Proposal and evaluation of Typical Illuminance Year (TIY) generation procedures from illuminance or irradiance data for daylight assessment in the long term

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Abstract

When assessing the long-term daylight availability or the performance of natural lighting systems in a given location, it is necessary to have representative data of local daylight conditions. The use of a daylight test reference year (TRY) becomes a good option in these cases. This paper proposes and evaluates a procedure for the generation of a typical illuminance year (TIY) considering illuminance as the only variable for selecting the typical periods that make up the reference year. Two versions of TIY are presented, one composed of 12 typical months selected from the series of observations and another composed of 365 typical days. Each of these versions is used to obtain a global illuminance TIY (TGIY) and a diffuse illuminance TIY (TDIY) from a 27-year dataset corresponding to the Vaulx-en-Velin station (France). Furthermore, 12 luminous efficacy models have been evaluated in order to obtain a TIY from a TRY generated from irradiance data when no illuminance data are available. Thus, a global luminous efficacy model and a diffuse model are selected after benchmarking different models, considering both their original coefficients and those adjusted to local conditions. The results reveal that the monthly version of the TGIY and the daily version of the TDIY show the best overall fit to the long-term dataset. TIYs obtained from illuminance data are also observed to be statistically indistinguishable from those obtained after applying a luminous efficacy model to an irradiance-based TRY.

Keywords

Typical Illuminance Year; Luminous efficacy models; Daylight

Nomenclature

$CDF_{i,\mathrm{mod}}$	cumulative distribution function of modeled illuminance.
$CDF_{i,\mathrm{obs}}$	cumulative distribution function of observed illuminance.
$CDF(y,d,i)$	long-term cumulative distribution function of the hourly means of illuminance of a day d.
$CDF(d,i)$	short-term cumulative distribution function of the hourly means of illuminance of a day d of a year y.
D	sky ratio or cloud ratio or diffuse fraction.
E_{ed}	diffuse horizontal irradiance (W·m^{-2}).
E_{eg}	global horizontal irradiance (W·m^{-2}).
E_{vd}	diffuse horizontal illuminance (lux).
E_{vg}	global horizontal illuminance (lux).
$\overline{E}_{v,d}$	mean value of daily illuminance of a day d of long-term data (lux).
$\overline{E}_{v,h}$	mean value of hourly illuminance of an hour h of long-term data (lux).
$\overline{E}_{v,m}$	mean value of monthly illuminance of a month m of long-term data (lux).
$E_{v,t}$	yearly illuminance of a typical illuminance year t (lux).
$E_{v,td}$	daily illuminance of a day d and a typical illuminance year t (lux).
$E_{v,th}$	hourly illuminance of an hour h and a typical illuminance year t (lux).
$E_{v,tm}$	monthly illuminance of a month m and a typical illuminance year t (lux).
$E_{v,y}$	yearly illuminance of a year y (lux).
$E_{v,yd}$	daily illuminance of a day d and a year y (lux).
$E_{v,yh}$	hourly illuminance of an hour h and a year y (lux).
$E_{v,ym}$	monthly illuminance of a month m and a year y (lux).
$E_{v,i,mod}$	modeled horizontal illuminance (lux).

$\bar{E}_{v,mod}$	mean modeled horizontal illuminance (lux).
$E_{v,i,obs}$	observed horizontal illuminance (lux).
$\bar{E}_{v,obs}$	mean observed horizontal illuminance (lux).
j	number of years of the historic data series.
K_d	diffuse luminous efficacy (lm·W^{-1}).
K_g	global luminous efficacy (lm·W^{-1}).
K_t	clearness index.
m	relative optical air mass.
n	number of global or diffuse horizontal illuminance values considered.
t	air dry-bulb temperature (K).
SEE_m	standard error of estimates on monthly illuminance of a month m (lux).
SEE_d	standard error of estimates on daily illuminance of a day d (lux).
SEE_h	standard error of estimates on hourly illuminance of an hour h (lux).
W	atmospheric precipitable water content (cm).
Z	zenith angle of the sun (radians).
α	angle of elevation of the sun above the horizon (radians).
ε	sky clearness.
Δ	sky brightness.
$\sigma_{\bar{E}_{v,m}}$	standard deviation of simple means of monthly illuminance of a month m (lux).
Ω	relative heaviness of overcast sky.

Abbreviation

TDIYd	typical diffuse illuminance year composed of typical days
TDIYd$_{ef}$	TDIYd obtained by applying a luminous efficacy model to a typical year generated from diffuse irradiance data
TDIYm	typical diffuse illuminance year composed of typical months
TDIYm$_{ef}$	TDIYm obtained by applying a luminous efficacy model to a typical year generated

	from diffuse irradiance data
TGIYd	typical global illuminance year composed of typical days
TGIYd_{ef}	TGIYd obtained by applying a luminous efficacy model to a typical year generated from global irradiance data
TGIYm	typical global illuminance year composed of typical months
TGIYm_{ef}	TGIYm obtained by applying a luminous efficacy model to a typical year generated from global irradiance data

1. Introduction

Over time, interest in the use of daylight for illumination purposes has experienced ups and downs related to the lack of artificial lighting systems, or the unavailability or high cost of the energy supply for such systems. Currently, the use of natural daylight for the illumination of indoor and outdoor spaces of buildings reduces energy consumption and improves the living and working conditions of the inhabitants.

When assessing daylight availability and, where appropriate, the performance of natural lighting systems in the long term in a given location, it is necessary to have representative data of the most frequent conditions of the place. The use of a typical meteorological year (TMY), also named the test reference year (TRY) by some authors, becomes a good option for evaluating the performance of natural daylight in the long term. Since the second half of the 1970's, numerous procedures have been published for the generation of these synthetic series of data representative of local conditions. Figure 1 shows a timeline with the year of publication of the main procedures proposed thus far. This figure does not include the procedures that arise from simplifications of other previously published procedures that do not involve a substantial modification.

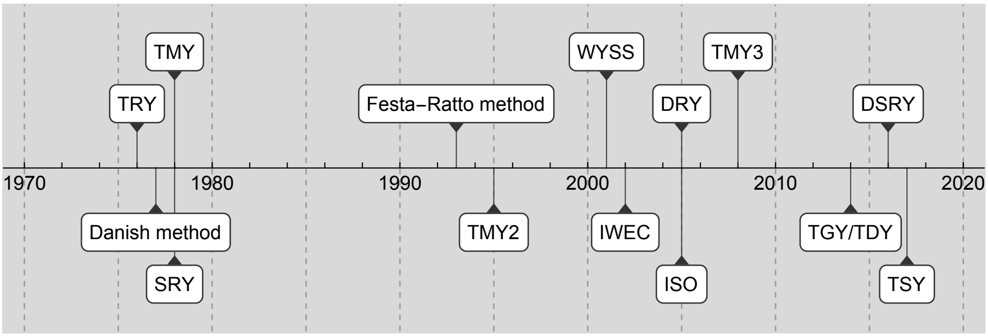

Figure 1. Timeline of the publication dates of the main TRY generation procedures.

In general, the published TRY generation procedures propose the concatenation of 12 typical meteorological months (TMM) belonging to the historical series of observations. However, some approaches, such as the TRY of the National Climatic Data Center (1976), propose the selection of a representative year selected from historical series of observations. An opposite case is represented by the so-called short reference years (SRY) (Feuermann et al., 1985; Lund, 1984; Petrie and McClintock, 1978), which propose the selection of a series of meteorological data shorter than one year. More recently, García and Torres (2018) proposed a temporal downscaling of the typical periods selected by 6 different procedures for TRY generation. As a result, in this case, the construction of a TRY is proposed from the concatenation of 365 typical days. This work revealed a global improvement of 5 of the 6 modified procedures when estimating the long-term production of a photovoltaic system.

One of the first procedures that proposed the generation of a TRY by selecting 12 TMMs was the so-called Danish method developed by Andersen et al. (1977) and Lund and Eidorff (1981), which subsequently resulted in the Festa-Ratto method (Festa and Ratto, 1993). Unlike the Danish method that defines the meteorological variables to be used, the Festa Ratto method is applicable to any set of variables. Moreover, in 1978 the Sandia National Laboratories (Hall et al., 1978) developed a method for obtaining the TMY, commonly known as the Sandia method. This widely used procedure proposes the selection of 12 TMM from the statistical analysis of 9 meteorological variables (i.e., maximum, average and minimum air temperature and relative humidity, maximum wind speed and global horizontal irradiance). The selection procedure of typical months begins by selecting 5 candidate months in accordance with the lower weighted sum (WS) of the Finkelstein-Schäfer (F_S) statistic (Finkelstein and Schäfer, 1971) calculated for each parameter considered. The F_S statistic is used to compare the short and long-term cumulative distribution functions of each variable. Then, the 5 candidate months are ranked according to the closeness of a given month to the long-term mean and median. Finally, the TMM that integrates the TMY is selected from the 5 candidates after performing a persistence analysis. The Sandia method was used by Siurna et al. (1984) to obtain the Canadian weather year for energy calculations (CWEC) and by Pissimanis et al. (1988) for the construction of a TMY for the city of Athens (Greece). For their part, Petrakis et al. (1998) used it for the generation of a TMY for Nicosia (Cyprus), Sawaqed et al. (2005) for the development of TMYs for 7 locations in Oman and Ohunakin et al. (2014) to obtain a TMY for Sokoto (Nigeria).

Mosalam Shaltout and Tadros (1994) applied a simplification of the original Sandia method to obtain a typical solar radiation year for Egypt consisting of the use of only the WS criterion of the F_S statistics of each variable considered. This simplification, called by some authors as the Finkesltein-Schäfer method, was used by Skeiker (2004) for the generation of a typical meteorological year for Damascus (Syria).

The TMY2 arises from a modification of the Sandia method carried out by the National Renewable Energy Laboratory (NREL) (Marion and Urban, 1995), in which the original procedure is maintained but one more meteorological variable is included (direct normal irradiance) and the weights assigned to each of the variables are modified. This procedure has been applied by Kalogirou (2003) to obtain the TMY2 for Nicosia

(Cyprus). Other modifications of the variables and their weights assigned by the original TMY2 have also been proposed by Chow et al. (2006) and Zang et al. (2012).

The international weather for energy calculations (IWEC) emerged from a subsequent review of the Sandia method carried out by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) (Thevenard and Brunger, 2002). This method maintains the selection procedure for the 5 candidate months but omits the persistence criterion since it can lead to the elimination of all candidate months. In this sense, the method for obtaining the TMY3 developed by Wilcox and Marion (2008) relaxes the persistence criteria of the Sandia method to ensure the selection of a candidate month.

Although most of the published procedures described to this point are of general application, some of them are proposals aiming at the long-term evaluation of specific solar systems or the energy performance of buildings. An example is the weather year for solar systems (WYSS) proposed by Gazela and Mathioulakis (2001). This is a TRY oriented towards the evaluation of the long-term behavior of solar hot water systems. The only criterion proposed for the selection of TMMs is the minimization of the squared error in the monthly solar gain prediction of the system.

For its part, the method proposed in the European Technical Standard EN ISO 15927-4 (European Committee for Standardization, 2005) is designed for the generation of a TRY suitable for evaluating the annual energy demand for heating and cooling in buildings. This procedure, known as the ISO method, includes 4 variables, i.e., temperature, relative humidity, solar radiation and wind speed. The first 3 variables are considered main variables and are used to select 3 candidate months. To this end, the F_S statistic is calculated for each of the 3 main variables. Then, for each ordinal month, the individual months are ranked from the multiyear record in order of increasing F_S values for each variable. The individual ranks of the 3 variables are summed before considering the same weight for all variables. The 3 months with the smallest sum are selected as candidates. Wind speed is used as a secondary variable in the final selection of the typical month among the 3 candidates previously selected. The above method has been used for the construction of two TRYs for Greenland (Kragh et al., 2005), for obtaining it in 6 locations in Estonia (Kalamees and Kurnitski, 2006) as well as for 7 cities in South Korea (Lee et al., 2010) and for Alūksne (Latvia) (Ruduks and Lešinskis, 2015). Pernigotto et al. (2014a) used this procedure to evaluate the energy performance of buildings in 5 cities in northern Italy, while García and Torres (García and Torres, 2015) demonstrated the applicability for a different purpose, that is, the long-term evaluation of photovoltaic systems. The ISO method has undergone modifications such as the two variations proposed by Pernigotto et al. (2014b) oriented to improve its representativeness for building energy calculations. Eames et al. (2015) also proposed a modification of this method that was used for the United Kingdom's TRY generation.

Other TRYs designed for the analysis of specific solar systems are the typical global year (TGY) and the typical direct year (TDY) proposed by NREL (Habte et al., 2014). They are oriented to the evaluation of photovoltaics and concentrating solar power projects, respectively. The generation procedure is based on TMY3, but they only consider one variable: horizontal global horizontal irradiance in the case of TGY and direct normal irradiance for TDY.

In line with TGY and TDY, Lara Fanego et al. (2017) defined the general concept of the typical solar year (TSY) as a TRY that only includes solar radiation data. As in the case of TGY/TDY, TSY can be oriented to the bankability analysis of specific solar energy projects. This work proposes a procedure named EVA, an acronym for the Spanish words for seasonality and variability, for the generation of a TSY by concatenating 12

TMMs. The peculiarity of the method is that it is necessary to establish an annual target value of probability of exceedance that the generated TSY must meet. The EVA method has been recommended in the Spanish standard UNE 206013:2017 (AENOR, 2017) for performing risk assessment for securing competitive financing in concentrating solar thermal power (CSTP) projects. The applicability of meteorological years generated by means of the EVA methodology for the probabilistic assessment of CSTP plants yield was tested by Fernández-Peruchena et al. (2018).

The proposals for the generation of TRYs aimed at establishing the daylight reference conditions at a given location with the objective of evaluating the long-term daylight are not at all usual. In fact, none of the numerous procedures described above employs illuminance as a selection variable for TMMs. A main problem that arises when generating a TRY suitable for daylight evaluation is the lack of illuminance data. Thus, a possible solution is to apply a luminous efficacy model to the irradiance data used in the generation of general purpose TRYs, as was reported by Reinhart and Herke (2000). In this line, the study performed by Wang et al. (2019) investigates whether TMYs allow accurate predictions of daylight quality and daylight-responsive control system performance.

If a sufficiently long daylight data (such as illuminance) series is available, it can be used to generate a TRY. One of the first attempts to generate a TRY from illuminance data was carried out by Petrakis et al. (1996), who generated two TRYs for Athens (Greece), one from illuminance data and one from irradiance data. However, the shortness of the data series used did not provide satisfactory results.

Darula et al. (2005) proposed the generation of a set of daylight reference years (DRYs) for the predetermination of typical annual profiles of outdoor daylighting for Athens (Greece) and Bratislava (Slovakia). In that published research, the possibility of obtaining these DRYs through 3 different methods, namely, a modification of the Sandia method, the Danish method and the Festa-Ratto method, was raised. The following variables were used for this purpose: global and diffuse horizontal illuminance, global and diffuse horizontal irradiance, zenith luminance, luminous turbidity factor, Linke turbidity factor and sunshine duration. Likewise, a second simplified method was proposed that only considered the sunshine duration. The results of that work revealed that the DRY that best represented the daylight conditions in both cities was the one obtained from the modified Sandia method. This proposal for DRY generation was included in the CIE Standard General Sky Guide (CIE, 2014).

In accordance with the aforementioned DRY proposal, Markou et al. (2007) applied 3 methods (the Festa-Ratto method, the modified Danish method and the modified Sandia method) with the objective of establishing typical occurrence frequencies of CIE Standard sky types in Athens and Bratislava. Although the length of the historical data series was shorter than 10 years in both locations, the authors concluded that the proposed variations of the Sandia method, which included a number of atmospheric parameters related to irradiance and illuminance, were the best for all skies analyzed and for the skies considered as normal. The criterion used for selecting the best procedure was the lowest root mean square difference between the frequency of occurrence of the long-term observed sky types for the month in question and that corresponding to the month selected to be part of the DRY.

More recently, Fabian et al. (2016) published a proposal for the generation of a Daylight Standard Reference Year (DSRY) for Bratislava using minute values of 7 variables, of which 5 had been measured (global horizontal illuminance and irradiance, diffuse horizontal illuminance and irradiance, zenith luminance) and two had been calculated from the former (direct illuminance and irradiance). The proposal presents two variants. In the first one, the selection of the typical month is based on the distance of the minute values of the considered variables with respect to their long-term average value, whereas in the second one the distance is relative to their median. The authors recommended the latter option arguing that the use of the median makes the result less sensitive to extreme values of the variables and more stable.

Regarding the present work, it pursues two main objectives and a secondary one. First, following the philosophy of TGY/TDY, a procedure has been proposed and evaluated for the generation of illuminance TRYs suitable to assess the long-term daylight in a given location. The procedure for obtaining these synthetic years, which will be generically called typical illuminance years (TIYs), uses only the illuminance variable. In this case, the use of global horizontal illuminance is proposed to obtain the typical global illuminance year (TGIY) and the use of diffuse horizontal illuminance for the construction of the typical diffuse illuminance year (TDIY). Likewise, two variants of the procedure are proposed: one oriented to the selection of 12 TMMs and another designed for the selection of 365 typical days according to the temporal downscaling of the typical periods proposed by García and Torres (2018). For the generation of these TIYs, a 27-year data series registered at the Vaulx-en-Velin station (France) has been employed. The use of TIYs is valuable for estimating the daylight conditions of indoor and outdoor spaces. This leads to a better design of artificial lighting and daylight control systems, which results in a more efficient use of energy. The methodology proposed in this work has the advantage of using a single variable (global or diffuse horizontal illuminance) for generating TIYs. Furthermore, this procedure allows the use of discontinuous data series without requiring a procedure for gap filling, thus avoiding possible errors derived from the application of gap-filling techniques.

Because it is more common to have available irradiance data than illuminance ones, the second main objective of this article is to evaluate the possibility of using the TIYs obtained by applying a luminous efficacy model to a TRY generated only from irradiance data. This adds an additional advantage to this proposal, that leads to the secondary objective of selecting the luminous efficacy models to be used and fitting them to the local conditions corresponding to Vaulx-en-Velin. Consequently, it has been necessary to carry out the appropriate literature review. Seven models of global luminous efficacy and 5 diffuse luminous efficacy models have been fitted from the same data series as the one selected for the generation of the different TIYs.

The article is organized in the following sections. Section 2 describes the meteorological information considered and the applied quality control. Section 3 presents the general methodology to generate and test the different 8 TIYs proposed in this work. In Section 0, a detailed description of the proposed methods to generate monthly and daily based TIYs is stated. Seven models for global luminous efficacy and 5 models for diffuse efficacy are reported in Section 5 with both original and calibrated coefficients for local conditions. Finally, Section 6 shows the results and Section 7 deploys the conclusions.

2. Meteorological data

Global and diffuse horizontal irradiance and illuminance data recorded at the Vaulx-en-Velin (France) International Daylight Measurement Programme (IDMP) station (45º46’43’’ N, 4º55’21’’ E, 170 m a.s.l.) have been employed in this study. The Vaulx-en-Velin station offers online accessible 5-minute frequency data from 1992 to 3rd March 2005 and one-minute frequency data since then until now. The provided data have undergone the quality control (QC) test defined by the CIE (1994). According to the description provided on the station website, Vaulx-en-Velin is located in the eastern part of Lyon. Within a radius of 5 km around the station, the environment consists of 70% urban housing and 30% cultivated fields and parks. The climate is temperate with a maritime influence (Mediterranean). The average duration of sunshine is 2,100 hours per year. The average number of days with fog is 55, occurring mostly in winter.

The procedures for the generation of TIYs proposed in Section 0 requires meteorological information at hourly and daily scales. For this reason, the original data series have been integrated to obtain the required frequencies. First, the 1-minute and 5-minute values corresponding to an hour have been aggregated into hourly average values. Within a certain hourly period, records may be missing either as a result of errors in the measurements and recording of the data or because they have not passed the QC test. In these cases, the decision was made to discard the hours in which the percentage of 1-minute or 5-minute gaps was greater than 20%. Second, the hourly values were integrated to obtain the corresponding daily values. Thus, the time series to be used corresponded to the daily values of the variables of interest for each month of the historical series of observations. In this case, the rejection criterion was again not to consider the months in which the daily gaps were greater than 20% of the data.

Figure 2 shows the valid data after having applied the above-described QC and the rejection criteria. Considering the whole time series, 82.87% days of the original time series were used.

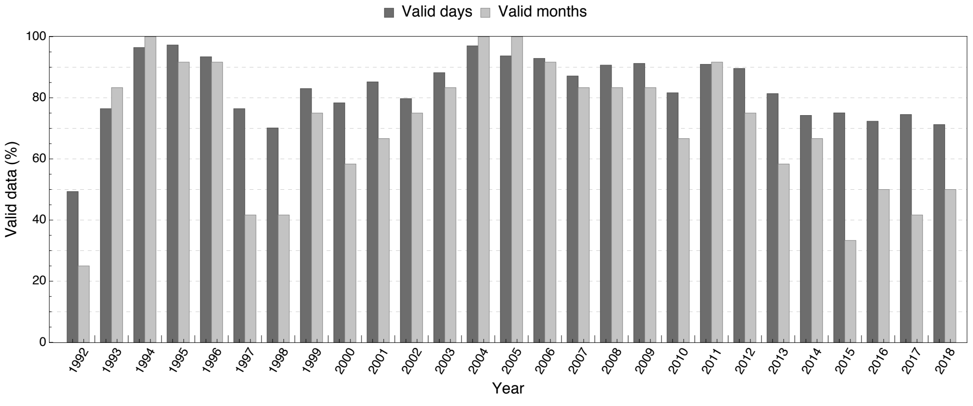

Figure 2. Percentage of valid data used for the generation of TIYs over the different years of the dataset.

Figure 3 shows a graphical presentation of the distribution of valid days (grey color) over the historical series of data from 1992 to 2018. The percentage of valid days for the generation of the different typical illumination years ranges from 49.32% in 1992 to 97.26% in 1995.

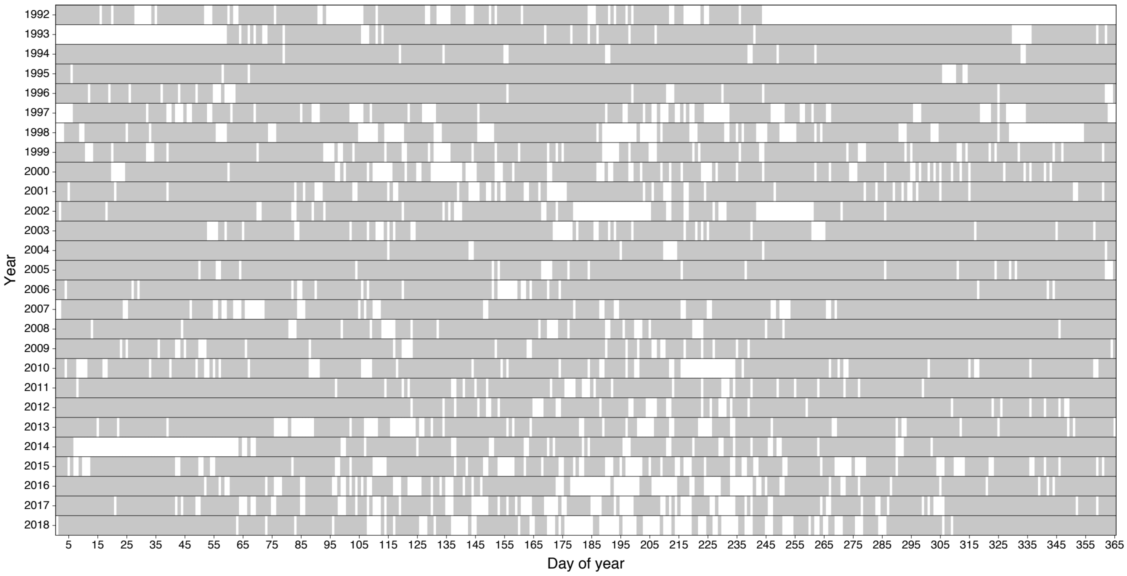

Figure 3. Grey squares show the days over the time series with valid data for the generation of the TIY. White squares correspond to rejected days that did not pass the QC test.

In reference to the monthly periods, the percentage of valid months was 70.68%, according to Figure 2. Figure 4 shows the distribution of valid months (in grey) considered over the historical series. There are 3 years (1994, 2004 and 2005) in which all the months are valid for generating the typical illumination years, whereas in 1992, only 3 months can be considered. In all cases, for each calendar month there are more than 11 years available in the period 1992-2018 to generate the typical illuminance year.

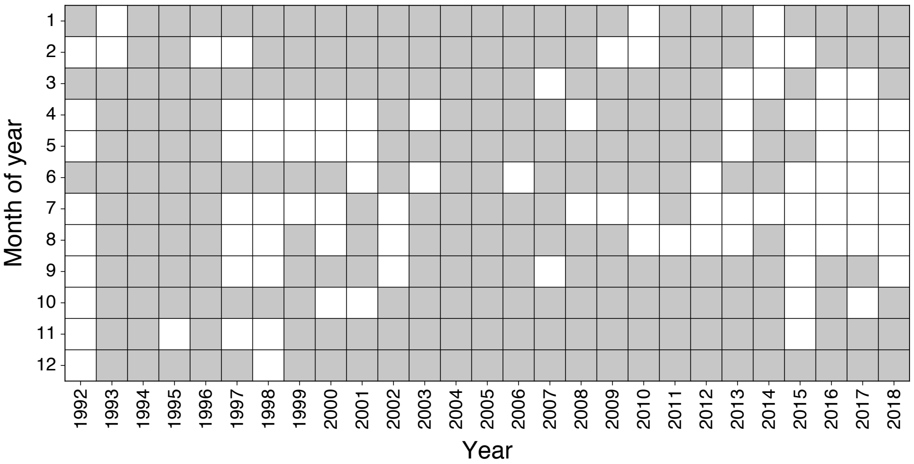

Figure 4. Grey squares show the months with measured data over the time series considered for the generation of the typical illuminance year. White squares represent the rejected months.

Despite the aforementioned gaps occurrence, the design of the TIY generation procedures proposed in Section 0 allows the use of discontinuous series without requiring a procedure for gap filling. Consequently, the series of years used to select each typical day or month may have a different length. In this way, errors derived from the application of gap-filling techniques are avoided. Thus, it is possible to generate a complete typical time series from an incomplete dataset.

3. Methodology

In accordance with the objectives described in the Introduction, 8 TIYs have been generated and evaluated in this work following the new procedures detailed in Section 0. Table 1 shows the codes assigned to each of the TIYs analyzed along with their parameters. Notice that subscript ‘ef’ has been added to those TIYs generated from irradiance data series to which a luminous efficacy model has been applied to obtain a TIY.

Table 1
Description of the TIYs considered.

TRY	Typical period	Parameter	Luminous efficacy model
TGIYm	Month	Global horizontal illuminance	-
TGIYd	Day	Global horizontal illuminance	-
$TGIYm_{ef}$	Month	Global horizontal irradiance	Global
$TGIYd_{ef}$	Day	Global horizontal irradiance	Global
TDIYm	Month	Diffuse horizontal illuminance	-
TDIYd	Day	Diffuse horizontal illuminance	-
$TDIYm_{ef}$	Month	Diffuse horizontal irradiance	Diffuse
$TDIYd_{ef}$	Day	Diffuse horizontal irradiance	Diffuse

To evaluate the suitability of the new TIYs proposed for evaluation of the long-term daylight resource, the general procedure established in Figure 5 has been followed. Although this diagram only refers to the global horizontal illuminance and irradiance, the same procedure has been applied to the diffuse component of both variables. The step-by-step procedure is described below:

- For each meteorological parameter (i.e., global horizontal illuminance and irradiance), calculate the hourly and daily means for each available year.
- Generate the TIYs from illuminance data:
  - From hourly illuminance values, construct TIYs composed of typical days.
  - From daily illuminance values, construct TIYs composed of typical months.
- Generate the TRYs from irradiance data:
  - From hourly irradiance values, construct TGYs composed of typical days.
  - From daily irradiance values, construct TGYs composed of typical months.
- From hourly global horizontal irradiance and illuminance data, adjust the coefficients of the selected global luminous efficacy models (G_1 to G_7) to local conditions.
- Evaluate the performance of luminous efficacy models considering both original coefficients and those adjusted locally. To achieve this goal, the evaluation metrics defined in Equations (1) to (5) are used, namely, determination coefficient

(R^2), relative root mean square error (rRMSE), relative mean bias error (rMBE), mean percentage error (MPE) and relative standard deviation (RSD).

$$R^2\,(-) = \frac{\left[\sum_{i=1}^{n}\left(E_{v,i,obs} - \bar{E}_{v,obs}\right)\cdot\sum_{i=1}^{n}\left(E_{v,i,mod} - \bar{E}_{v,mod}\right)\right]^2}{\sum_{i=1}^{n}\left(E_{v,i,obs} - \bar{E}_{v,obs}\right)^2\cdot\sum_{i=1}^{n}\left(E_{v,i,mod} - \bar{E}_{v,mod}\right)^2}. \tag{1}$$

$$rRMSE\,(\%) = \frac{100}{\bar{E}_{v,obs}}\sqrt{\frac{\sum_{i=1}^{n}\left(E_{v,i,obs} - E_{v,i,mod}\right)^2}{n}}. \tag{2}$$

$$rMBE\,(\%) = \frac{100}{\bar{E}_{v,obs}}\frac{\sum_{i=1}^{n}\left(E_{v,i,obs} - E_{v,i,mod}\right)}{n}. \tag{3}$$

$$MPE\,(\%) = \frac{100}{n}\sum_{i=1}^{n}\left(\frac{E_{v,i,obs} - E_{v,i,mod}}{E_{v,i,obs}}\right). \tag{4}$$

$$RSD\,(\%) = 100\sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\frac{E_{v,i,obs} - E_{v,i,mod}}{E_{v,i,obs}}\right)^2}. \tag{5}$$

- Select the global luminous efficacy model that best fits the local irradiance and illuminance data series.
- Apply the best-fit luminous efficacy model to the TGYs generated from irradiance data. The TIYs are obtained this way.
- Compare each TIY with the long-term illuminance dataset using 8 statistical indicators depicted by Equations (6) to (13).
  - Yearly illuminance:

$$F_1 = \sqrt{\frac{\sum_{y=1}^{j}\left(E_{v,y} - E_{v,t}\right)^2}{j}}. \tag{6}$$

  - Monthly illuminance:

$$F_2 = \frac{1}{12}\sum_{m=1}^{12} SEE_m = \frac{1}{12}\left[\sum_{m=1}^{12}\left[\frac{\sum_{y=1}^{j}\left(E_{v,ym} - E_{v,tm}\right)^2}{j}\right]^{0.5}\right]. \tag{7}$$

$$F_3 = \chi^2 = \sum_{m=1}^{12} \left(\frac{\overline{E}_{v,m} - E_{v,tm}}{\sigma_{\overline{E}_{v,m}}} \right)^2 . \tag{8}$$

$$F_4 = \left[\frac{1}{12} \sum_{m=1}^{12} \left(\overline{E}_{v,m} - E_{v,tm} \right)^2 \right]^{1/2} . \tag{9}$$

- Daily illuminance:

$$F_5 = \frac{1}{365} \sum_{d=1}^{365} SEE_d = \frac{1}{365} \left[\sum_{d=1}^{365} \left[\frac{\sum_{y=1}^{j} \left(E_{v,yd} - E_{v,td} \right)^2}{j} \right]^{0.5} \right] . \tag{10}$$

$$F_6 = \left[\frac{1}{365} \sum_{d=1}^{365} \left(\overline{E}_{v,d} - E_{v,td} \right)^2 \right]^{1/2} . \tag{11}$$

- Hourly illuminance:

$$F_7 = \frac{1}{8760} \sum_{h=1}^{8760} SEE_h = \frac{1}{8760} \left[\sum_{h=1}^{8760} \left[\frac{\sum_{y=1}^{j} \left(E_{v,yh} - E_{v,th} \right)^2}{j} \right]^{0.5} \right] . \tag{12}$$

$$F_8 = \left[\frac{1}{8760} \sum_{h=1}^{8760} \left(\overline{E}_{v,h} - E_{v,th} \right)^2 \right]^{0.5} . \tag{13}$$

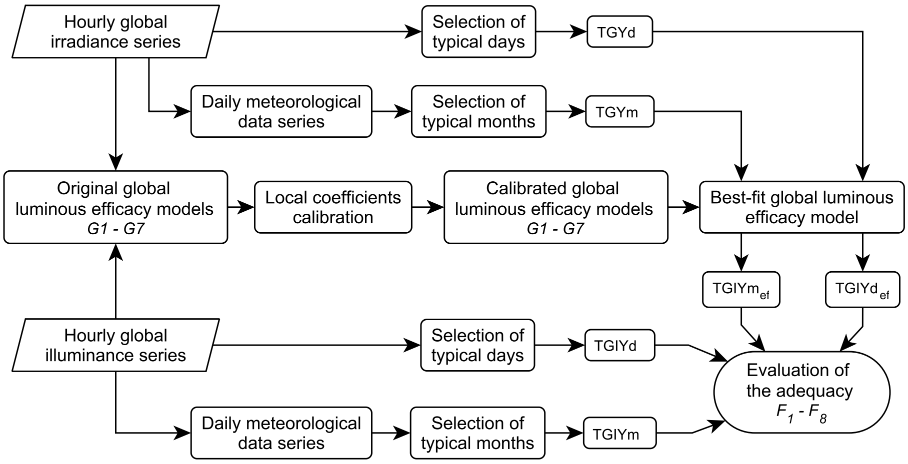

Figure 5. General procedure for assessing global TIY adequacy.

As noted in the last step of the general procedure, each TIY generated is compared with the long-term daylight data series using 8 metrics. Six of them (F_1 to F_6) are proposed by Gazela and Mathioulakis (2001) and the last two (F_7 and F_8) by García and Torres (2018). Indicator F_1 obtained from Equation (6) is the root mean square difference of the yearly illuminance. The indicators F_2, F_5 and F_7 denote the total standard error of estimates of monthly (SEE_m), daily (SEE_d) and hourly (SEE_h) illuminances, respectively. Indicator F_3 is the chi-square (χ^2) parameter of the monthly illuminance, and it can be calculated from Equation (8). Indicators F_4, F_6 and F_8, which are derived from Equations (9), (11) and (13), are the root mean squares of the mean illuminance of the historic data series minus the TIY monthly, daily and hourly illuminance, respectively.

4. Proposed methods for the generation of TIYs

The TIY generation procedure composed of the concatenation of 12 typical months selected from the historical series of observations is shown in Figure 6. For its part, the procedure for obtaining the TIY composed of 365 typical days is described below (see Figure 7). The method for the selection of typical months has not been detailed since its structure is identical to the procedure described below except that the data series to be used must be on a daily than on an hourly scale. Moreover, although the procedure's description refers to the global horizontal illuminance variable, it can be applied to the global horizontal irradiance as well as to the diffuse components of both illuminance and irradiance to obtain the different TIYs shown in Table 1.

- Calculate the hourly global horizontal illuminance means for each year included in the time series.
- For each ordinal day, the Finkelstein-Schäfer (F_S) statistic is calculated for the illuminance variable according to Equation (14).

  $$F_S(y,d) = \sum_{i=1}^{n} |CDF(y,d,i) - CDF(d,i)|, \tag{14}$$

  where $CDF(y,d,i)$ is the short-term cumulative distribution function of the mean hourly illuminance for a day d of a year y, and $CDF(d,i)$ is the long-term cumulative distribution function of the mean hourly illuminance of a day d.

- For each ordinal day, 5 candidate days are selected having the smallest F_S statistic.
- The 5 candidate days are ranked with respect to closeness of the day to the long-term mean and median. Relative differences are calculated between the mean and median global horizontal illuminance of each specific day and the respective long-term mean and median. The maximum of the two relative differences is assigned.
- The persistence of the global horizontal illuminance is evaluated by determining the frequency and run length below the 33rd percentile (consecutive low illuminance hours).
- The persistence criteria are used to select the day to be used in the TGIYd from the 5 candidate days. The highest ranked candidate day from the previous step that meets the persistence criteria is used in the TGIYd. The persistence criteria exclude the day with the longest run, the day with most runs, and the day with zero runs. However, a candidate day is only excluded if it has more runs than every other candidate day. Thus, if two candidate days tie for the most runs, neither is eliminated by the TGIYd procedure. Additionally, if the TGIYd persistence procedure eliminates all candidate days, the persistence is ignored and the closest day to the long-term mean and median is selected.

Although it is typical to apply a cubic spline to the last values of the previous month and the initial values of the following one to obtain a smooth transition between the selected typical months, it has not been applied in this work since this adjustment refers to hours in which the illuminance is zero or very low.

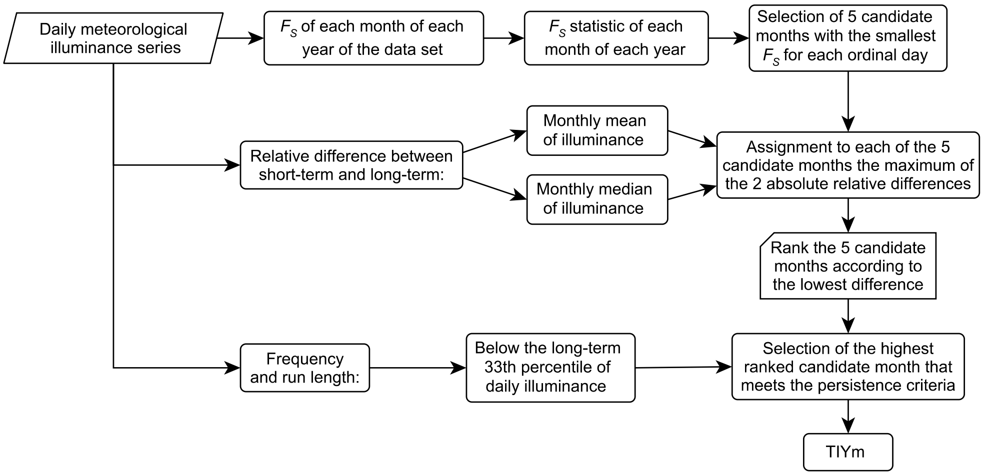

Figure 6. Proposed procedure for obtaining monthly-based TIYs.

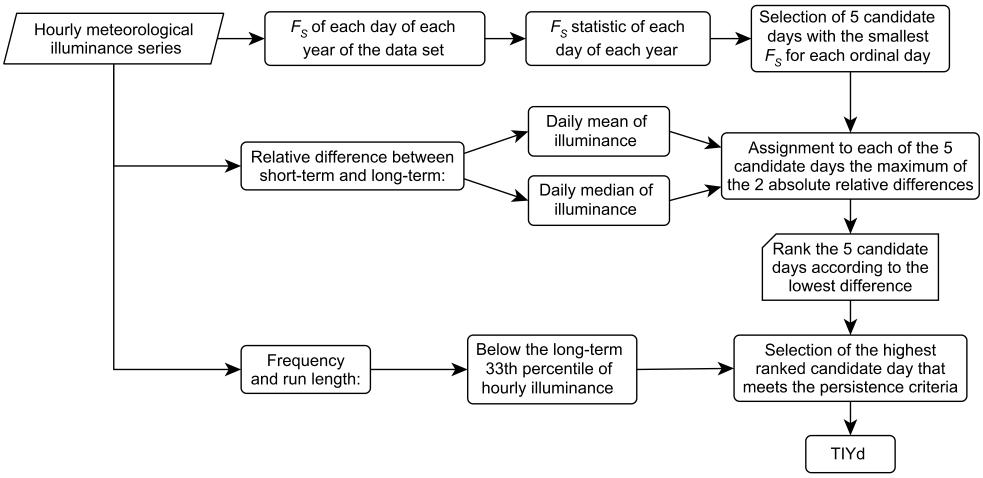

Figure 7. Proposed procedure for obtaining daily-based TIYs.

5. Luminous efficacy models

The daylight luminous efficacy is defined as the ratio between daylight illuminance (E_v) and solar irradiance (E_e). More specifically, the global luminous efficacy (K_g) refers to the ratio between E_{vg} and E_{eg}, as seen in Equation (15). However, in terms of the diffuse component in both variables, the luminous efficacy for diffuse irradiance (K_d) is used, which can be calculated according to Equation (16).

$$K_g = \frac{E_{vg}}{E_{eg}}. \tag{15}$$

$$K_d = \frac{E_{vd}}{E_{ed}} \,. \tag{16}$$

The scientific literature contains numerous models of global and diffuse luminous efficacy as a function of different variables, some of which even comprise a simple multiplier that converts irradiance to illuminance. Given that a luminous efficacy model is required to convert a whole TGY to a TIY, those suitable for application to all-sky conditions and applicable from the variables measured at Vaulx-en-Velin station have been selected among the published models. Specifically, 7 global luminous efficacy models and 5 diffuse luminous efficacy models have been chosen. The coefficients of each of the selected models have been calibrated according to the local conditions of the Vaulx-en-Velin station using Mathematica 12® software. To perform this adjustment, half of the data series available at hourly scale have been used. The other half have been employed for validation of the models both in their original version and in their locally calibrated one, implying two sets of 12448 hourly data points corresponding to 27 years of measurements.

5.1. Global luminous efficacy models

The 7 global luminous efficacy models analyzed in this work, named G1 to G7 and summarized in Table 2, are described in the following subsections. In addition to the model structures, original and locally calibrated coefficients are provided.

Table 2
Global luminous efficacy models.

Model	Authors	Year	Variables
G1	Perez et al. (1990)	1990	ε, W, Z, Δ
G2	Chung (1992)	1992	D, α, Ω
G3	Muneer and Kinghorn (1997)	1997	K_t
G4	Ruiz et al. (2001)	2001	α, K_t
G5	Mahdavi and Dervishi (2011)	2013	t, K_t
G6	Chaiwiwatworakul and Chirarattananon (2013)	2013	ε, Z
G7	Dieste-Velasco et al. (2019)	2019	α, K_t

5.1.1. *Perez et al. global luminous efficacy model (G1)*

Perez et al. (1990) presented a set of models aimed at assessing the availability of daylight and irradiance that include global, diffuse and direct luminous efficacy models, a model for the estimation of diffuse irradiance and illuminance on tilted surfaces and a sky luminance angular distribution. Equation (17) shows the structure of the global luminous efficacy model, which depends on atmospheric water content (W), solar zenith angle (Z) and sky brightness (Δ). The model coefficients (a_{G1}, b_{G1}, c_{G1}, d_{G1}) are categorized into 8 sky-clearness bins (ε). The original coefficients, as well as the values obtained after fitting them to the local data, are presented in Table 3.

$$K_g = a_{G1} + b_{G1}W + c_{G1}\cos(Z) + d_{G1}\ln(\mathit{\Delta}) \ . \tag{17}$$

Table 3
Original and locally calibrated coefficients of the Perez et al. global luminous efficacy model (G1).

Sky clearness	Original coefficients				Calibrated coefficients			
	a_{G1}	b_{G1}	c_{G1}	d_{G1}	a_{G1}	b_{G1}	c_{G1}	d_{G1}
$1 < \varepsilon \leq 1.065$	96.63	-0.47	11.5	-9.16	86.176	1.587	15.129	10.030
$1.065 < \varepsilon \leq 1.230$	107.54	0.79	1.79	-1.19	91.960	3.273	11.267	-3.817
$1.230 < \varepsilon \leq 1.500$	98.73	0.7	4.4	-6.95	86.289	4.112	15.663	-4.084
$1.500 < \varepsilon \leq 1.950$	92.72	0.56	8.36	-8.31	81.985	4.648	14.732	5.989
$1.950 < \varepsilon \leq 2.800$	86.73	0.98	7.1	-10.94	82.939	4.277	15.423	4.415
$2.800 < \varepsilon \leq 4.500$	88.34	1.39	6.06	-7.6	79.282	4.461	17.584	-4.452
$4.500 < \varepsilon \leq 6.200$	78.63	1.47	4.93	-11.37	67.097	4.404	16.821	-10.064
$\varepsilon > 6.200$	99.65	1.86	-4.46	-3.15	87.737	3.842	12.006	1.715

5.1.2. *Chung global luminous efficacy model (G2)*

Chung (1992) studied the global, diffuse and direct luminous efficacy of Hong Kong and proposed a series of models for its estimation depending on the sky condition. In this case, the sky condition was parametrized according to the sky ratio (D), namely, the ratio of horizontal diffuse irradiance to global horizontal irradiance. Different expressions proposed for clear ($D < 0.3$), partly cloudy ($0.3 < D < 0.8$) and overcast skies ($D > 0.8$) are shown in Equation (18).

$$K_g = \begin{cases} a_{G2} + b_{G2}\alpha + c_{G2}\alpha^2 & D < 0.3 \\ D(d_{G2} + e_{G2}D) + \left(f_{G2} + g_{G2}\alpha + h_{G2}\alpha^2\right)(1 - D) & 0.3 < D < 0.8 \\ \left(i_{G2} + j_{G2}\alpha + k_{G2}\alpha^2\right)\left(l_{G2} + m_{G2}\Omega + n_{G2}\Omega^2\right) & D > 0.8 \end{cases}, \tag{18}$$

where α is solar elevation and Ω corresponds to the ratio of global horizontal irradiance to the sine of the solar elevation. Original and adjusted coefficients are presented in Table 4.

Table 4
Original and locally calibrated coefficients of the Chung global luminous efficacy model (G2).

Coefficient	a_{G2}	b_{G2}	c_{G2}	d_{G2}	e_{G2}	f_{G2}	g_{G2}	h_{G2}	i_{G2}	j_{G2}	k_{G2}	l_{G2}	m_{G2}	n_{G2}
Original	102.2	0.69	$-5.9\cdot10^{-3}$	135.3	-25.7	48.5	1.67	$-9.8\cdot10^{-3}$	102.2	0.67	$-5.9\cdot10^{-3}$	1.18	$-8.7\cdot10^{-4}$	$9.3\cdot10^{-7}$
Calibrated	89.68	37.20	-19.09	93.57	17.90	76.74	84.29	-47.83	101.28	17.45	-7.10	1.26	$-7.82\cdot10^{-4}$	$5.25\cdot10^{-7}$

5.1.3. Muneer and Kinghorn global luminous efficacy model (G3)

Muneer and Kinghorn (1997) proposed a global and a diffuse luminous efficacy model based on the clearness index (K_t), the structure of which is shown in Equation (19); the original and fitted coefficients are listed in Table 5.

$$K_g = a_{G3} + b_{G3}K_t + c_{G3}K_t^2\ . \tag{19}$$

Table 5
Original and locally calibrated coefficients of the Muneer and Kinghorn global luminous efficacy model (G3).

Coefficient	a_{G3}	b_{G3}	c_{G3}
Original	136.6	-74.541	57.3421
Calibrated	114.482	-51.070	53.122

5.1.4. Ruiz et al. global luminous efficacy model (G4)

The work of Ruiz et al. (2001) proposed and assessed a total of 4 models to estimate global luminous efficacy and global horizontal illuminance and 4 other models to estimate diffuse luminous efficacy and diffuse horizontal illuminance. Regarding the two luminous efficacy models included in the first group, one uses K_t as the only independent variable, while the other considers two independent variables, namely, K_t and α. After evaluating the model behavior, the one considering two independent variables, shown in

Equation (20), exhibits the best fit to the experimental data. Table 6 shows the original and adjusted model coefficients.

$$K_g = a_{G4}\, sin(\alpha)^{b_{G4}}\, K_t^{c_{G4}}\, . \tag{20}$$

Table 6
Original and locally calibrated coefficients of the Ruiz et al. global luminous efficacy model (G4).

Coefficient	a_{G4}	b_{G4}	c_{G4}
Original	104.83	0.026	0.108
Calibrated	105.325	0.097	-0.118

5.1.5. Mahdavi and Dervishi global luminous efficacy model (G5)

The global luminous efficacy model proposed by Mahdavi and Dervishi (2011) also considers the K_t as independent variable in addition to air temperature (t), as seen in Equation (21). Original coefficients based on data from Vienna (Austria) as well as locally adjusted coefficients are presented in Table 7.

$$K_g = a_{G5} + b_{G5}t + c_{G5}K_t + d_{G5}tK_t + e_{G5}t^2 + f_{G5}K_t^2\, . \tag{21}$$

Table 7
Original and locally calibrated coefficients of the Mahdavi and Dervishi global luminous efficacy model (G5).

Coefficient	a_{G5}	b_{G5}	c_{G5}	d_{G5}	e_{G5}	f_{G5}
Original	140.9	0.273	-102	0.6	-0.001	77.28
Calibrated	108.415	0.701	-50.833	0.484	-0.020	41.599

5.1.6. JGSEE global luminous efficacy model (G6)

This model, proposed by Chaiwiwatworakul and Chirarattananon (2013), takes its name from the Joint Graduate School of Energy and Environment (JGSEE) located in Bangkok (Thailand). As seen in Equation (22) the variables involved in this model are ε and Z.

$$K_g = (a_{G6} + b_{G6}\varepsilon^{c_{G6}})\cos(Z)^{(d_{G6}+e_{G6}\varepsilon^{f_{G6}})}\, . \tag{22}$$

Original model coefficients and locally fitted coefficients are shown in Table 8.

Table 8
Original and locally calibrated coefficients of the JGSEE global luminous efficacy model (G6).

Coefficient	a_{G6}	b_{G6}	c_{G6}	d_{G6}	e_{G6}	f_{G6}
Original	101.65	13.92	-3.49	-0.18	0.19	-1.25
Calibrated	109.825	3.053	-5.920	0.129	-0.082	-0.352

5.1.7. Dieste-Velasco et al. global luminous efficacy model (G7)

The work of Dieste-Velasco et al. (2019) presents a benchmarking of 18 global luminous efficacy models. The researchers proposed a new model suitable for all-sky conditions (see Equation (23)), in addition to 3 models that are adapted to clear, partly-cloudy and overcast skies.

$$K_g = a_{G7} \exp[b_{G7} K_t \sin(c_{G7} \alpha^2)] \; . \qquad (23)$$

Original coefficients based on data recorded in Burgos (Spain) as well as locally adjusted coefficients are presented in Table 9.

Table 9
Original and locally calibrated coefficients of the Dieste-Velasco et al. global luminous efficacy model (G7).

Coefficient	a_{G7}	b_{G7}	c_{G7}
Original	111.616	-0.127	1.232
Calibrated	104.048	-0.020	5.107

5.2. Diffuse luminous efficacy models

The 5 diffuse luminous efficacy models analyzed in this work, named D1 to D5 and summarized in Table 10, are described in the following subsections. In addition to the model structures, original and locally calibrated coefficients are presented.

Table 10
Diffuse luminous efficacy models.

Model	Authors	Year	Variables
D1	Perez et al. (1990)	1990	$\varepsilon, W, Z, \Delta$
D2	Chung (1992)	1992	D, α, Ω
D3	Muneer and Kinghorn (1997)	1997	K_t
D4	Robledo and Soler (2001)	2001	α, Δ
D5	Kong and Kim (2013)	2013	$\alpha, \mathrm{m}, \Delta, K_t$

5.2.1. *Perez et al. diffuse luminous efficacy model (D1)*

As seen in Equation (24), the model proposed by Perez et al. (1990) for the estimation of the diffuse luminous efficacy has the same structure as the global version of the model expressed in Equation (17). However, the coefficients take different values.

$$K_d = a_{D1} + b_{D1}W + c_{D1}\cos(Z) + d_{D1}\ln(\Delta)\,. \tag{24}$$

Table 11 shows the original and calibrated coefficients of this model.

Table 11
Original and locally calibrated coefficients of the Perez et al. diffuse luminous efficacy model (D1).

Sky clearness	Original coefficients				Calibrated coefficients			
	a_{D1}	b_{D1}	c_{D1}	d_{D1}	a_{D1}	b_{D1}	c_{D1}	d_{D1}
$1 < \varepsilon \le 1.065$	97.24	-0.46	12	-8.91	99.356	1.482	2.884	7.278
$1.065 < \varepsilon \le 1.230$	107.22	1.15	0.59	-3.95	92.556	2.325	4.590	-13.994
$1.230 < \varepsilon \le 1.500$	104.97	2.96	-5.53	-8.77	85.682	2.956	2.315	-22.221
$1.500 < \varepsilon \le 1.950$	102.39	5.59	-13.95	-13.9	84.647	3.500	5.489	27.290
$1.950 < \varepsilon \le 2.800$	100.71	5.94	-22.75	-23.74	76.746	5.421	19.957	38.176
$2.800 < \varepsilon \le 4.500$	106.42	3.83	-36.15	-28.83	68.682	5.524	-33.042	-46.841
$4.500 < \varepsilon \le 6.200$	141.88	1.9	-53.24	-14.03	87.4012	6.039	-41.825	-37.073
$\varepsilon > 6.200$	152.23	0.35	-45.27	-7.98	114.591	4.530	42.515	23.827

5.2.2. *Chung diffuse luminous efficacy model (D2)*

Chung's proposal for diffuse luminous efficacy (Chung, 1992) differs from its global model, as seen in Equation (25). While the model's structure is identical in the case of overcast skies ($D > 0.8$), a constant value is considered for clear skies ($D < 0.3$). For its part, the model depends only on D when considering partly-cloudy skies ($0.3 < D < 0.8$).

$$K_d = \begin{cases} a_{D2} & D < 0.3 \\ b_{D2} + c_{D2}\cdot D & 0.3 < D < 0.8 \\ \left(d_{D2} + e_{D2}\cdot\alpha + f_{D2}\cdot\alpha^2\right)\left(g_{D2} + h_{D2}\cdot\Omega + i_{D2}\cdot\Omega^2\right) & D > 0.8 \end{cases}. \tag{25}$$

Original and adjusted coefficients are shown in Table 12.

Table 12
Original and locally calibrated coefficients of the Chung diffuse luminous efficacy model (D2).

Coefficient	a_{D2}	b_{D2}	c_{D2}	d_{D2}	e_{D2}	f_{D2}	g_{D2}	h_{D2}	i_{D2}
Original	137	135.3	-25.7	102.2	0.67	$-5.9 \cdot 10^{-3}$	1.18	$-8.7 \cdot 10^{-4}$	$9.3 \cdot 10^{-7}$
Calibrated	142.38	161.92	-61.09	100.59	5.72	3.90	1.35	$-5.79 \cdot 10^{-4}$	$3.48 \cdot 10^{-7}$

5.2.3. Muneer and Kinghorn diffuse luminous efficacy model (D3)

The Muneer and Kinghorn (1997) model structure for the estimation of the diffuse luminous efficacy (see Equation (26)) is identical to the one proposed for global luminous efficacy despite the different original and adjusted coefficients, as seen in Table 13.

$$K_d = a_{D3} + b_{D3}K_t + c_{D3}K_t^2 \ . \tag{26}$$

Table 13
Original and locally calibrated coefficients of the Muneer and Kinghorn diffuse luminous efficacy model (D3).

Coefficient	a_{D3}	b_{D3}	c_{D3}
Original	130.2	-39.828	49.9797
Calibrated	115.143	53.482	-24.137

5.2.4. Robledo and Soler diffuse luminous efficacy model (D4)

Robledo and Soler (2001) presented 3 diffuse luminous efficacy models that are suitable for all sky types: an extended model with two independent variables (Δ and α), a simplified model depending solely on Δ and 3 specific models for each of the 3 sky types categorized according to ε (Perez et al., 1990). The results of that study concluded that the use of specific models for each sky type only improved the estimation accuracy in the case of overcast skies. In contrast, the extended (Equation (27)) and simplified (Equation (28)) models had similar behavior; thus, both have been included in this paper as model D4.1 and D4.2, respectively.

$$K_d = a_{D4.1} \sin(\alpha)^{b_{D4.1}} \, \Delta^{c_{D4.1}} \ . \tag{27}$$

$$K_d = a_{D4.2}\Delta^{b_{D4.2}} \ . \tag{28}$$

Original and calibrated coefficients for both models are presented in Table 14.

Table 14
Original and locally calibrated coefficients of the Robledo and Soler diffuse luminous efficacy model (D4).

Coefficient	$a_{D4.1}$	$b_{D4.1}$	$c_{D4.1}$
Original 4.1	86.68	-0.034	-0.266
Calibrated 4.1	87.240	-0.078	-0.228
Original 4.2	91.07	-0.254	-
Calibrated 4.2	96.683	-0.207	-

5.2.5. Kong and Kim diffuse luminous efficacy model (D5)

In Kong and Kim's work (Kong and Kim, 2013), a diffuse luminous efficacy model was proposed depending on α, m, Δ and K_t, the structure of which is shown in Equation (29).

$$K_d = a_{D5} + b_{D5}\alpha + c_{D5}m + d_{D5}\Delta + e_{D5}K_t\ . \quad (29)$$

The original model coefficients, adjusted for Yongin (South Korea) skies, as well as those fitted to the local conditions considered in this paper, are shown in Table 15.

Table 15
Original and locally calibrated coefficients of the Kong and Kim diffuse luminous efficacy model (D5).

Coefficient	a_{D5}	b_{D5}	c_{D5}	d_{D5}	e_{D5}
Original	164.403	0.166	-5.759	-20.393	-46.974
Calibrated	176.733	-14.064	0.605	-165.868	0.915

6. Results

6.1. Evaluation and selection of the luminous efficacy models

This Section presents the evaluation results of the global and diffuse luminous efficacy models considered. Table 16 shows the results obtained by each of the global luminous efficacy models for the 5 statistical indicators of Section 3. As seen, the locally fitted G1 model (Perez et al., 1990) achieves the best results for all indicators except for rMBE. For this specific indicator, the locally adjusted G4 model (Ruiz et al., 2001) presents the best result. In fact, this model provides very similar results to those of the G1 model for the 5 indicators. Taking these results into account, the locally adjusted G1 model has finally been selected for conversion of the TGYs obtained from the multi-year global horizontal irradiance dataset in TGIYs.

Table 16
Evaluation metrics of the global luminous efficacy models. Those that exhibit the best value for the corresponding indicator are shadowed.

Model	Coefficients	R^2 (-)	rRMSE (%)	rMBE (%)	MPE (%)	RSD (%)
G1	Original	0.998	4.318	2.105	4.066	7.703
	Calibrated	0.998	3.521	0.077	0.252	4.826
G2	Original	0.995	13.547	8.798	6.336	10.985
	Calibrated	0.998	3.790	0.113	0.260	5.159
G3	Original	0.997	8.275	6.958	9.864	12.904
	Calibrated	0.997	5.211	-1.302	0.457	7.179
G4	Original	0.997	8.898	-6.647	-6.235	8.822
	Calibrated	0.998	3.576	0.007	0.287	4.947
G5	Original	0.997	17.172	14.294	15.819	17.607
	Calibrated	0.997	4.346	-0.908	0.360	6.363
G6	Original	0.995	8.096	4.105	10.953	19.285
	Calibrated	0.998	3.737	0.182	0.294	5.239
G7	Original	0.996	6.334	0.617	4.665	10.673
	Calibrated	0.997	4.962	-1.648	0.480	7.340

The same phenomenon occurs regarding the diffuse luminous efficacy. In this case, the locally fitted D1 model (Perez et al., 1990) exhibits the best behavior when predicting diffuse illuminance from diffuse irradiance data for the 5 indicators considered (see Table 17). Thus, this model is selected for conversion of the TGYs obtained from the multi-year diffuse irradiance dataset in diffuse TDIYs.

Table 17
Evaluation metrics of the diffuse luminous efficacy models. Those that exhibit the best value for the corresponding indicator are shadowed.

Model	Coefficients	R^2 (-)	rRMSE (%)	rMBE (%)	MPE (%)	RSD (%)
D1	Original	0.991	8.149	-0.164	0.016	8.139
	Calibrated	0.992	7.555	-0.041	0.505	7.253
D2	Original	0.991	9.348	-2.967	-5.861	11.444
	Calibrated	0.989	10.268	1.707	-0.888	10.127
D3	Original	0.988	12.116	-3.885	-7.895	14.444
	Calibrated	0.988	17.622	6.418	1.818	13.411
D4.1	Original	0.990	8.873	2.507	2.906	9.578
	Calibrated	0.990	8.19	-0.218	0.687	8.524
D4.2	Original	0.990	9.790	3.660	3.047	10.203
	Calibrated	0.991	9.258	2.271	0.962	9.411
D5	Original	0.984	15.504	-7.771	-14.047	20.388
	Calibrated	0.988	9.559	-0.503	0.644	8.506

6.2. TIY generation

After applying the different procedures for generating TIYs to the illuminance and irradiance data series, a comparison of the typical periods selected in each case has been carried out according to their monthly or daily scale. With respect to the monthly TIYs, Figure 8a shows the selected typical months that make up the TGIYm and TGIYm$_{ef}$, that is, the TIY obtained from the global horizontal illuminance data series and the one obtained after applying the selected global luminous efficacy model to the TGY generated from the global horizontal irradiance data. A coincidence of 50% can be observed (6 typical months). Moreover, Figure 8b shows the typical months that make up the TIYs related to the diffuse illuminance variable (TDIYm) and diffuse irradiance variable (TDIYm$_{ef}$). In this case, only 16% of the months show a match.

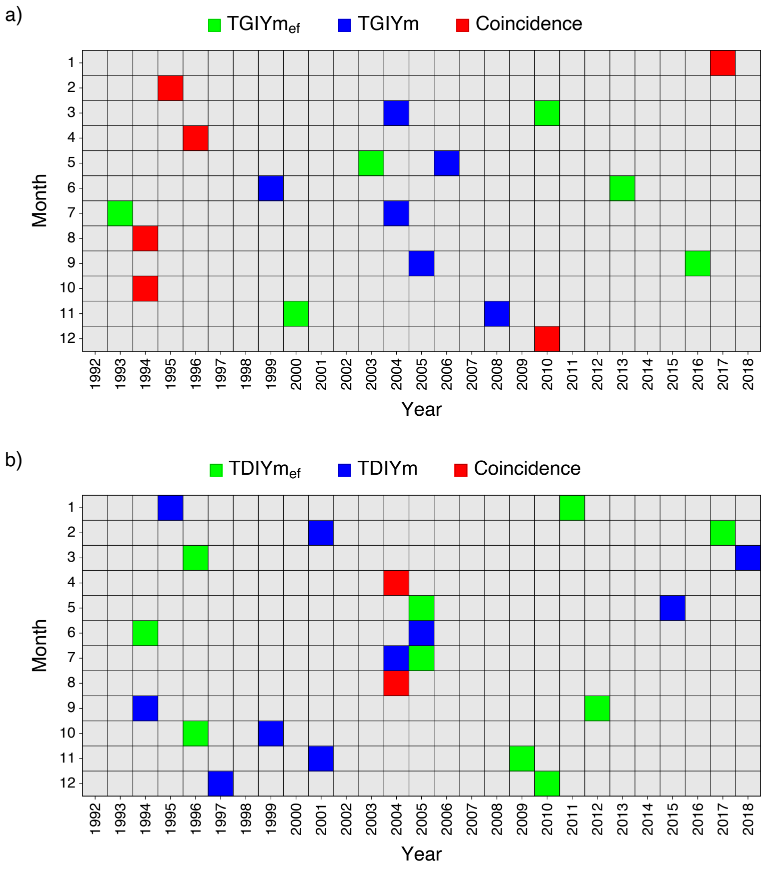

Figure 8. Composition of the considered global (a) and diffuse (b) TIYs. Coincident years are shown in red.

Figure 9 shows the typical days that make up the daily global versions of the TIY, that is, the one generated from the illuminance data series (TGIYd) and that obtained through analysis of the irradiance data series and subsequently submitted to the global luminous efficacy model (TGIYd$_{ef}$). The coincidence of typical days between both TIYs (marked in red in the figure) amounts to 66.3%.

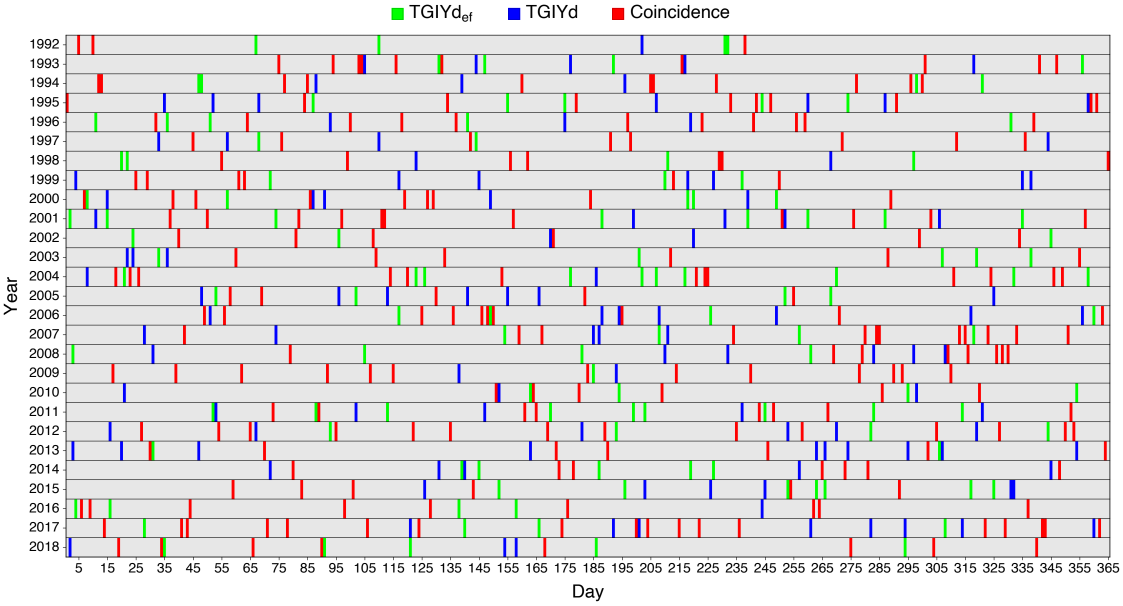

Figure 9. Typical days that make up TGIYd and TGIYd$_{ef}$. As an example, the 1st of January of TGIYd and TGIYd$_{ef}$ are both from 1995. In contrast, the 2nd of January of TGIYd is from 2018 whereas that of TGIYd$_{ef}$ is from 2001. Coincident days are shown in red.

The distribution of typical days integrating the daily diffuse versions of the TIY can be appreciated in Figure 10, that is, the one resulting from the analysis of the diffuse illuminance data series (TDIYd) and that generated from the irradiance data series to which the selected diffuse luminous efficacy model (TDIYd$_{ef}$) has been applied. Here, the coincidence of typical days between both TIYs decreases to 26.3%.

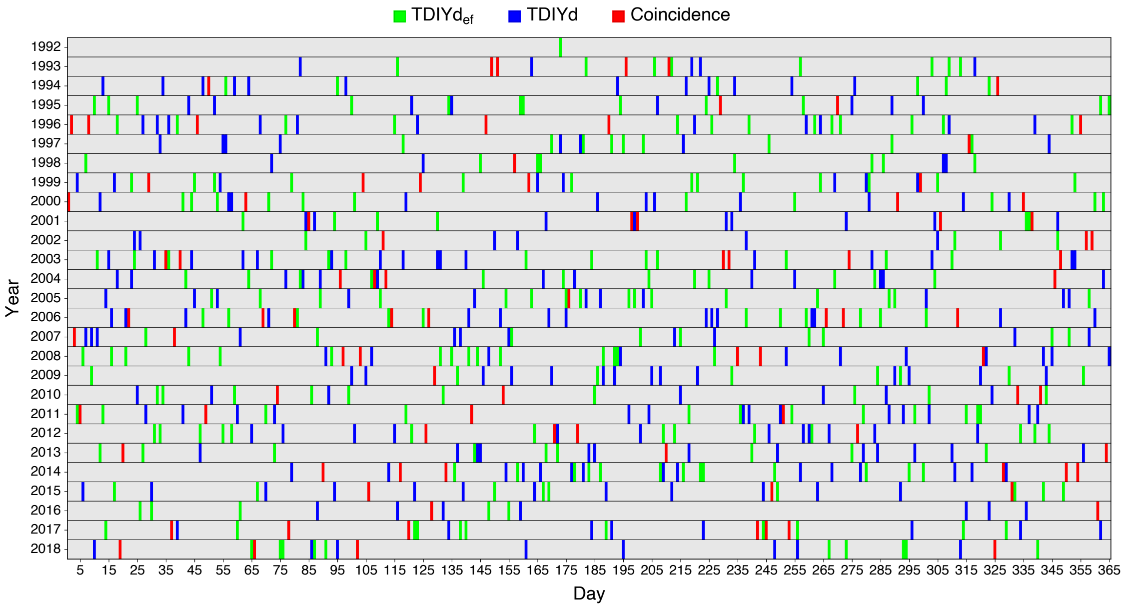

Figure 10. Typical days that make up TDIYd and TDIYd$_{ef}$. As an example, the 1st of January of TDIYd and TDIYd$_{ef}$ are both from 2000 and the 2nd of January are both from 1996. Coincident days are shown in red.

6.3. TIY evaluation

After comprising the different TIYs through concatenation of the selected typical days or typical months, the indicators F_1 to F_8 described in Section 3 were applied. The purpose of these indicators is to quantify the degree of agreement between the different TIYs and the long-term global and diffuse global illuminance data series on an annual, monthly, daily and hourly time scale. In addition to the aforementioned indicators, F_G was additionally calculated, which evaluates the overall performance of TIY and was calculated in accordance with Equation (30).

$$F_G = R_{F1} + (R_{F2} + R_{F3} + R_{F4})/3 + (R_{F5} + R_{F6})/2 + (R_{F7} + R_{F8})/2\,, \qquad (30)$$

where R_{F1} to R_{F8} are the resulted order of each indicator F_1 to F_8 obtained by a TIY regarding the set of studied TIYs.

The analysis of the TIYs corresponding to the global and diffuse illuminance variable has been performed separately. Table 18 shows the indicator values obtained by each global TIY. The TIY consisted of typical months selected from the analysis of the illuminance series (TGIYm) presents the best overall performance, closely followed by the one consisted of typical days (TGIYd). When analyzing the annual indicator (F_1), the year obtained by selecting typical months from the irradiance series and subsequent application of a global luminous efficacy model (TGIYm$_{ef}$) exhibits the best performance among the 4 TIYs analyzed. However, TGIYm behaves the best from the perspective of monthly indicators (F_2 to F_4). For its part, TIY obtained by concatenating typical days selected from the global illuminance series (TGIYd) exhibits the best daily and hourly behavior (F_5 to F_7), followed by the daily TIY obtained by applying a luminous efficacy model (TGIYd$_{ef}$).

Table 18
Values of F_1 to F_8 indicators and F_G value (overall performance) obtained for each global TIY (the ranked order of each value is shown in brackets).

TIY	TGIYd$_{ef}$		TGIYd		TGIYm$_{ef}$		TGIYm	
F_1 (R_{F1})	14314.92	(3)	14825.97	(4)	7861.24	(1)	8627.86	(2)
F_2 (R_{F2})	1665.69	(3)	1683.09	(4)	1453.98	(2)	1415.64	(1)
F_3 (R_{F3})	8.79	(4)	8.77	(3)	5.31	(2)	3.72	(1)
F_4 (R_{F4})	1324.98	(3)	1340.40	(4)	806.77	(2)	738.13	(1)
F_5 (R_{F5})	132.78	(2)	132.20	(1)	167.96	(4)	164.13	(3)
F_6 (R_{F6})	55.24	(2)	52.44	(1)	132.77	(4)	123.30	(3)
F_7 (R_{F7})	15.37	(2)	15.20	(1)	17.12	(3)	17.15	(4)
F_8 (R_{F8})	10.78	(2)	10.33	(1)	14.39	(4)	14.33	(3)
F_G		10.33		9.67		10.50		9.50

Table 19 shows the value of the indicators F_1 to F_8 reached by the 4 diffuse TIYs studied. In this case, TDIYd obtains the best overall result (F_G). For its part, TDIYm exhibits the best yearly performance, whereas the monthly-based TIY obtained from the irradiance series and the application of a diffuse efficacy model (TDIYm$_{ef}$) achieves the best results in monthly indicators (F_2 to F_4). As in the case of global TIYs, TDIYd exhibits the best daily and hourly behavior (F_5 to F_8).

Table 19
Values of F_1 to F_8 indicators and F_G value (overall performance) obtained for each diffuse TIY (the ranked order of each value is shown in brackets).

TIY	TDIYd$_{ef}$		TDIYd		TDIYm$_{ef}$		TDIYm	
F_1 (R_{F1})	10012.10	(4)	9538.28	(3)	6226.82	(2)	5080.20	(1)
F_2 (R_{F2})	907.35	(4)	872.37	(3)	688.96	(1)	713.90	(2)
F_3 (R_{F3})	21.83	(4)	14.40	(3)	4.87	(1)	7.18	(2)
F_4 (R_{F4})	738.98	(4)	723.43	(3)	362.75	(1)	435.49	(2)
F_5 (R_{F5})	54.52	(2)	54.22	(1)	68.46	(4)	66.03	(3)
F_6 (R_{F6})	21.75	(2)	20.97	(1)	52.69	(4)	49.36	(3)
F_7 (R_{F7})	7.28	(2)	7.17	(1)	7.89	(3)	7.89	(4)
F_8 (R_{F8})	5.36	(2)	5.05	(1)	6.48	(3)	6.50	(4)
F_G		12.00		8.00		10.00		10.00

6.4. Comparison between TIYs generated from illuminance and irradiance datasets

One of the main objectives of this paper is to verify whether TIYs obtained by applying a luminous efficacy model to TRYs generated from irradiance data can replace TIYs obtained from illuminance data. It must be recalled that this proposal arises from the small number of stations recording illuminance data compared with those that register irradiance ones. Thus, both proposals were compared at 3 levels: (1) comparison of means, (2) comparison of standard deviations and (3) comparison of cumulative distributions.

Figure 11 shows the average annual illuminance values and standard deviation for the different TIYs. The average annual illuminance values and standard deviation are very similar when comparing TIYs obtained from illuminance data and those generated by applying a luminous efficacy model to the irradiance-based TRY. This situation occurs both in the case of global and of diffuse illuminances and when the TIYs are obtained by concatenation of months or of typical days.

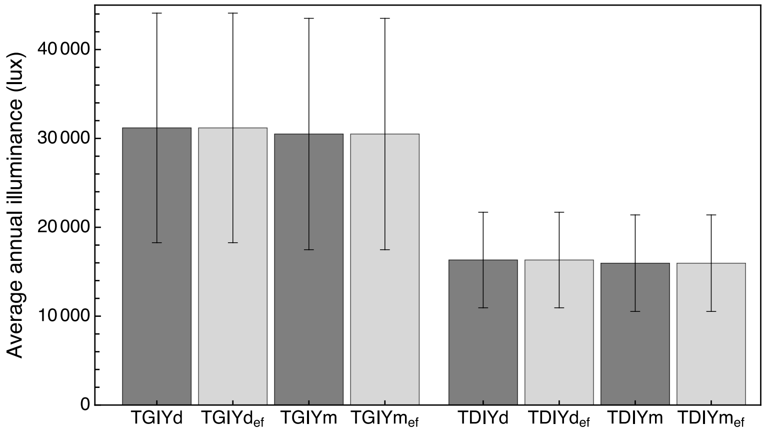

Figure 11. Annual average and standard deviation (represented by the error bars) of the illuminance values in the different typical years considered.

Regarding the third comparison level, Figure 12 shows the CDFs of the illuminance values corresponding to the different TIYs analyzed. It can be seen that both distribution functions corresponding to the illuminance-based TIYs and those based on irradiance data and subsequently submitted to a luminous efficacy model are very similar. The biggest differences are between the CDFs of the monthly TDIYs (Figure 12d).

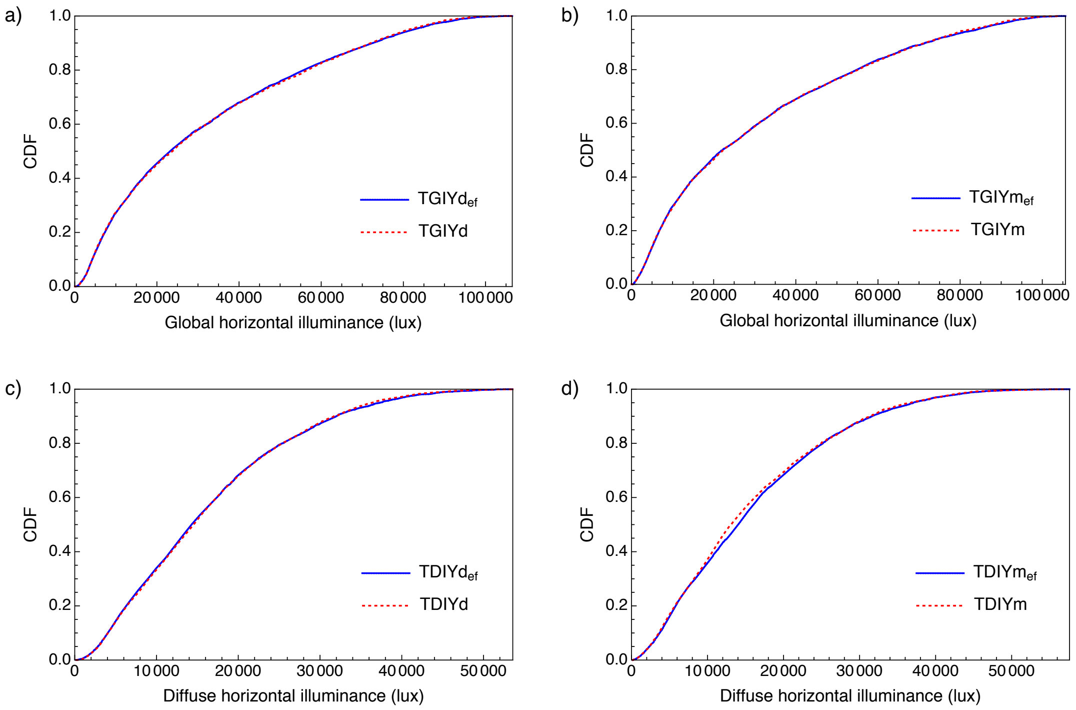

Figure 12. Comparison of the CDFs of the illuminance values corresponding to the TIYs generated from illuminance data and obtained from irradiance data and submitted to a luminous efficacy model: (a) daily-based TGIYs, (b) monthly-based TGIYs, (c) daily-based TDIYs and (d) monthly-based TDIYs.

The comparison of CDFs has been carried out using the Kolmogorov-Smirnov distance (KSD), which is presented in Equation (31).

$$KSD = \mathrm{Max}\left|CDF_{i,\mathrm{mod}} - CDF_{i,obs}\right| , \tag{31}$$

where $CDF_{i,mod}$ is the CDF of the modeled illuminance (obtained by applying a luminous efficacy model to the TRY generated from irradiance data) and $CDF_{i,obs}$ is the CDF of the observed or measured illuminance.

Table 20 shows the KSD values corresponding to the CDFs of the modeled and observed TIYs. In all cases, the obtained KSD are lower than the critical values established by Massey (1951), for a 99% level of significance considering a sample size greater than 35.

Table 20
KSDs among the CDFs of the observed and modeled meteorological years.

TIY	TGIYd vs TGIYd$_{ef}$	TGIYm vs TGIYm$_{ef}$	TDIYd vs TDIYd$_{ef}$	TDIYm vs TDIYm$_{ef}$
KSD	0.0105	0.0091	0.0113	0.0371

7. Conclusions

Accurate information on global or diffuse illuminance is becoming essential in an increasing number of applications that consider daylight for energy-efficient design purposes. A procedure was proposed and evaluated in the present work for the generation of a typical illuminance year (TIY) considering illuminance as the only variable for selecting the typical periods that make up the reference year. Two versions of TIY were presented, one composed of 12 typical months selected from the series of observations and another composed of 365 typical days. The methodology allowed the generation of TIYs for both global and diffuse illuminance in most locations. In the case that no illuminance data available, the application of a luminous efficacy model to a TRY generated from irradiance data to obtain a TIY was proposed. Thus, 12 luminous efficacy models were calibrated and tested for the local conditions of Vaulx-en-Velin from a 27-

year dataset. The fitted G1 and D1 models for global and diffuse illuminance, respectively, exhibited the best behavior and, therefore, they were selected to be applied to the TRYs generated from irradiance data to obtain a TIY_{ef}.

A comparison of the selected typical periods to be concatenated for the generation of TIYs from the illuminance and irradiance data series at daily and monthly scales resulted in a number of coincidences ranging from 66.3% of days in the case of TGIYd and $TGIYd_{ef}$ to only 16% of months for TDIYm and $TDIYm_{ef}$.

The obtained daily and monthly TIYs for the global and the diffuse illuminance were compared to the long-term global and diffuse illuminance data series for different time scales with the aid of 9 statistical indicators. The monthly version of TIY obtained from measured illuminance data (TGIYm) exhibited the best overall performance regarding global illuminance, closely followed by the one consisted of typical days (TGIYd). The daily version (TDIYd) had the best overall result for diffuse illuminance. Notwithstanding, the best resulting TIY changed for the different considered time scales.

Finally, different statistics were used to validate the proposed methodology for TIY generation by applying a luminous efficacy model to TRYs based on irradiance data. Taking into account the similarity to means, typical deviations and cumulative distribution functions, it can be concluded that the illuminance-based TIYs and irradiance-based TIYs are statistically indistinguishable regardless of the typical periods considered (months or days). Therefore, it is possible to recommend the use of a TIY obtained after applying a luminous efficacy model to a TRY generated from irradiance data when it comes to assess the long-term daylight in a given location.

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