

Original research paper

UDC 539.16:621.383(497)

DOI 10.7251/IJECC2001010M

# Models for the Calculation of Diffuse Radiation on Solar Collectors

Jovan Mikulović, Željko Đurišić

School of Electrical Engineering, University of Belgrade, Belgrade, Serbia

E-mail address: mikulovic@etf.rs, djurisic@etf.rs

**Abstract**—For the design and exploitation of solar energy systems, information of both direct and diffuse component of solar radiation is necessary. However, the measurement data that are available are usually restricted to total horizontal irradiance. Therefore, many models have been developed to determine the diffuse component of the irradiance on solar collectors. This paper discusses the most well-known isotropic and anisotropic models for the calculation of the diffuse component of the solar irradiance. A modification of the isotropic clear day model for determining the diffuse component of solar radiation on a horizontal surface has been presented. The presented model has the same form as a simple clear day model, with the parameters determined using the least squares method and measurement data on horizontal irradiance in the region of Belgrade, Serbia. The applicability of isotropic clear day models was examined. The paper also discusses the applicability of the models for determining the diffuse irradiance on tilted collectors in real weather conditions during the year. The basic expressions are given and the characteristics of individual models are highlighted. Based on the measurement data on horizontal irradiance, the possibilities of applying different models for the calculation of the diffuse component of irradiance on solar collectors located in the region of Belgrade were examined.

**Keywords**—diffuse irradiance; horizontal irradiance, isotropic model; anisotropic model; solar collector

## I. INTRODUCTION

For the calculation of electricity produced from photovoltaic collectors, or thermal energy obtained from solar thermal collectors, it is necessary to estimate the intensity of solar radiation on the collectors. The total radiation that reaches the inclined collector surface consists of direct, diffuse and reflected radiation [1]. Direct radiation is radiation that reaches the solar collector in a straight line. Diffuse radiation on the solar collector comes from various directions as a consequence of the scattering of solar radiation due to the presence of clouds, air molecules and aerosols in the atmosphere. Multiple reflections of radiation between the ground and clouds also contribute to diffuse radiation on the solar collector. Reflected radiation on the solar collector occurs as a consequence of the reflection of direct and diffuse radiation from the surface on which the collector is located and also from the surrounding objects.

Pyranometers are the most commonly used devices for measuring the intensity of solar radiation. They measure the total solar irradiation on a horizontal surface. However, for the optimal design and operation of solar energy systems, information on both direct and diffuse components of solar radiation is necessary. Both components depend on the sky conditions during the year. During cloudy days, the diffuse radiation component may have values that exceed the direct

radiation component. During clear days, direct radiation dominates, but it is necessary to respect the presence of the diffuse component even then. Diffuse radiation is more difficult to determine than direct radiation, given the many factors that affect it.

For the purpose of diffuse radiation estimation, isotropic and anisotropic models have been developed [3-20]. Isotropic models assume a uniform distribution of diffuse radiation from the celestial hemisphere. Anisotropic models consider areas of the sky with different diffuse radiation intensities: circumsolar region, the background region with uniform radiation, and the region near the horizon line [12].

This paper provides the comparative analysis of different models for the evaluation of the diffuse component of radiation on solar collectors. The paper examines the possibility of applying different models for the assessment of diffuse radiation to solar panels located in the region of Belgrade, Serbia.

## II. MODELS FOR CALCULATION OF DIFFUSE RADIATION

### A. Isotropic model

The simplest models for estimating diffuse radiation are isotropic models that assume a uniform distribution of diffuse radiation. These models first estimate the value of diffuse irradiance falling on the horizontal surface, and then calculate the value of diffuse irradiance falling on the tilted solar collector. In the case of clear weather without clouds, the

This paper is a revised and expanded version of the paper presented at the XIX International Symposium INFOTEH-JAHORINA 2020

diffuse component of the irradiance  $I_{DH}$  falling on a horizontal surface is proportional to the irradiance of direct radiation  $I_B$ , regardless of the position of the sun in the sky:

$$I_{DH} = C \cdot I_B, \quad (1)$$

where  $C$  is the diffuse constant.

The diffuse constant  $C$  can be determined according to the following empirical expression used in the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) Clear Day model [1]:

$$C = 0.095 + 0.04 \sin\left(\frac{360}{365}(n-100)\right), \quad (2)$$

where  $n$  is the ordinal number of the day in the year.

The previous expression was derived based on the *Liu-Jordan* correlation between direct and diffuse radiation established by measuring solar radiation at 98 locations in the United States and Canada [2]. To ensure a wider application of the previous model for diffuse radiation, Machler and Iqbal proposed the following expression for calculating the diffuse constant [3]:

$$C = 0.1180 + 0.0175 \sin\left(\frac{360}{365}(n-100)\right). \quad (3)$$

The previous expressions for estimating the diffuse component of horizontal radiation have limited accuracy and can only be used in case of clear weather. In the case when measurements of irradiance on a horizontal surface are available, it is more convenient to use empirical relations to estimate the diffuse component of horizontal irradiance. These expressions give the dependence of the ratio of diffuse and total horizontal insolation on the clearness index in the form of a polynomial from the first to the fourth order. The clearness index is defined as the ratio of the mean daily insolation  $\bar{I}_H$  on the horizontal surface of the Earth (at the measuring point) and the mean daily extraterrestrial insolation  $\bar{I}_{0H}$  on the horizontal surface of the Earth's atmosphere, at the latitude and longitude corresponding to the measuring point on the Earth:

$$K_T = \frac{\bar{I}_H}{\bar{I}_{0H}}. \quad (4)$$

A higher value of the clearness index means that the sky is not cloudy and that the atmosphere is clean, and vice versa. By integrating the total extraterrestrial radiation from sunrise to sunset and by projecting it on the horizontal surface, the expression for daily horizontal insolation of extraterrestrial radiation is obtained:

$$\bar{I}_{0H} = \frac{24}{\pi} I_{SC} \left(1 + 0,034 \cdot \cos\left(\frac{360n}{365}\right)\right) (\cos L \cos \delta \sin H_{SS} + H_{SS} \sin L \sin \delta). \quad (5)$$

where  $I_{SC}=1367 \text{ W/m}^2$  represents the solar constant,  $n$  is ordinal number of the day in the year,  $H_{SS}$  is sunset hour angle,  $L$  is latitude,  $\delta$  is solar declination.

The sunset hour angle and solar declination are defined as

$$H_{SS} = \arccos(-\text{tg}L \text{tg}\delta), \quad (6)$$

$$\delta = 23.45 \sin\left(\frac{360}{365}(n-81)\right). \quad (7)$$

In the previous formulas, the hour angle  $H$  is expressed in the plane of the celestial equator in the mathematically negative (retrograde) direction from the defined basic direction to the gamma point, which corresponds to the vernal equinox. The sunset hour angle is the positive angle obtained from the condition that the altitude angle of the sun is equal to zero.

The best known and most widely used empirical relation for estimating the diffuse component of horizontal radiation is the *Liu-Jordan* relation from 1960 [1]. This relation expresses the share of the diffuse component in the total horizontal insolation as a function of the clearness index in the form of the following polynomial:

$$\frac{\bar{I}_{DH}}{\bar{I}_H} = 1,39 - 4,027K_T + 5,531K_T^2 - 3,108K_T^3, \quad (8)$$

In addition to *Liu-Jordan's* relation, expressions given by other authors can be found in the literature, the most famous of which are: Page, Orgill and Holland, Collares-Pereira and Rabl, Erbs and co-authors, Miguel and others [4-9].

In order to examine the possibility of applying the previous expressions for calculating the diffuse constant in the region of Belgrade, ten-minute measurements of horizontal irradiance  $I_{Hi}$  were performed for the region of Belgrade in a period of one year. Based on ten-minute measurement data and *Liu-Jordan's* relation (8), ten-minute values of the diffuse component  $I_{DHi}$  of horizontal irradiance were calculated. According to these values it was conclude that the profile from the original relation (2) for the annual variation of the diffuse constant  $C$  should be retained [10]. However, the existing values of internal constant  $C_1$  and  $C_2$  had to be changed in the equation for determining diffuse constant:

$$C = C_1 + C_2 \cdot \sin\left(\frac{360}{365} \cdot (n-100)\right). \quad (9)$$

The internal constants  $C_1$  and  $C_2$  can be determined by applying method of least squares to all clear sky intervals over a year. Based on (1) and (9), the following minimization problem can be defined:

$$\sum_{i=1}^N \left( \left( C_1 + C_2 \sin\left(\frac{360}{365} \cdot (n-100)\right) \right) I_{Bi} - I_{DHi} \right)^2 \rightarrow \min. \quad (10)$$

The ten-minute values of direct beam irradiance  $I_{Bi}$  can be calculated according to ten-minute values of horizontal irradiance  $I_{Hi}$  and its diffuse component  $I_{DHi}$ , since they are known from the results of measurements:

$$I_{Bi} = \frac{I_{Bi}}{\cos \theta_i} = \frac{I_{Hi} - I_{DHi}}{\sin \beta_i} \quad (11)$$

where  $\theta_i$  is the  $i$ -th value of the incident radiation angle of direct beam radiation  $I_{Bi}$  in relation to the normal on the horizontal surface,  $\beta_i$  is the  $i$ -th value of the solar elevation angle corresponding to the direct beam irradiance  $I_{Bi}$ .

The expressions for optimum values of coefficients  $C_1$  and  $C_2$  that define the diffuse constant  $C$  are obtained:

$$C_1 = \frac{\sum_{i=1}^N I_{DHi} I_{Bi} \cdot \sum_{i=1}^N I_{Bi}^2 (\sin f_i)^2 - \sum_{i=1}^N I_{DHi} I_{Bi} \cdot \sin f_i \cdot \sum_{i=1}^N I_{Bi}^2 \sin f_i}{\sum_{i=1}^N I_{Bi}^2 \cdot \sum_{i=1}^N I_{Bi}^2 (\sin f_i)^2 - \left( \sum_{i=1}^N I_{Bi}^2 \sin f_i \right)^2} \quad (12)$$

$$C_2 = \frac{\sum_{i=1}^N I_{DHi} I_{Bi} \sin f_i \cdot \sum_{i=1}^N I_{Bi}^2 - \sum_{i=1}^N I_{DHi} I_{Bi} \cdot \sum_{i=1}^N I_{Bi}^2 \sin f_i}{\sum_{i=1}^N I_{Bi}^2 \cdot \sum_{i=1}^N I_{Bi}^2 (\sin f_i)^2 - \left( \sum_{i=1}^N I_{Bi}^2 \sin f_i \right)^2} \quad (13)$$

The optimum values  $C_1=0.2018$  and  $C_2=0.0143$  have been obtained. The analytical forms of diffuse constant variations in the modified model is:

$$C = 0.2018 + 0.0143 \sin \left( \frac{360}{365} (n-100) \right) \quad (14)$$

The values of the diffuse constant  $C$  over the year according to the ASHRAE, Machler-Iqbal's and modified expressions are shown in Fig. 1.

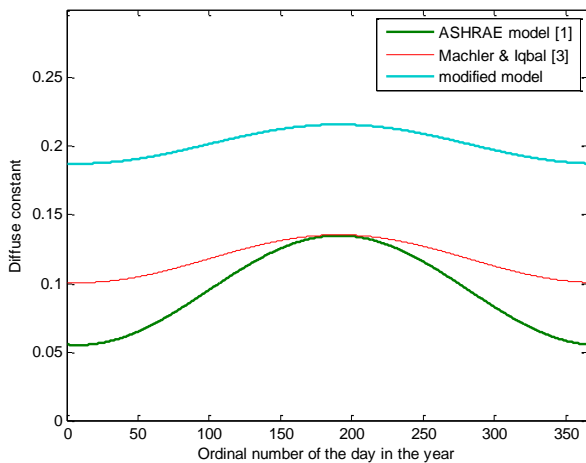


Figure 1. The values of the diffuse constant  $C$  over the year according to the ASHRAE, Machler-Iqbal's and modified expressions

The previous methods can be used to determine diffuse radiation on a horizontal surface, i.e. on the collector laid in the horizontal plane. In order to determine the diffuse component of the irradiance on a tilted solar collector, a simple isotropic model is most often used. This model assumes a uniform distribution of diffuse radiation in a cylindrical coordinate system [1], [11]. In this case, the model used can be represented in a plane, as shown in Fig. 2.

In order to determine the diffuse component of the irradiance on the collector, the quantity  $I_{D\theta}=dI_D/d\theta$  is introduced, which gives the distribution of the total diffuse irradiance  $I_D$  by the incident angle  $\theta$  [11]. The diffuse component of the irradiance on the horizontal surface, i.e. on the collector laid in the horizontal plane, will be:

$$I_{DH} = \int_{-\pi/2}^{\pi/2} I_{D\theta} \cos \theta d\theta = 2I_{D0} \quad (15)$$

For an arbitrary tilt angle  $\Sigma$  of the collector, the diffuse component of the irradiance on the collector surface, according to this model is:

$$I_{DC} = \int_{-\pi/2}^{\pi/2-\Sigma} I_{D\theta} \cos \theta d\theta = I_{D0} (1 + \cos \Sigma) = I_{DH} \frac{1 + \cos \Sigma}{2} \quad (16)$$

The previous expression gives the maximum value of diffuse irradiance  $I_{DC}=I_{DH}$  in the case of a horizontally placed collector ( $\Sigma = 0$ ) and  $I_{DC}=I_{DH}/2$  in the case of a vertically placed collector ( $\Sigma = \pi / 2$ ).

Due to its simplicity, the cylindrical model is the most commonly used model for calculating isotropic diffuse radiation on solar collectors. This model fits especially well when estimating diffuse radiation on rows of photovoltaic modules in photovoltaic power plants.

The previous model of diffuse radiation on the collector is also called a two-dimensional model because the direction from which the diffuse radiation comes is characterized only by the zenith angle. A model that seems to be more in line with reality is a three-dimensional model in which the direction from which the diffuse radiation comes is defined on the basis of two angles: zenith and azimuth angles [12,13].

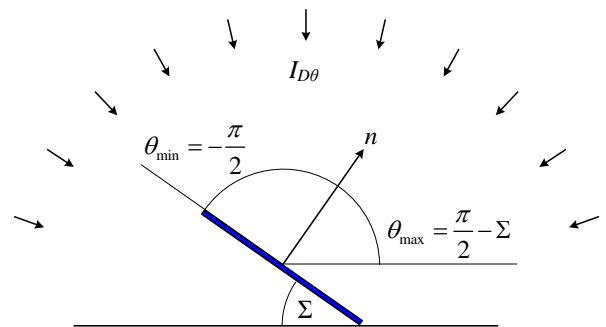


Figure 2. Cylindrical model for calculating diffuse radiation on a collector

To determine three-dimensional diffuse radiation on an arbitrarily tilted collector, it is necessary to use a quantity that defines the distribution of diffuse radiation from the celestial hemisphere. For this purpose, the radiance  $L_D$  is used, which in this case is defined as the diffuse irradiance from a certain direction per unit of spatial angle  $d\Omega$ , which is normal to the axis of the spatial angle [14]:

$$L_D = \frac{dI_D}{d\Omega \cos \theta}, \quad (17)$$

where  $\theta$  is the angle between the normal to the collector surface and the axis of the spatial angle  $d\Omega$ . Spatial angle is expressed in steradians (sr) and the radiance in  $W/(m^2 \text{ sr})$ .

The three-dimensional isotropic model assumes that diffuse radiation to the solar collector comes with equal intensity from all directions. However, the effective radiation on the solar collector depends on the incident radiation angle  $\theta$  in relation to the normal on the collector. Fig. 3 shows a model of the celestial hemisphere with corresponding angles for determining the diffuse radiation component on a surface collector  $dA$ .

The elementary spatial angle  $d\Omega$  corresponding to the surface  $dS$  on the celestial hemisphere is:

$$d\Omega = \frac{dS}{R^2} = \frac{Rd\theta Rd\psi \sin \theta}{R^2} = \sin \theta d\theta d\psi. \quad (18)$$

In the case of a horizontally placed collector, the entire diffuse radiation from the celestial hemisphere falls on the collector. Based on (17) and (18), the diffuse irradiance to the solar collector placed horizontally is:

$$I_{DH} = \int_0^{2\pi} \int_0^{\pi/2} L_D \sin \theta \cos \theta d\theta d\psi = \pi L_D. \quad (19)$$

The diffuse component of the radiation on the tilted collector at an angle  $\Sigma$  is obtained by omitting the diffuse radiation from the section defined by the inclination angle, when integrating the radiance  $L_D$  along the celestial hemisphere:

$$I_{DC} = \int_0^{\pi} \int_0^{\pi/2} L_D \sin \theta \cos \theta d\theta d\psi + \int_{\pi}^{2\pi} \int_0^{\pi/2-\Sigma} L_D \sin \theta \cos \theta d\theta d\psi. \quad (20)$$

By solving the previous integral, the expression for the diffuse irradiance on the tilted collector at an angle  $\Sigma$  is obtained:

$$I_{DC} = \pi L_D \frac{3 + \cos 2\Sigma}{4} = I_{DH} \frac{3 + \cos 2\Sigma}{4}. \quad (21)$$

The previous expression gives the maximum value of diffuse irradiance  $I_{DC}=I_{DH}$  in the case of a horizontally placed collector ( $\Sigma = 0$ ) and  $I_{DC}=I_{DH}/2$  in the case of a vertically placed collector ( $\Sigma = \pi / 2$ ).

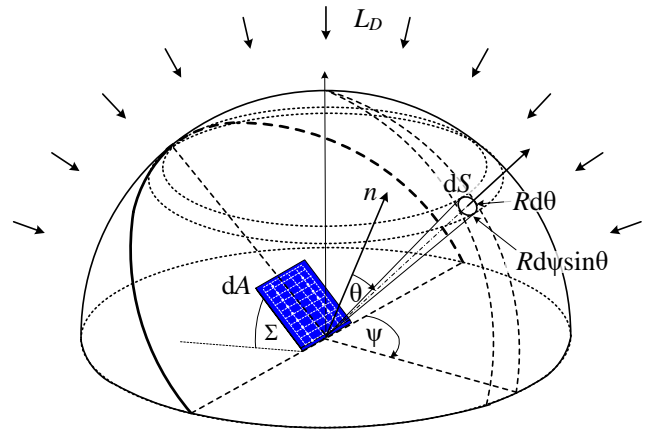


Figure 3. Spherical model for calculating diffuse radiation on a collector

Isotropic models of diffuse radiation often give results that deviate from actual meteorological data. Isotropic models give good results when the sky is completely covered with clouds. When the sky is partially covered by clouds, isotropic models give unreliable results [15].

### B. Anisotropic models

Anisotropic models consider areas with different diffuse radiation intensities from the celestial hemisphere: the circumsolar region with increased diffuse radiation intensity, the background area with uniform diffuse radiation, and the area near the horizon that may be lighter or darker than the background area [12].

A simple modification of the isotropic model for south-facing collectors was performed by Koronakis by introducing the assumption that the south-facing vertical plane captures 2/3 of the total diffuse radiation [16]:

$$I_{DC} = I_{DH} \frac{2 + \cos \Sigma}{3}. \quad (22)$$

Another simple model, the circumsolar model, assumes that the total diffuse radiation comes from the area where the solar disk is located at a given moment [14,15]. This model treats diffuse radiation as direct radiation:

$$I_{DC} = I_{DH} \frac{\cos \theta}{\cos \theta_z}, \quad (23)$$

where  $R_B = \cos \theta / \cos \theta_z$  is the tilt factor and  $\theta_z$  is the zenith angle.

Temps and Coulson also modified the isotropic model by introducing a term representing diffuse radiation coming from the vicinity of the Sun's disk and a term representing diffuse radiation from the area near the horizon [17]:

$$I_{DC} = I_{DH} \frac{1 + \cos \Sigma}{2} \left( 1 + \cos^2 \theta \sin^3 \theta_z \right) \left( 1 + \sin^3 \left( \frac{\Sigma}{2} \right) \right), \quad (24)$$

where  $\theta$  is the incident angle of incoming direct beam radiation on the collector.

Klucher upgraded the previous model by introducing a function  $F$  that defines the degree of cloud cover [18]:

$$I_{DC} = I_{DH} \frac{1 + \cos \Sigma}{2} \left( 1 + F \cos^2 \theta \sin^3 \theta_Z \right) \left( 1 + F \sin^3 \left( \frac{\Sigma}{2} \right) \right), \quad (25)$$

where:

$$F = 1 - \left( \frac{I_{DH}}{I_{BH} + I_{DH}} \right)^2. \quad (26)$$

The anisotropic model proposed by Hay and Davies assumes that diffuse radiation comes from the Sun's disk and from the rest of the sky with isotropic radiation [8,15]:

$$I_{DC} = I_{DH} \left( \frac{I_{BH}}{I_{0H}} R_B + \frac{1 + \cos \Sigma}{2} \left( 1 - \frac{I_{BH}}{I_{0H}} \right) \right), \quad (27)$$

where  $I_{BH}$  is the direct irradiance on the horizontal surface and  $I_{0H}$  is the extraterrestrial irradiance on the horizontal surface.

Reindl upgraded the previous model by introducing a term for diffuse radiation coming from the area near the horizon [19]:

$$I_{DC} = I_{DH} \left( \frac{I_{BH}}{I_{0H}} R_B + \frac{1 + \cos \Sigma}{2} \left( 1 - \frac{I_{BH}}{I_{0H}} \right) \left( 1 + \sqrt{\frac{I_{BH}}{I_{BH} + I_{DH}}} \sin^3 \frac{\Sigma}{2} \right) \right). \quad (28)$$

Perez's model is the most complex anisotropic model [8], [11], [15], [20]. The model adopts three areas in the sky with different diffuse radiation intensities: the circumsolar area, the area near the horizon, and the rest of the sky with isotropic diffuse radiation. The diffuse irradiance on the tilted collector at an angle  $\Sigma$  is:

$$I_{DC} = I_{DH} \left( (1 - F_1) \frac{1 + \cos \Sigma}{2} + F_1 \frac{a}{b} + F_2 \sin \Sigma \right), \quad (29)$$

where  $F_1$  and  $F_2$  are the coefficients of sky brightness for the circumsolar area and the area above the horizon. Coefficients  $a$  and  $b$  take into account the corresponding incident angles of circumsolar radiation on the inclined and horizontal surfaces. The coefficients  $a$  and  $b$  are determined on the basis of solar geometry:

$$a = \max(0, \cos \theta), \quad (30)$$

$$b = \max(\cos 85^\circ, \cos \theta_Z). \quad (31)$$

In order to determine the coefficients  $F_1$  and  $F_2$ , the degree of sky clearness  $\varepsilon$  is calculated:

$$\varepsilon = \frac{1}{1 + 5,535 \cdot 10^{-6} \theta_Z^3} \cdot \left( \frac{I_{DH} + I_B}{I_{DH}} + 5,535 \cdot 10^{-6} \theta_Z^3 \right), \quad (32)$$

and then its categorization is performed by assigning it an integer value  $\varepsilon_b$  according to Table I. Based on the category of clearness  $\varepsilon_b$ , the values of Perez coefficients  $F_{11}$ ,  $F_{12}$ ,  $F_{13}$ ,  $F_{21}$ ,  $F_{22}$  and  $F_{23}$  are determined according to Table II.

The coefficients  $F_1$  and  $F_2$  are calculated according to the expressions:

$$F_1 = \max \left( 0, \left( F_{11} + F_{12} \frac{I_{DH}}{I_0} m + \frac{\pi \theta_Z}{180^\circ} F_{13} \right) \right), \quad (33)$$

$$F_2 = F_{21} + F_{22} \frac{I_{DH}}{I_0} m + \frac{\pi \theta_Z}{180^\circ} F_{23}, \quad (34)$$

where  $I_{DH}$  is the diffuse irradiance on the horizontal surface,  $I_0$  is the extraterrestrial irradiance on the surface normal to the radiation direction and  $m$  is the coefficient of air mass.

### III. MODELS FOR CALCULATION OF DIFFUSE RADIATION

In order to examine the possibility of applying different models for calculating the diffuse component of irradiance on solar collectors located in the area of Belgrade, ten-minute measurement data on horizontal irradiance [ $\text{W}/\text{m}^2$ ] during 2014 for Belgrade were used. By employing the Liu-Jordan relation (8), the ten-minute values of horizontal diffuse irradiance were calculated. Then, ten-minute values of the direct beam irradiance were calculated according to (11).

TABLE I. CATEGORIZATION OF SKY CLEARNESS INDEX

$\varepsilon_b$	Lower limit	Upper limit
1	1	1,065
2	1,065	1,230
3	1,230	1,500
4	1,500	1,950
5	1,950	2,800
6	2,800	4,500
7	4,500	6,200
8	6,200	-

TABLE II. VALUES OF PEREZ'S COEFFICIENTS

$\varepsilon_b$	$F_{11}$	$F_{12}$	$F_{13}$	$F_{21}$	$F_{22}$	$F_{23}$
1	-0,008	0,588	-0,062	-0,060	0,072	-0,022
2	0,130	0,683	-0,151	-0,019	0,066	-0,029
3	0,330	0,487	-0,221	0,055	-0,064	-0,026
4	0,568	0,187	-0,295	0,109	-0,152	-0,014
5	0,873	-0,392	-0,362	0,226	-0,462	0,001
6	1,132	-1,237	-0,412	0,288	-0,823	0,056
7	1,060	-1,600	-0,359	0,264	-1,127	0,131
8	0,678	-0,327	-0,250	0,156	-1,377	0,251

However, the corresponding values of diffuse horizontal irradiance, calculated on the basis of expressions (1), (2), (3) and (14), do not correspond to the values of diffuse horizontal irradiance obtained on the basis of measurement data and Liu-Jordan relation (8), as shown in Fig. 4 to Fig. 7, not even in the case of clear day. In terms of daily insolation (energy on horizontal surface) of diffuse radiation, the modified model gives better results for clear days compared to remaining two models, as shown in Table III.

Since the clear sky models based on isotropic radiation do not give the appropriate shape of the diffuse horizontal irradiance curve during the day, the incorrect values for diffuse irradiance on tilted solar collectors can be calculated. Therefore, it is recommended to use measurement data to determine the diffuse horizontal irradiance whenever possible.

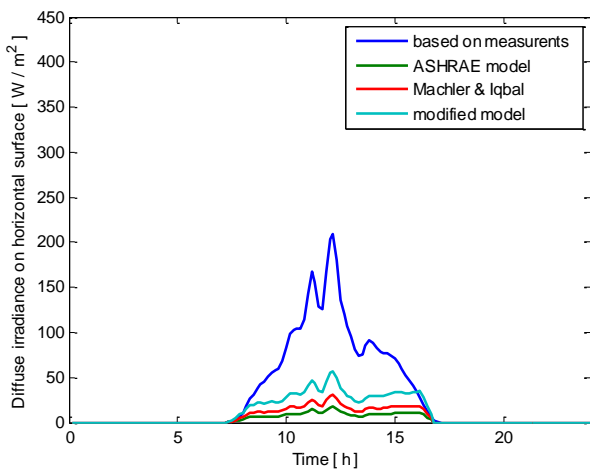


Figure 4. Diffuse component of irradiance on the horizontal surface for a cloudy winter day (February 2, 2014), according to different models

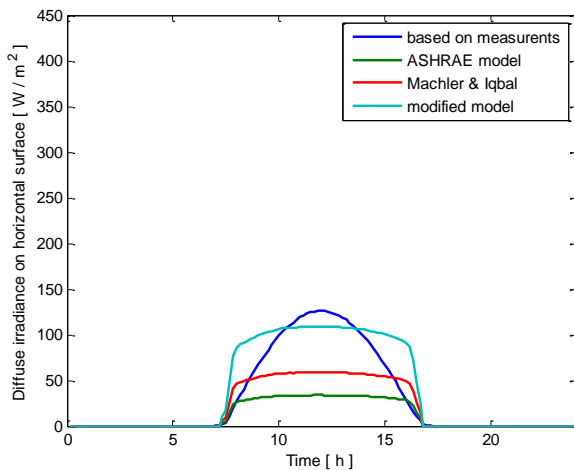


Figure 5. Diffuse component of irradiance on the horizontal surface for a clear winter day (February 3, 2014), according to different models

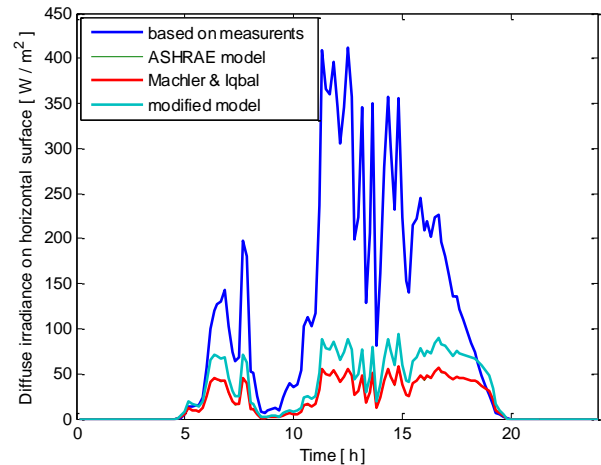


Figure 6. Diffuse component of irradiance on the horizontal surface for a clear summer day (July 3, 2014), according to different models

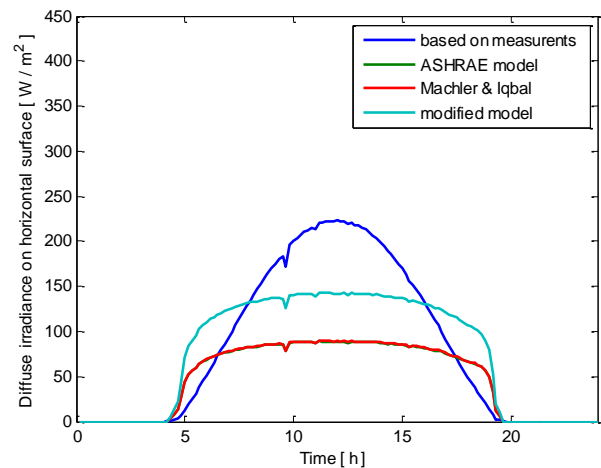


Figure 7. Diffuse component of irradiance on the horizontal surface for a clear summer day (July 4, 2014), according to different models

TABLE III. DAILY DIFFUSE INSOLATION

	Insolation [kWh/m <sup>2</sup> ]	
	Clear winter day (Feb. 3, 2014)	Clear summer day (July 4, 2014)
Based on measurements	0.749	1.971
ASHRAE model [1]	0.281	1.144
Machler & Iqbal's model [3]	0.490	1.150
Modified model	0.906	1.834

Based on the measurement data on horizontal irradiance, the possibilities of applying different models for the calculation of the diffuse irradiation on tilted solar collectors located in the area of Belgrade were examined. Using different models, the diffuse component of the irradiance on the tilted solar collector at the optimal angle  $\Sigma=34^\circ$  were calculated. The calculated ten-minute values of diffuse irradiance on the solar collector for a cloudy winter day, for a clear winter day, for a cloudy summer day and for a clear summer day are shown in Figs. 8-11.

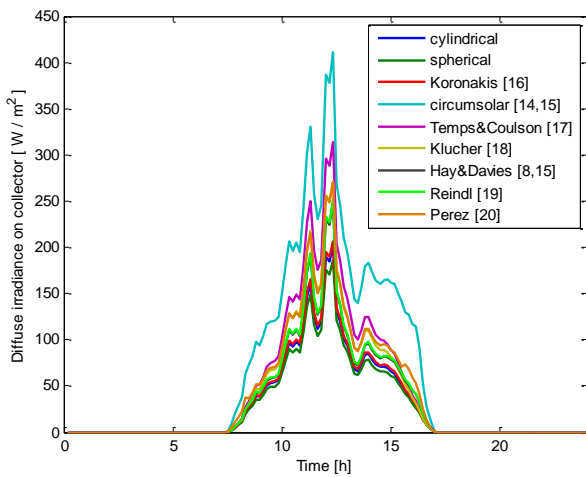


Figure 8. Diffuse component of irradiance on the solar collector for a cloudy winter day (February 2, 2014), according to different models

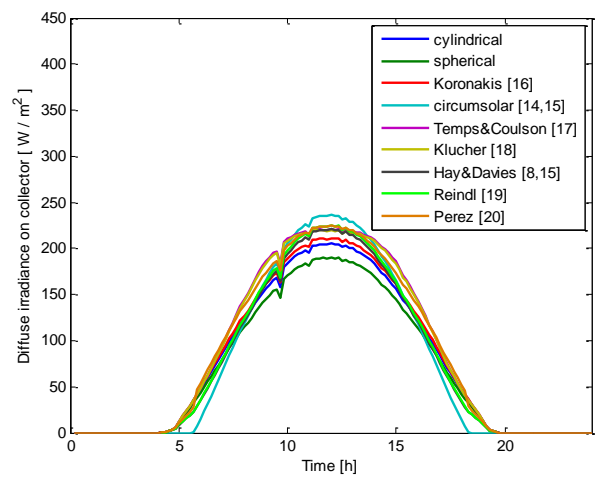


Figure 11. Diffuse component of irradiance on the solar collector for a clear summer day (July 4, 2014), according to different models

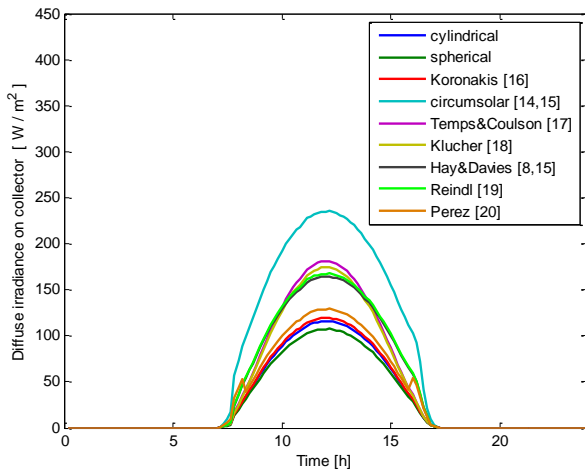


Figure 9. Diffuse component of irradiance on the solar collector for a clear winter day (February 3, 2014), according to different models

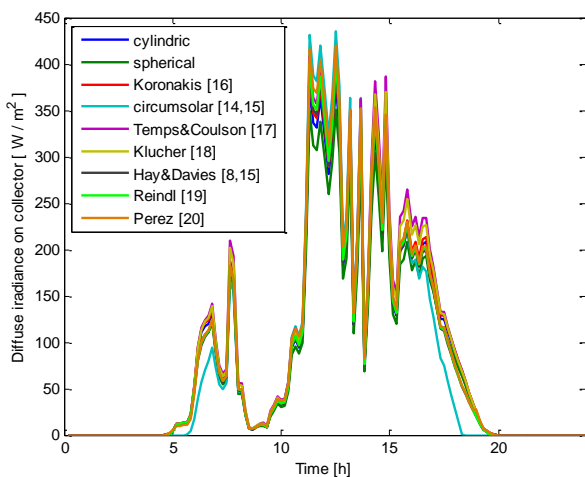


Figure 10. Diffuse component of irradiance on a solar collector for a cloudy summer day (July 3, 2014), according to different models

Based on the obtained results of diffuse irradiance calculations for characteristic winter and summer days, it can be noticed that the diffuse irradiance varies greatly on cloudy days, reaching relatively high and relatively low values. This can be explained by different degrees of cloudiness. In conditions of moderate cloudiness there is an increase of the scattering of solar radiation. In conditions of high cloudiness direct solar radiation is difficult to pass through the clouds, so there is little scattering of radiation. Also, in conditions of high cloudiness, smaller differences in the values of diffuse irradiance were obtained on the basis of different models (isotropic and anisotropic).

The obtained results of diffuse irradiance calculations according to different models differ more in the winter days. Isotropic models give lower values of diffuse irradiance on the solar collector compared to anisotropic models. The cylindrical isotropic model gives higher values of diffuse irradiance than the spherical isotropic model. Therefore, the values given by the cylindrical isotropic model are closer to the values given by the anisotropic models. Although seemingly less realistic, the cylindrical model for diffuse radiation calculation applied to south-oriented solar collectors partially favors diffuse radiation coming from the south, which is largely circumsolar radiation (since the sun moves predominantly on the south side of the sky). The circumsolar anisotropic model treats the whole diffuse radiation as circumsolar, which results in higher values of the diffuse irradiance on the collector than in the case of any other model (except in the morning and evening). Perez's anisotropic model is cited as the most complex [8], and often as the most precise model of diffuse radiation [15]. Based on the obtained results of diffuse irradiance calculations on the solar collector, it can be seen that Perez's anisotropic model gives values for diffuse irradiance that are slightly higher than the corresponding values obtained by isotropic models, but usually less than the corresponding values obtained by other anisotropic models. One shortcoming of Perez's model can be noticed in Figs. 9 and 11: due to the use of discrete values for the sky clearness degree  $\varepsilon_b$ , as well as discrete values for the coefficients  $F_{11}$ ,  $F_{12}$ ,  $F_{13}$ ,  $F_{21}$ ,  $F_{22}$  and  $F_{23}$ , the calculated diffuse irradiance has leap changes in the morning and evening (due to leap changes in the degree of clearness  $\varepsilon$  in the model).

## IV. CONCLUSION

When analyzing the solar potential for the purpose of planning and designing solar energy systems, one should keep in mind the differences in values given by different models for the calculation of diffuse irradiance on the solar collectors. Since the clear sky models based on isotropic radiation do not give the reliable values of diffuse horizontal irradiance, it is recommended to use measurement data to determine the diffuse horizontal irradiance whenever possible. Based on the presented results of the calculation of diffuse irradiance on tilted collectors, it can be concluded that the isotropic cylindrical model gives values that are closer to the corresponding values obtained by the anisotropic models. Since even more complex anisotropic models have certain shortcomings, a simple expression given in the cylindrical isotropic model is recommended for calculating the diffuse irradiance on tilted solar collectors. The values of diffuse irradiance given by the cylindrical isotropic model are slightly smaller than the corresponding values obtained by the much more complex Perez's anisotropic model.

## ACKNOWLEDGMENT

The authors are grateful to the Ministry of Science and Technological Development of Serbia for the financial support of this work through technological project III42009 and TR-33037.

## REFERENCES

- [1] G. M. Masters, *Renewable and Efficient Electric Power Systems*, 2nd ed., John Wiley & Sons, 2013.
- [2] B. Liu and R. Jordan, "The Interrelationship and Characteristic Distribution of Direct, Diffuse and Total Solar Radiation," *Solar Energy*, Vol. 4, No. 3, pp. 1-19, 1960.
- [3] M. A. Machler, M. Iqbal "A modification of the ASHRAE clear sky irradiation model," *ASHRAE Trans.* 1967, 91, pp. 106-115.
- [4] S. Drvishi, A. Mahdavi, "Computing diffuse fraction of global horizontal solar radiation: A model comparison", *Solar Energy*, 86(2012), 1796-1802.
- [5] K. Scharmer, J. Greif, "The European Solar Radiation atlas", Paris, 2000.
- [6] A. M. Noorian, I. Moradi, G. A. Kamali, "Evaluation of 12 models to estimate hourly diffuse irradiation on inclined surfaces", *Renewable Energy*, 33(2008), 1406-1412.
- [7] F. J. Batlles, M. A. Rubio, J. Tovar, F. J. Olmo, L. Alados-Arboledas, "Empirical modeling of hourly direct irradiance by means of hourly global irradiance", *Energy*, 25(2000), 675-688.
- [8] D. Włodarczyk and H. Nowak, "Statistical analysis of solar radiation models into inclined planes for climatic conditions of Lower Silesia in Poland," *Archives of Civil and Mechanical Engineering*, Vol. IX, No.2, pp. 127-144, 2009.
- [9] L. T. Wong, W. K. Chow, "Solar radiation model", *Applied Energy*, 69 (2001), 191-224.
- [10] R. Kostić and J. Mikulović, "The empirical models for estimating solar insolation in Serbia by using meteorological data on cloudiness," *Renewable Energy*, Vol. 114, pp. 1281-1293, 2017.
- [11] Č. Zeljković, *Renewable energy sources – Solar engineering*, School of Electrical Engineering, University of Banja Luka, Academic Mind, 2018.
- [12] V. Badescu, "3D isotropic approximation for solar diffuse irradiance on tilted surfaces," *Renewable Energy*, Vol. 26, No. 2, pp. 221-233, 2002.
- [13] J. Mikulović, Ž. Đurišić, *Solar engineering*, School of Electrical Engineering, University of Belgrade, Academic Mind, 2019.
- [14] M. Iqbal, *An Introduction to Solar Radiation*, Academic Press Canada, 1983.
- [15] T. Muneer and H. Kambezidis, *Solar Radiation and Daylight Models*, 2nd ed., Elsevier, 2004.
- [16] P. Koronakis, "On the choice of the angle of tilt for south facing solar collectors in the Athens basin area," *Solar Energy*, Vol. 36, No. 3, pp. 217-225, 1986.
- [17] R. C. Temps and K. L. Coulson, "Solar radiation incident upon slopes of different orientations," *Solar Energy*, Vol. 2, pp. 179-184, 1977.
- [18] T. M. Klucher, "Evaluation of models to predict insolation on tilted surfaces," *Solar Energy*, Vol. 23, pp. 111-114, 1979.
- [19] D. T. Reindl, W. A. Beckman, and J. A. Duffie, "Evaluation of hourly tilted surface radiation models," *Solar Energy*, Vol. 45, No.1, pp. 9-17, 1990.
- [20] R. Perez, P. Ineichen, R. Seals, J. Michalsky, and R. Stewart, "Modeling daylight availability and irradiance components from direct and global irradiance," *Solar Energy*, Vol. 44, No.5, pp. 271-289, 1990.



**Jovan Mikulović** is a full professor at the University of Belgrade, School of Electrical Engineering, where he has been a faculty member since 2002. Throughout his career he has gained experiences of all aspects of electric power systems and renewable energy sources. His research interests lie in the area of power quality, solar engineering, and high voltage technology.



**Željko Đurišić** obtained the Dipl. Eng, MSc. and PhD degree in electrical engineering from the University of Belgrade, Serbia, in 1999, 2006 and 2013, respectively. He has experience as a researcher in field of renewable energy, power quality and power system protection. He has worked on many projects in topics of wind and solar resource assessment, wind and solar power plants feasibility analysis and grid connection of distribution power generation. Presently, he is an associate professor with the University of Belgrade, School of Electrical Engineering