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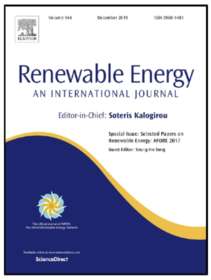

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A new diffuse luminous efficacy model for daylight availability in Burgos, Spain

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Abstract

The determination of optimal illumination conditions in buildings is of great interest both for reducing energy consumption and for exploiting solar resources with greater efficiency and sustainability. The most commonplace method of estimating daylight is the luminous efficacy approach, using the more widely measured solar irradiance. In this present study, a new model of diffuse luminous efficacy over a horizontal surface is proposed. A comparative study of twenty-two classic models is presented, to obtain diffuse illuminance, using both, the original mathematical models and the adapted models with local coefficients, in order to determine the most suitable models for Burgos, a city located in north-western Spain. With this purpose in mind, twelve models are selected for all sky conditions, five models for modelling clear sky, two for partly cloudy sky, and three for overcast sky. These twenty-two models are then compared with the new model both for all sky conditions and for particular sky conditions (clear, partly cloudy, and overcast). The behaviour of the new model showed greater accuracy than most of the classic models under analysis. Hence, the advantage of the diffuse luminous efficacy model that can be applied both to all sky and to particular sky conditions.

Keywords: Luminous Efficacy Models, Diffuse Illuminance, Irradiance, Modelling

Nomenclature

a_i, b_i, c_i, d_i: Perez's coefficients
D: cloud ratio or sky ratio or diffuse fraction
E_{bh}: horizontal beam irradiance (W/m^2)
E_{dh}: horizontal diffuse irradiance (W/m^2)
E_{gh}: horizontal global irradiance (W/m^2)
I: normal incidence direct irradiance (W/m^2)
I_0: extraterrestrial irradiance (W/m^2)
K_d: diffuse luminous efficacy (lm/W)
K_D: ratio of diffuse to extraterrestrial irradiance
K_t: clearness index
L_{bh}: horizontal beam illuminance (lux)
L_{dh}: horizontal diffuse illuminance (lux)
L_{gh}: horizontal global illuminance (lux)
m: relative optical airmass
MBE: Mean Bias Error (%)
n: number of data
p_0, p_1, p_2, p_3: coefficients of the new model
$RMSE$: Root Mean Square Error (%)
T_d: three-hourly surface dew point temperature $(^{\circ}C)$
W: atmospheric precipitable water (cm)
$X_{measured}$: measured variable
X_{model}: predicted variable
Z: solar zenith angle (rad)
α: solar altitude angle (rad)
Δ: sky brightness
ε: sky clearness
Ω: relative heaviness of overcast sky

1. Introduction

Maximization of natural lighting coupled with sustainable and ecological development for the reduction of energy consumption are now essential building design strategies [1]. Bearing these aims in mind, artificial light should be used to complement daylight, in order to maintain rather than increase energy demand [2]. When considering the design of energy efficient buildings, which rely on daylight, and efficient sizing of both cooling and heating systems, quantitative information is necessary on the levels of illumination and solar irradiance received on surfaces with different inclinations. Horizontal illuminance data, among many other uses, are of particular importance for the study and the development of solar roofs and skylights. Illuminance data processed by specialized software for interior lighting calculations [3], will provide more sustainable, healthy, and energy efficient buildings; natural lighting in buildings will therefore contribute to energetic and environmental objectives. However, illuminance is not an easily measured parameter, since the number of facilities devoted to illuminance measurements is scarce compared to those available for radiance measurements. An alternative method to increase illuminance data is through the use of luminous efficacy. Once the ratio of luminance to irradiance (i.e. luminous efficacy $(\mathrm{K_d})$), is known, then the measured irradiance $(\mathrm{E_{dh}})$ values can be converted to illuminance values $(\mathrm{L_{dh}})$ as defined by Equation (1).

$$K_d = \frac{L_{dh}}{E_{dh}} \quad (lm/W) \tag{1}$$

Over the past few years, there has therefore been a tendency to develop luminous efficacy models that are based on experimental irradiance measurements, from which the illuminance data can then be obtained.

In this present study, twenty-two classic models from the literature are reviewed and tested for the city of Burgos (Spain) using both the original form, proposed by the authors of these models, and their local adaptation to the place under study. Traditional statistical indicators RMSE (%) and MBE (%) were used to classify the models and to determine their accuracy. Data measurements over one year and nine months were used in this study (one year to obtain the local coefficients of the models and nine months for their validation). In addition, a new model to predict diffuse horizontal illuminance to the sky conditions of the city of Burgos is proposed in this present study. This new model is analysed for all sky conditions and for particular sky conditions (clear, partly cloudy, and overcast), showing improved illuminance prediction over most of the twenty-two previously tested models.

The study will be structured as follows: First a literature review of classic models will be conducted in Section 2. Then, in Section 3, the experimental meteorological facility and the data used for the study will be described. In Section 4, the diffuse luminous efficacy models on horizontal surfaces that are reviewed in this work will be presented. The results of benchmarking the twenty-two luminous efficacy models under review will then be discussed in Section 5. The new model will be proposed in Section 6 for the area under study and compared with the other models under review. In Section 7, validation of both the new model and the twenty-two luminous efficacy models will be presented and, finally, the main conclusions of this study will be outlined.

2. Literature review

Various studies on the analysis of diffuse luminous efficacy have been developed, among which those of Pérez et al. [4] should be mentioned. Those authors proposed different models to analyse global, diffuse, and beam luminous efficacy for all sky conditions, as a function of the atmospheric precipitable water content, the sky brightness, and the zenith angle. Their models were developed from experimental measurements in geographical locations around the USA and Europe with different weather conditions [4]. Chung proposed another interesting model [5] to measure luminous efficacy in Hong Kong. The model he developed is applicable to different sky types, which are classified according to the cloud ratio or sky ratio, defined as the ratio between horizontal diffuse irradiance and horizontal global irradiance [5]. Lam and Li also developed luminous efficiency models with constant values for the city of Hong Kong [6]. The sky classification that these authors employed was based on the clearness index (K_t), defined as the ratio between global and extraterrestrial irradiance [7]. Likewise, the research of Muneer and Kinghorn [8] proposed a diffuse luminous efficacy model for five UK stations where the clearness index was shown to be the main parameter influencing both global and diffuse luminous efficacy.

Further studies, such as those of Robledo and Soler [9] developed luminous efficacy models from irradiance and illuminance measurements for Madrid (Spain). These authors employed two independent variables, solar altitude and sky brightness. Their models produced better predictions for clear skies than other models, developed by the same authors, which only employed solar altitude as independent variable. However, they recommended the simplified model for partly cloudy sky and overcast sky, which only takes account of sky brightness [9]. In contrast, the work of Ruiz et al. [10] showed the suitability of both the Muneer and the Kinghorn models [8] to determine the diffuse luminous efficacy in Madrid (Spain). Moreover, Ruiz et al. also developed and evaluated other models based on that of Muneer and Kinghorn [8]. In addition, the same authors showed that using the ratio between diffuse and extraterrestrial irradiance (K_D) improved the diffuse luminous efficacy prediction, compared with the results generated with the clearness index [10].

In turn, Souza and Robledo [11] evaluated the luminous efficacy models proposed by Muneer and Kinghorn [8], Chung [5], Ruiz et al. [10], and Robledo and Soler [9] in the city of Florianapolis (Brazil). They showed that when using local optimized coefficients for Florianapolis, the model of Robledo and Soler [9] provided better statistical results and was at the same time the model that best predicted the behaviour of the luminous efficacy values for all solar altitudes. In another work, Souza and Robledo [11] evaluated several models specifically obtained for clear skies and showed that the results of these models were no better than those obtained with all sky models when used to estimate illuminance for clear sky [11]. Other authors used a constant value to model the diffuse luminous efficacy: De Rosa el al. [12] proposed a constant value for all sky, clear sky, intermediate, and overcast sky conditions in Arcavacata di Rende (Italy) and compared those values with others from Geneva (Switzerland), Vaulx-en-Velin (France), Bratislava (Slovakia), and Osaka (Japan). Likewise, Cucumo et al. [13] employed a constant value of 127.41 lm/W to predict the diffuse luminous efficacy for all sky conditions in Arcavacata di Rende (Italy). These authors compared their approach with the results of other models in the literature and concluded that the use of a constant value to estimate diffuse luminous efficacy is valid as an initial estimation of diffuse illuminance [13]. Fakra et al. [14] offers a further example, estimating an average diffuse luminous efficacy value of 139.98 lm/W for Saint-Pierre (Reunion Island). The study likewise examined different indices to classify the sky types. Among their results, the authors pointed out that the diffuse fraction was the most appropriate index to define the sky types for that geographical location [14]. Those authors also observed that the luminous efficacy values remained constant during the day, but varied significantly at sunrise and sunset, as a function of solar altitude. This fact may be used to explain the deviations that exist when a constant value is employed to model luminous efficacy [14]. Another constant value for modelling diffuse luminous efficacy was proposed by Azad et al. [15], who suggested a value of 121.8 lm/W for New Delhi (India).

Mayhoub and Carter [16] analysed the luminous efficacy values at ten geographical locations in both Europe and North Africa. They proposed three luminous efficacy models. The first model was based on the solar altitude, the second one employed both the solar altitude and the cloud amount, and the third model employed the sky clearness index. They likewise affirmed that the statistical performance of the first model was better than the other two and had the additional characteristic of simplicity [16].

Further studies such as those of Kong and Kim [17] determined the diffuse luminous efficacy at Yongin (South Korea) by using the solar altitude, the relative optical air mass, the sky brightness, and the clearness index as their independent variables. They also compared their proposed model with other luminous efficacy models in the bibliography, mentioning that better statistical results were provided by the model of Muneer and Kinghorn [8] at this geographical location [17]. In turn, in a study by Patil et al. [18], the luminous efficacy models of Perez et al. [4], Muneer and Kinghorn [8], and Littlefair [19] were analysed . The models were locally evaluated with experimental data from six stations, covering different climatic conditions in India. Those authors mentioned in their results that the model of Perez et al. was the best from among the three models discussed in their study [18]. Finally, in the study of Chaiwiwatworakul and Chirarattananon [20] a diffuse luminous efficacy model was proposed for Bangkok (Thailand) for all sky conditions, as a function of the sky clearness and the zenith angle values.

3. Daylight diffuse illuminance and solar diffuse irradiance measurements

A meteorological and radiometric facility, shown in Figure 1, was used to collect the experimental data used in this present study. This equipment was placed on the roof of the Higher Polytechnic School building at Burgos University (Spain), (latitude and longitude: 42°21′04″N and 3°41′20″W), located at 856 m above mean sea level as shown in Figure 2.

Figure 1. Experimental Equipment

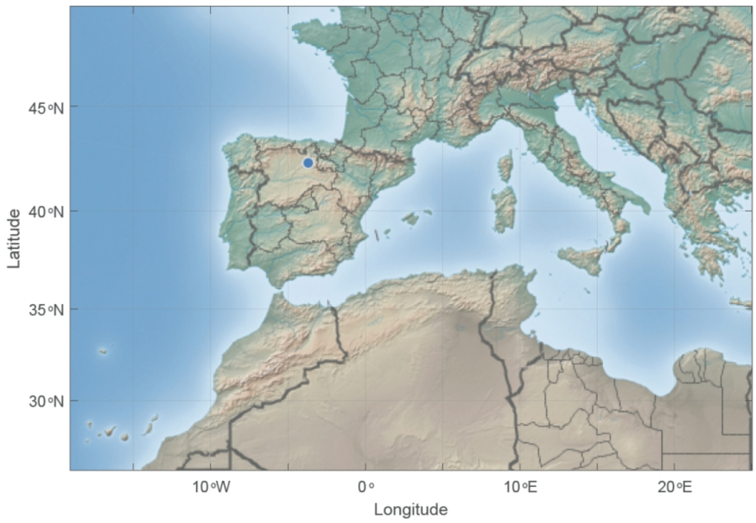


Figure 2. Burgos (Spain) (42°21′04″N; 3°41′20″W; 856 m above mean sea level)

Temperature, wind velocity and direction, atmospheric pressure, humidity and rainfall were measured. Moreover, global, beam, and diffuse horizontal irradiance (E_{gh}, E_{bh}, E_{dh}), and illuminance data (L_{gh}, L_{bh}, L_{dh}) were all recorded [21]. Class 1 Hukseflux SR11 pyranometers and an EKO ML020SO Luxmeter were employed to measure irradiance and illuminance data. The facility includes a SONA201D All Sky Camera Day and a MS-321LR sky scanner, both from EKO. The experimental data were recorded on a CAMPBELL CR3000 datalogger. These experimental data were measured, from 1st April

2017 to 31st March 2018, with a sampling time of thirty seconds. Average values were recorded every 10 minutes, for determination of the diffuse luminous efficacy models. The same experimental procedure was followed between 1st April 2018 and 31st December 2018, in order to measure the data for testing the models. The experimental values of E_{gh}, E_{bh}, E_{dh}, and L_{gh}, L_{bh}, L_{dh} were analysed and filtered using traditional quality criteria [22].

4. Diffuse luminous efficacy models on horizontal surfaces

The twenty-two classic luminous efficacy models analysed in this present study encompass models that use solar altitude as their only independent variable, models that employ other parameters such as sky brightness, sky clearness, diffuse fraction, zenith angle and clearness index, and models that propose a constant value for modelling luminous efficacy. Moreover, the models analysed in this study are applied either to particular sky conditions (clear sky, partly cloudy sky, and overcast sky) or to all sky conditions.

The models under review are presented in two ways: either by using the original coefficients given by their authors or adapted to local conditions. The previously described experimental data were used to calculate the local coefficients of the model. The data were fitted with non-linear least squares method using the Matlab™ R2018b fit function.

4.1. Perez et al. model (1990)

Perez et al. [4] modelled diffuse luminous efficacy with Equation (2), where a_i, b_i, c_i, d_i are the original coefficients of the model shown in Table 1(a). The local adaptation of these coefficients to the city of Burgos, is presented in Table 1(b). In this model, W is the atmospheric precipitable water content, which may be obtained from Equation (3), Z is the solar zenith angle, and Δ is the sky brightness, which can be obtained from Equation (4).

$$K_d = a_i + b_i W + c_i \cos(Z) + d_i \ln(\Delta)\ (lm/W) \tag{2}$$

$$W = e^{(0.07T_d - 0.075)} \tag{3}$$

$$\Delta = \frac{E_{dh} * m}{I_0} \tag{4}$$

Perez el al. classified the different sky types by using the sky clearness parameter, which is shown in Equation (5), where $k = 1.041$ for Z in radians [4].

$$\varepsilon = \left[(E_{dh} + I)/E_{dh} + kZ^3 \right] / \left[1 + kZ^3 \right] \tag{5}$$

Table 1. Perez et al. model (1990)

			a) Original diffuse luminous efficacy coefficients				b) Local diffuse luminous efficacy coefficients for Burgos, Spain			
ε category	Lower bound	Upper bound	a_i	b_i	c_i	d_i	a_i	b_i	c_i	d_i
1	1.000	1.065	97.24	-0.46	12.00	-8.91	100.65	1.66	0.41	-8.75
2	1.065	1.230	107.22	1.15	0.59	-3.95	100.29	3.23	-12.62	-14.39
3	1.230	1.500	104.97	2.96	-5.53	-8.77	89.80	4.50	-20.54	-26.82
4	1.500	1.950	102.39	5.59	-13.95	-13.90	94.27	3.67	-28.53	-28.39
5	1.950	2.800	100.71	5.94	-22.75	-23.74	111.36	3.10	-37.40	-20.99
6	2.800	4.500	106.42	3.83	-36.15	-28.83	86.01	4.16	-25.01	-27.07
7	4.500	6.200	141.88	1.90	-53.24	-14.03	138.24	3.02	-35.73	-7.28
8	6.200	---	152.23	0.35	-45.27	-7.98	143.04	2.94	-28.65	-2.97

4.2. The Chung model (1992)

This model uses the sky ratio or diffuse fraction (D) to classify the sky types. The diffuse fraction is defined as the ratio of horizontal diffuse irradiance over horizontal global irradiance, as shown in Equation (6). This author classifies the sky conditions as clear ($D < 0.3$), partly cloudy ($0.3 < D < 0.8$), and overcast ($D > 0.8$) [5]. Table 2 shows the models and their corresponding adaptation to the city of Burgos.

$$D = \frac{E_{dh}}{E_{gh}} \tag{6}$$

Table 2. Chung model equations for modelling diffuse luminous efficacy, K_d (lm/W), and for the different sky conditions. The original coefficients were calculated from the experimental data recorded at Hong Kong. The locally adapted coefficients were calculated from the experimental data recorded at Burgos, Spain.

Clear sky	*Original model*	$K_d = 137$
	Locally adapted model	$K_d = 126.609$
Overcast sky	*Original model*	$K_d = (102.2 + 0.67\alpha - 0.0059\alpha^2) * (1.18 - 8.7 * 10^{-4}\Omega + 9.3 * 10^{-7}\,\Omega^2)$

	Locally adapted model	$K_d = (101.340 + 14.113\alpha - 10.079\alpha^2) * (1.140 - 3.45 * 10^{-4}\Omega + 2.44 * 10^{-7}\,\Omega^2)$
Partly Cloudy sky	*Original model*	$K_d = 135.3 - 25.7\mathrm{D}$
	Locally adapted model	$K_d = 126.368 - 17.861D$

In the overcast model, Chung employed solar altitude (α) and the relative heaviness of overcast sky (Ω), obtained from Equation (7), as independent variables. On the other hand, he employed the diffuse fraction or cloud ratio (D) for partly cloudy sky [5]:

$$\Omega = E_{gh}/\sin\alpha \tag{7}$$

4.3. Lam and Li model (1996)

These authors proposed the following sky-type classification, based on the clearness index (K_t) as follows [6]: clear sky $(K_t > 0.65)$; partly cloudy sky $(0.3 < K_t \leq 0.65)$, and overcast sky $(0 < K_t \leq 0.3)$, where (K_t) is defined as the ratio of global to extraterrestrial irradiance [7]. The models and their local adaptation to the city of Burgos are presented in Table 3.

Table 3. Lam and Li equations for modelling diffuse luminous efficacy calculations, K_d (lm/W), and for the different sky conditions. The original coefficients were calculated from the experimental data recorded at Hong Kong. The locally adapted coefficients were calculated from the experimental data recorded at Burgos, Spain.

Clear sky	*Original model*	$K_d = 130.6$
	Locally adapted model	$K_d = 117.122$
Overcast sky	*Original model*	$K_d = 116.2$
	Locally adapted model	$K_d = 116.244$

4.4. Muneer and Kinghorn model (1998)

The model of Muneer and Kinghorn [8] and its adaptation to the local conditions of Burgos are shown in Table 4.

Table 4. Muneer and Kinghorn equations for modelling diffuse luminous efficacy calculations, K_d (lm/W). The original coefficients were calculated from data recorded at five different UK locations. The locally adapted coefficients were calculated from the experimental data recorded at Burgos, Spain.

All sky	*Original model*	$K_d = 130.2 - 39.828K_t + 49.979K_t^2$
	Locally adapted model	$K_d = 127.869 - 72.341K_t + 92.354K_t^2$

4.5. Robledo and Soler model (2001)

The sky conditions employed by Robledo and Soler were based on the sky clearness (ε). These conditions are defined as follows [9]: overcast sky: ($\varepsilon < 1.20$); partly cloudy sky ($1.20 < \varepsilon < 5.0$) and clear sky ($\varepsilon > 5.0$), where (ε) is obtained from Equation (5). The original expressions and the local adaptation of the models to the city of Burgos are presented in Table 5.

Table 5. Robledo and Soler equations for modelling diffuse luminous efficacy, K_d (lm/W). The original coefficients were calculated from the experimental data recorded at Madrid, Spain. The locally adapted coefficients were calculated from the experimental data recorded at Burgos, Spain.

All sky	*Original (model 1)*	$K_d = 86.68(sin\alpha)^{-0.034}\Delta^{-0.266}$
	Locally adapted (model 1)	$K_d = 97.101(sin\alpha)^{-0.046}\Delta^{-0.115}$
All sky	*Original (model 2)*	$K_d = 91.07\Delta^{-0.254}$
	Locally adapted (model 2)	$K_d = 100.908\Delta^{-0.105}$
Clear sky	*Original (model 1)*	$K_d = 68.30(sin\alpha)^{-0.175}\Delta^{-0.343}$
	Locally adapted (model 1)	$K_d = 120.187(sin\alpha)^{-0.187}\Delta^{-0.022}$
Clear sky	*Original (model 2)*	$K_d = 160.670(sin\alpha)^{-0.114}$
	Locally adapted (model 2)	$K_d = 127.986(sin\alpha)^{-0.182}$
Overcast sky	*Original model*	$K_d = 109.68(sin\alpha)^{-0.012}\Delta^{-0.116}$
	Locally adapted model	$K_d = 106.433(sin\alpha)^{-0.001}\Delta^{-0.056}$
Partly cloudy sky	*Original model*	$K_d = 82.240(sin\alpha)^{-0.052}\Delta^{-0.296}$
	Locally adapted model	$K_d = 89.786(sin\alpha)^{-0.110}\Delta^{-0.163}$

4.6. Ruiz et al. model (2001)

Ruiz et al. employed two independent variables, solar altitude (α) and the ratio between diffuse and extraterrestrial irradiance (K_D), in order to obtain two all sky type models [10]. The equations of the models and their adaptation to the local conditions of Burgos are presented in Table 6.

Table 6. Ruiz et al. equations for modelling diffuse luminous efficacy, $K_d\ (lm/W)$. The original coefficients were calculated from the experimental data recorded at Madrid, Spain. The locally adapted coefficients were calculated from the experimental data recorded at Burgos, Spain.

All sky	*Original (model 1)*	$K_d = 160.61 - 47.05K_D - 196.94K_D^2$
	Locally adapted (model 1)	$K_d = 144.990 - 149.439K_D + 168.178K_D^2$
All sky	*Original (model 2)*	$K_d = 86.970(sin\alpha)^{-0.143}K_D^{-0.218}$
	Locally adapted (model 2)	$K_d = 98.109(sin\alpha)^{-0.048}K_D^{-0.115}$

4.7. Souza and Robledo model (2004)

The sky conditions that Souza and Robledo used to classify sky types were overcast sky ($\varepsilon < 1.20$), partly cloudy sky ($1.20 < \varepsilon < 5.0$), and clear sky ($\varepsilon > 5.0$) [11]. Table 7 shows the original form of the model and its local adaptation to the city of Burgos.

Table 7. Souza and Robledo equations for modelling diffuse luminous efficacy, $K_d\ (lm/W)$. The original coefficients were calculated from the experimental data recorded at Florianopolis, Brazil. The locally adapted coefficients were calculated from the experimental data recorded at Burgos, Spain.

Clear sky	*Original model*	$K_d = 259.03\alpha^{-0.177}$
	Locally adapted model	$K_d = 132.250\alpha^{-0.125}$

4.8. Cucumo et al. model (2008)

Cucumo et al. used a constant value for modelling diffuse luminous efficacy [13]. Their model and its local adaptation to the city of Burgos are shown in Table 8.

Table 8. Cucumo et al. equations for modelling diffuse luminous efficacy, $K_d\ (lm/W)$. The original coefficients were calculated from the experimental data recorded at Aravaca di Rende, Italy. The locally adapted coefficients were calculated from the experimental data recorded at Burgos, Spain

All sky	*Original model*	$K_d = 127.410$
	Locally adapted model	$K_d = 115.202$

4.9. Mayhoub and Carter model (2011)

Mayhoub and Carter diffuse luminous efficacy models [16] and the form of their local adaptation to the city of Burgos are shown in Table 9.

Table 9. Mayhoub and Carter equations for modelling diffuse luminous efficacy, K_d (lm/W). The original coefficients were calculated from the experimental data recorded at ten locations in Europe and North Africa. The locally adapted coefficients were calculated from the experimental data recorded at Burgos, Spain

All sky	*Original (model 1)*	$K_d = 122.740 + 0.0164\alpha$
	Locally adapted (model 1)	$K_d = 116.732 - 0.285\alpha$
All sky	*Original (model 2)*	$K_d = 121.830 + 3.5567K_t - 18.305K_t^2 + 29.492K_t^3$
	Locally adapted (model 2)	$K_d = 115.072 - 4.700K_t - 10.500K_t^2 + 46.371K_t^3$

4.10. Fakra et al. model (2011)

Table 10 shows the model of Fakra et al. [14] and its local adaptation to the city of Burgos.

Table 10. Fakra et al. equations for modelling diffuse luminous efficacy, K_d (lm/W). The original coefficients were calculated from the experimental data recorded at Saint-Pierre, Reunion Island. The locally adapted coefficients were calculated from the experimental data recorded at Burgos, Spain.

All sky	*Original model*	$K_d = 139.980$
	Locally adapted model	$K_d = 115.202$

4.11. Chaiwiwatworakul and Chirarattananon model (2013)

These authors proposed a diffuse luminous efficacy model as a function of the sky clearness and the zenith angle [20]. Table 11 shows the original model and its local adaptation to the city of Burgos.

Table 11. Chaiwiwatworakul and Chirarattananon equations for modelling diffuse luminous efficacy, K_d (lm/W). The original coefficients were calculated from the experimental data recorded at Bangkok, Thailand. The locally adapted coefficients were calculated from the experimental data recorded at Burgos, Spain.

All sky	*Original model*	$K_d = \left(107.14 + 12.59\varepsilon^{0.24}\right) + \left(30.35 - \frac{30.1}{\varepsilon^{1.5}}\right)Z$
	Locally adapted model	$K_d = \left(102.613 + 0.081\varepsilon^{1.872}\right) + \left(45.171 - \frac{35.962}{\varepsilon^{1.026}}\right)Z$

4.12. Kong and Kim model (2013)

These authors proposed a model for all sky conditions as a function of the solar altitude, the relative optical airmass, the sky brightness, and the clearness index [17]. Table 12 shows this model and its local adaptation to the city of Burgos.

Table 12. Kong and Kim equations for modelling diffuse luminous efficacy calculations, K_d (lm/W). The original coefficients were calculated from the experimental data recorded at Yongin, South Korea. The locally adapted coefficients were calculated from the experimental data recorded at Burgos, Spain.

All sky	*Original model*	$K_d = 164.403 + 0.166\alpha - 5.759m - 20.393\Delta - 46.974K_t$
	Locally adapted model	$K_d = 137.549 - 13.101\alpha + 0.673m - 79.543\Delta + 18.539K_t$

A summary of the main features of the models reviewed and the parameters used by each of them is shown in Table 13.

Table 13. Summary of the diffuse luminous efficacy models reviewed in this work. Literature reference of the original model, year, authors, sky type classification, input parameters used in the models, and the location where the model was first developed.

Ref.	**Year**	**Authors**	**Sky types**	**Model parameters**	**Location**
[4]	1990	Perez et al.	All	W, Z, Δ	USA and Europe
[5]	1992	Chung	Clear	$137\ lm/W$	China
			Overcast	α, Ω	
			Partly	D	
[6]	1996	Lam and Li	Clear	$130.6\ lm/W$	China
			Overcast	$116.2\ lm/W$	
[8]	1998	Muneer and Kinghorn	All	K_t	UK
[9]	2001	Robledo and Soler (model 1)	All	α, Δ	Spain
[9]	2001	Robledo and Soler (model 2)	All	Δ	Spain
[9]	2001	Robledo and Soler (model 1)	Clear	α, Δ	Spain
		Robledo and Soler (model 2)	Clear	α	
		Robledo and Soler	Overcast	α, Δ	
			Partly	α, Δ	
[10]	2001	Ruiz et al. (model 1)	All	K_D	Spain
		Ruiz et al. (model 2)	All	α, K_D	Spain

[11]	2004	Souza and Robledo	Clear	α	Brazil
[13]	2008	Cucumo et al.	All	$127.41\ lm/W$	Italy
[16]	2011	Mayhoub and Carter (model 1)	All	α	Europe and North Africa
[16]	2011	Mayhoub and Carter (model 2)	All	K_t	Europe and North Africa
[14]	2011	Fakra et al.	All	$139.98\ lm/W$	Reunion Island
[20]	2013	Chaiwiwatworakul and Chirarattananon	All	Z, ε	Thailand
[17]	2013	Kong and Kim	All	α, m, Δ, K_t	South Korea

5. Evaluation of the twenty-two classic diffuse luminous efficacy models on a horizontal plane

The goodness-of-fit of the models was calculated by means of the statistical indicators MBE (%) (Mean Bias Error) and RMSE (%) (Root Mean Square Error) [14] [23]. MBE shows the trend of the model either to over-estimate or to under-estimate the data. In contrast, RMSE provides a measure of the deviation between the predicted values using the fitted models and the experimental measurements. Equations (8) and (9) show the statistical estimators employed in this present study.

$$MBE\ (\%) = 100\frac{\sum_n (X_{model} - X_{measured})}{\sum_n X_{measured}} \quad (8)$$

$$RMSE\ (\%) = 100\frac{\sqrt{\frac{\sum_n (X_{model} - X_{measured})^2}{n}}}{\frac{\sum_n X_{measured}}{n}} \quad (9)$$

Tables 14-17 present the results of applying the statistical estimators shown in Equations (8) and (9) to the models analysed in this study. Table 14 shows the results obtained for all sky conditions (twelve models). It can be observed that, when local coefficients are used, the Perez et al. [4] model showed the lowest RMSE (4.93 %) followed by the model of Ruiz et al. (Model 1, 4.97 %) [10].

Table 14. Evaluation of the diffuse luminous efficacy models for all skies

Model	Original coefficients		Local coefficients	
	MBE (%)	RMSE (%)	MBE (%)	RMSE (%)
Perez et al.	1.98	6.42	-0.26	4.93
Ruiz et al. (Model 1)	6.50	15.11	-0.32	4.97

Robledo and Soler (Model 2)	10.81	13.75	-0.48	5.11
Robledo and Soler (Model 1)	9.11	12.02	-0.71	5.12
Ruiz et al. (Model 2)	5.57	8.69	-0.72	5.13
Chaiwiwatworakul and Chirarattananon	9.54	13.88	0.03	5.77
Cucumo et al.	8.67	14.61	-1.74	6.67
Fakra et al.	19.39	26.71	-1.74	6.67
Kong and Kim	6.12	15.43	-0.64	6.69
Mayhoub and Carter (Model 1)	4.70	10.60	-0.62	6.90
Muneer and Kinghorn	6.39	11.92	1.03	8.09
Mayhoub and Carter (Model 2)	5.68	11.30	1.17	8.14

Table 15 shows the results obtained for the case of clear sky (five models). The models with the lowest RMSE values, when local coefficients are employed, are those of Robledo and Soler [9] (5.35 % and 5.40 %) followed by the Souza and Robledo model [11] (5.43 %).

Table 15. Evaluation of the diffuse luminous efficacy models for clear skies

Model	Original coefficients		Local coefficients	
	MBE (%)	RMSE (%)	MBE (%)	RMSE (%)
Robledo and Soler (Model 1)	31.61	32.30	0.11	5.35
Robledo and Soler (Model 2)	24.56	26.16	0.58	5.40
Souza and Robledo	97.26	100.77	0.57	5.43
Chung	4.82	12.45	-3.13	9.20
Lam and Li	6.93	16.22	-4.10	9.75

Table 16 shows the results obtained for the case of partly cloudy sky (two models). Using the local coefficients, the Robledo and Soler [9] model yielded the lowest RMSE value (6.16 %).

Table 16. Evaluation of the diffuse luminous efficacy models for partly cloudy skies

Model	Original coefficients		Local coefficients	
	MBE (%)	RMSE (%)	MBE (%)	RMSE (%)
Robledo and Soler	7.71	11.47	-0.70	6.16
Chung	4.31	8.88	0.48	6.23

Table 17 shows the results obtained for the overcast sky conditions (three models). Using local coefficients, the Chung [5] and the Robledo and Soler models [9] yielded the lowest RMSE values, respectively, 2.64% and 2.85%.

Table 17. Evaluation of the diffuse luminous efficacy models for overcast skies

Model	Original coefficients		Local coefficients	
	MBE (%)	RMSE (%)	MBE (%)	RMSE (%)
Chung	-6.20	7.69	-0.07	2.64
Robledo and Soler	11.08	12.56	-0.21	2.85
Lam and Li	0.10	4.35	0.14	4.35

As was expected *a priori*, from the results obtained in Tables 14-17, it can be affirmed that the models fitted with data from the local measurements provided lower RMSE values than those obtained when using original coefficients.

6. Proposal of a new model to predict diffuse luminous efficacy

In this section, a new model is proposed to predict diffuse luminous efficacy on horizontal surfaces. The dependence of diffuse luminous efficacy (K_d) on different variables (solar altitude, clearness index, sky clearness, sky brightness, zenith angle, diffuse fraction, etc.) was analysed and several models were tested, in order to obtain the final model. From these studies, a model for obtaining the luminous efficacy value was proposed. This new model is based on a sigmoidal function that employs the solar altitude (α) and the diffuse fraction (D) as the independent variables. In first place, it may be highlighted that the proposed model has a determinist term (p_0). As can be seen in the present work, that term is similar to the value obtained with the models that propose the use of only one constant to model luminous efficacy. However, the fact of considering a single constant for modelling luminous efficacy means that proper modelling of the behaviour of luminous efficacy throughout the day is not possible. In the case of the new model, there are another two variables, in addition to a determinist term. One of those variables is the diffuse fraction (D), as Equation (10) shows, which is defined as the ratio of horizontal diffuse irradiance to horizontal global irradiance, and which can be used to define the clearness of the sky. The other variable that the model employs is solar altitude (α). In addition, solar altitude varies throughout the day and, as a result, in some way takes the amount of incident surface energy into account. The function that models the behaviour of luminous efficacy better than any other can be seen to be a function of a sigmoidal type, for data gathered in Burgos. Its advantage is that two easily obtained independent variables are employed, as most radiometric facilities are able to obtain both global and diffuse irradiance and the solar altitude can be easily determined.

Figure 3 shows the experimental diffuse illuminance versus the experimental diffuse irradiance on the horizontal surface at Burgos. As previously mentioned, measurements gathered from 1st April 2017 to 31st March 2018 were employed to develop the models and measurements gathered from 1st April 2018 to 31st December 2018 to test the models. The model was firstly proposed for all sky conditions and then applied for particular sky conditions (clear, partly cloudy, and overcast).

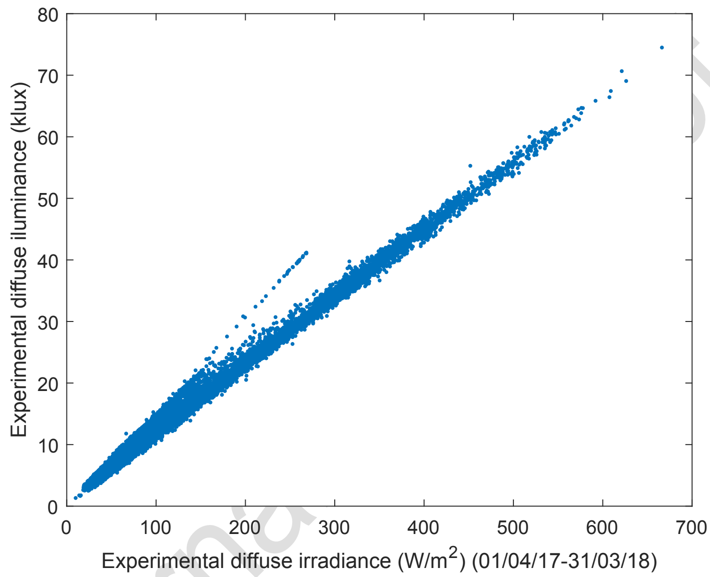


Figure 3. Experimental diffuse illuminance vs experimental diffuse irradiance on the horizontal surface at Burgos

Figures 4a and 4b depict the experimental diffuse illuminance and irradiance vs. diffuse fraction (D) at Burgos (Spain) and Figures 4c and 4d depict the experimental diffuse illuminance and irradiance vs. solar altitude (α) at Burgos (Spain). In figures 4a and 4b, it can be seen that the experimental values of illuminance and irradiance present a similar behaviour, as would be expected. In addition, the values are lower for clear skies, which is logical because the diffuse component was lower. In the case of partly cloudy and overcast skies, higher values of both illuminance and irradiance can be seen, with greater variability, as a consequence of the sky conditions.

With respect to the experimental data of illuminance and irradiance versus solar altitude, it may be seen that the lower the values of both illuminance and irradiance, the lower the value of solar altitude and with less variability than the values observed when the solar altitude increases, which is logical, as the sky conditions will affect illuminance and irradiance to a greater extent.

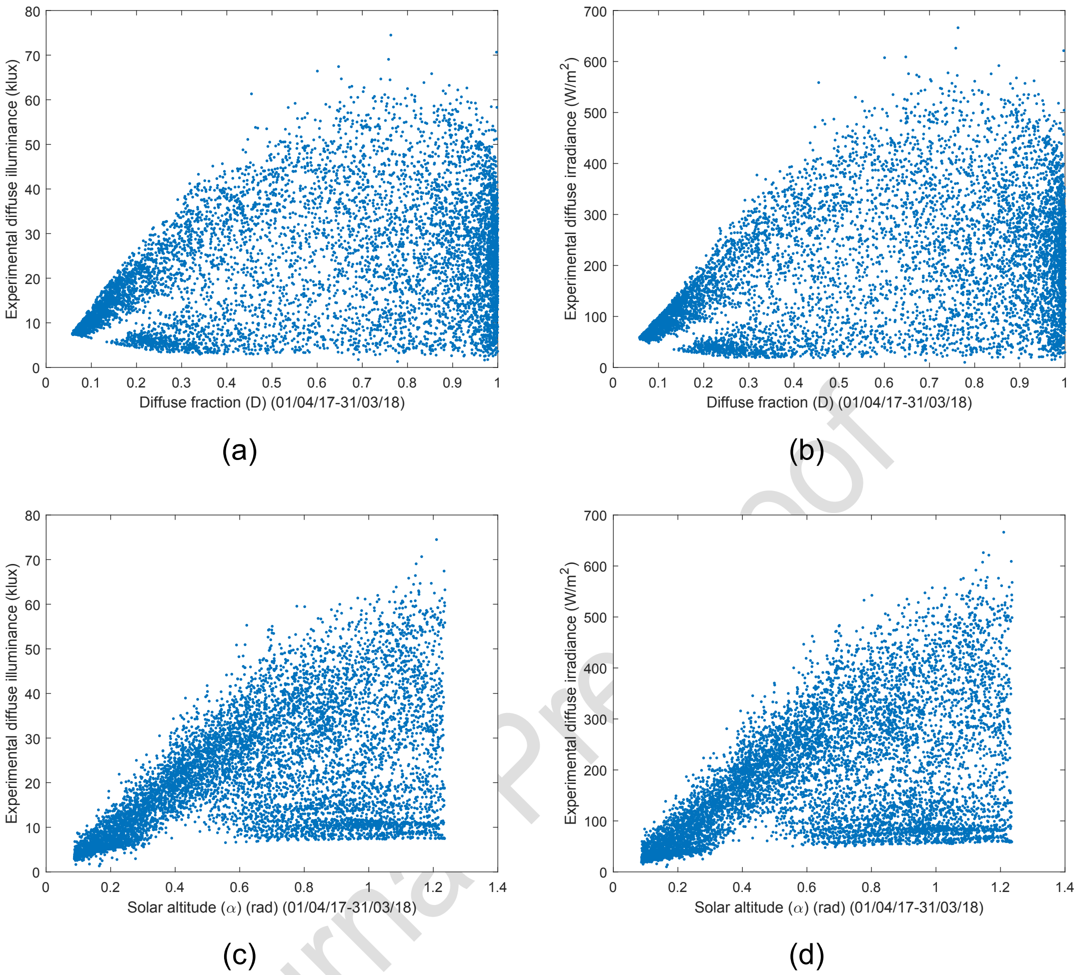


Figure 4. (a,b) Experimental diffuse illuminance and irradiance vs. diffuse fraction (D) at Burgos (Spain) and (c,d) Experimental diffuse illuminance and irradiance vs. solar altitude (α) at Burgos (Spain)

6.1. All sky conditions

Equation (10) shows the general form of the new diffuse luminous efficacy model: firstly proposed to determine the diffuse illuminance on horizontal surfaces for all sky conditions; and, subsequently adjusted for specific sky conditions (clear, partly cloudy, and overcast). As will be shown, this model can feasibly be employed for any of the above sky conditions. It can be observed that the independent variables of the new model are the solar altitude (α) and the diffuse fraction (D), defined by Equation (6). The local model adjusted to the city of Burgos is shown by Equation (11).

$$K_d = p_0 + \frac{p_1}{1 + e^{(p_2 \sin(\alpha) + p_3 D)}} \; (lm/W) \tag{10}$$

$$K_d = 112.018 + \frac{271.743}{1 + e^{(2.637 \sin(\alpha) + 4.569 D)}} \; (lm/W) \tag{11}$$

With the new model, shown in Equation (11), values of RMSE = 4.77 % and MBE = -0.10 % were obtained for all sky types. It can be observed from both Table 14 and Table 18 that the RMSE obtained with this new model was lower than any of the all sky classic models considered in this present study (twelve models). Figure 5 shows the estimated surface and the experimental data. The new model provides good estimations of the experimental data.

Table 18. Comparison between the best performing model for all sky conditions vs the new model for all sky conditions

Model	Local coefficients	
	MBE (%)	RMSE (%)
New model, All sky - Equation (11)	**-0.10**	**4.77**
Perez et al.	-0.26	4.93

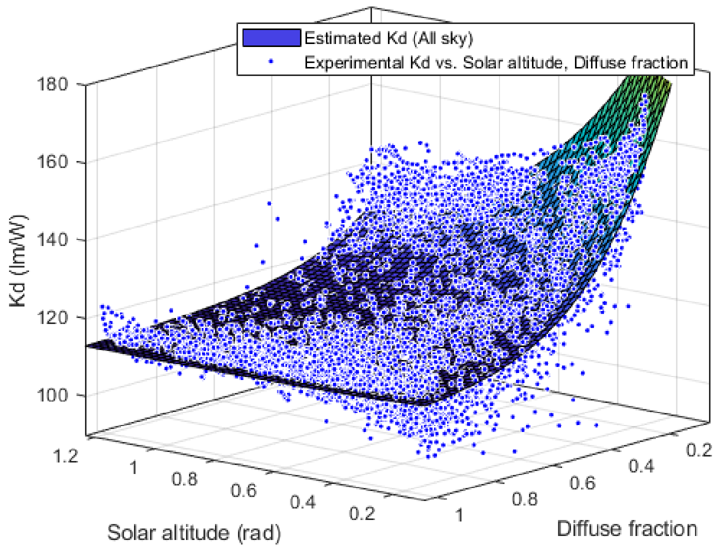


Figure 5.- Estimated diffuse luminous efficacy using the new model for all sky conditions, Equation (11), and experimental values for all sky conditions.

Figure 6 shows the estimated diffuse illuminance with the new model versus measured diffuse illuminance for all sky conditions. As can be observed, the new model adequately predicts the diffuse illuminance values for all sky conditions.

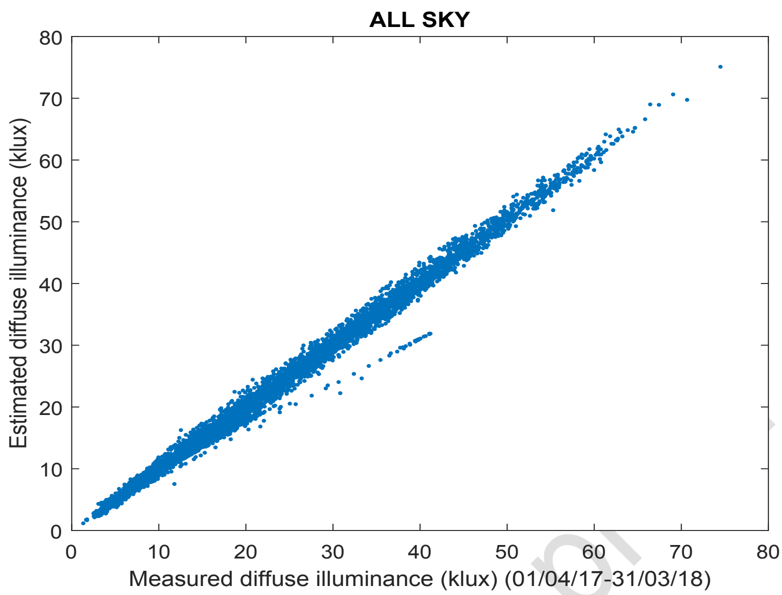


Figure 6.- Estimated diffuse illuminance with the new model vs measured diffuse illuminance for all sky conditions

From the results presented above, it can be concluded that the new model proposed in Equation (11) yields acceptable predictions of diffuse illuminance for all sky types and fitted the experimental data gathered in Burgos, Spain.

The data were fitted with the non-linear least-squares method using the Matlab™ R2018b fit function. For each type of sky, the data were selected with the specific sky conditions and had previously been filtered. In each case, it was necessary to select the variables that would be used. In the case of our model, the variables were defined as solar altitude and diffuse fraction. Those variables are two data vectors that will have been filtered by sky type. With the results and the experimental data on luminous efficacy (K_d), previously obtained and likewise filtered, the adjustment can be made by using the Matlab™ R2018b functions.

6.2. Clear sky

Equation (12) shows the new model, locally adapted for the clear sky condition, defined from ($\varepsilon > 5$). This sky condition is employed by the models of Robledo and Soler [9] that have the lowest RMSE values of all the models shown in Table 15. The new model, which is shown in Equation (12) yields an MBE = 0.14 % and an RMSE = 5.34 %. As can be observed, the RMSE was slightly lower than those obtained with the models of Robledo and Soler [9]. Moreover, as can be observed from Table 19, the new model in Equation (11), locally fitted for all sky conditions, yields an RMSE value close to those locally fitted for a clear sky.

$$K_d = 123.114 + \frac{190.220}{1 + e^{(3.252\sin(\alpha) + 3.340D)}}\ (lm/W) \tag{12}$$

Table 19. Comparison between the best performing model for clear sky vs the new model (same sky conditions $\varepsilon > 5$)

Model	Local coefficients	
	MBE (%)	RMSE (%)
New model, Clear sky - Equation (12)	**0.14**	**5.34**
Robledo and Soler (Model 1)	0.11	5.35
New model, All sky - Equation (11)	-1.32	5.92

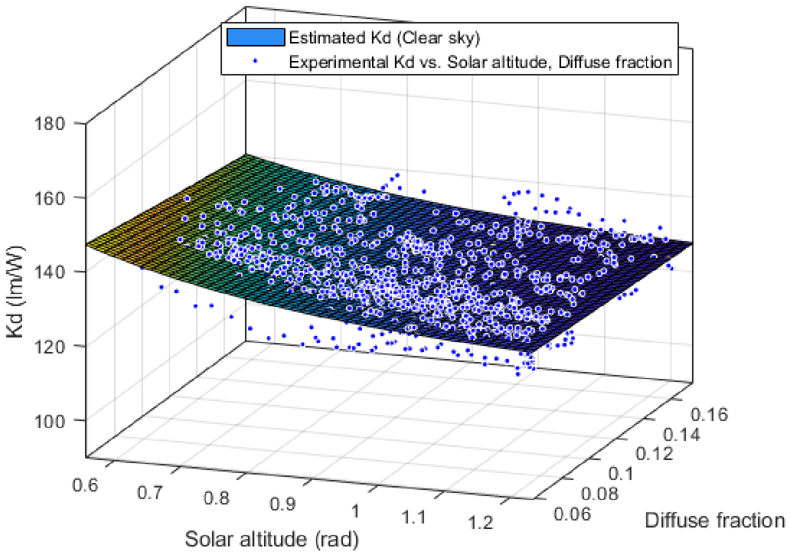


Figure 7.- Estimated diffuse luminous efficacy using the new model for clear sky, Equation (12), and experimental values for clear sky

Figure 7 shows the estimated luminous efficacy by using the new model, which is shown in Equation (12) for clear sky as well as the experimental values. Likewise, Figure 8 shows the estimated diffuse illuminance with the new model versus the measured diffuse illuminance for clear sky conditions.

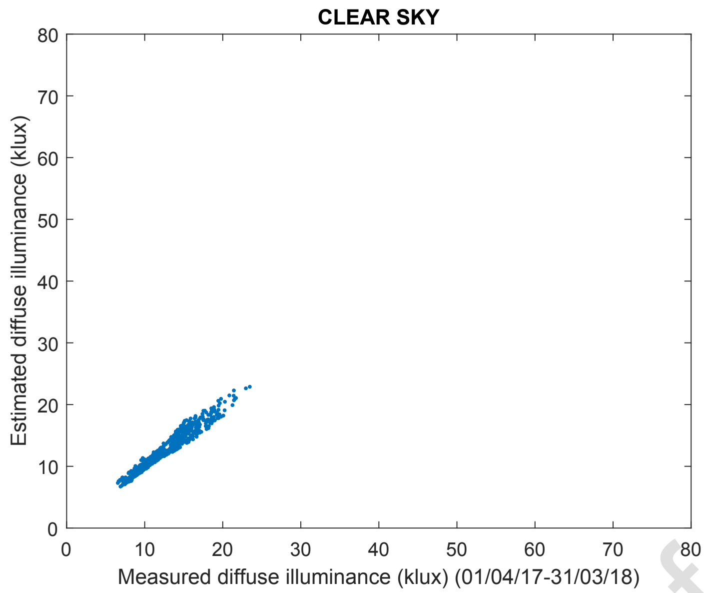


Figure 8.- Estimated diffuse illuminance using the new model vs measured diffuse illuminance for clear sky conditions given by $\varepsilon > 5$

6.3. Partly cloudy sky

Equation (13) shows the new model locally fitted for partly cloudy sky conditions, defined by $(1.2 < \varepsilon < 5.0)$, which is the sky condition employed by the model of Robledo and Soler [9], because that model has the lowest RMSE values of all the models shown in Table 16. The new model, shown by Equation (13) yields an RMSE value of 5.76 %. Moreover, as shown in Table 20, the new model in Equation (11), locally fitted for all sky conditions, yields an RMSE value of 5.98 %; both slightly lower than the values obtained with the model of Robledo and Soler [9].

$$K_d = 108.635 + \frac{240.293}{1 + e^{(2.515\sin(\alpha) + 3.656D)}} \ (lm/W) \tag{13}$$

Table 20. Comparison between the best performing model for partly cloudy sky and the new model, using the same sky conditions $(1.2 < \varepsilon < 5.0)$

Model	Local coefficients	
	MBE (%)	RMSE (%)
New model, Partly cloudy sky - Equation (13)	**-0.38**	**5.76**
New model, All sky - Equation (11)	-0.74	5.98
Robledo and Soler	-0.70	6.16

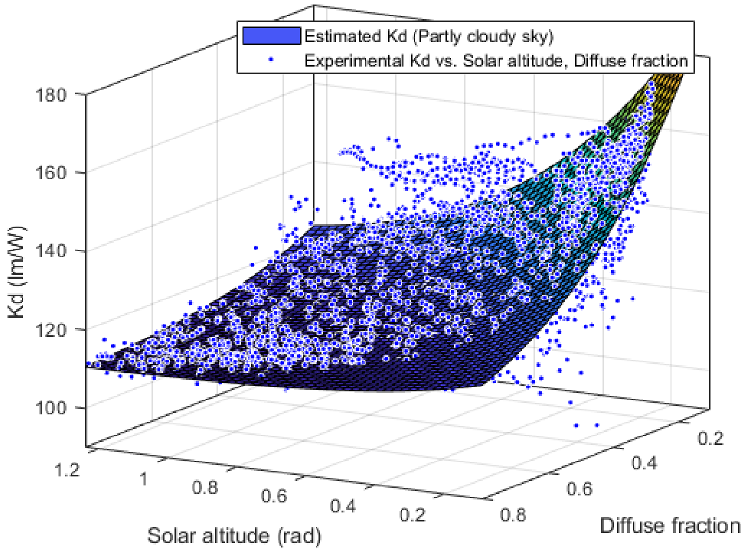


Figure 9.- Estimated diffuse luminous efficacy using the new model for partly cloudy sky, Equation (13), and experimental values for partly cloudy sky

Figure 9 shows the estimated luminous efficacy using the new model, which is shown in Equation (13) for partly cloudy sky, as well as the experimental values. Likewise, Figure 10 shows the estimated diffuse illuminance with the new model versus measured diffuse illuminance for partly cloudy sky conditions. It can be observed that the new model, given by Equation (13), produces acceptable predictions of the diffuse illuminance values for partly cloudy skies.

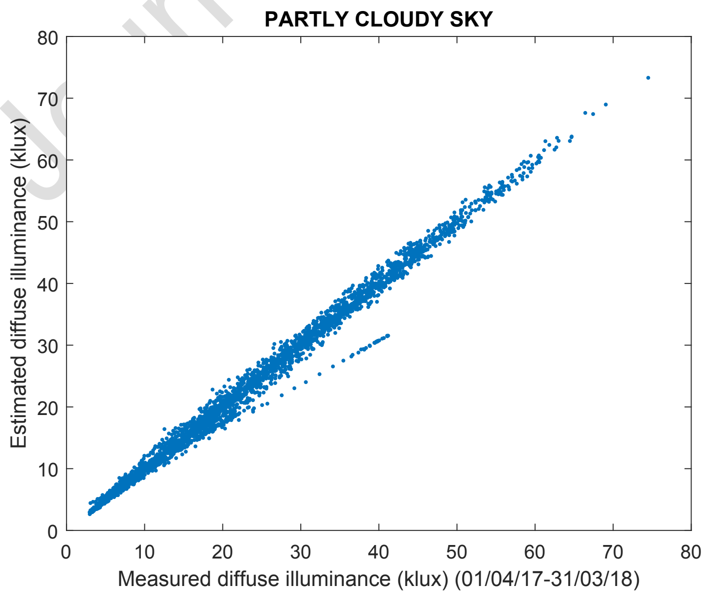


Figure 10.- Estimated diffuse illuminance with the new model vs measured diffuse illuminance for partly cloudy sky conditions $(1.2 < \varepsilon < 5.0)$

6.4. Overcast sky conditions

Equation (14) shows the new model locally fitted for overcast sky conditions given by ($D > 0.8$), which are those employed by the Chung Model [5], because this model yielded the lowest RMSE (2.64 %) from among those shown in Table 17. The new model in Equation (14) yields an RMSE value of 2.83 %, slightly higher than the previous one. Moreover, as can be observed in Table 21, an RMSE of 2.96 % was attained with the new model locally fitted with all data (all sky conditions). It can therefore be noted that these RMSE values are similar to those obtained by the Chung Model [5].

$$K_d = 113.516 + \frac{203.807}{1 + e^{(3.296 \sin(\alpha) + 5.712D)}} \ (lm/W) \tag{14}$$

Table 21. Comparison between the best performing model for overcast skies and the new model, using the same sky conditions ($D > 0.8$)

Model	Local coefficients	
	MBE (%)	RMSE (%)
Chung Model	-0.07	2.64
New model, Overcast sky - Equation (14)	**-0.06**	**2.83**
New model, All sky - Equation (11)	-0.73	2.96

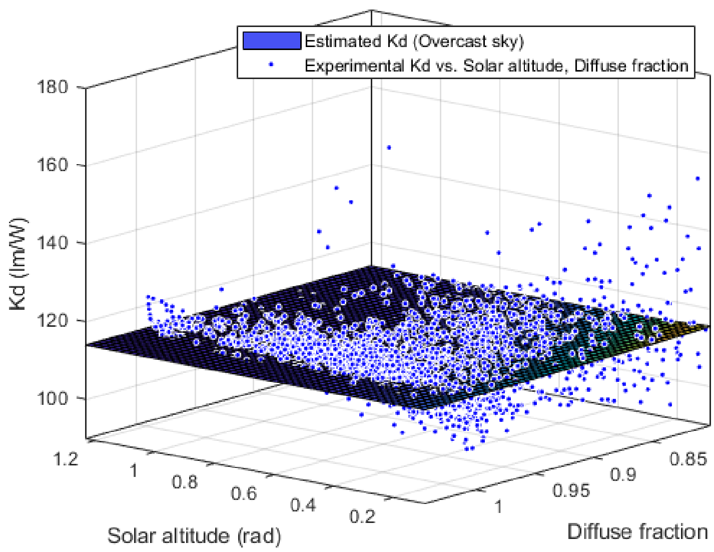


Figure 11.- Estimated diffuse luminous efficacy using the new model for overcast sky, Equation (14), and experimental values for overcast sky

Figure 11 shows the estimated luminous efficacy using the new model, which is shown in Equation (14) for overcast sky as well as the experimental values. As can be observed, this model yields acceptable predictions of luminous efficacy, which is approximately constant in the interval defined by the sky ratio. Figure 12 shows the estimated diffuse illuminance with the new model versus measured diffuse illuminance for overcast sky conditions. As can be noted, the new model is able to predict the diffuse illuminance for overcast sky conditions.

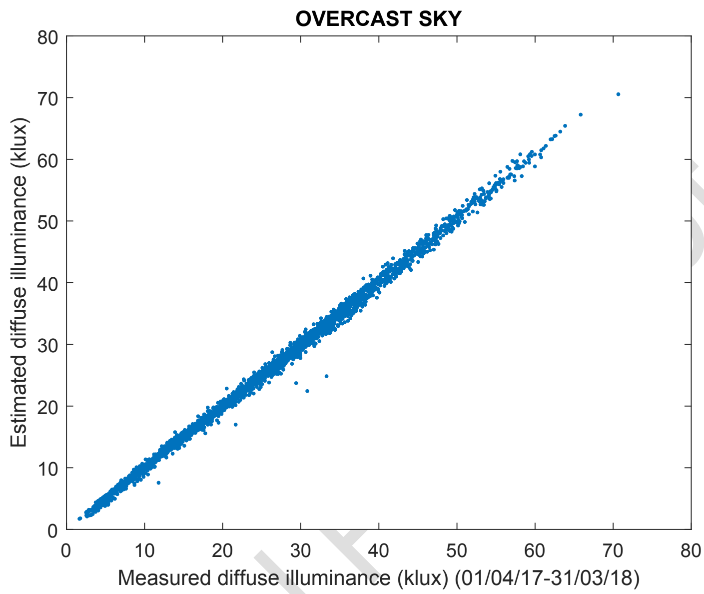
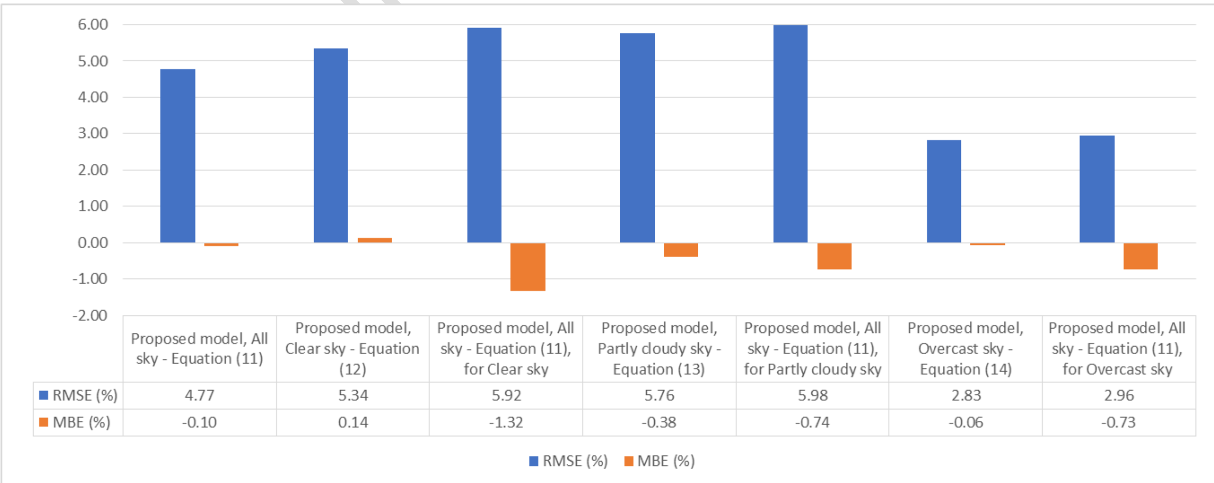


Figure 12.- Estimated diffuse illuminance with the new model vs measured diffuse illuminance for overcast sky conditions ($D > 0.8$)



	Proposed model, All sky - Equation (11)	Proposed model, Clear sky - Equation (12)	Proposed model, All sky - Equation (11), for Clear sky	Proposed model, Partly cloudy sky - Equation (13)	Proposed model, All sky - Equation (11), for Partly cloudy sky	Proposed model, Overcast sky - Equation (14)	Proposed model, All sky - Equation (11), for Overcast sky
RMSE (%)	4.77	5.34	5.92	5.76	5.98	2.83	2.96
MBE (%)	-0.10	0.14	-1.32	-0.38	-0.74	-0.06	-0.73

Figure 13.- RMSE (%) and MBE (%) using the new model for the sky conditions analysed in this study

Figure 13 shows a comparison between the RMSE and MBE values using the new model for all sky and for particular sky conditions (clear, partly cloudy, and overcast). It can be observed that the new model provides acceptable predictions of diffuse illuminance both for all sky and for particular sky conditions (clear, partly cloudy, and overcast).

7. Validation of the diffuse illuminance models

In Section 4, the diffuse luminous efficacy models from twenty-two existing models in the literature were fitted to local data from Burgos (Spain) and, in Section 5, the same models were evaluated. In Section 6, a new model was fitted and analysed for all sky and for particular sky conditions, using the same data as the previously mentioned models. In this Section, all of these models will now be validated by employing nine months of additional measurements gathered between 1st April 2018 and 31st December 2018. These measurements were taken, following the same procedure described in Section 3. Figure 14 shows the experimental data employed for testing the global luminous efficacy models. The figure shows measured diffuse illuminance versus measured diffuse irradiance on the horizontal surface at Burgos over the test period.

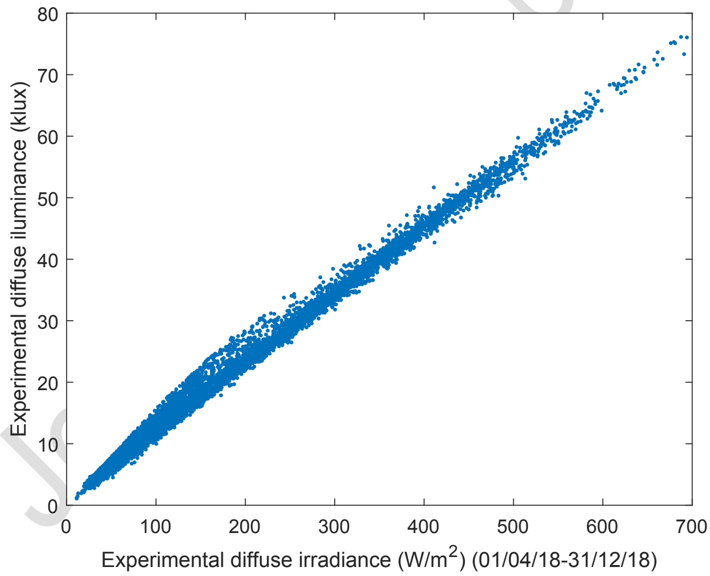
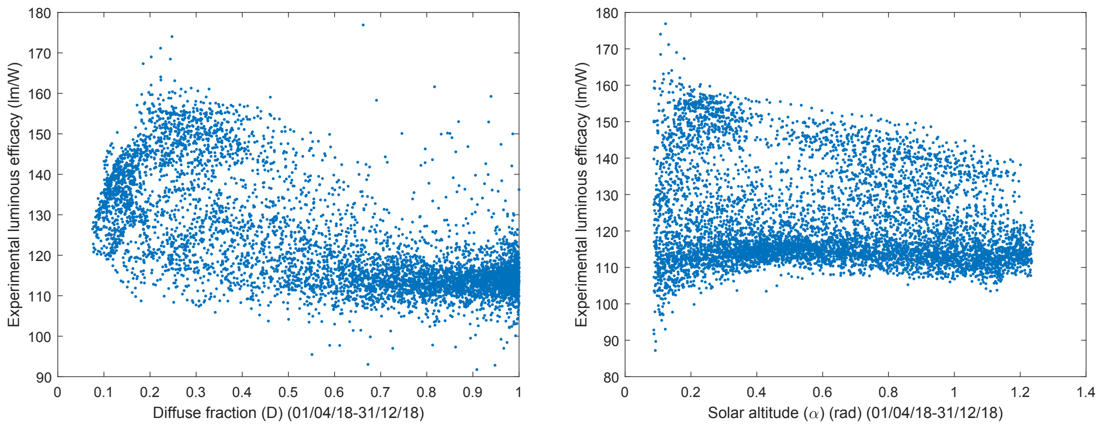


Figure 14.- Experimental diffuse illuminance vs experimental diffuse irradiance on the horizontal surface at Burgos (test period)

As can be observed, Figure 15(a) shows the experimental diffuse luminous efficacy versus the diffuse fraction and Figure 15(b) shows the experimental diffuse luminous efficacy versus solar altitude, both for all sky conditions, using data gathered during the test period.



(a) (b)

Figure 15.- (a) Experimental diffuse luminous efficacy vs Diffuse fraction (D) and (b) Experimental diffuse luminous efficacy vs solar altitude (α) for all sky (test period)

Data from these additional nine months of measurement are used to re-evaluate both RMSE and MBE in the models previously fitted with experimental data (local models), in order to validate the results. Tables 22-25 present the results of evaluating the statistical estimators shown in Equation (8) and in Equation (9) using the luminous efficacy models analysed in this study. The results obtained from the different sky conditions under study are also shown. To that end, the specific sky conditions proposed by each author were applied, in order to define the different sky types (clear sky, partly cloudy sky, and overcast sky). The new model proposed in this study was also validated both for all sky conditions and for particular sky types (clear, partly cloudy, and overcast). In the latter case, the conditions employed by the model with the lowest RMSE value were used to define the sky type. Table 22 shows the MBE and RMSE results of the tests for all sky conditions using the twelve classic models and the new model. It is shown in the validation that, the model of Perez et al. [4] (4.32 %) provided slightly lower results than the new model (4.44 %).

Table 22. Validation of the diffuse luminous efficacy models for all skies

Model	Local coefficients	
	MBE (%)	RMSE (%)
Perez et al.	-0.51	4.32
New model, All sky – Equation (11)	-0.90	4.44
Ruiz et al. (Model 1)	-1.28	4.97
Robledo and Soler (Model 2)	-1.55	5.04
Robledo and Soler (Model 1)	-1.86	5.21
Ruiz et al. (Model 2)	-1.87	5.22

Chaiwiwatworakul and Chirarattananon	-1.06	5.39
Cucumo et al.	-1.90	6.74
Fakra et al.	-1.90	6.74
Mayhoub and Carter (Model 1)	-0.78	6.93
Kong and Kim	-2.36	7.33
Muneer and Kinghorn	0.29	8.11
Mayhoub and Carter (Model 2)	0.49	8.14

The results obtained from classic clear sky models (five models) and the new model are shown in Table 23. In addition, the results from the validation of the all sky model, given by Equation (11) for this particular sky type are also compared. It is shown that the models with the lowest RMSE values were those of the Souza and Robledo model [11] (5.89 %) and the Robledo and Soler model (Model 2) [9] (5.89 %). The new model given by Equation (12) yielded similar values to those obtained with the previously mentioned models (5.97 %). Moreover, the model obtained for all sky conditions provided an RMSE value of (6.90 %), higher than the one obtained with particular sky conditions given by ($\varepsilon > 5$), which were used by Souza and Robledo [11] and Robledo and Soler [9].

Table 23. Validation of the diffuse luminous efficacy models for clear sky conditions

Model	Local coefficients	
	MBE (%)	RMSE (%)
Souza and Robledo	0.32	5.89
Robledo and Soler (Model 2)	0.27	5.89
Robledo and Soler (Model 1)	-0.54	5.96
New model, Clear sky – Equation (12)	-0.52	5.97
New model, All sky – Equation (11)	-2.66	6.90
Chung	-4.64	9.59
Lam and Li	-4.62	9.79

Likewise, Table 24 shows the results obtained for classic partly cloudy sky models. It can be noted that the model with the lowest RMSE value is the new model for all sky conditions, defined by Equation (11) (5.72 %), followed by the new model for partly cloudy sky, defined by Equation (13) (6.01 %) and the Chung model [5] (6.01 %).

Table 24. Validation of the diffuse luminous efficacy models for partly cloudy sky

Model	Local coefficients	
	MBE (%)	RMSE (%)

New model, All sky – Equation (11)	-1.00	5.72
New model, Partly cloudy sky - Equation (13)	1.88	6.01
Chung	-1.21	6.01
Robledo and Soler	-2.51	6.35

Table 25. Validation of the diffuse luminous efficacy models for overcast sky

Model	Local coefficients	
	MBE (%)	RMSE (%)
Chung	-0.25	2.44
Robledo and Soler	-0.43	2.78
New model, All sky – Equation (11)	-0.80	2.93
New model, Overcast sky - Equation (14)	1.06	3.19
Lam and Li	-0.02	3.79

Finally, Table 25 shows the results obtained for the classic overcast sky models (three models), which are also compared with the new models. It can be noted that the model with the lowest RMSE values is the model of Chung [5] (2.44 %). Moreover, it can be observed that the models proposed in this present study fitted both for all sky conditions (2.93 %) and for overcast sky conditions (3.19 %) provide similar values to those of the Chung model [5]. As Figure 16 shows, in the case of all sky conditions, both the classic models and the new models analysed in this study with data from the test period present a similar tendency to that observed with data gathered to fit the models. A similar behaviour was also attained for particular sky conditions (clear, partly cloudy, and overcast).

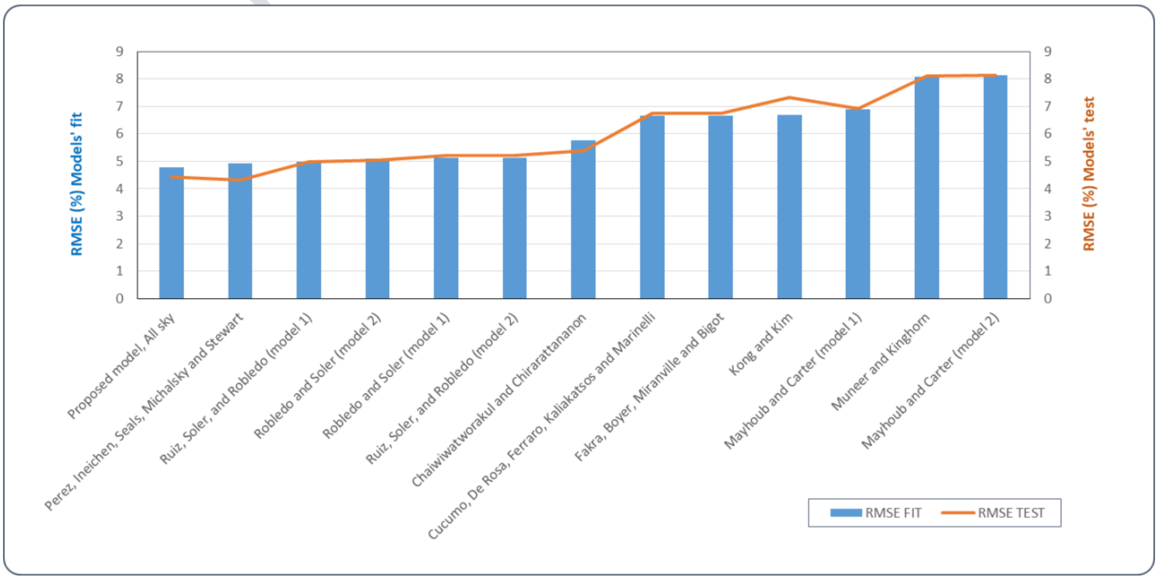


Figure 16.- Comparison between the RMSE values obtained with the classic models and the new model in the fit period (1st April 2017 to 31st March 2018) and in the validation period (1st April 2018 to 31st December 2018)

Figure 17 shows the results obtained with the data gathered during the test period (1st April 2018 - 31st December 2018). These figures were obtained both for all sky and for particular sky conditions using the new models developed in this present study. These figures show the experimental measurements and the estimated diffuse luminous efficacy. A similar behaviour to the one obtained with the data employed to fit the models (1st April 2017 to 31st March 2018) can be observed.

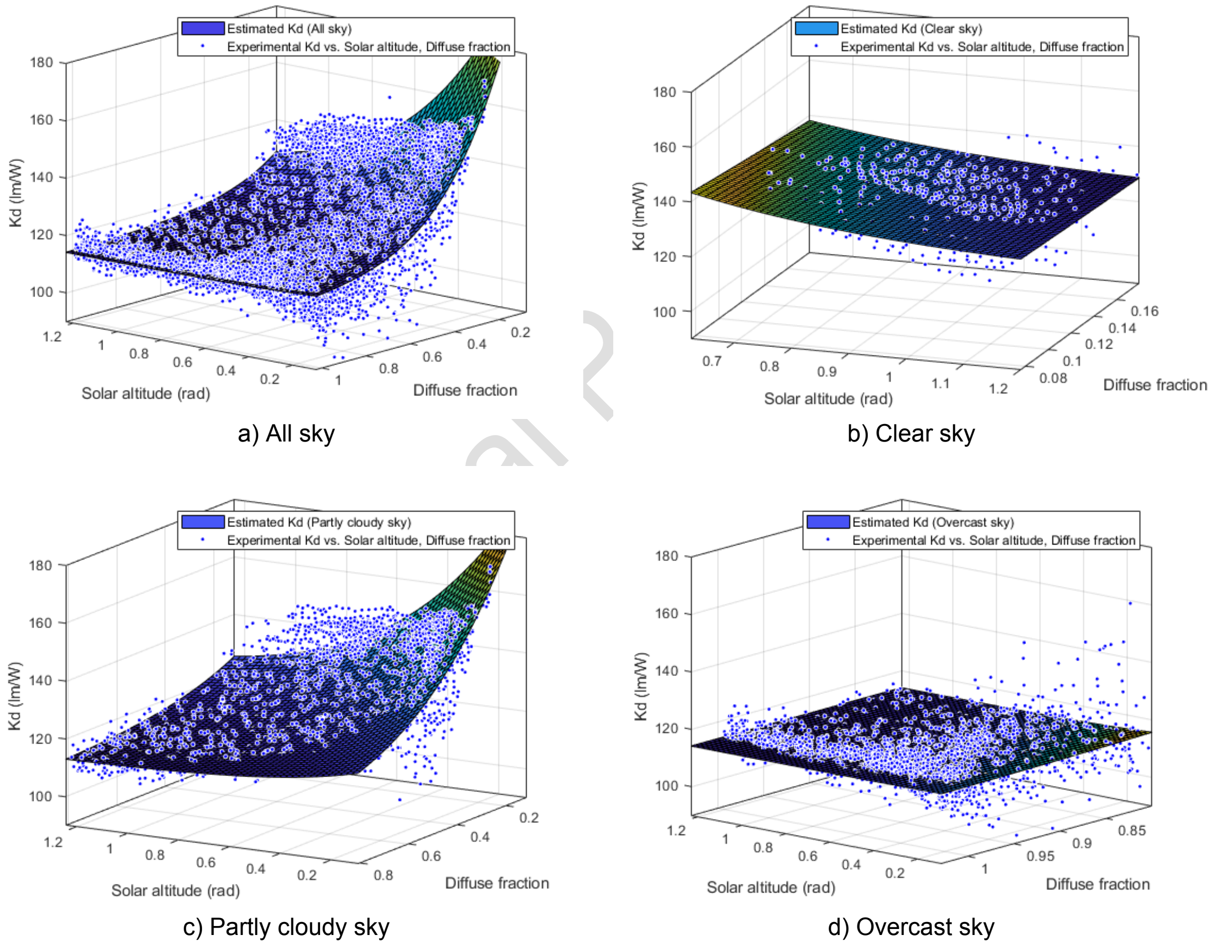


Figure 17.- Estimated K_d and measured values for all sky and for particular sky conditions using measurements gathered in the test period (1st April 2018 - 31st December 2018).

In addition, state of the art literature was consulted and the uncertainty values for solar altitude proposed in the work of H. Kambezidis, 2012 [24], were selected. Likewise, the results that are shown in both the pyranometer manual [25] and the state of the art: I.

Reda [26] and T. Muneer et al. [27] were considered, to account for the uncertainty of the irradiance measurement in the experimental measurements. On the basis of those uncertainty values, the uncertainty of the diffuse fraction (D) may be calculated. This uncertainty, together with the uncertainty of the solar altitude, makes it possible to evaluate the uncertainty of the luminous efficacy model proposed in this work. Having determined the uncertainty, a graphic representation of the values that our model yields is possible. Therefore, when evaluating the data collected over the test period (01/04/18-31/12/18), the uncertainty of the model adopts a form that is shown in Figure 18. The uncertainty values that the model provides are relatively small in relation to the values of luminous efficacy. It may therefore be affirmed that the proposed model is acceptable.

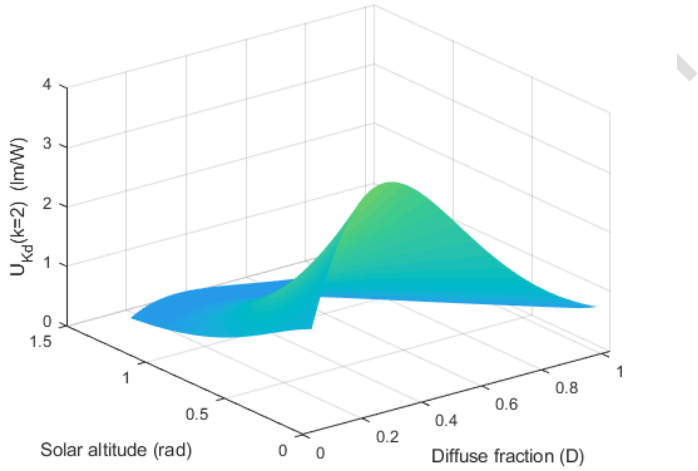


Figure 18. Luminous efficacy uncertainty of the proposed model for all sky conditions

8. Conclusions

In this present study, twenty-two classic diffuse luminous efficacy models from the existing literature have been evaluated, both with their original coefficients and locally adapted coefficients estimated from the experimental data recorded at Burgos (Spain), between 1st April 2017 and 31st March 2018. The local behaviour of the models has been noted, which leads to lower RMSE and MBE values than those obtained by using their original coefficients.

A new diffuse luminous efficacy model has been proposed and analysed in this present study, in order to predict the illuminance on horizontal surfaces. This new model has been fitted for all sky types and for particular sky types (clear, partly cloudy, and overcast). This new model employs two independent variables: the diffuse fraction (D), which is easily obtained from most radiometric facilities that can measure both global and diffuse irradiance, and the solar altitude (α) that is also easily obtained whatever the geographical location.

The new model fitted with data collected during the period (1st April 2017 - 31st March 2018) yields an RMSE value lower than any of the classic models analysed in this study for all sky conditions, as can be observed in Table 18. Moreover, the new model initially proposed for all sky conditions, shown in Equation (11), could be used either for all sky or for particular sky conditions (clear, partly cloudy, and overcast).

In turn, the new model fitted for particular sky conditions (clear, partly cloudy and overcast), with the data collected during the period (1st April 2017 - 31st March 2018), provides lower RMSE results than any of the classic models analysed in this study for clear sky and partly cloudy sky and it yields similar values in the case of overcast sky than the best performing models for this particular sky condition.

The models yielded similar RMSE values both for the results of the validation data recorded during the period between 1st April 2018 and 31st December 2018 and for the data recorded between 1st April 2017 and 31st March 2018, for all sky conditions, as shown in Figure 16. Likewise, a similar behaviour was observed for particular sky conditions (clear sky, partly cloudy and overcast sky).

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Highlights

- A new model of diffuse luminous efficacy over a horizontal surface is proposed
- A comparative study of twenty-two classic luminous efficacy models is presented
- The proposed model behaves in a better way than most of the classic models analysed
- Diffuse illuminance in all sky and in particular sky conditions can be determined