components (G_d and G_b respectively) as input data.

In the case of PVGIS, Muneer's model (1990) is applied to estimate G_T , which proved the best overall performance in the research developed by ESRA, *ESRA User Guidebook* (2000).

The aim of this research was to consider other models for the estimation of the global irradiance on inclined surfaces and compare their ability with the one shown by Muneer's model, in order to validate the latter or, otherwise substitute it by a more accurate estimation model.

1.1. Models for the estimation of the solar global radiation on tilted surfaces

Global irradiance on a tilted surface, G_T , is the sum of the beam, G_{bT} , and diffuse, G_{dT} , irradiance components plus the irradiance received from ground reflections G_{rT} .

$$G_T = G_{bT} + G_{dT} + G_{rT} \quad (1)$$

Since the beam component can be described as coming directly from the solar disc, once the value of the beam irradiance on the horizontal plane is known, G_b , the estimation of the beam irradiance reaching an inclined surface follows a purely geometric relation which depends on the surface's inclination and orientation angles and the sun's coordinates, as shown in Eq. 2:

$$G_{bT} = G_b \cdot \frac{\cos \xi}{\cos \sigma_z} \quad (2)$$

where ξ is the incidence angle of the sun's rays on the tilted plane and σ_z is the solar zenith angle.

The reflected irradiance, G_{rT} , is usually assumed ideally isotropic, meaning that both the diffuse and beam irradiances are reflected identically and the horizon is uniform and free of obstacles. Besides these simplified assumptions, the main uncertainty may derive from the ground albedo value used, as it may have a great impact on the irradiance finally received by the surface, especially for those with high inclination angles. In this regard, Kambezidis et al. (1994) used three different albedo values, constant, seasonally varying and anisotropic, concluding that the last two options don't improve significantly the performance of the estimations of G_T with regard to using a fixed albedo value, usually 0.2. Demain et al. (2006) also observed that considering an isotropic reflection provided better results than the two anisotropic model formulation applied. However, these authors obtained the lowest RMSD and MBD values in the estimation of G_T when considering the daily albedo variation, and also lower MBD values when applying seasonal variations than when a constant albedo value was used. Notwithstanding, since the albedo is not commonly measured in weather stations, a constant value can be applied. According to these considerations, the reflected irradiance, G_{rT} , is assumed isotropic and calculated using the following Eq. 3:

$$G_{rT} = G \cdot \rho \cdot \frac{(1 - \cos \beta)}{2} \quad (3)$$

where ρ is the ground's albedo, defined as a constant value, and β is the surface's inclination angle with regard to the horizontal plane.

Most models estimate the beam and reflected irradiances on the tilted surface using the previous mathematical expressions. On the contrary, the way the diffuse irradiance is calculated differs from model to model. In fact, this is one of the main differences to classify this type of models into different categories.

The diffuse irradiance is the result of the solar radiation being scattered by the atmosphere's components and therefore it is not uniform throughout the sky dome. Notwithstanding, in some models it is considered uniform and isotropic, despite the discontinuous effects of cloud cover and the scattering process in the atmosphere. Although the cloud cover's effect is not usually considered, there are other models that try to describe the outcome of the scattering processes by adding to the isotropic background, the diffuse irradiance coming from the circumsolar region and the horizon band. Therefore, the models for the estimation of G_T can be classified into two main groups: isotropic and anisotropic. This latter group of models can also be divided depending on whether they consider, apart from the isotropic background, both the circumsolar and horizon band regions, or just the irradiance coming from the circumsolar region. Anisotropic models will be, from now on, classified as using 3 or 2 diffuse "components".

The next three sections contain a brief description of the various models considered in this study.

1.1.1. Isotropic models

Four different isotropic models have been applied.

Liu-Jordan (1962) assumed the diffuse irradiance to be uniformly distributed over the sky dome (Eq. 4), similarly to what is observed under homogeneously overcast situations.

$$G_{dT} = G_d \cdot \frac{(1 + \cos \beta)}{2} \quad (4)$$

However, an inclined plane facing south in the northern hemisphere (facing north in the southern one), receives more diffuse radiation than another plane with the same inclination angle facing the opposite direction. In fact, the sky's southern part, in the northern hemisphere, seems to be responsible for about the 63% of the total diffuse radiation. To account for this effect, Korokanis (1986) modified the Liu-Jordan model and proposed Eq. 5:

$$G_{dT} = G_d \cdot \frac{(2 + \cos \beta)}{3} \quad (5)$$

Similarly to Korokanis, Badescu (2002) defined the next mathematical expression, Eq. 6:

$$G_{dT} = G_d \cdot \frac{(3 + \cos 2\beta)}{4} \quad (6)$$

Jimenez et al (1986) supposed the diffuse irradiance on the horizontal plane to be 20% of the global irradiance, so its value on the inclined plane is estimated according to Eq. 7:

$$G_{dT} = 0.2 \cdot G \cdot \frac{(1 + \cos \beta)}{2} \quad (7)$$

Consequently, for this model, the beam irradiance on the inclined plane is calculated using Eq. 8:

$$G_{bT} = 0.8 \cdot G \cdot \frac{\cos \xi}{\cos \sigma_z} \quad (8)$$

1.1.2. Anisotropic models

The Circumsolar model (Iqbal, 1983) considers that all the diffuse irradiance comes from the direction of the sun and it is treated like the beam irradiance as shown in Eq. 9.

$$G_{dT} = G_d \cdot \frac{\cos \xi}{\cos \sigma_z} \quad (9)$$

1.1.2.1. Anisotropic models considering two “components”

Bugler (1977) added a corrective term to the isotropic model defined by Liu-Jordan, which depends on the Sun’s zenith angle and a new “component” to account for the diffuse irradiance coming from the Sun’s disc direction. (Eq. 10)

$$G_{dT} = \left(G_d - 0.05 \cdot \frac{G_{bT}}{\cos \sigma_z} \right) \cdot \left(\frac{1 + \cos \beta}{2} \right) + 0.05 \cdot G_{bT} \cdot \cos \xi \quad (10)$$

The model developed by Hay (1979) considers both the isotropic and circumsolar diffuse “components” weighted according to an isotropic index (G_b/G_0), as shown in Eq. 11:

$$G_{dT} = G_d \cdot \left[\left(\frac{G_b}{G_0} \cdot \frac{\cos \xi}{\cos \sigma_z} \right) + \left(1 - \frac{G_b}{G_0} \right) \cdot \left(\frac{1 + \cos \beta}{2} \right) \right] \quad (11)$$

G_0 is the extraterrestrial global solar irradiance on the horizontal plane.

Under overcast situations, an important part of the diffuse radiation comes from the zenith region. To account for this effect, which diminishes as the cloud cover disappears, Skartveit and Olseth (1986) modified Hay’s model as follows, (Eqs. 12 and 13):

$$G_{dT} = G_d \cdot \left[\left(\frac{G_b}{G_0} \cdot \frac{\cos \xi}{\cos \sigma_z} \right) + Z \cdot \cos \beta + \left(1 - \frac{G_b}{G_0} - Z \right) \cdot \left(\frac{1 + \cos \beta}{2} \right) \right] \quad (12)$$

$$Z = \max \left[0.3 - 2 \cdot \frac{G_b}{G_0}, 0 \right] \quad (13)$$

The model developed by Willmott (1982), Eqs 14 and 15, also considers the circumsolar diffuse irradiance and similarly to Hay’s model introduces an anisotropic index ($G_{bn} \cdot \cos(\xi)/G_{sc}$).

$$G_{dT} = G_d \cdot \left[\left(\frac{G_{bn}}{G_{sc}} \cdot \frac{\cos \xi}{\cos \sigma_z} \right) + C_\beta \cdot \left(1 - \frac{G_{bn}}{G_{sc}} \right) \right] \quad (14)$$

$$C_\beta = 1.0115 - 0.20293\beta - 0.080823\beta^2 \quad (15)$$

where G_{sc} is the solar constant (1367 Wm^{-2}) The plane’s inclination angle, β , has to be in radians.

Gueymard (1987) suggests calculating the diffuse irradiance as the sum of the irradiance of the clear and overcast skies, using a “cloud opacity” weighted factor, N_G . Eqs. 16 – 27.

$$G_{dT} = G_d \cdot [(1 - N_G) \cdot R_{d0} + N_G \cdot R_{d1}] \quad (16)$$

$$N_G = \max[\min(Y, 1), 0] \quad (17)$$

$$\text{If } \frac{G_d}{G} \leq 0.227 \quad Y = 6.6667 \cdot \frac{G_d}{G} - 1.4167 \quad (18)$$

$$\text{If } \frac{G_d}{G} > 0.227 \quad Y = 1.2121 \cdot \frac{G_d}{G} - 0.1758 \quad (19)$$

$$R_{d0} = \exp(a_0 + a_1 \cdot \cos \xi + a_2 \cdot (\cos \xi)^2 + a_3 \cdot (\cos \xi)^3) + F(\beta) \cdot G(h) \quad (20)$$

$$a_0 = -0.897 - 3.364h' + 3.960h'^2 - 1.909h'^3 \quad (21)$$

$$a_1 = 4.448 - 12.962h' + 34.601h'^2 - 48.784h'^3 + 27.511h'^4 \quad (22)$$

$$a_2 = -2.770 + 9.164h' - 18.876h'^2 + 23.774h'^3 - 13.014h'^4 \quad (23)$$

$$a_3 = 0.312 - 0.217h' - 0.805h'^2 + 0.318h'^3 \quad (24)$$

$h' = 0.01 \alpha_s$, where α_s is the solar elevation angle ($^\circ$)

$$F(\beta) = \frac{1 - 0.2249 \cdot (\sin \beta)^2 + 0.1231 \cdot \sin(2\beta) - 0.0342 \cdot \sin(4\beta)}{1 - 0.2249} \quad (25)$$

$$G(h) = 0.408 - 0.323h' + 0.384h'^2 - 0.170h'^3 \quad (26)$$

$$R_{d1} = \left(\frac{1 + \cos \beta}{2} \right) - \frac{\left(\frac{\beta \cos \beta - \sin \beta}{\pi} + \frac{1 - \cos \beta}{2} \right)}{\left(1 + \frac{3}{2b} \right)} \quad (27)$$

with $b = 1.5$.

The model implemented in PVGIS, developed by Muneer (1990) can be classified in this category of anisotropic models. The model's equations to estimate G_{dT} distinguish between clear and overcast sky conditions and sunlit and shaded surfaces as shown in Eqs. 28 – 30.

For shaded surfaces or overcast situations:

$$G_{dT} = G_d \cdot \left[\left(\frac{1 + \cos \beta}{2} \right) + 0.25227 \cdot \left(\sin \beta - \beta \cdot \cos \beta - \pi \cdot \left(\sin \frac{\beta}{2} \right)^2 \right) \right] \quad (28)$$

For sunlit surfaces under non overcast sky conditions.

$$G_{dT} = G_d \cdot \left[\left(\frac{1 + \cos \beta}{2} \right) + \left(\sin \beta - \beta \cdot \cos \beta - \pi \cdot \left(\sin \frac{\beta}{2} \right)^2 \right) \cdot \left(0.00263 - 0.712 \cdot \frac{G_b}{G_0} - 0.6883 \cdot \left(\frac{G_b}{G_0} \right)^2 \right) \cdot \left(1 - \frac{G_b}{G_0} \right) + \left(\frac{G_b}{G_0} \cdot \frac{\cos \xi}{\cos \sigma_s} \right) \right] \quad (29)$$

Under these circumstances, a correction has to be applied when the solar elevation angle, α_s , is low. Therefore, if $\alpha_s < 0.1$ rad, G_{dT} is calculated following Eq. 30:

$$G_{dT} = G_d \cdot \left[\left(\frac{1 + \cos \beta}{2} \right) + \left(\sin \beta - \beta \cdot \cos \beta - \pi \cdot \left(\sin \frac{\beta}{2} \right)^2 \right) \cdot \left(0.00263 - 0.712 \cdot \frac{G_b}{G_0} - 0.6883 \cdot \left(\frac{G_b}{G_0} \right)^2 \right) \right] \cdot \left(1 - \frac{G_b}{G_0} \right) + \left(\frac{G_b}{G_0} \cdot \frac{\sin \beta \cdot \cos(\gamma_T - \gamma_s)}{0.1 - 0.008 \cdot \alpha_s} \right) \quad (30)$$

For this study, the sky conditions are classified using the clearness index modified by Perez et al (1990), kt' , (Eq. 31) in order to make it independent of the solar elevation angle.

$$k_t' = \frac{k_t}{0.1 + 1.031 \cdot \exp \left(\frac{-1.4}{0.9 + \frac{9.4}{AM}} \right)} \quad (31)$$

where k_t is the clearness index (G/G_0) and AM is the air mass.

Overcast skies are defined by $kt' < 0.3$, following Ineichen's (Ineichen, 2011) sky condition classification into three categories, which are coherent with other classifications using other parameters. However, in opposition to other parameters, to calculate kt' only G data is required. The limits of Ineichen's classification also agree with the data registered in Ispra.

1.1.2.2. Anisotropic models considering three "components"

The model developed by Temps and Coulson (1977), simulates the anisotropy of the sky under clear conditions, including the irradiance coming from the vicinity of the sun and the brightening of the sky near the horizon, according to Eq. 32.

$$G_{dT} = G_d \cdot \left[\left(\frac{1 + \cos \beta}{2} \right) \cdot \left(1 + \left(\sin \frac{\beta}{2} \right)^3 \right) \cdot \left(1 + (\cos \xi)^2 \cdot (\sin \sigma_z)^3 \right) \right] \quad (32)$$

Klucher (1979), Eq. 33, modified Temps and Coulson's model by introducing a function, F (Eq 34), which defines the degree of cloud cover, in order to represent partly cloudy conditions.

$$G_{dT} = G_d \cdot \left[\left(\frac{1 + \cos \beta}{2} \right) \cdot \left(1 + F \cdot \left(\sin \frac{\beta}{2} \right)^3 \right) \cdot \left(1 + F \cdot (\cos \xi)^2 \cdot (\sin \sigma_z)^3 \right) \right] \quad (33)$$

$$F = 1 - \left(\frac{G_d}{G} \right)^2 \quad (34)$$

Reindl et al. (1990), Eqs. 35 and 36, added the diffuse irradiance coming from the horizon band to the Hay model, using the term already introduced by Temps and Coulson. The horizon band's intensity is controlled by a modulating factor, f , Eq. 37. This combination of models is why this one is usually called HDKR model.

$$G_{dT} = G_d \cdot \left[(1 - A_i) \cdot \left(\frac{1 + \cos \beta}{2} \right) \cdot \left(1 + f \cdot \left(\sin \frac{\beta}{2} \right)^3 \right) + \left(A_i \cdot \frac{\cos \xi}{\cos \sigma_z} \right) \right] \quad (35)$$

$$A_i = \frac{G_b}{G_0} \quad (36)$$

$$f = \sqrt{\frac{G_d}{G}} \quad (37)$$

The model developed by Perez et al (1990) is one of the most used models for the estimation of G_T as it represents a more detailed description of the anisotropic origin of the diffuse irradiance. This model uses empirically derived coefficients (Table 1) which are selected according to the sky condition described by two parameters defined by the authors, the sky clearness index, ε , and sky brightness, Δ .

The diffuse irradiance on the tilted plane is the sum of the background isotropic irradiance, the irradiance coming from the circumsolar region and the horizon band, as shown in Eq. 38.

$$G_{dT} = G_d \cdot \left[(1 - F_i) \cdot \left(\frac{1 + \cos \beta}{2} \right) + F_1 \cdot \frac{a_t}{b_t} + F_2 \cdot \sin \beta \right] \quad (38)$$

$$a_t = \max(0, \cos \xi) \quad (39)$$

$$b_t = \max(\cos 85^\circ, \cos \sigma_z) \quad (40)$$

$$F_1 = \max[0, (f_{11} + f_{12} \cdot \Delta + \sigma_z \cdot f_{13})] \quad (41)$$

$$F_2 = f_{21} + f_{22} \cdot \Delta + \sigma_z \cdot f_{23} \quad (42)$$

Sky brightness, ε , interval	f_{11}	f_{12}	f_{13}	f_{21}	f_{22}	f_{23}
[1 - 1.065)	-0.196	1.084	-0.006	-0.114	0.180	-0.019
[1.065 - 1.230)	0.236	0.519	-0.180	-0.011	0.020	-0.038
[1.230 - 1.500)	0.454	0.321	-0.255	0.072	-0.098	-0.046
[1.500 - 1.950)	0.866	-0.381	-0.375	0.203	-0.403	-0.049
[1.950 - 2.800)	1.026	-0.711	-0.426	0.273	-0.602	-0.061
[2.800 - 4.500)	0.978	-0.986	-0.350	0.280	-0.915	-0.024
[4.500 - 6.200)	0.748	-0.913	-0.236	0.173	-1.045	0.065
≥ 6.2	0.318	-0.757	0.103	0.062	-1.698	0.236

Table1. Coefficients used by Perez's model for the estimation of global irradiance on tilted surfaces

2. Methodology

The estimated irradiance values derived from the various models were compared with different types of datasets.

2.1 Datasets of irradiance values

2.1.1. PVGIS data

The global, diffuse and beam Irradiance values on tilted plane (G_T , G_{dT} and G_{bT}) were obtained using the PVGIS web application, for three different locations in Europe (Spain, France and

Denmark). Since PVGIS takes into account the horizon height surrounding the selected location in the estimation of the solar resource, the three sites were chosen trying to minimize the horizon elevation, as its effect on the available solar resource cannot be considered when applying the estimation models.

Table 2 shows the information of the five inclined surfaces considered in every site.

	I1	I2	I3	I4	I5
Inclination angle, β ($^{\circ}$)	40	30	20	20	90
Orientation angle*, γ ($^{\circ}$)	0	-30	30	-30	0

Table 2. Inclination and orientation angles of the tilted surfaces considered in the PVGIS dataset

*. Orientation angle: East -90° , South 0° , West 90° .

This dataset contains irradiance values every 15 minutes, from sunrise to sunset, for the characteristic or representative day of every month for a hypothetical year.

In order to apply the different models, the global, diffuse and beam irradiance on the horizontal plane (G , G_d and G_b) were required as input data. These values were also obtained from the web application.

2.1.2. Ispra meteo tower. Averaged values

The 1-minute irradiance data registered from the meteo tower are averaged, in order to obtain an average daily profile for every month.

The global irradiance on three inclined planes, facing south, is recorded. The pyranometer's inclination angles are shown in Table 3.

	IS90	IS45	IS60
Inclination angle, β ($^{\circ}$)	90	45	60
Orientation angle*, γ ($^{\circ}$)	0	0	0

Table 3. Inclination and orientation angles of the tilted surfaces, pyranometers, used in the Ispra meteo tower

Irradiance G , G_d and G_{bn} are also recorded, averaged and used as input data.

2.1.3. Ispra meteo tower. Selected days.

This third dataset contains the irradiance values registered in the meteo tower during a certain number of days with specific sky conditions: cloud free skies (clear) and completely overcast situations. On the one hand by light cloud cover (bright overcast) and, on the other hand, by dark cloud cover (dark overcast). The number of days for each sky type is 8, 11 and 2 respectively.

Data are averaged every 10 minutes. The values of G , G_d and G_{bn} are used as input data, and the global irradiance on the three inclined surfaces described in Table 3. are used as measured values in opposition to the estimated values derived from the different models.

2.2. Quality control

A very simple quality control procedure was applied to the data. The irradiance values from a particular moment were all dismissed if:

- $\alpha_s < 0^{\circ}$ (for some datasets a minimum level of 5° was considered as well)
- $G < 0 \text{ Wm}^{-2}$

- $G_d < 0 \text{ Wm}^{-2}$
- $G_b < 0 \text{ Wm}^{-2}$

3. Results

The ability of the different models to estimate the irradiance values on tilted surfaces is analysed by means of the mean bias difference (MBD) and the root mean square difference (RMSD) in both absolute (Wm^{-2}) and relative values (%). These parameters are calculated using Eqs. 43 and 44:

$$MBDr (\%) = 100 \cdot \frac{MBD}{\text{measured value}} = 100 \cdot \frac{\frac{\sum_{i=1}^n (\text{estimated}_i - \text{measured}_i)}{N}}{\text{measured value}} \quad (43)$$

$$RMSDr (\%) = 100 \cdot \frac{RMSD}{\text{measured value}} = 100 \cdot \frac{\sqrt{\frac{\sum_{i=1}^n (\text{estimated}_i - \text{measured}_i)^2}{N}}}{\text{measured value}} \quad (44)$$

3.1. Estimated irradiance values against PVGIS dataset

In this section the irradiance values derived from the different models (G_T , G_{dT} , G_{bT}) are compared to the data provided by the Muneer model implemented in PVGIS. This comparison is not a real validation of Muneer model, but an analysis of the performance of the other models regarding this one, in order to see whether they show a tendency to overestimate or underestimate the PVGIS data.

From the analysis of the results obtained for the different inclined surfaces and sites, it can be concluded that:

- considering every plane separately
 - every model behaves similarly in the three locations. Meaning that they tend to overestimate or underestimate the PVGIS data whatever the emplacement.
 - the magnitude of MBDr and RMSDr of each model is similar for all the sites. But the differences between the PVGIS values and those estimated by the models are lower for the Spanish site than for the other two. The decrease in the MBDr and RMSDr values is especially noticeable for the Perez, Jimenez and Circumsolar models.
 - in general, for all the models and sites, the RMSDr values and the absolute value of MBDr decrease from the vertical plane to less inclined surfaces.
- analyzing the different models:
 - the isotropic models provide lower irradiance values (G_T and G_{dT}) than Muneer, while the Circumsolar model tends to overestimate the PVGIS data.
 - the models by Perez and Gueymard provide the lowest MBDr, overestimating the first one and underestimating the second. The other models tend to underestimate as well, although it depends on the site and surface.

- In terms of RMSDr values, Perez shows the lowest values in the Spanish site followed by Gueymard's model. In the other two sites, the order varies, being Gueymard model the one providing lowest RMSDr values.

3.2. Estimated global irradiance values against averaged values from the Ispra meteo tower dataset

In this dataset only the global irradiance values can be compared, G_T . Those measured in the three inclined surfaces previously described (IS90, IS45, IS60) and the values derived from the different models. From this comparison it is observed that:

- considering every plane separately
 - the isotropic models tend to underestimate the solar resource received by the different planes, except the one developed by Jimenez et al. The Circumsolar model overestimates the global irradiance, showing the highest MBDr of all the models considered, as well as RMSDr.
 - the anisotropic models considering both the circumsolar region and the horizon band overestimate the data registered in the meteo tower.
 - the anisotropic models considering two “components” show a better ability to estimate the average irradiance values. Depending on the model and surface, MBDr may be positive or negative.
 - the difference between the MBDr values derived from both types of anisotropic models increases as the inclination angle of the planes increases as well. This could be explained by the fact that the irradiance from horizon band represents a bigger part of the solar resource received by the surface as its inclination angle increases. Only the three “component” models account for this region. Besides, the station has nearby buildings towards the south direction which block part of the irradiance coming from the horizon band. These two facts explain why three “component” models tend to overestimate the irradiance values measured on inclined surfaces.
 - with regard to the RMSDr values, the isotropic models perform worse than the anisotropic ones. Among these, there is not a clear trend as some two “component” models have lower RMSDr values than other three “component” models.
- analyzing the different models:
 - models behave better for the less inclined surface. For most models, the RMSDr values for the plane IS90 is approximately double than for the IS45.
 - Models overestimate or underestimate whatever the inclination angle. Only the sign of the MBDr values changed from plane to plane for the Hay, Skartveit, Willmott and Korokanis models, as values are close to 0%.
 - Gueymard's model and Muneer have very similar MBD and RMSD values.
 - In terms of MBDr values, Skartveit, Hay and Reindl have the closest values to 0%. However, in terms of RMSDr, it is not so clear which models behave best. Depending on the surface, it is Gueymard, Muneer or Klucher, followed by Temps and Korokanis' isotropic model that performs better than some anisotropic models.

For this dataset, the models have been compared excluding the moments with low solar elevation (5°). The dataset goes from 8670 values to 7912. The conclusions obtained agree with the ones presented above, except from the RMSDr values. In this case, the models showing lowest

RMSDr are not Gueymard or Muneer, but Hay, Skartveit or Reindl. Models which include the term $(1/\cos \sigma_z)$ in their formulae see the RMSDr value considerably reduced when excluding low solar elevation angles. Models like Reindl, Hay, Skartveit, Willmott, Jimenez and the Circumsolar have the RMSDr value reduced by one-half. With regard to the MBDs values, whether the models overestimate or underestimate the G_T values, remains the same as when all the data were considered. The MBDr and RMSDr derived from the different models are shown in Table A1 in the Annex. The lowest values are highlighted in red, while Muneer's are in grey.

3.3. Estimated global irradiance values against data from the Ispra meteo tower registered during selected days.

The experimental irradiance values from this dataset are the 10 minutes interval averaged irradiance values for real days with specific sky conditions, clear and overcast.

- analyzing the results for clear days:
 - the isotropic models, except the one developed by Jimenez, underestimate the G_T registered on the three inclined planes.
 - the Circumsolar model has the worst performance of all the models analysed, both in terms of MBDr and RMSDr values.
 - on average, the anisotropic models overestimate the irradiance received by the vertical surface. As the inclination angle decreases, the MBDr values derived from the two “component” models become negative. However, on average the MBDr values for the two “component” modes vary between -0.8 and 0.5%, whilst for the other type of anisotropic model, it goes from 0.25 to 0.5% approximately.
 - each model's tendency to overestimate or underestimate the solar resource is maintained in the three surfaces. Only Gueymard's model overestimate in one plane and underestimate in the other two (IS45 and IS60).
 - in terms of RMSDr values, the three “component” models perform better than the other type. RMSDr values improve as the inclination angle decreases.
 - the best performance is shown by models developed by Temps, Klein, Gueymard, Perez, Reindl and Muneer.
 - the same models' behavior is observed when low solar elevation angle moments ($\alpha_s < 5^\circ$) are dismissed from this study. Although, both MBDr and RMSDr improve considerably. Especially for Reindl, Hay, Skartveit, Willmott, Jimenez and the Circumsolar models, as explained when working with the previous dataset.
- analyzing the results for bright overcast days:
 - the isotropic models, except the one developed by Jimenez, underestimate the G_T registered on the three inclined planes.
 - the Circumsolar model has the worst performance both in terms of MBDr and RMSDr values, followed by Jimenez's model.
 - for this type of sky condition, models' performance worsen considerably in comparison to clear sky situation, especially for Temps' model.
 - in general, three “component” anisotropic models tend to overestimate whilst two “component” models underestimate.

- each model’s tendency to overestimate or underestimate the solar resource is maintained in the three surfaces. Only Reindl and Korokanis models change MBDr from positive to negative depending on the surface.
- in opposition to what is observed under clear sky conditions, in terms of RMSDr values, the two “component” models perform better than the other type. However, for both types the RMSDr values improve as the inclination angle decreases.
- regarding MBDr values, they decrease as the inclination angle decreases. Therefore models overestimating the solar resource for the vertical plane improve their performance for the other two. However, the performance of those models underestimating the vertical plane irradiance values, worsen for the other two surfaces.
- the best performance is shown by models developed by Muneer, Reindl, Hay, Perez and Gueymard.
- when moments near sunrise and sunset ($\alpha_s < 5^\circ$) are excluded, both the RMSDr and the MBDr values decrease, which means that for some models the extent to which they underestimate the solar resource increases.
- analyzing the results for dark overcast days:
 - the highest MBD and RMSD values are observed under this type of sky condition. Further analysis should be developed as, so far, only two days data were used.
 - in opposition to the previous sky conditions, the isotropic models overestimate the solar irradiance values. For the vertical plane all models but Skartveit have positive MBD values. As inclination angle decreases models like Muneer, Gueymard, Skartveit underestimate the solar resource.
 - the Circumsolar model has the worst performance followed by Jimenez’s and Temps’ models.
 - in general, three “component” anisotropic models have higher RMSDr and MBDr values than the two “component” models. For both types of anisotropic models RMSDr values improve as the inclination angle decreases.
 - the best performance is shown by models developed by Muneer, Gueymard, and Skartveit. Isotropic models like those proposed by Liu-Jordan or Badescu have better results than the three “component” anisotropic model developed by Perez et al.
 - The general performance of the various models improve when moments near sunrise and sunset ($\alpha_s < 5^\circ$) are excluded, both in terms of RMSDr and MBDr values.

Table 4 contains the best model for the different sky types and tilted planes considered in this dataset after considering both MBDr and RMSDr values.

	IS90	IS45	IS60
Clear	Gueymard	Temps	Temps
Bright overcast	Reindl	Reindl	Reindl
Dark overcast	Muneer	Skartveit	Gueymard

Table 4. Best model for the estimation of the global irradiance on the three tilted surfaces considered under the different sky type condition

The MBD_r and RMSD_r derived from the different models, when low solar elevation moments are excluded, are shown in Tables A2-A4 of the Annex. There is one table for each type of sky. The lowest values are highlighted in red, while Muneer's results are in grey.

4. Conclusions

After analysing the various models with the different datasets, it is not advisable to replace the existing model implemented in PVGIS by any of the isotropic models, nor the Circumsolar model which clearly overestimate the solar resource. As shown in the first dataset, the anisotropic models developed by Gueymard (two "component") and Perez (three "component") provide similar irradiance values to those derived from PVGIS tool (Muneer model).

When the models' real ability to estimate the global irradiance on tilted surfaces is checked, also for Muneer's model, by comparison with the meteo tower data, there is not a model that outperforms the others for the three inclination angles and sky conditions. Depending on the data set, surface or sky type, some models perform better than others, although these are usually those developed by Gueymard, Temps, Muneer, Skartveit or Reindl.

Muneer's model, although it doesn't always provide the lowest RMSD_r or MBD_r values, it is among the best models for the different datasets and surfaces considered. The difference between Muneer's MBD_r and RMSD_r values and those resulted from the best model for every case analysed are not very high, especially in terms of RMSD_r values, as it can be seen in the tables shown in the Annex.

The magnitude of the MBD_r and RMSD_r values observed in the present study are, in general, lower than the values reported by other authors using hourly irradiance values (Notton et al. 2006). The models' performance under clear sky conditions is very similar to those obtained by Gueymard for 10 minute data (Gueymard, 2009)

Models perform better for clear sky conditions than for overcast skies. Therefore, the solar resource is more accurately estimated when the irradiance values are higher, which, in addition, contribute to a greater extent to the overall energy output provided by PV systems, under both clear and overcast situations.

Having analysed the different models with the three dataset, we can conclude that the model implemented in PVGIS is validated and that there is no need to replace it by another, since there is not a particular model that outperforms the rest for all the various scenarios considered.

In addition to this, PVGIS provides hourly averaged irradiance values. The performance of the models for this time interval should be better than for those analysed here, 10 minutes and 1 minute values. Under clear sky situations, irradiance values change slowly and smoothly over 1 minute interval. Therefore, hourly RMSD_r values shouldn't be as high as those observed for 1 minute values. As for cloudy conditions, when irradiance levels may vary rapidly, hourly RMSD_r values won't be as high as those observed considering 1 minute data.

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ANNEX

		Isotropic				C	Anisotropic "2 component"						Anisotropic "3 component"			
		L-J	KO	BA	J		BU	HY	SK	W	GU	MU	T	K	R	P
90	%MBD	-3.20	4.04	-3.20	5.44	13.67	-4.72	0.66	0.59	0.59	5.76	5.34	8.83	6.86	4.78	8.04
	%RMSD	8.71	9.63	8.71	14.28	28.06	9.52	7.56	7.56	7.60	9.36	9.56	11.54	10.12	8.89	12.65
60	%MBD	-4.29	-2.83	-7.39	2.18	9.34	-7.19	-0.45	-0.47	-1.47	1.19	1.34	3.73	2.53	0.32	4.03
	%RMSD	6.36	5.28	9.20	7.39	15.44	8.85	3.77	3.77	4.18	3.85	3.89	5.54	4.52	3.68	6.30
45	%MBD	-4.18	-1.53	-8.16	3.41	11.56	-6.63	0.10	0.07	-0.71	2.54	2.83	5.09	3.63	1.70	5.59
	%RMSD	7.21	5.85	10.56	9.84	19.87	9.06	5.31	5.31	5.48	5.81	6.02	7.47	6.29	5.50	8.73

Table A1 MBDr and RMSDr values derived from the various models for the different surfaces, considering the average irradiance values registered in Ispra meteo tower. The lowest MBDr and RMSDr values are highlighted in red, while Muneer's results are in grey

Isotropic models: Liu-Jordan (L-J), Korokanis (KO), Badescu (Ba) and Jimenez (J)

Anisotropic models:

Circumsolar (C)

"2 components": Bugler (BU), Hay (HY), Skartveit and Olseth (SK), Willmott (W), Gueymard (GU) and Muneer (MU)

"3 components": Temps and Coulson (T), Klucher (K), Reindl (R) and Perez (P)

CLEAR SKY		Isotropic				C	Anisotropic "2 component"						Anisotropic "3 component"			
		L-J	KO	BA	J		BU	HY	SK	W	GU	MU	T	K	R	P
90	%MBD	-6.36	-4.44	-6.36	-5.02	10.62	-8.50	1.20	1.19	1.31	0.78	2.79	-1.32	-1.76	2.12	1.14
	%RMSD	8.79	7.08	8.79	9.85	12.84	10.36	5.92	5.93	6.01	5.08	6.14	4.92	5.20	5.93	5.29
60	%MBD	-6.09	-5.22	-7.39	-4.92	9.10	-9.77	0.71	0.70	0.61	-0.22	1.81	-0.80	-1.22	1.15	0.50
	%RMSD	8.55	7.75	9.80	9.16	11.03	11.47	5.64	5.65	5.74	5.07	5.67	4.61	4.85	5.60	5.14
45	%MBD	-5.46	-4.93	-6.59	-4.42	8.19	-10.09	0.66	0.66	0.47	-0.33	1.46	-0.49	-0.86	0.89	0.42
	%RMSD	7.49	6.98	8.60	7.81	9.66	11.39	4.77	4.77	4.89	4.30	4.78	3.82	4.01	4.74	4.25

Table A2 MBD_r and RMSD_r values derived from the various models for the different surfaces under clear sky conditions, considering the 1-minute irradiance values registered in Ispra meteo tower. The lowest MBD_r and RMSD_r values are highlighted in red, while Muneer's results are in grey

BRIGHT OVERCAST SKY		Isotropic				C	Anisotropic "2 component"						Anisotropic "3 component"			
		L-J	KO	BA	J		BU	HY	SK	W	GU	MU	T	K	R	P
90	%MBD	-4.53	19.19	-4.53	256.29	324.89	-5.08	-1.60	-22.06	-2.47	-15.21	-13.38	79.82	-2.75	-0.09	18.45
	%RMSD	47.90	49.72	47.90	336.49	427.50	50.08	40.79	53.83	41.06	48.29	40.02	116.86	41.32	39.70	49.87
60	%MBD	-6.84	2.05	-20.19	177.98	226.69	-7.60	-4.76	-12.43	-8.90	-12.90	-11.62	64.64	-5.27	-4.16	9.51
	%RMSD	31.93	28.47	42.95	217.69	278.09	35.04	26.51	31.71	29.09	32.49	27.05	88.05	26.27	25.85	29.33
45	%MBD	-7.35	-2.58	-17.46	135.04	172.65	-8.12	-5.74	-9.85	-10.66	-11.04	-10.12	48.52	-6.08	-5.46	5.28
	%RMSD	27.35	24.17	37.33	176.90	226.96	30.89	22.57	26.01	26.88	27.53	23.38	71.41	22.36	22.18	22.25

Table A3 MBD_r and RMSD_r values derived from the various models for the different surfaces under bright overcast sky conditions, considering the 1-minute irradiance values registered in Ispra meteo tower. The lowest MBD_r and RMSD_r values are highlighted in red, while Muneer's results are in grey

DARK OVERCAST SKY		Isotropic					Anisotropic "2 component"						Anisotropic "3 component"			
		L-J	KO	BA	J	C	BU	HY	SK	W	GU	MU	T	K	R	P
90	%MBD	27.29	62.21	27.29	413.29	512.51	27.21	27.45	-3.91	26.06	8.29	0.53	151.56	26.98	28.35	37.60
	%RMSD	39.83	84.63	39.83	531.39	658.15	39.70	40.12	19.58	38.46	20.97	19.92	207.80	39.87	41.44	58.78
60	%MBD	9.49	20.79	-7.45	245.43	306.21	9.40	9.59	-0.56	4.22	-0.05	-3.94	100.25	9.25	9.90	15.83
	%RMSD	16.99	29.95	15.82	316.47	394.31	16.83	17.18	11.97	12.96	11.99	13.00	140.25	17.16	17.60	27.80
45	%MBD	3.38	9.06	-8.65	173.73	217.73	3.29	3.45	-1.64	-2.50	-2.31	-4.63	69.81	3.20	3.59	7.97
	%RMSD	9.75	14.78	14.90	224.18	280.56	9.57	9.88	9.27	9.65	9.60	10.65	98.87	9.98	10.03	16.46

Table A4 MBD_r and RMSD_r values derived from the various models for the different surfaces under dark overcast sky conditions, considering the 1-minute irradiance values registered in Ispra meteo tower. The lowest MBD_r and RMSD_r values are highlighted in red, while Muneer's results are in grey

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Abstract

The web application PVGIS offers information regarding the global, diffuse and beam irradiance received by any surface located in Europe, Africa or South-West Asia. Based on these values, the software also provides an estimation of the energy output generated by any photovoltaic system. For the estimation of the irradiance on tilted surfaces, the model developed by Muneer (1990) is applied. In this study other models, both isotropic and anisotropic, were considered and compared in order to validate the model implemented at present in PVGIS and to analyse the possibility of replacing Muneer's model by another showing a better performance in the estimation of global irradiance on tilted surfaces.

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