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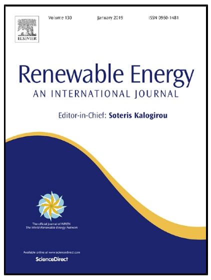

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Abstract

Daylighting is recognized as an important and useful strategy in the design of energy efficient buildings. Daylight is still the best source of light for good colour rendering and visual comfort. In this study, a new model of global luminous efficacy over a horizontal surface is proposed. A comparative study of eighteen classic models is presented, to obtain global horizontal illuminance, using both, the original formulation and new formulae with local adaptations, in order to determine the most suitable models for the conditions in Burgos (Spain). With this aim in mind, the selected models consisted of six models developed for all sky conditions, five models for clear sky conditions, three for partly cloudy sky and four for modelling overcast sky conditions. These eighteen models were also compared with the proposed model using experimental global illuminance measurements for different sky conditions. It was shown that the proposed model behaved in a better way than most of the classic models selected from the literature; both for all sky conditions and for particular sky conditions (clear, cloudy and overcast). The proposed model was therefore generally applicable, with no need to employ a different model for each particular sky condition.

Keywords: Luminous Efficacy Models, Illuminance, Irradiance, Modelling

Nomenclature section

a_i, b_i, c_i, d_i: Perez coefficients

m: relative optical airmass

C: cloud cover

D: cloud ratio or sky ratio or diffuse fraction

E_0: correction factor for the sun-earth distance

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: extra-terrestrial irradiance (W/m^2)

I_{sc}: solar constant

K_g: global luminous efficacy (lm/W)

K_t: clearness index

L_{bh}: horizontal beam illuminance (lux)

L_{dh}: horizontal diffuse illuminance (lux)

L_{gh}: horizontal global illuminance (lux)

MBE: Mean Bias Error (%)

n: number of data

p_0, p_1, p_2: coefficients of the proposed model

RMSE: Root Mean Square Error (%)

t: outdoor air temperature (ºC)

T_d: three-hourly surface dew point temperature (ºC)

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

Solar-energy-based conversion systems and daylighting schemes are recognized as an important design strategy to generate clean energy that is sustainable and environmentally friendly, thereby reducing peak electricity consumption and cooling demands and saving on the total energy consumption of the building. The availability of natural light is also recommendable for reasons of visual comfort, and the physical and mental well-being of building occupants [1]. Daylighting not only improves aesthetic values, but can also lead to savings, using appropriate controls, of up to 50% on lighting energy [2]. International recommendations of energy standards and green building rating systems strongly advise architects to incorporate daylighting strategies in their building designs [3]. Illuminance data are essentially for the incorporation of daylighting in the design of energy-efficient buildings and for suitable dimensioning of both the cooling and the heating systems. The availability of daylight has been recognized to be site-specific, although the measurement of daylight is not so common on a long-term basis [4]. An alternative method to increase illuminance data is through the use of luminous efficacy.

Once the ratio of luminance to irradiance, i.e., the luminous efficacy, is known, then measured irradiance values can be converted to illuminance values, which can in turn be used as input for a daylight simulation tool for the calculation of available daylight. The luminous efficacy value is not a constant, but will vary with solar altitude, cloud cover, and the amounts of aerosol and water vapour in the atmosphere [5]. The luminous efficacy models based on atmospheric conditions are also strongly dependent on those local variables [6]. Hence the importance of studying models of luminous efficacy to predict the values of illuminance at any one location.

Several studies have followed that pattern, mostly studying the local behaviour of luminous efficacy and its variability. Littlefair [5] reviewed different models of luminous efficacies formulated by different authors prior to 1985 at several global locations, highlighting the strong dependency of luminous efficacy on local climatic conditions. Vartiainen [7] studied the behaviour of five models of luminous efficacy in Finland, showing that Perez's model [8] was the only one that improved the predictions of the constant luminous efficacy model. De Souza [9] showed the local dependency of the luminous efficacy models, improving the results obtained when local coefficients were calculated for different models. Patil et al. [10] remarked on the good behaviour of Perez's model with a locally adapted coefficient for different climatic zones in India, and Azad et al. [11] proposed new global and luminous efficacy models with constant forms for New Delhi.

As previously mentioned, eighteen models of luminous efficacy are reviewed and tested in this study in the city of Burgos, Spain, using both the original form of these models proposed by their authors and their local adaption to the location under study. Traditional statistical indicators RMSE (%) and MBE (%) were used to classify the models and to determine their accuracy. One year and a half of experimental data on illuminance were used in this study. In addition, a new model to predict global horizontal illuminance is proposed. This new model is analysed for all sky conditions and for particular sky conditions (clear, partly cloudy and overcast) showing the improvement in the illuminance prediction over the eighteen previously tested models for the city of Burgos, Spain.

The structure of this paper will be as follows: the experimental meteorological facility and data used for the study will be described in Section 2. Section 3 will describe the global luminous efficacy models on horizontal surfaces that are reviewed in this work. The benchmarking results of the eighteen luminous efficacy models under review will be presented in Section 4. The new model proposed for the area under study and its comparison with the others models under review will be shown in Section 5. In Section 6, the validation of both the proposed model and the eighteen luminous efficacy models under review will be presented and, finally, the main conclusions of this study will be outlined, remarking on the goals of the work and future lines of study.

2. Daylight global illuminance and solar global irradiance measurements

The experimental data for this study were gathered at a meteorological and radiometric facility located on the roof of the Higher Polytechnic School building at Burgos University (42°21′04″N; 3°41′20″O; 856 m above mean sea level). This five-storey building, in an area with no other buildings of comparable height, has a horizon elevation angle that is lower than 10º with regard to the surface where the radiometric station is located. The experimental equipment is shown in Figure 1.

Figure 1: Experimental Equipment

The following meteorological data were measured: temperature, wind velocity and direction, atmospheric pressure, humidity and rainfall. Global, beam and diffuse horizontal irradiation (E_{gh}, E_{bh}, E_{dh}) and illuminance data (L_{gh}, L_{bh}, L_{dh}) were all recorded. Class 1 Hukseflux SR11 pyranometers and an EKO ML020SO Luxmeter were used to measure irradiance and illuminance data, respectively. 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. Experimental data were measured with a sampling time of thirty seconds, with average values recorded every 10 minutes, from 1st October 2016 to 31st March 2018, in order to determine the luminous efficacy models. The same experimental procedure was followed from 1st April 2018 to 31st May, in order to measure the data for testing the models. The experimental thirty-second values of E_{gh}, E_{bh}, E_{dh}, and L_{gh}, L_{bh}, L_{dh} were properly analysed and filtered using traditional quality criteria [12],[13]. Whenever a thirty-second data item failed to match the quality criteria, the values were eliminated. Figure 2 shows the experimental values of horizontal global illuminance, L_{gh} (lux) versus horizontal global irradiance, E_{gh} (W/m^2) measured in Burgos.

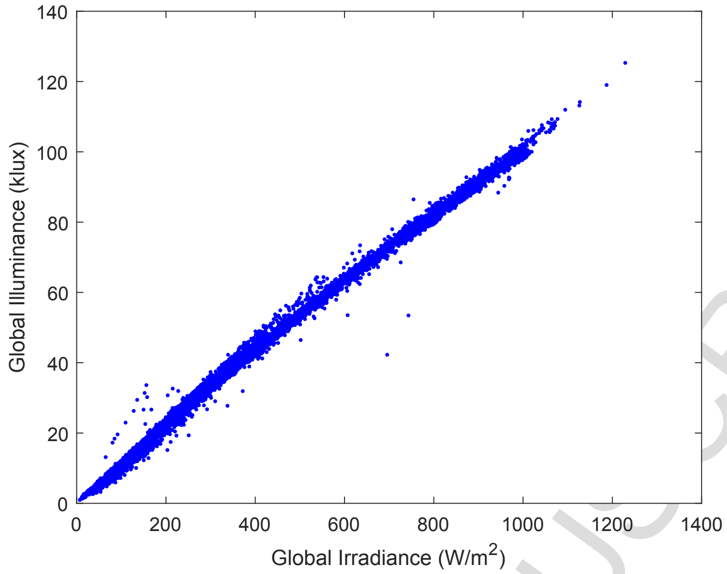

Figure 2: Measured global illuminance vs measured global irradiance on horizontal surfaces, Burgos, (Spain).

3. Global luminous efficacy models on horizontal surfaces

The global luminous efficacy values (K_g) were obtained by simultaneously measuring both illuminance and irradiance on a specified surface and then computing their ratio, as shown in Equation (1):

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

where, L_{gh} is the global horizontal illuminance (lux) value and E_{gh} is the horizontal global irradiance (W/m^2) value. Alternatively, both the illuminance and the irradiance of particular sky elements can be measured to calculate the luminous efficacy. It is a convenient quantity for the calculation of daylight availability and lighting energy use in buildings. It enables daylight data to be generated from the more widely measured solar irradiance data for places where measured outdoor illuminance data are not recorded.

As previously mentioned, eighteen models of global horizontal luminous efficacy that cover different sky types will be reviewed in the following sections. Luminous efficacy models can be classified according to the number and type of input variables needed for their calculation: there are models of constant luminous efficacy, while others depend exclusively on solar altitude and others depend on more climatic variables. In some cases, the luminous efficacy model has a different form depending on the characteristics of the sky (clear, intermediate or overcast), while other models are applied to all types of sky. In the following paragraphs, the models used in this work are described. The models under review are presented in two ways: using the original coefficients given by their authors and adapted to local conditions. The previously described experimental data were used to calculate the local coefficients of the models. The non-linear Least Squares method was employed using the Matlab^{TM} 2017 fit function.

3.1. Perez et al. model (1990)

One widely used model of luminous efficacy is the Perez model [8]. Applied at different locations around the world, it has consistently provided good illuminance prediction values. Diffuse, global and beam luminous efficacy can be modelled using the Perez model for all kind of skies. Equation (2) allows the calculation of global luminous efficacy from radiance and the type of sky. These models were developed from illuminance data gathered at ten United States locations and three European cities covering different climatic conditions, from high altitude desert to temperate oceanic, oceanic and subtropical climates [8].

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

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, are presented in Table 1(b). W is the atmospheric precipitable water content, defined by Equation (3). Z is the solar zenith angle, and Δ is the sky's brightness as shown in Equation (4) [8].

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

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

The sky's clearness parameter allows the classification of the sky, as in Equation (5):

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

where, k=1.041 for Z in radians.

Table 1: Perez Model (1990)

			a) Original global luminous efficacy coefficients				**b) Local global 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	96.63	-0.47	11.50	-9.16	109.53	0.04	-4.10	-3.14
2	1.065	1.230	107.54	0.79	1.79	-1.19	111.34	-0.63	-5.79	-2.00
3	1.230	1.500	98.73	0.70	4.40	-6.95	109.13	0.42	-5.68	-0.72
4	1.500	1.950	92.72	0.56	8.36	-8.31	103.61	0.57	2.39	1.09
5	1.950	2.800	86.73	0.98	7.10	-10.94	101.73	0.87	7.55	3.64
6	2.800	4.500	88.34	1.39	6.06	-7.60	116.20	0.61	11.61	11.03
7	4.500	6.200	78.63	1.47	4.93	-11.37	113.23	0.23	0.83	4.98
8	6.200	---	99.65	1.86	-4.46	-3.15	110.20	0.16	-17.50	-1.69

3.2. The Chung model (1992)

The Chung model [14] describes the luminous efficacy from the solar altitude, α, for the case of clear sky. This model was tested in the city of Hong Kong. In models for partly cloudy sky and overcast sky, the sky conditions are included in the models through the sky ratio of cloud ratio parameter, D, defined as the ratio of horizontal diffuse irradiance to horizontal global irradiance. The cloud ratio classifies the sky conditions as clear (D<0.3), partly cloudy (0.3<D<0.8) and overcast (D>0.8), and it gives different expressions for K_g calculations. These expressions and the corresponding adaptation of the model to the city of Burgos are shown in Table 2.

Table 2: Chung model equations for the calculation of luminous efficacy, K_g (lm/W), and for the different conditions of the sky. The original coefficients were calculated from experimental data recorded in Hong Kong. The locally adapted coefficients were calculated from the experimental data measured in Burgos, Spain.

Clear sky	*Original model*	$K_g = 102.2 + 0.69\alpha - 0.0059\alpha^2\ (lm/W)$	(6)
	Locally adapted model	$K_g = 95.106 + 22.493\alpha - 16.129\alpha^2\ (lm/W)$	(7)
Overcast sky	*Original model*	$K_g = \left(102.2 + 0.67\alpha - 0.0059\alpha^2\right) * \left(1.18 - 8.7 * 10^{-4}\Omega + 9.3 * 10^{-7}\Omega^2\right)\ (lm/W)$	(8)
	Locally adapted model	$K_g = \left(101.958 + 7.144\alpha - 7.387\alpha^2\right) * \left(1.135 - 2.32 * 10^{-4}\Omega + 1.77 * 10^{-7}\Omega^2\right)\ (lm/W)$	(9)
Partly cloudy sky	*Original model*	$K_g = D(135.3 - 25.7D) + \left(48.5 + 1.67\alpha - 0.0098\alpha^2\right)(1 - D)\ (lm/W)$	(10)
	Locally adapted model	$K_g = \mathrm{D}(104.118 + 8.894\mathrm{D}) + \left(83.401 + 56.696\alpha - 40.159\alpha^2\right)(1 - \mathrm{D})\ (\mathrm{lm}/W)$	(11)

In Table 2, $\Omega = E_{gh}/\sin\alpha$ shows the relative heaviness of overcast sky conditions and it represents the solar energy that passes though the cloud.

3.3. Lam and Li model (1996)

The clearness index, K_t, is obtained from Equation (12) and is defined as the ratio of the global radiation at ground level on a horizontal surface and the extra-terrestrial global solar irradiation [15]. This is the main parameter of this model, also tested in the city of Hong Kong [16].

$$K_t = \frac{E_{gh}}{I_0 \sin\alpha} \tag{12}$$

$$I_0 = I_{sc} E_0 \tag{13}$$

The clearness index classifies the sky as: clear sky (K_t>0.65), partly cloudy sky (0.3<K_t≤0.65) and overcast sky (0< K_t≤0.3). Following this classification, K_g is obtained through the mathematical expressions shown in Table 3. The local adaptation of the model to the city of Burgos is also presented in Table 3.

Table 3: Lam and Li and model equations for luminous efficacy calculations, K_g (lm/W), and for the different conditions of the sky. The original coefficients were calculated from experimental data recorded in Hong Kong. The locally adapted coefficients were calculated from the experimental data measured in Burgos, Spain.

Clear sky	*Original model*	$K_g = (59.15 + 1.12\alpha - 0.0061\alpha^2)(1-D) + 130.6\,D\ (lm/W)$	(14)
	Locally adapted model	$K_g = (118.752\ - 0.513\alpha + 0.003\ \alpha^2)(1-D) + 108.837\,D\ (lm/W)$	(15)
Overcast sky	*Original model*	$K_g = 116.2\ lm/W$	(16)
	Locally adapted model	$K_g = 111.744\ \ lm/W$	(17)
Partly cloudy sky	*Original model*	$K_g = (59.15 + 1.12\alpha - 0.0061\alpha^2)(1-D) + (130.6 - 14.4C)D\ (lm/W)$	(18)
	Locally adapted model	$K_g = (62.240 + 2.436\alpha - 0.031\alpha^2)(1-D) + (111.693 - 0.973C)D\ (lm/W)$	(19)

3.4. Muneer and Kinghorn model (1998)

Muneer and Kinghorn [17] proposed a model of K_g valid for all sky conditions that was tested in five different locations of UK. This polynomial model has the clearness index K_t, as an input parameter. The original expressions and the local adaptation of the model to the city of Burgos are presented in Table 4.

Table 4: Muneer and Kinghorn model equations for luminous efficacy calculations, K_g (lm/W). The original coefficients were calculated with data from five different UK locations. The locally adapted coefficients were calculated with the experimental data measured in Burgos, Spain.

All sky model	*Original model*	$K_g = 136.6 - 74.541K_t + 57.3421K_t^2\,(lm/W)$	(20)
	Locally adapted model	$K_g = 112.952 - 5.809K_t - 9.487K_t^2\,\,(lm/W)$	(21)

3.5. Robledo and Soler model (2000)

Two different models of luminous efficacy, A and B for clear sky conditions were proposed by Robledo and Soler [18] using experimental data of illuminance and irradiance measured in Madrid, Spain. The clear sky condition was determined through sky brightness (Δ<0.12) and sky clearness (ε>5.0). Both parameters were previously defined by Equation (4) and Equation (5). Table 5 shows the mathematical expressions of these models and their local adaptation to the city of Burgos.

Table 5: Robledo and Soler model equations for luminous efficacy calculations, K_g (lm/W). The original coefficients were calculated from experimental data recorded in Madrid, Spain. The locally adapted coefficients were calculated from the experimental data measured in Burgos, Spain.

All sky model A	*Original model*	$K_g = 100.97 + 0.32\alpha - 0.000019\alpha^3 + 6.6257 * 10^{-9}\alpha^5\,(lm/W)$	(22)
	Locally adapted model	$K_g = 99.854 + 15.570\alpha - 24.505\alpha^3 + 9.459\alpha^5\,(lm/W)$	(23)
All sky model B	*Original model*	$K_g = 129.46(sin\alpha)^{0.122}e^{-0.0029\alpha}\,(lm/W)$	(24)
	Locally adapted model	$K_g = 115.827\,(sin\alpha)^{0.048}e^{-0.132\alpha}\,(lm/W)$	(25)

3.6. Ruiz et al. model (2001)

This all sky model for luminous efficacy has the solar altitude, α, and the clearness index (K_t) as its input parameters. It was proposed by Ruiz et al. [19]

for the city of Madrid, Spain. The equation of the model and its adaptation to the local conditions of Burgos are presented in Table 6.

Table 6: Ruiz et al. model equations for luminous efficacy calculations, K_g (lm/W). The original coefficients were calculated from experimental data recorded in Madrid, Spain. The locally adapted coefficients were calculated from the experimental data measured in Burgos, Spain.

All sky model	*Original model*	$K_g = 104.83(sin\alpha)^{0.026}K_t^{-0.108}\ (lm/W)$	(26)
	Locally adapted model	$K_g = 101.086\ (sin\alpha)^{-0.021}K_t^{-0.060}\ (lm/W)$	(27)

3.7. Robledo et al. model (2001)

Robledo et al. [20] proposed two different models of global luminous efficacy for overcast skies (Models A and B) and a third for partly cloudy skies. The sky classifications were established from the sky clearness parameter (ε) defined previously by Equation (5). The overcast sky condition was (ε<1.2) and the partly cloudy sky condition was (1.2<ε<5.0). The solar altitude (α) and sky brightness (Δ), which is defined by Equation (4), were the input parameters of the models the mathematical expressions of which and their adaptation to the local conditions are shown in Table 7.

Table 7: Robledo et al. model equations for luminous efficacy calculations, K_g (lm/W). The original coefficients were calculated from experimental data recorded in Madrid, Spain. The locally adapted coefficients were calculated from the experimental data measured in Burgos, Spain.

Overcast Sky model A	*Original model*	$K_g = [129.46(sin\alpha)^{0.122}e^{-0.0029\alpha}] * (1.361 - 1.091\Delta + 1.0334\Delta^2)\ (lm/W)$	(28)
	Locally adapted model	$K_g = [115.905\ (sin\alpha)^{0.055}e^{-116\ \alpha}] * (1.128 - 0.418\Delta + 0.531\Delta^2)\ (lm/W)$	(29)
Overcast Sky model B	*Original model*	$K_g = 128.16(sin\alpha)^{0.122}e^{-0.0029\alpha}\Delta^{-0.105}\ (lm/W)$	(30)
	Locally adapted model	$K_g = 117.070\ (sin\alpha)^{-0.041}e^{-0.104\ \alpha}\Delta^{-0.022}\ (lm/W)$	(31)

Partly cloudy sky	*Original model*	$K_g = 120.26(sin\alpha)^{0.077} e^{-0.0019\alpha} \Delta^{0.002}\ (lm/W)$	(32)
	Locally adapted model	$K_g = 138.173(sin\alpha)^{0.137} e^{-0.234\alpha} \Delta^{0.022}(lm/W)$	(33)

3.8. De Souza et al. model (2006)

De Souza et al. [9] proposed a clear sky model of luminous efficacy for Florianopolis, Brazil. The clear sky condition was defined by (Δ<0.12 and $\varepsilon \geq 5.0$), where parameters Δ and ε are defined by Equation (4) and Equation (5), respectively. Table 8 collects the original form of the model and the form of its local adaption to the city of Burgos.

Table 8: De Souza et al. model equations for luminous efficacy calculations, K_g (lm/W). The original coefficients were calculated from experimental data recorded in Florianopolis, Brazil. The locally adapted coefficients were calculated from the experimental data measured in Burgos, Spain.

Clear sky model	*Original model*	$K_g = 99.10 + 0.927\alpha - 0.0298\alpha^2 + 0.000422\alpha^3 - 2.2 * 10^{-6}\alpha^4\ (lm/W)$	(34)
	Locally adapted model	$K_g = 101.104\ - 1.700\alpha + 1.362\alpha^2 - 0.294\alpha^3 - 0.241\alpha^4(lm/W)$	(35)

3.9. Fakra et al. model (2011)

Fakra et al. [21] established an all sky type luminous efficacy model for Saint-Pierre (Reunion Island) based on a constant form. This model and its adaptation to the local conditions of Burgos are shown in Table 9.

Table 9: Fakra et al. model equations for luminous efficacy calculations, K_g (lm/W). The original coefficients were calculated from experimental data recorded at Saint-Pierre, Reunion Island. The locally adapted coefficients were calculated from the experimental data measured in Burgos, Spain.

All sky model	*Original model*	$K_g = 121.5\ lm/W$	(36)
	Locally adapted model	$K_g = 103.428\ lm/W$	(37)

3.10. Mahdavi and Dervishi model (2011)

Clearness index (K_t), and the outdoor air temperature (t) are the input parameters used by Mahdavi and Dervishi [22] to calculate the global luminous efficacy in Vienna, Austria, for all sky types, as shown in Table 10, joined to the local adaptation for the city of Burgos.

Table 10: Mahdavi and Dervishi model equations for luminous efficacy calculations, K_g (lm/W). The original coefficients were calculated from experimental data recorded at Vienna, Austria. The locally adapted coefficients were calculated from the experimental data measured in Burgos, Spain.

All sky model	*Original model*	$K_g = 140.9 + 0.273t - 102K_t + 0.60t * K_t - 0.001t^2 + 77.28K_t^2\ (lm/W)$	(38)
	Locally adapted model	$K_g = 112.554 + 0.139\ t - 5.331K_t - 0.040\ t * K_t - 0.008t^2 - 7.140K_t^2\ \ (lm/W)$	(39)

3.11. Chaiwiwatworakul and Chirarattananon model (2013)

Global and diffuse luminous efficacy were evaluated by Chaiwiwatworakul and Chirarattananon [4] at Bangkok, Thailand. The Perez clearness index (ε) and zenith angle (Z) were used as input parameters for the all sky type model as shown in Table 13. In Table 11, the local adaptation of this model is also shown.

Table 11: Mahdavi and Dervishi model equations for luminous efficacy calculations, K_g (lm/W). The original coefficients were calculated from experimental data recorded at Bangkok, Thailand. The locally adapted coefficients were calculated from the experimental data measured in Burgos, Spain.

All sky model	*Original model*	$K_g = \left(101.65 + 13.92\varepsilon^{-3.49}\right)(cosZ)^{\left(-0.18 + 0.19\varepsilon^{-1.25}\right)}\ (lm/W)$	(40)
	Locally adapted model	$K_g = \left(101.076 + 7.898\varepsilon^{-2.181}\right)(cosZ)^{\left(-8.475 + 8.453\varepsilon^{-0.002}\right)}\ \ (lm/W)$	(41)

A summary of the main features of the models reviewed and the parameters used by each of them is shown in Table 12.

Table 12: Summary of the global luminous efficacy models reviewed in this work. Literature reference of the original model, year, Sky type classification, input parameters used in the models and the original place of development of the model.

Ref.	**Year**	**Authors**	**Sky types**	**Model parameters**	**Location**
[8]	1990	Perez et al.	All	Δ, Z, W	USA and Europe
[14]	1992	Chung	Clear	α	China
			Overcast	α, Ω	
			Partly	α, D	
[16]	1996	Lam and Li	Clear	α, D	China
			Overcast	116.2 lmW^{-1}	
			Partly	α, C, D	
[17]	1998	Muneer and Kinghorn	All	K_t	UK
[18]	2000	Robledo and Soler (Model A) and Robledo and Soler (Model B)	Clear	α	Spain
[19]	2001	Ruiz et al.	All	α, K_t	Spain
[20]	2001	Robledo et al.	Partly	α, Δ	Spain
		Robledo et al. (Model A) and Robledo et al. (Model B)	Overcast		
[9]	2006	De Souza et al.	Clear	α	Brazil
[21]	2011	Fakra et al.	All	121.5 lmW^{-1}	Reunion Island
[22]	2011	Mahdavi and Dervishi	All	K_t, t	Austria
[4]	2013	Chaiwiwatworakul and Chirarattananon	All	Z, ε	Thailand

4. Evaluation of the global 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) [21],[23]. MBE shows the trend of the model to either over-estimate or under-estimate the data. RMSE provides a measure of the deviation between the predicted values using the fitted models and the experimental measurements. Equations (42) and (43) show the statistical estimators employed in the present study.

$$MBE\ (\%) = 100\frac{\sum_{n}(X_{model} - X_{measured})}{\sum_{n} X_{measured}} \tag{42}$$

$$RMSE\ (\%) = 100\frac{\sqrt{\frac{\sum_{n}\left(X_{model} - X_{measured}\right)^{2}}{n}}}{\sum_{n}\frac{X_{measured}}{n}} \tag{43}$$

Table 13-Table 16 present the results obtained following the application of the statistical estimators shown by Equation (42) and (43) to the models analysed in this study. Table 13 shows the results obtained for the case of all sky conditions (six models). It can be observed that, when local coefficients were used, the model with the lowest RMSE was that of Chaiwiwatworakul and Chirarattananon [4] (3.61 %) followed by the Mahdavi and Dervishi model [22] (3.65 %) and the Perez model [8] (3.68 %).

Table 13: Evaluation of the global luminous efficacy models for all skies

Model	Original coefficients		Local coefficients	
	MBE (%)	RMSE (%)	MBE (%)	RMSE (%)
Chaiwiwatworakul and Chirarattananon	3.18	5.34	-0.41	3.61
Mahdavi and Dervishi	15.36	24.14	-0.20	3.65
Perez et al.	6.03	11.97	0.15	3.68
Ruiz et al.	4.16	6.99	-0.17	3.81
Muneer and Kinghorn	8.62	12.89	-0.28	3.86
Fakra et al.	15.11	21.24	-2.01	5.11

Table 14 shows the results obtained for the case of a clear sky (five models). The models with the lowest RMSE values, when local coefficients were employed, were those of Robledo and Soler [18] (1.86 %) followed by the model of Lam and Li [16] (2.02 %).

Table 14: Evaluation of the global luminous efficacy models for clear skies

Model	Original coefficients		Local coefficients	
	MBE (%)	RMSE (%)	MBE (%)	RMSE (%)
Robledo and Soler (Model A)	0.00	2.26	-0.06	1.86
Robledo and Soler (Model B)	23.94	24.98	-0.11	1.86
Lam and Li	6.28	8.59	0.02	2.02

Chung	1.29	2.76	-0.15	2.08
De Souza et al.	-1.31	2.57	-1.00	2.34

Table 15 shows the results obtained for the case of partly cloudy skies (three models). When local coefficients were used, the model with the lowest RMSE value was that of Robledo et al. [20] (3.07 %), followed by the model of Chung [14] (3.38 %).

Table 15: Evaluation of the global luminous efficacy models for partly cloudy skies

Model	Original coefficients		Local coefficients	
	MBE (%)	RMSE (%)	MBE (%)	RMSE (%)
Robledo et al.	12.10	16.63	-0.01	3.07
Chung	-15.79	20.89	-0.28	3.38
Lam and Li	6.15	10.19	0.19	4.43

Finally, Table 16 shows the results obtained for the case of overcast sky conditions (four models). It can be noted that when using local coefficients, the models with the lowest RMSE values were those of Robledo et al. (Model A) [20] (4.27 %) and Robledo et al. (Model B) [20] (4.35 %).

Table 16: Evaluation of the global luminous efficacy models for overcast skies

Model	Original coefficients		Local coefficients	
	MBE (%)	RMSE (%)	MBE (%)	RMSE (%)
Robledo et al. (Model A)	22.04	29.46	-0.74	4.27
Robledo et al. (Model B)	21.48	29.09	-0.84	4.35
Chung	-6.15	10.49	-0.78	4.60
Lam and Li	3.93	8.44	-0.06	7.09

As was expected *a priori*, it can be affirmed from the results in Table 13-Table 16 that the models fitted with data from local measurements provided lower RMSE values than those obtained when using original coefficients.

5. Proposal of a new model to predict global luminous efficacy

In this Section, the proposed model to predict global luminous efficacy on horizontal surfaces is presented. Several models were analysed for modelling global luminous efficacy as a function of both the clearness index (K_t) and the solar altitude (α). From these results, the function that had the best fit was found to be the model shown in Equation (44). The advantage of the two parameters that this new model uses as its independent variables is that they are easily obtained. The model was firstly proposed for all sky conditions, yielding lower RMSE than any of the models shown in Table 13. Likewise, this new model also yielded lower RMSE values than the lowest ones shown in Table 14 (clear sky), Table 15 (partly cloudy sky) and Table 16 (overcast sky conditions). Therefore, as will be shown afterwards, this model can be generally applied either for all sky conditions or for other particular sky conditions.

$$K_g = p_0 * e^{p_1 * K_t * sin(p_2 * \alpha^2)} \quad (lm/W) \tag{44}$$

Figure 3 represents the experimental global luminous efficacy, $K_g\,(lm/W)$, versus the clearness index (K_t) and Figure 4 shows the experimental global luminous efficacy, $K_g\,(lm/W)$ versus the solar altitude (α).

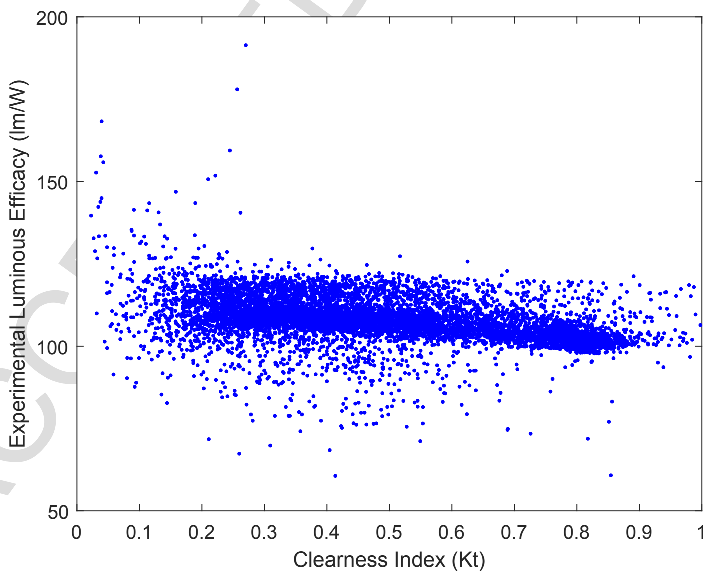

Figure 3: Experimental luminous efficacy vs clearness index at Burgos

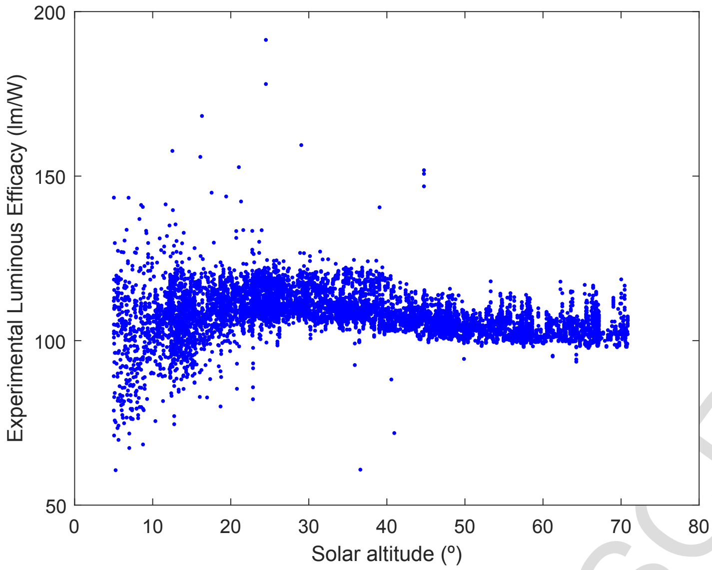

Figure 4: Experimental luminous efficacy vs solar altitude at Burgos

5.1. All sky conditions

The model fitted with experimental data measured in the city of Burgos is shown in Equation (45).

$$K_g = 111.616 * e^{-0.127 * K_t * sin(1.232 * \alpha^2)} \quad (lm/W) \tag{45}$$

The model shown in Equation (45) yielded an RMSE = 3.27 % and an MBE = -0.19% for all sky conditions. This RMSE value was lower than any of the six RMSE values obtained with the models shown in Table 13. As can be observed in Table 13 and in Table 17, the lowest RMSE value was provided by Chaiwiwatworakul and Chirarattananon [4] (RMSE = 3.61 %), higher than that obtained with the proposed model. Therefore, it can be affirmed that the proposed model was capable of predicting the global illuminance for all sky conditions more accurately than the other models analysed in Table 13, for local data measured in Burgos.

Table 17: Comparison between the best performing model for all sky and the proposed model

Model	Local coefficients	
	MBE (%)	RMSE (%)
Proposed model, All sky (p0 = 111.616; p1 = -0.127; p2 = 1.232)	-0.19	3.27

Chaiwiwatworakul and Chirarattananon	-0.41	3.61

Figure 5 shows the estimated global illuminance with the proposed model vs the measured global illuminance for all sky conditions. As can be observed in this figure, the proposed model acceptably predicted the global illuminance values for all sky conditions.

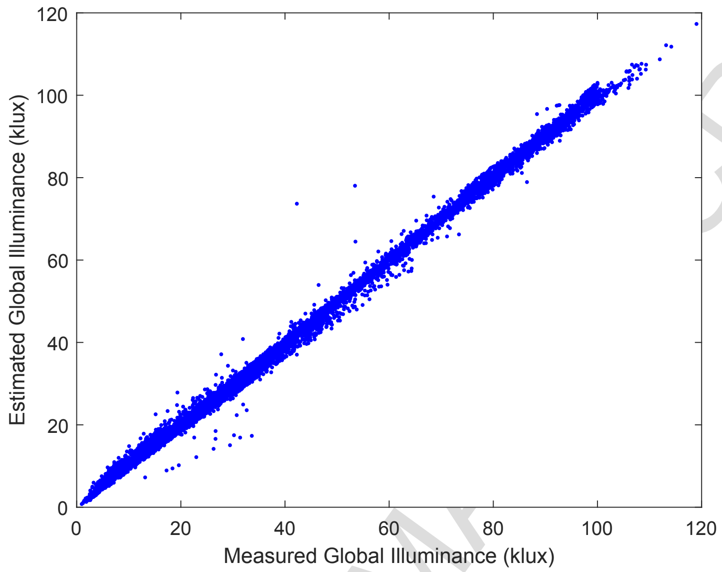

Figure 5: Estimated global illuminance with the proposed model vs measured global illuminance for all sky conditions

5.2. Clear sky

Equation (46) shows the proposed model, adapted for the particular case of clear sky which is defined by (ε>5.0 and Δ<0.12). These conditions are employed by the Robledo and Soler models [18] that have the lowest RSME values of all the models shown in Table 14. The new proposed model yielded an MBE=-0.03 % and an RMSE=1.80 %. As can be observed, the RMSE was slightly lower than the one obtained with the models of Robledo and Soler [18] (1.86 %). Moreover, as can be observed in Table 18, the proposed model in Equation (45), locally fitted for all sky conditions, showed a similar RMSE value to the previous ones.

$$K_g = 108.591 * e^{-0.111 * K_t * sin\left(1.031 * \alpha^2\right)} \quad (lm/W) \tag{46}$$

Table 18: Comparative between the best performing model for clear sky and the proposed model, using the same sky conditions ε>5.0 and Δ<0.12

Model	Local coefficients	
	MBE (%)	RMSE (%)
Proposed model, Clear sky (p0 = 108.591; p1 = -0.111; p2 = 1.031)	-0.03	1.80
Robledo and Soler (Model A)	-0.06	1.86
Robledo and Soler (Model B)	-0.11	1.86
Proposed model, All sky (p0 = 111.616; p1 = -0.127; p2 = 1.232)	0.88	2.01

Figure 6 shows the estimated global illuminance with the proposed model versus the measured global illuminance for clear sky conditions (given by ε>5.0 and Δ<0.12). As can be observed, the proposed model adequately predicted the global illuminance in the case of clear sky conditions.

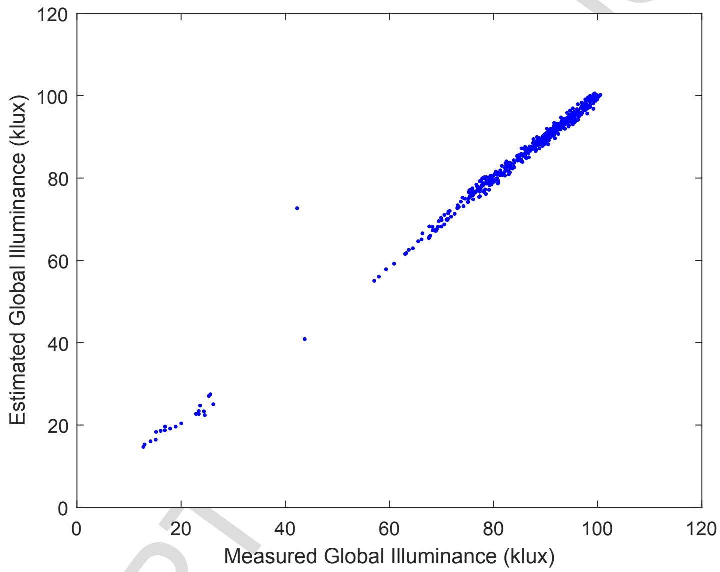

Figure 6: Estimated global illuminance with the proposed model vs measured global illuminance for clear sky conditions given by ε>5.0 and Δ<0.12

5.3. Partly cloudy sky

Equation (47) shows the proposed model, adapted for the particular case of partly cloudy sky conditions defined by (1.20<ε<5.0). These conditions were employed by model of Robledo et al. [20], which is the model with the lowest RSME value of all the models shown in Table 15. The new model shown in Equation (47) yielded an RMSE of 2.89 %, slightly lower than the value (3.07%) obtained with the model of Robledo et al. [20]. As observed in Table 19, the new model, locally fitted for all sky, as shown in Equation (45), yielded a lower RMSE value than the previous ones.

$$K_g = 109.152 * e^{-0.100 * K_t * sin(1.013 * \alpha^2)} \quad (lm/W) \tag{47}$$

Table 19: Comparison between the best performing model for partly cloudy sky and the proposed model, using the same sky conditions (1.20<ε<5.0)

Model	Local coefficients	
	MBE (%)	RMSE (%)
Proposed model, All sky (p0 = 111.616; p1 = -0.127; p2 = 1.232)	0.31	2.84
Proposed model, Partly cloudy sky (p0=109.152; p1=-0.100; p2=1.013)	0.04	2.89
Robledo et al.	-0.01	3.07

Figure 7 shows the estimated global illuminance with the proposed model versus measured global illuminance for partly cloudy sky conditions. As can be observed, the proposed model acceptably predicted global illuminance values for partly cloudy sky conditions defined from (1.20<ε<5.0).

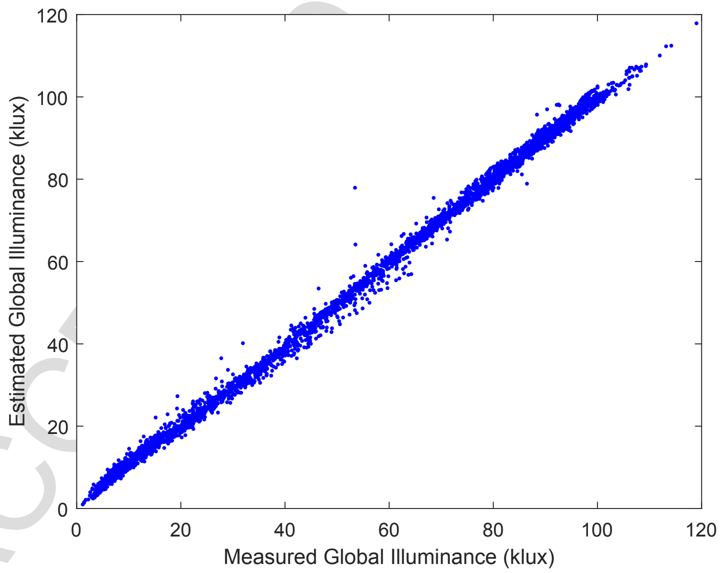

Figure 7: Estimated global illuminance with the proposed model vs measured global illuminance for partly cloudy sky conditions (1.20<ε<5.0)

5.4. Overcast sky conditions

Equation (48) shows the proposed model, adapted for the particular case of overcast sky defined by (ε<1.2). This condition is employed by Robledo et al. (Model A) [20], which has the lowest RSME value of all the models shown in Table 16. The new model shown in Equation (48) yielded an RMSE of 4.22 %, a slightly lower value than the one obtained with Model A (Robledo et al.) [20]. On the other hand, as can be observed in Table 20, the new model, locally fitted for all sky, which is shown by Equation (45), yielded an RMSE value similar to the previous ones.

$$K_g = 111.693 * e^{-0.103 * K_t * sin(1.241 * \alpha^2)} \quad (lm/W) \tag{48}$$

Table 20. Comparison between the best performing model for overcast skies and the proposed model, using the same sky conditions (Overcast skies: ε<1.2)

Model	Local coefficients	
	MBE (%)	RMSE (%)
Proposed model, Overcast sky (p0 = 111.693; p1 = -0.103; p2 = 1.241)	-0.81	4.22
Robledo et al. (Model A)	-0.74	4.27
Proposed model, All sky (p0 = 111.616; p1= -0.127; p2 = 1.232)	-1.37	4.40

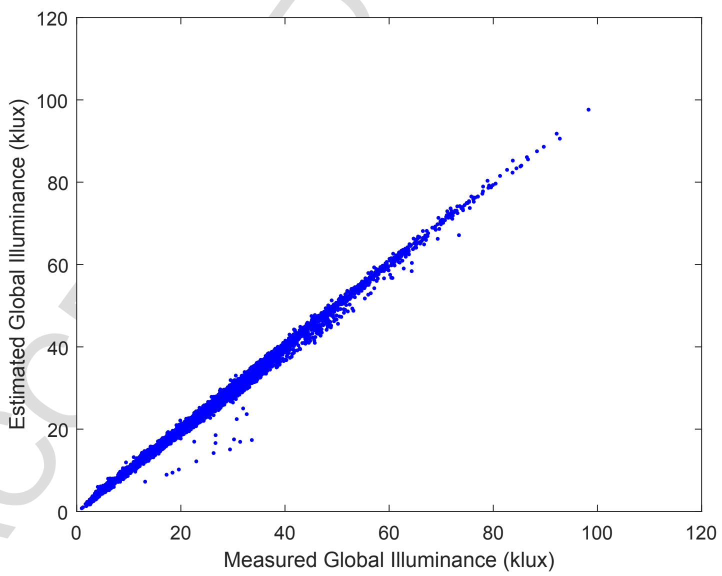

Figure 8: Estimated global illuminance with the proposed model vs measured global illuminance for overcast sky (ε<1.2)

Figure 8 shows estimated global illuminance with the proposed model versus measured global illuminance for overcast sky conditions. As can be observed, the proposed model acceptably predicts the global illuminance values for overcast sky conditions.

In this section, the new proposed model has been presented and analysed. It has been demonstrated that this new model yielded lower RMSE values than all the eighteen classic models considered in this study. These values have been verified both for all sky conditions and for particular (clear, partly cloudy and overcast sky) conditions. Moreover, as can be observed in Table 18-Table 20, the new model proposed for all sky conditions, which is shown in Equation (45), also provided values close to those obtained with models adapted for particular sky conditions (clear, partly and overcast).

6. Validation of the global illuminance models.

In Section three, global luminous efficacy models from eighteen existing models in the literature were fitted by using local data from Burgos (Spain) and the models were then evaluated in Section four. Moreover, the results of fitting and analysing a new model for all sky and for particular sky conditions, using the same data as the previous mentioned models, has been presented above in Section 5. In the present Section, validation of all these models is shown by employing two additional months of measurements (from 1st April 2018 to 31st May 2018). These measurements were taken, following the procedure shown in Section 2. Figure 9 shows the experimental data employed for testing the global luminous efficacy models. This figure compares measured global illuminance versus measured global irradiance on the horizontal surface at Burgos over the test period.

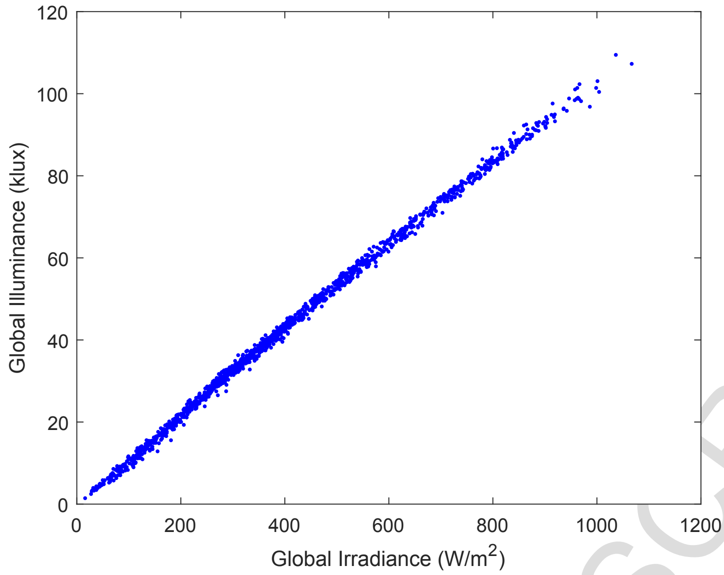

Figure 9: Measured global illuminance vs measured global irradiance on the horizontal surface at Burgos. Test data (01/04/18-31/05/18)

Data obtained from these two additional months were used to re-evaluate both RMSE and MBE in the models that had previously been fitted with experimental data (local models). Table 21-Table 24 show the results obtained after evaluating the statistical estimators shown in Equation (42) and in Equation (43) taken from the luminous efficacy models that have been analysed in this study. The results obtained from the different sky conditions under study are also shown. To that end, particular sky conditions proposed by each author were applied, in order to define different sky types (clear sky, partly cloudy sky and overcast sky). The new model proposed in this study was also validated in both all sky and particular sky conditions (clear, partly cloudy and overcast). In the latter case, the conditions employed by the model with the lowest RMSE value were used in order to define the sky type.

Table 21 shows the results obtained with the testing data for the case of all sky conditions (seven models). The model of Ruiz et al. [19] (2.57%) was slightly lower than the new proposed model (2.66 %). However, the MBE obtained with the proposed model (-0.01 %) was ten times lower than the one obtained with the previous model (-0.1 %).

Table 21: Validation of the global luminous efficacy models for all skies

Model	Local coefficients	
	MBE (%)	RMSE (%)
Ruiz et al.	-0.10	2.57
Proposed model. Equation (45)	-0.01	2.66
Chaiwiwatworakul and Chirarattananon	1.23	2.81
Mahdavi and Dervishi	0.94	2.94
Perez et al.	1.31	2.98
Muneer and Kinghorn	0.36	3.22
Fakra et al.	-2.52	3.64

The results obtained from classic clear sky models (five models) and the proposed model are shown in Table 22. In addition, the results obtained when the all sky model, given by Equation (45), was validated for this particular sky type are also compared. It is shown that the new model proposed in this study yielded the lowest RMSE values, both after validation with the all sky model coefficients (0.66 %) and with the coefficients fitted with data from clear sky conditions (1.40 %), followed by Robledo and Soler (Model A) [18] (1.53 %).

Table 22: Validation of the global luminous efficacy models for clear skies

Model	Local coefficients	
	MBE (%)	RMSE (%)
Proposed model (All sky). Equation (45).	-0.26	0.66
Proposed model (Clear sky). Equation (46).	-1.21	1.40
Robledo and Soler (Model A)	-1.25	1.53
Robledo and Soler (Model B)	-1.32	1.65
Lam and Li	-0.20	2.07
Chung	-1.84	2.30
De Souza et al.	-3.07	3.43

Likewise, Table 23 shows the results obtained for classic partly cloudy sky models (three models) and these three models are also compared with the new proposed models. It can be noted that models with the lowest RMSE values are those of Robledo et al. [20] (2.43 %) and the new model for partly cloudy sky (2.46 %) followed by the model of Chung [14] (2.67 %).

Table 23: Validation of the global luminous efficacy models for partly cloudy skies

Model	Local coefficients	
	MBE (%)	RMSE (%)
Robledo et al.	0.51	2.43
Proposed model (Partly sky). Equation (47)	-0.09	2.46
Chung	0.93	2.67
Proposed model (All sky). Equation (45).	0.27	2.80
Lam and Li	2.25	3.44

Finally, Table 24 shows the results obtained for the case of classic overcast sky models (four models) and these models are also compared with the new proposed models. It can be noted that the models proposed in this study yielded the lowest RMSE values when fitted with either overcast or with all sky conditions, followed by those of Robledo et al. (Model B) [20] (2.52 %) and Robledo et al. (Model A) [20] (2.65 %).

Table 24: Validation of the global luminous efficacy models for overcast skies

Model	Local coefficients	
	MBE (%)	RMSE (%)
Proposed model (Overcast sky). Equation (48).	0.65	2.30
Proposed model (All sky). Equation (45).	-0.21	2.48
Robledo et al. (Model B)	0.71	2.52
Robledo et al. (Model A)	0.86	2.65
Chung	1.27	2.76
Lam and Li	2.56	4.16

Table 21-Table 24 show the results obtained after validating the models with two additional measurements months. From these results, it can be observed that the proposed model, fitted for a specific sky condition, yield lower RMSE values for both overcast sky (Equation (48), 2.30 %) and clear sky (Equation (46), 1.40 %) than any of the analysed models. With regard to partly cloudy sky conditions, the RMSE obtained with the proposed model (Equation (47), 2.46 %) was approximately equal to that of Robledo et al. [20] (2.43 %), and the RMSE obtained with the proposed model (Equation (45), 2.66 %) for all sky conditions was slightly higher than that of the model of Ruiz et al. [19] (2.57 %).

It should be mentioned that the model fitted with all the data (all sky conditions), shown in Equation (45), can be generally applied for modelling particular sky types (clear, partly cloudy and overcast), because the RMSE values obtained after validating this model in these specific sky types were 0.66 %, 2.80 %, and 2.48 %, respectively.

7. Conclusions

Eighteen classic global luminous efficacy models, from the existing literature, have been evaluated, both with their original coefficients and locally fitted with experimental data measured in Burgos (Spain), between 1st October 2016 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 model to predict the global luminous efficacy on horizontal surfaces has been proposed and analysed in this study. This new model has been fitted for either all sky types or particular sky types (clear, partly cloudy and overcast). It employs the solar altitude and the clearness index (K_t) as independent variables, which have the advantage of being two easily obtained parameters.

It has been shown that with data employed for fitting the models over the period of study (01/10/16 to 31/03/18) in the city of Burgos (Spain), the new proposed model has provided lower RMSE values than any of the eighteen classic models analysed in this study, for either all sky or particular sky conditions (clear, partly cloudy and overcast). Moreover, this new model provides lower MBEs than most of the classical models analysed in this study. With regard to the results obtained with the validation data measured in the period (01/04/18 to 31/05/18), the proposed model has provided lower RMSE values for clear sky and overcast sky conditions than any of the classic models and it has provided similar RMSE values to those obtained with the models that presented the lowest RMSE values for all sky and partly cloudy sky conditions.

It can be affirmed from these results that the model fitted for all sky conditions, shown in Equation (45), can also be applied for modelling the global illuminance in all sky types and in particular sky conditions (clear sky, partly cloudy and overcast), with no need to employ different luminous efficacy models for each specific sky type.

As future work, the proposed model could be applied to data gathered in different locations, in order to compare the results and to determine its applicability to the modelling of horizontal global illuminance.

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References

1. Hwang, T. and T.K. Jeong, *Effects of indoor lighting on occupants' visual comfort and eye health in a green building.* Indoor and Built Environment, 2011. **20**(1): p. 75-90.
2. Ihm, P., A. Nemri, and M. Krarti, *Estimation of lighting energy savings from daylighting.* Building and Environment, 2009. **44**(3): p. 509-514.
3. Aalto University School of Science and Technology, I.E.A., *Guidebook on Energy Efficient Electric Lighting for Buildings. Raisio, IEA publications*, 2010.
4. Chaiwiwatworakul, P. and S. Chirarattananon, *Luminous efficacies of global and diffuse horizontal irradiances in a tropical region.* Renewable Energy, 2013. **53**: p. 148-158.
5. Littlefair, P.J., *The luminous efficacy of daylight: a review.* Lighting research & technology, 1985. **17**(4): p. 162-182.
6. Littlefair, P.J., *Measurements of the luminous efficacy of daylight.* Lighting research & technology, 1988. **20**(4): p. 177-188.
7. Vartiainen, E., *A comparison of luminous efficacy models with illuminance and irradiance measurements.* Renewable Energy, 2000. **20**(3): p. 265-277.
8. Perez, R., et al., *Modeling daylight availability and irradiance components from direct and global irradiance.* Solar Energy, 1990. **44**(5): p. 271-289.
9. de Souza, R.G., et al., *Evaluation of global luminous efficacy models for Florianópolis, Brazil.* Building and Environment, 2006. **41**(10): p. 1364-1371.
10. Patil, K.N., S.N. Garg, and S.C. Kaushik, *Luminous efficacy model validation and computation of solar illuminance for different climates of India.* Journal of Renewable and Sustainable Energy, 2013. **5**(6).
11. Azad, A.S., D. Rakshit, and K.N. Patil, *Model development and evaluation of global and diffuse luminous efficacy for humid sub-tropical region.* Renewable Energy, 2018. **119**: p. 375-387.
12. Gueymard, C.A. and J.A. Ruiz-Arias, *Extensive worldwide validation and climate sensitivity analysis of direct irradiance predictions from 1-min global irradiance.* Solar Energy, 2016. **128**: p. 1-30.
13. *CIE 108-1994. Technical Report: Guide to recommended practice of daylight measurement. Commission International de l'Éclairage. 1994.*

14. Chung, T.M., *A study of luminous efficacy of daylight in Hong Kong.* Energy and Buildings, 1992. **19**(1): p. 45-50.
15. Iqbal, M., *Introduction to solar radiation*. 1983: Academic Press.
16. Lam, J.C. and D.H.W. Li, *Luminous efficacy of daylight under different sky conditions.* Energy Conversion and Management, 1996. **37**(12): p. 1703-1711.
17. Muneer, T. and D. Kinghorn, *Luminous efficacy models - Evaluation against UK data.* Journal of the Illuminating Engineering Society, 1998. **27**(1): p. 163-169.
18. Robledo, L. and A. Soler, *Luminous efficacy of global solar radiation for clear skies.* Energy Conversion and Management, 2000. **41**(16): p. 1769-1779.
19. Ruiz, E., A. Soler, and L. Robledo, *Assessment of Muneer's luminous efficacy models in Madrid and a proposal for new models based on his approach.* Journal of Solar Energy Engineering, Transactions of the ASME, 2001. **123**(3): p. 220-224.
20. Robledo, L., A. Soler, and E. Ruiz, *Luminous efficacy of global solar radiation on a horizontal surface for overcast and intermediate skies.* Theoretical and Applied Climatology, 2001. **69**(1-2): p. 123-134.
21. Fakra, A.H., et al., *A simple evaluation of global and diffuse luminous efficacy for all sky conditions in tropical and humid climate.* Renewable Energy, 2011. **36**(1): p. 298-306.
22. Mahdavi, A. and S. Dervishi, *A comparison of luminous efficacy models based on data from Vienna, Austria.* Building Simulation, 2011. **4**(3): p. 183-188.
23. López, G. and C.A. Gueymard, *Clear-sky solar luminous efficacy determination using artificial neural networks.* Solar Energy, 2007. **81**(7): p. 929-939.

Highlights

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