# Temporal downscaling of test reference years: effects on the long-term evaluation of photovoltaic systems

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## ABSTRACT

Representative meteorological data from a given location are necessary to assess the long-term performance of photovoltaic (PV) systems. Test reference years (TRYs) or typical meteorological years (TMYs) are widely used as input to PV models. Most of current procedures propose the construction of TRYs by concatenating 12 months belonging to different years of a dataset. This paper evaluates the effects of the temporal downscaling of typical periods that compose different TRYs on the long-term assessment of PV systems. The Festa-Ratto TRY, WYSS, EN ISO 15927-4 TRY, TMY3, TGY and TDY are used. Thus, an adapted version of these six methodologies aimed at the selection of typical days rather than months is proposed. The electricity production obtained by simulation for daily and monthly TRYs is compared with simulations performed for each actual year of the dataset. This analysis is performed for seven locations in the USA considering a 5.6 kWp grid-connected PV system. The results reveal that the timescale reduction improves the behavior of Festa-Ratto TRY, WYSS, TMY3, TDY and TDY when estimating the long-term production of a PV system considering the hourly, daily, monthly and annual timescales, while the modified EN ISO 15927-4 TRY performs worse than its monthly version.

## KEYWORDS

test reference year; temporal downscaling; PV systems

## NOMENCLATURE

| | |
|---|---|
| $EP_y$ | yearly electricity production of a year $y$ (kWh). |
| $EP_t$ | yearly electricity production of a reference year $t$ (kWh). |
| $j$ | number of years of the historic data series. |
| $SEE_m$ | standard error of estimates on monthly electricity production of a month $m$. |
| $EP_{ym}$ | monthly electricity production of a month $m$ and a year $y$ (kWh). |
| $EP_{ymd}$ | daily electricity production of a day $d$ of a month $m$ of a year $y$ (kWh). |
| $\overline{EP}_m$ | mean value of monthly electricity production of a month $m$ of long-term data (kWh). |
| $EP_{tm}$ | monthly electricity production of a month $m$ of a test reference year $t$ (kWh). |
| $\sigma_{\overline{EP_m}}$ | standard deviation of simple means of monthly electricity production of a month $m$ (kWh). |
| $SEE_d$ | standard error of estimates on daily electricity production of a day $d$. |
| $EP_{yd}$ | daily electricity production of a day $d$ of a year $y$ (kWh). |
| $EP_{td}$ | daily electricity production of a day $d$ of a test reference year $t$ (kWh). |
| $\overline{EP}_d$ | mean value of daily electricity production of a day $d$ of long-term data (kWh). |
| $SEE_h$ | standard error of estimates on hourly electricity production of an hour $h$. |
| $EP_{yh}$ | hourly electricity production of an hour $h$ of a year $y$ (kWh). |
| $EP_{th}$ | hourly electricity production of an hour $h$ of a test reference year $t$ (kWh). |
| $\overline{EP}_h$ | mean value of hourly electricity production of an hour $h$ of long-term data (kWh). |
| $\Phi(p,d,i)$ | long-term cumulative distribution function of the hourly means of a day $d$ for a climatic parameter $p$. |
| $K(i)$ | rank order of the $i^{th}$ hourly value of a parameter $p$ for a day $d$. |
| $N$ | total number of hours for a specific day over all the available years. |
| $F(p,y,d,i)$ | short-term cumulative distribution function of the hourly means for a day $d$ of a year $y$ for a climatic parameter $p$. |
| $J(i)$ | rank order of the $i^{th}$ value of the hourly means within a day $d$ of a year $y$ |
| $n$ | number of hours for a specific day. |
| $F_S(p,y,d)$ | Finkelstein-Schafer statistic of a day $d$ within a year $y$ for a climatic parameter $p$. |
| $WS(y,d)$ | weighing sum of the $F_S$ statistic of each parameter of a day $d$ within a year $y$. |
| $WF_x$ | weighing factor of parameter $x$. |
| $P$ | total number of parameters considered for the TMY3. |

## 1. INTRODUCTION

Representative or typical meteorological data of the most frequent weather conditions at a given location are frequently used to assess the long-term performance of photovoltaic (PV) projects at the design stage. These datasets may be used for the simulation of electrical energy supplied by a PV system over the long-term.

One of the first approaches that uses real measurements to characterize local climates over the long term is the test reference year (TRY) of the National Climatic Data Center [1], which consists of a selection of one whole year of meteorological measurements. This method results in a particularly mild year as it progressively excludes years with extreme weather conditions. As a result, most of the subsequent approaches propose the construction of a TRY through the concatenation of 12 typical months belonging to different years of a dataset. The dataset for this year thus includes 8,760 records corresponding to the concatenation of hourly measurements for each selected month. The meteorological data used for the generation of a TRY could come from both observed or synthetic data. This issue is addressed by Lhendup and Lhundup [2] in a review of different methodologies to generate TMY data when long-term observed meteorological data is not available for a particular location.

One of the most commonly used approaches for the selection of a set of 12 typical real months is the method developed by the Sandia National Laboratories (cited hereafter as the Sandia method) [3], that leads to obtain the typical meteorological year (TMY). Here, the Finkelstein-Schafer statistic ($F_S$) [4] is used to compare cumulative distribution functions (CDFs) for both short- and long-term daily mean values of each meteorological parameter considered. Then, for each month of the year, five candidate months are selected according to the lower weighed sum (*WS*) of $F_S$ values obtained for each parameter. These five candidate months are ranked based on the closeness of a given month to the long-term mean and median. Finally, a persistence analysis is carried out to select from the five candidates the typical meteorological month (TMM) that integrates the TMY.

This method has been used by Pissimanis et al. [5] in the construction of a TMY for the city of Athens (Greece) and by Petrakis et al. [6] for its construction for Nicosia (Cyprus).

Sawaqed et al. [7] describe a step-by-step application of the Sandia method in developing TMYs for seven locations in Oman while varying the weights proposed for the original methodology. Ohunakin et al. [8] used this detailed description of the Sandia method to obtain a TMY for Sokoto (Nigeria).

A subsequent modification of the Sandia National Laboratory methodology developed by the NREL that led the development of the TMY2 [9] maintains $F_S$ statistic treatment although it modifies the considered climatic parameters and their weighing factors (*WF*). This method has been used by Kalogirou [10] in the generation of a TMY2 for Nicosia (Cyprus). In this way, modifications to the climatic variables and weighting coefficients proposed for the original Sandia method have been recommended by authors such as Chow et al. [11] and Zang et al. [12].

In 2002, the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) developed a procedure for obtaining the International Weather for Energy Calculations (IWEC) [13]. This method follows the TMY procedure in terms of selecting five candidate months, i.e., the five months with the lowest *WS* values. However, the persistence criterion applied for the original Sandia method is omitted. According to the authors, this criterion can lead to the rejection of all five candidate months, particularly when data for only a few years are available. Instead, a typical month is selected by choosing the candidate with the smallest deviation of monthly means and medians from the long-term mean and median for dry-bulb temperature and solar radiation.

Following from the IWEC philosophy, some proposals apply the Sandia procedure regardless of the persistence criterion involved. In certain instances, the month with the lowest *WS* of Finkelstein-Schafer statistics obtained for each meteorological variable is integrated into the TMY. This was done by Chan et al. [14] in generating a TMY for Hong Kong using 25 years of weather data. An updated Hong Kong TMY was recently produced by Chan [15] on the basis of a 35-year measured weather dataset. Likewise, this work presents a novel means of optimizing weights considered in the *WS* via the use of a genetic algorithm. This procedure allows one to determine different sets of weighting factors based on the energy system under evaluation. The Sandia modified procedure has also been used for the generation of TMY datasets for 8 locations in Turkey representing distinct climatic zones in the country [16] and for the construction of a TMY for 15 locations in the Argentine Littoral Region [17].

The elimination of all candidate months resulting from a strict application of the TMY procedure was addressed by Wilcox and Marion [18] in the development of the TMY3. Using this approach, the persistence criterion is relaxed to ensure that a candidate month is selected. Thus, when the TMY3 persistence procedure eliminates all candidate months, persistence is ignored and the candidate month with the closest mean and median to the long-term mean and median is selected.

The European technical standard EN ISO 15927-4 [19] describes another proposal based on the $F_S$ statistic. It is aimed at the construction of a reference year suitable to evaluate the annual energy demand for heating and cooling in buildings. However, unlike the above-mentioned procedures, the EN ISO 15927-4 method (cited hereafter as the ISO method) assigns the same weight to all climatic variables considered. This method has been used by Kragh et al. [20] for the construction of two TRYs for Greenland. Likewise, Kalamees and Kurnitski [21] used the ISO method for TRY generation for 6 locations in Estonia and Lee et al. [22] used the method for TRY construction for 7 cities in South Korea. Ruduks and Lešinskis [23] also generated an ISO TRY for Alūksne (Latvia) by analyzing 30 years of weather data. In this case, due to unavailable solar radiation measurements, the parameter was replaced with cloud coverage.

The ISO method proposes the use of dry bulb temperature, global horizontal radiation and relative humidity as the main climatic variables. These three parameters are used to select 3 candidate months. Then, wind speed is employed as a secondary parameter for the selection of a typical month. Through the modified version proposed by Kalamees et al. [24], only temperature and solar radiation are used as the main variables. This work analyzed the influence of different climatic variables on a building's heating and cooling energy consumption with the aim of developing weighting factors for the different climatic variables. After observing that the air temperature has the strongest influence on a building's energy consumption, a seasonally dependent weighting factor was developed for this variable.

The behavior of the ISO TRY in evaluating the energy performance of buildings was assessed by Pernigotto et al. [25] in reference to five cities in northern Italy. Along the same line of research, Pernigotto et al. [26] developed two variations of the original ISO method to improve its representativeness for building energy simulation.

The ISO method was also employed by Eames et al. [27] to replace the UK's TRY released in 2006 [28]. Here, a modification was included so that once 3 candidate months are selected according to the original procedure, the one with the lowest $F_S$ statistic for wind speed is chosen as the representative month.

While ISO TRY is specifically designed for the evaluation of buildings' thermal energy demand, the suitability of this reference year when assessing the long-term performance of PV systems was proved by García and Torres [29]. In this work, electricity produced through a ISO TRY simulation was compared with that produced from the Weather Year for Solar Systems (WYSS) [30]. Comparisons were performed for seven locations in the USA in consideration of two 5.6 kWp grid-connected PV systems. The WYSS is a system-oriented approach that only considers monthly energy collected by the system as a selection parameter of typical months. Therefore, a simulation process is involved when applying this method. In fact, this is one of the few proposals that does not employ meteorological variables for the selection of typical months that compose the TRY.

In line with the development of reference years focused on the evaluation of specific energy systems, the National Renewable Energy Laboratory (NREL) recently developed the typical global year (TGY) and typical direct year (TDY) [31]. These TRYs are suitable for the evaluation of photovoltaics and concentrating solar power projects. These reference years are the result of an application of TMY3 except that in this case, weighting is focused on irradiance rather than on meteorological data.

Between the different energy systems studied in the exhaustive work of Argiriou et al. [32], a PV array of 5.8 $m^2$ facing south with a tilt angle of 40º was considered. Here, a comparison of different methodologies to TRY generation was performed for the city of Athens (Greece). Regarding the aforementioned PV system, of the 17 TRYs produced, the three best were the Danish method [33,34], the modified Festa-Ratto method [35] and one of the nine TMYs that only differs in terms of weights assigned to weather variables. Despite the widespread use of the $F_S$ statistic for comparing short- and long-term cumulative distribution functions of variables involved, the Danish method and its modification listed in the Festa-Ratto proposal use the Kolmogorov-Smirnov D-statistic (*KS*) [36].

A subsequent evaluation of TRYs involving comparisons of the long-term performance of different solar systems (thermal, passive and PV) was conducted by Bilbao et al. [37] in reference to two cities in Spain. With regard to the PV system considered, this work shows that the methods generating better results for PV systems were the Festa-Ratto modified for Madrid and the Danish method for Valladolid.

All of the procedures described thus far for the generation of test reference years propose the selection of a set of twelve typical months composing the TRY. Nevertheless, it seems reasonable to assume that a reduction in the timescale of selected typical periods could produce a more accurate assessment of the long-term behavior of PV systems. A typical meteorological day (TMD) approach to predicting the performance of solar energy systems was developed in the mid-1980s [38]. However, this methodology provides for the selection of a single day of a time series that characterizes the long-term behavior of a given system. Apart from this basic proposal, no existing studies present the composition of a TRY from a concatenation of 365 typical real days of a dataset.

Against this backdrop, this work pursues a dual objective. First, the effects of the temporal downscaling of typical periods that compose six different TRYs on the long-term assessment of PV systems are evaluated. Specifically, the Festa-Ratto TRY, WYSS, ISO TRY, TMY3, TGY and TDY are used. To this end, an adapted version of these six methodologies aimed at the selection of typical days rather than typical months is proposed. Second, the performance of the TRYs based on meteorological variables is compared with that of TRYs derived from an analysis of the electrical output of the PV system.

## 2. METEOROLOGICAL DATA

The meteorological data used in this work were provided by the Surface Radiation Budget Network (SURFRAD). As shown in Fig. 1, the network includes a total of seven stations covering climatologically diverse regions across the USA. Basic geographic data for each station are shown in Table 1.

**Table 1.** Geographic data of the SURFRAD network stations.

| Station | Code | Latitude (N) | Longitude (W) | Elevation (m) |
|---|---|---|---|---|
| Bondville, Illinois | BON | 40° 3' 6" | 88° 22' 24" | 230 |
| Table Mountain, Boulder, Colorado | TBL | 40° 7' 32" | 105° 14' 16" | 1689 |
| Desert Rock, Nevada | DRA | 36° 37' 14" | 116° 1' 403" | 1007 |
| Fort Peck, Montana | FPK | 48° 18' 29" | 105° 6' 6" | 634 |
| Goodwin Creek, Mississippi | GWN | 34° 15' 17" | 89° 52' 22" | 98 |
| Penn. State Univ. Pennsylvania | PSU | 40° 43' 13" | 77° 55' 51" | 376 |
| Sioux Falls, South Dakota | SXF | 43° 44' 4" | 96° 37' 24" | 473 |

Despite the fact that SURFRAD stations measure and register numerous meteorological variables, only five were used for this work, namely dry-bulb air temperature, relative humidity, wind speed, global horizontal irradiance and direct normal irradiance. Regarding the length of the time series, the first SURFRAD stations established began recording in 1994 and the last one established began recording in 2003, and thus, all of them have a series of more than ten years of measurements. In fact, some offer almost double this amount (see Table 2).

Meteorological data are quality controlled by SURFRAD following the procedure recommended by the Baseline Surface Radiation Network (BSRN) [39]. Measurements are organized into daily files and are reported every three minutes to 31 December 2008. Since this date, daily files of one-minute data are provided. The results of our analysis of missing data performed on each dataset corresponding to the different stations are presented in Table 2. Each meteorological variable has been analyzed independently for the determination of percentages shown in the table. Thus, if for a given moment a record of any of the four variables considered is missing or does not pass quality control specifications, the whole moment is not discarded. As is shown, data for most of the available years show few gaps. Years with over 10% of records missing have been removed from the dataset. Isolated gaps up to one day or erroneous data found for the remaining years have been filled by the simple linear interpolation method between previous and subsequent days without missing data proposed by Argiriou et al. [32].

**Table 2.** Annual percentages of missing data and time series considered for each station.

| Year | Station code | | | | | | |
|---|---|---|---|---|---|---|---|
| | BON | TBL | DRA | FPK | GWN | PSU | SXF |
| 1996 | 2.80 | 1.80 | - | - | 1.00 | - | - |
| 1997 | 5.80 | 1.00 | - | 5.80 | 3.20 | - | - |
| 1998 | 0.40 | 0.40 | - | 1.60 | 1.00 | - | - |
| 1999 | 12.80 | 0.00 | 0.20 | 0.60 | 0.80 | 0.00 | - |
| 2000 | 0.20 | 0.20 | 0.80 | 0.00 | 0.00 | 1.60 | - |
| 2001 | 0.00 | 0.20 | 0.20 | 4.60 | 0.20 | 0.00 | - |
| 2002 | 0.60 | 0.20 | 1.20 | 0.20 | 0.00 | 0.20 | - |
| 2003 | 0.00 | 0.20 | 0.00 | 0.20 | 9.40 | 0.00 | - |
| 2004 | 0.20 | 0.20 | 0.00 | 0.40 | 12.80 | 5.20 | 0.00 |
| 2005 | 0.40 | 0.20 | 2.40 | 0.20 | 0.00 | 1.00 | 0.40 |
| 2006 | 2.40 | 0.20 | 1.00 | 0.80 | 0.00 | 0.80 | 0.80 |
| 2007 | 0.00 | 0.00 | 0.00 | 0.00 | 1.20 | 4.00 | 0.40 |
| 2008 | 0.20 | 0.20 | 2.00 | 0.20 | 0.80 | 0.40 | 0.00 |
| 2009 | 1.00 | 0.60 | 0.00 | 0.00 | 2.00 | 0.60 | 0.00 |
| 2010 | 0.00 | 0.20 | 3.00 | 0.00 | 3.40 | 0.00 | 0.00 |
| 2011 | 0.00 | 0.20 | 0.00 | 0.00 | 3.60 | 0.20 | 0.20 |
| 2012 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.00 |
| 2013 | 0.20 | 0.20 | 0.00 | 0.00 | 2.20 | 1.00 | 0.20 |
| 2014 | 0.00 | 0.00 | 0.20 | 0.20 | 2.80 | 0.20 | 0.20 |
| Period considered | 1996-2014 | 1996-2014 | 1999-2014 | 1997-2014 | 1996-2014 | 1999-2014 | 2004-2014 |
| Removed years | 1999 | - | - | - | 2004 | - | - |
| Total years | 18 | 19 | 16 | 18 | 18 | 16 | 11 |

## 3. METHODOLOGY

For this work, six different methodologies for the generation of TRYs were adapted and evaluated:

1) **Festa-Ratto method:** the procedure proposed by Festa and Ratto [35] allows for the use of any variable (empirical meteorological data or results of calculations such as estimations of the performance of a certain solar energy system). We took advantage of the method's flexibility. On the one hand, it was studied the behavior of the Festa-

Ratto TRY obtained from meteorological variables. On the other hand, a similar evaluation was performed for the Festa-Ratto TRY generated on the basis of electrical outputs of a PV system.

2) **WYSS method:** this is a system-oriented approach, as the selection of the typical months that compose the TRY is based on analysis of the solar gain of the system and not directly on meteorological parameters. Thus, technical characteristics of the system concerned are implicitly involved in the selection of typical months to obtain a reference year that minimizes the error involved in estimating the amount of energy generated [30]. Despite the fact that this method was originally developed to assess the long-term performance of solar thermal systems, for this work, it was modified for use in PV systems as proposed in [29].
3) **ISO method:** the methodology proposed in the standard EN ISO 15927-4 bases the selection of typical months on the comparison of short- and long-term CDFs of the different meteorological variables considered.
4) **TMY3 method:** the procedure described by Wilcox and Marion [18] for the generation of the TMY version 3 (TMY3) data sets, was created based on the methodology developed by Sandia National Laboratories to create the original TMYs from the 1952-1975 SOL-MET/ERSATZ data [3]. The Sandia method bases the selection of the typical months in the analysis of nine climatic parameters. However, for the second version of the TMY (TMY2) and TMY3, an index for direct normal irradiation was added. Also, for the TMY3, the persistence criteria were relaxed to ensure that a candidate month would be selected from data series with fewer years than those used in the two previous versions.
5) **TDY and TGY methods:** the methods developed by the NREL for obtaining typical direct (normal irradiance) year (TDY) and typical global (horizontal) year (TGY)

data sets follow the principles of the TMY3. The only difference between the TMY3 and TDY and TGY data sets is the $WF$ used for generating the data sets. The TDY data set is developed using 100% weighting for direct normal irradiance, whereas the TGY data set uses 100% weighting for global horizontal irradiance.

The original formulation of the six methods outlined above proposes the selection of twelve typical months from a historical series of observations that will integrate the TRY. As noted above, this paper aims to evaluate the effects of reducing the timescale of typical periods on the adequacy of these TRYs for assessing the performance of PV systems over the long term. Hence, each of the six methods was adapted with the objective of selecting typical days rather than typical months. As a result of such variation, the new TRYs obtained will result from the concatenation of 365 typical days selected from the multi-year dataset. Codes given to each of the fourteen TRYs analyzed along with their parameters and $WFs$ are shown in Table 3. As can be seen, 10 meteorological parameters and one production parameter have been considered, namely maximum, minimum and mean dry-bulb air temperature ($T_{max}$, $T_{min}$, $\overline{T}$) and relative humidity ($RH_{max}$, $RH_{min}$, $\overline{RH}$), maximum and mean wind speed ($W_{max}$, $\overline{W}$), global horizontal irradiance ($\overline{G}$), direct normal irradiance ($\overline{D}$) and electricity production of the PV system ($\overline{EP}$). Given that the study was extended to seven stations, 98 TRYs were considered in total.

**Table 3.** Description of the TRYs and parameters considered.

| TRY | Method | Typical period | Parameters and weighing factors | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | $T_{max}$ | $T_{min}$ | $\overline{T}$ | $RH_{max}$ | $RH_{min}$ | $\overline{RH}$ | $W_{max}$ | $\overline{W}$ | $\overline{G}$ | $\overline{D}$ | $\overline{EP}$ |
| $\mathrm{TRY}_{\mathrm{ISOm}}$ | EN ISO | Month | - | - | 1/3 | - | - | 1/3 | - | * | 1/3 | - | - |
| $\mathrm{TRY}_{\mathrm{ISOd}}$ | EN ISO | Day | - | - | 1/3 | - | - | 1/3 | - | * | 1/3 | - | - |
| $\mathrm{TRY}_{\mathrm{WYSSm}}$ | WYSS | Month | - | - | - | - | - | - | - | - | - | - | 1 |
| $\mathrm{TRY}_{\mathrm{WYSSd}}$ | WYSS | Day | - | - | - | - | - | - | - | - | - | - | 1 |
| $\mathrm{TRY}_{\mathrm{FRMm}}$ | Festa-Ratto | Month | - | - | 1/4 | - | - | 1/4 | - | 1/4 | 1/4 | - | - |
| $\mathrm{TRY}_{\mathrm{FRMd}}$ | Festa-Ratto | Day | - | - | 1/4 | - | - | 1/4 | - | 1/4 | 1/4 | - | - |
| $\mathrm{TRY}_{\mathrm{FRPm}}$ | Festa-Ratto | Month | - | - | - | - | - | - | - | - | - | - | 1 |
| $\mathrm{TRY}_{\mathrm{FRPd}}$ | Festa-Ratto | Day | - | - | - | - | - | - | - | - | - | - | 1 |
| $\mathrm{TRY}_{\mathrm{TMY3m}}$ | TMY3 | Month | 1/20 | 1/20 | 2/20 | 1/20 | 1/20 | 2/20 | 1/20 | 1/20 | 5/20 | 5/20 | - |
| $\mathrm{TRY}_{\mathrm{TMY3d}}$ | TMY3 | Day | 1/20 | 1/20 | 2/20 | 1/20 | 1/20 | 2/20 | 1/20 | 1/20 | 5/20 | 5/20 | - |
| $\mathrm{TRY}_{\mathrm{TGYm}}$ | TGY | Month | - | - | - | - | - | - | - | - | 1 | - | - |
| $\mathrm{TRY}_{\mathrm{TGYd}}$ | TGY | Day | - | - | - | - | - | - | - | - | 1 | - | - |
| $\mathrm{TRY}_{\mathrm{TDYm}}$ | TDY | Month | - | - | - | - | - | - | - | - | - | 1 | - |
| $\mathrm{TRY}_{\mathrm{TDYd}}$ | TDY | Day | - | - | - | - | - | - | - | - | - | 1 | - |

* In the ISO method the mean wind speed is used as a secondary parameter for the selection of a typical month, so it does not have a specific weight.

To assess the suitability of each TRY for estimating the long-term performance of a PV system, for each of the stations referenced, the general procedure set out in Fig. 2 and described below was followed:

- For each meteorological parameter, calculate the hourly and daily means for each year included in the time series.
- Generate TRYs based on meteorological variables:
    - From hourly meteorological files, construct TRYs composed of typical days.
    - From daily meteorological files, construct TRYs composed of typical months.
- Estimate the hourly and daily electrical energy generated by the PV system for each year of the dataset via PVSOL software simulation.
- Generate TRYs based on analysis of PV system production:
    - From hourly production files, construct TRYs composed of typical days.
    - From daily electricity production files, construct TRYs composed of typical months.

- Estimate the hourly electrical energy production of each TRY via PVSOL simulation.
- Compare electricity production results obtained for each TRY with simulations performed for each year of the dataset using eight statistical indicators depicted by Equations (1)-(8) and described below.
- Finally, for each TRY, calculate the weighted average of the eight statistical indicators and classify of the values obtained.

As is shown in Fig. 2, annual, monthly and daily electric production results obtained are compared with the results of simulations carried out for each year of the dataset using eight different metrics. Six of them ($F_1$ to $F_6$) are proposed in [30]. Indicator $F_1$ obtained from Equation (1) is the root mean square difference of the yearly energy productions of the system. Equations (2) and (5) are used to determine indicators $F_2$ and $F_5$. These are the total standard error of estimates of monthly and daily energy outputs, respectively. Indicator $F_3$ is the chi square parameter of monthly solar production, and it can be calculated from Equation (3). Indicators $F_4$ and $F_6$, which are derived from Equations (4) and (6), are the root mean squares of the mean energy production of the historic data series minus TRY monthly and daily production, respectively.

Given the temporal downscaling step proposed in this paper for selecting typical moments, besides these six parameters, two more indicators ($F_7$ and $F_8$) are included. These two metrics are aimed at evaluating the fit between hourly production simulated for each TRY and long-term production. Specifically, indicator $F_7$, which is expressed in Equation (7), is the total standard error of estimates of hourly energy outputs. Equation (8) can be used to calculate indicator $F_8$. Analogously to indicators $F_4$ and $F_6$, it corresponds to the root mean square of the mean hourly energy production of the historic data series minus hourly TRY production levels.

- Yearly electric energy production:

$$F_1 = \sqrt{\frac{\sum_{y=1}^{j} \left(EP_y - EP_t\right)^2}{j}} \tag{1}$$

- Monthly electric energy production:

$$F_2 = \frac{1}{12} \cdot \sum_{m=1}^{12} SEE_m = \frac{1}{12} \cdot \left\{ \sum_{m=1}^{12} \left[ \frac{\sum_{y=1}^{j} \left(EP_{ym} - EP_{tm}\right)^2}{j} \right]^{1/2} \right\} \tag{2}$$

$$F_3 = \chi^2 = \sum_{m=1}^{12} \left( \frac{\overline{EP}_m - EP_{tm}}{\sigma_{\overline{EP}_m}} \right) \tag{3}$$

$$F_4 = \left[ \frac{1}{12} \cdot \sum_{m=1}^{12} \left( \overline{EP}_m - EP_{tm} \right)^2 \right]^{1/2} \tag{4}$$

- Daily electric energy production:

$$F_5 = \frac{1}{365} \cdot \sum_{d=1}^{365} SEE_d = \frac{1}{365} \cdot \left\{ \sum_{d=1}^{365} \left[ \frac{\sum_{y=1}^{j} \left(EP_{yd} - EP_{td}\right)^2}{j} \right]^{1/2} \right\} \tag{5}$$

$$F_6 = \left[ \frac{1}{365} \cdot \sum_{d=1}^{365} \left( \overline{EP}_d - EP_{td} \right)^2 \right]^{1/2} \tag{6}$$

- Hourly electric energy production:

$$F_7 = \frac{1}{8760} \cdot \sum_{h=1}^{8760} SEE_h = \frac{1}{8760} \cdot \left\{ \sum_{h=1}^{8760} \left[ \frac{\sum_{y=1}^{j} \left(EP_{yh} - EP_{th}\right)^2}{j} \right]^{1/2} \right\} \tag{7}$$

$$F_8 = \left[ \frac{1}{8760} \cdot \sum_{h=1}^{8760} \left( \overline{EP}_h - EP_{th} \right)^2 \right]^{1/2} \tag{8}$$

### 3.1. The modified Festa-Ratto method

Festa and Ratto [35] seek to increase the accuracy of variable standardization and to compare the frequency distribution of each month in the database with the long-term frequency distribution through the use of the *KS* D-statistic [36]. Likewise, the temporal correlation between daily values of the different variables is taken into account by considering products of standardized residuals of each variable on consecutive days.

In this work, an adapted version of the original Festa-Ratto method aimed at the selection of representative days rather than representative months is proposed. The modified procedure (see Fig. 3) is described below:

- For each ordinal hour of each ordinal day of the year, calculate the long-term average $\mu_x(d,h)$ together with the corresponding long-term standard deviation $\sigma_x(d,h)$ of each considered variable $x$.
- From Equation (9), calculate the standardized residuals of all hourly values of the database $x(y,d,h)$ with respect to the long-term trend.

$$X(y,d,h)=\frac{x(y,d,h)-\mu_x(d,h)}{\sigma_x(d,h)} \tag{9}$$

- For each hourly datum of variables considered in the database, calculate the product of standardized residuals with respect to the trend from Equation (10).

$$z(y,d,h)=X(y,d,h)\cdot X(y,d,h+1) \tag{10}$$

- For each ordinal hour of each ordinal day of the year, calculate the long-term average $\mu_z(d,h)$ together with the corresponding long-term standard deviation $\sigma_z(d,h)$ of each variable considered $z$.
- For each hourly value of the considered variables, calculate the standardized residuals of $z(y,\mathrm{d},h)$ with respect to long-term trends from Equation (11).

$$Z(y,d,h)=\frac{z(y,d,h)-\mu_z(d,h)}{\sigma_z(d,h)} \tag{11}$$

- For each $X$ and $Z$ parameter, calculate the following short-term quantities: the average, standard deviation and CDF of each individual day of the multi-year data series and variable.
- For each $X$ and $Z$ parameter, calculate the following long-term quantities: the average, standard deviation and CDF of each ordinal day of the year and variable.
- For each day $d$ of each year $y$, calculate the distances between the short- and long-term daily averages $d_{av}(y,d)$ and standard deviations $d_{sd}(y,d)$ as well as the Kolmogorov-Smirnov parameter $d_{ks}(y,d)$ based on each $X(y,d,h)$ and $Z(y,d,h)$ parameter.
- For each day $d$ of each year $y$ and variable, calculate the composite distance of the $X(y,d,h)$ and $Z(y,d,h)$ parameters according to Equation (12).

  $$d(y,d)=(1-\alpha-\beta)\cdot d_{ks}(y,d)+\alpha\cdot d_{av}(y,d)+\beta\cdot d_{sd}(y,d) \tag{12}$$

  where $\alpha = \beta = 0.1$ as suggested for the original methodology. Therefore, for each day and for each variable, two distances are available: $d(y,d)$ relative to the standardized residuals $X(y,d,h)$ and $d(y,d)$ relative to the standardized residuals $Z(y,d,h)$.
- Assign to each day the worst (maximum) distance $d_{max}(y,d)$ of the distances calculated for this individual day.
- Finally, for each ordinal day, designate the day $d$ of the year $y$ that presents the lowest value of $d_{max}(y,d)$ among those assigned in the previous step as indicated in Equation (13). This day is considered typical and is selected for the TRY.

  $$d_{\min\ \max}(d)=\min\left\{\, d_{\max}(y,d)\ \middle|\ 1\le y\le j \,\right\} \tag{13}$$

### 3.2. The modified WYSS method

The WYSS procedure is aimed at the determination of a set of typical weather data suitable for the evaluation of the long-term performance of solar hot water systems (SHWS). In doing so, the only parameter considered is the energy gain of a solar thermal system. Nevertheless, the adapted version of the original method proposed and applied in [29] for the long-term evaluation of PV systems, was used in this work. This implies that the first stage of WYSS generation involves the simulation of the electrical production of each year of a dataset. According to the original method, the selection of typical months involves the minimization of errors in PV system monthly solar gain prediction. Thus, a total of twelve typical months are selected from the dataset.

The modification of the original method performed in this work for selecting typical days involves determining the daily output of the PV system for each year of the series. The modified WYSS method described below is illustrated in Fig. 4:

- Calculate the long-term daily mean value of electric production from Equation (14).

$$\overline{EP}_d = \frac{\left(\sum_{y=1}^{j} EP_{yd}\right)}{j} \tag{14}$$

- From Equation (15), calculate the squared difference between the daily electricity production of day $d$ of year $y$ and the mean value of the daily energy output of the same day from the long-term data.

$$\tau_{yd} = \left(EP_{yd} - \overline{EP}_d\right)^2 \tag{15}$$

- Select the day $d$ of the year $y$ with the lowest value of $\tau_{yd}$. This day is considered typical and is selected for the WYSS.

### 3.3. The modified EN ISO 15927-4 method

The standard EN ISO 15927-4 [19] describes a method for constructing a reference year suitable for evaluating the annual heating and cooling long-term energy needs of buildings. The procedure is designed to build a year of hourly meteorological data in which the mean value of individual variables, the cumulative distribution function and correlations between different variables of each month are as similar as possible to the values for the corresponding calendar month of the historical series.

The modified version of the original method proposed in this paper aims to reduce typical periods from months to days. As recommended through the procedure, the dry bulb temperature, global horizontal solar radiation and relative humidity are considered as the main selectors of days that make up the reference year with the wind speed used as a secondary selection parameter. This new approach, which is illustrated in Fig. 5, involves employing the following for each climatic parameter $p$, where $p$ is the dry bulb temperature, global horizontal irradiance and relative humidity:

- For each ordinal day, the long-term cumulative distribution function of hourly values for all years of the dataset is calculated for each parameter by sorting all hourly values in increasing order and by then using Equation (16).

$$\Phi(p,d,i)=\frac{K(i)}{N+1} \tag{16}$$

- For each year of the dataset, the short-term cumulative distribution function of hourly values for each ordinal day is calculated by sorting all hourly values for that day and year in increasing order and then using Equation (17).

$$F(p,y,d,i)=\frac{J(i)}{n+1} \tag{17}$$

- For each ordinal day, the $F_S$ statistic is calculated for each year of the dataset using Equation (18).

$$F_S(p,y,d)=\sum_{i=1}^{n}\left| \; F(p,y,d,i)-\Phi(p,d,i) \; \right| \quad (18)$$

- For each ordinal day, individual days are ranked from the multiyear record in order of increasing $F_S$ statistic for each parameter. Then, the individual ranks of the three climate parameters are summed to determine the total ranking.
- For each ordinal day, for the three days with the lowest ranking, the deviation of the daily mean wind speed from the corresponding multi-year ordinal day is calculated. The day with the lowest deviation in wind speed is selected as the best day to include in the reference year.

Finally, the original method involves the use of a cubic spline for smoothing the transitioning of climatic variables from each selected month to the next. Given that this adjustment refers to hours in which solar radiation is zero or very low, this aspect was not taken into consideration in this work.

During the last step of this process, some coincidences in the sum of rank orders of the $F_S$ statistic of the three main variables can occur. Therefore, in certain cases, it is not possible to select the three months or days with the lowest ranking. In an attempt to address this problem, García and Torres [29] proposed the use of a secondary selection criterion whereby when there is a tie in the total ranking, priority is given to months or days with the lowest individual order of $F_S$ in the radiation variable. This particular selection condition, which is illustrated in Fig. 5 as a dashed line, was used in the present study.

### 3.4. The modified TMY3 method

The TMY3 procedure is an empirical approach based on the Sandia method that selects individual months from different years occurring in the period of record. As was done for the previous methods, an adapted version of the original TMY3 method aimed at the selection of representative days is proposed (see Fig. 6). The modified procedure is described below:

- For each ordinal day, 5 candidate days are selected having the smallest *WS* of the $F_S$ statistic (Equation (18)) of each of the 10 hourly parameters, calculated according to Equation (19).

$$WS(y,d)=\sum_{x=1}^{P} WF_x \cdot F_{S,x}(y,d) \tag{19}$$

- 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 air temperature and global horizontal irradiance of each specific day and the respective mean and medians over the long term. The maximum of the four relative differences is assigned.
- The persistence of hourly dry bulb temperature and global horizontal irradiance are evaluated by determining the frequency and run length above and below fixed long-term percentiles. For hourly dry bulb temperature, the frequency and run length above the 67th percentile (consecutive warm hours) and below the 33rd percentile (consecutive cool hours) are determined. For global horizontal irradiance, the frequency and run length below the 33rd percentile (consecutive low radiation hours) are determined.
- The persistence data are used to select, from the five candidate days, the day to be used in the TMY3. The highest ranked candidate day from the previous step that meets the persistence criteria is used in the TMY3. The persistence criteria exclude the day with the longest run, the day with the 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. So, if two candidate days tie for the most runs, neither is eliminated by the TMY3 procedure. Also, if the TMY3 persistence procedure

eliminated all candidate days, persistence is ignored and the closest day to the long-term mean and median is selected.

Applying a cubic spline to flatten the variable transition from a month to the next is recommended in the original procedure. However, for the reasons already stated, it has not been applied in this work.

Along with the TMY3 method, the original procedures for obtaining TDY and TGY data sets have been modified for the selection of typical days instead of months. To obtain the daily versions of TDY and TGY, the modified procedure described above for TMY3 is applicable with the difference that only the direct normal irradiance is used for TDY generation and global horizontal irradiance for TGY. Therefore, in both cases, the ranking of the five candidate days according to the relative distance in mean and median as well as the determination of the frequency and run length below the 33rd percentile is restricted to the only variable used.

# 4. RESULTS AND DISCUSSION

## 4.1. TRY generation

First, following the procedures described in Section 3, TRYs based on meteorological variables were generated, namely, both daily and monthly $TRY_{FRM}$, $TRY_{ISO}$, $TRY_{TMY3}$, $TRY_{TDY}$ and $TRY_{TGY}$.

Meanwhile, the generation of production-based TRYs ($TRY_{FRP}$ and $TRY_{WYSS}$) involves a previous simulation of electrical energy generated from the PV system for each year of the time series and for each location. For this, as is explained above, PVSOL simulation software was used. The input weather file used in the program consisted of a list of 8,760 hourly values of dry bulb temperature, global horizontal irradiance, relative humidity and wind speed. Diffuse and direct components of global irradiance are determined by PVSOL through the correlation proposed by Reindl with reduced coefficients [40] and the anisotropic model developed by Hay and Davis [41] is used by the software to estimate the diffuse irradiance on the tilted surface.

The behavior of the different TRYs was evaluated by comparing electrical outputs provided through a grid-connected 5.60 kWp PV system (see Table 4). As shown in the last row of the Table 4, the tilt angle of the collector surface was set up at each location according to the maximum interception of solar energy for the entire measurement period.

**Table 4.** Technical data of the PV system.

| | |
|---|---|
| PV power (kWp) | 5.60 |
| Number of PV modules | 56 |
| Number of PV modules in series | 14 |
| Number of PV modules in parallel | 4 |
| Solar tracking system | No |
| System azimuth angle (ºS) | 0 |
| System tilt angle (º) | Local optimum (long-term) |

Given the length of the different series of observations, 116 executions of the simulation software were performed. The electricity production results obtained were used for the construction of monthly and daily $TRY_{WYSS}$ and $TRY_{FRP}$, and to assess the adequacy of each TRY in estimating the long-term behavior of the PV system. This analysis is presented in Section 4.2.

After selecting typical days or months that make up the different reference years, each TRY was built to create a set of 8,760 values corresponding to the four meteorological variables considered. In using PVSOL again, the energy output of the PV system provided for each reference year was simulated.

### 4.2. TRY evaluation

As described in Section 3, the last step of the general procedure involves the determination of the eight statistical indicators (Equations (1)-(8)) suitable for assessing the adequacy of different TRYs at estimating the long-term energy produced by the PV system.

The values of the eight metrics obtained for each TRY for the seven locations considered are shown in Table 5-Table 12. To facilitate analysis of the results, each table classifies TRYs by station. A score of '1' is assigned to the TRY with a lower value of the corresponding indicator, and a value of '14' is assigned to that with the highest value. This implies an ordering of TRYs from best to worst while attending to the indicator and station considered in each case. These rank orders are shown in brackets next to each value. Furthermore, the sum of various orders reached by each TRY based on all stations is shown in the last column. The fourteen different TRYs have been ordered from lowest to highest value of orders' sum for each table.

Table 5 shows the results of the annual indicator $F_1$ for each location, i.e., the root mean square difference of the yearly energy productions. $TRY_{WYSSm}$ presents the lowest deviation in estimating annual production levels for four of the seven stations analyzed. This is followed closely by $TRY_{WYSSd}$, which takes the first position for two stations, while $TRY_{TDYm}$ shows the lowest deviation for the remaining station. However, $TRY_{ISOm}$ also achieves a better result than $TRY_{TDYm}$ when all stations are considered. In fact, $TRY_{TDYm}$ ranks fourth followed by $TRY_{TMY3m}$ and $TRY_{TGYm}$. The daily version of the ISO reference year, the $TRY_{ISOd}$, generates $F_1$ values that are significantly higher than those of any of the other TRYs.

**Table 5.** Values of $F_1$ indicator (root mean square difference of the yearly energy productions in kWh) for each TRY and station (the ranked order of each value is shown in brackets).

| TRY | Station Code | | | | | | | | | | | | | | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | BON | | DRA | | FPK | | GWN | | PSU | | SXF | | TBL | | |
| WYSSm | 315.57 | (1) | 177.33 | (1) | 258.84 | (2) | 354.61 | (1) | 256.42 | (4) | 233.28 | (1) | 200.47 | (3) | (13) |
| WYSSd | 322.24 | (5) | 186.10 | (4) | 258.83 | (1) | 357.94 | (4) | 252.05 | (2) | 239.91 | (3) | 200.31 | (1) | (20) |
| ISOm | 319.60 | (4) | 206.49 | (7) | 294.16 | (3) | 355.89 | (3) | 266.94 | (7) | 233.67 | (2) | 211.34 | (5) | (31) |
| TDYm | 340.10 | (7) | 183.23 | (3) | 317.02 | (5) | 360.94 | (5) | 251.86 | (1) | 308.08 | (7) | 391.75 | (9) | (37) |
| TMY3m | 317.01 | (3) | 178.93 | (2) | 319.91 | (6) | 392.27 | (8) | 270.68 | (8) | 429.85 | (11) | 247.92 | (7) | (45) |
| TGYm | 326.91 | (6) | 186.96 | (5) | 321.19 | (7) | 371.08 | (6) | 277.74 | (10) | 284.95 | (5) | 303.50 | (8) | (47) |
| FRPd | 391.07 | (10) | 188.07 | (6) | 315.27 | (4) | 372.17 | (7) | 283.37 | (11) | 349.28 | (8) | 202.69 | (4) | (50) |
| TGYd | 316.63 | (2) | 727.03 | (13) | 529.93 | (12) | 354.76 | (2) | 259.85 | (5) | 380.87 | (10) | 590.98 | (13) | (57) |
| FRMm | 425.66 | (12) | 345.16 | (8) | 404.74 | (8) | 414.20 | (9) | 506.21 | (13) | 286.28 | (6) | 200.44 | (2) | (58) |
| TMY3d | 370.97 | (8) | 496.87 | (9) | 432.56 | (9) | 416.08 | (10) | 287.72 | (12) | 262.52 | (4) | 440.67 | (10) | (62) |
| FRPm | 377.16 | (9) | 501.34 | (10) | 491.08 | (11) | 754.73 | (13) | 271.99 | (9) | 675.48 | (12) | 216.50 | (6) | (70) |
| TDYd | 441.97 | (13) | 660.38 | (12) | 490.39 | (10) | 436.39 | (11) | 260.98 | (6) | 362.77 | (9) | 513.94 | (11) | (72) |
| FRMd | 393.02 | (11) | 598.80 | (11) | 552.68 | (13) | 604.79 | (12) | 252.48 | (3) | 987.90 | (13) | 582.23 | (12) | (75) |
| ISOd | 1253.60 | (14) | 927.60 | (14) | 1429.31 | (14) | 1506.60 | (14) | 1131.04 | (14) | 1298.79 | (14) | 1288.19 | (14) | (98) |

The results concerning monthly indicators $F_2$ (total standard error of estimates of monthly energy outputs), $F_3$ (chi square parameter of monthly solar production) and $F_4$ (root mean square of the mean energy production of the historic data series minus TRY monthly production) are presented in Table 6-Table 8. In this case, we find that for almost all the locations, TRY$_{\text{WYSSm}}$ works best, followed by TRY$_{\text{WYSSd}}$. A unique exception is found for Fort Peck, for which this latter reference year occupies first place of the $F_2$ and $F_4$ rankings. Nevertheless, in both cases, we found a minimal difference between values obtained for the daily and monthly TRY$_{\text{WYSS}}$. Meanwhile, TRY$_{\text{TGYm}}$ and TRY$_{\text{FRPd}}$ occupy the fourth and fifth positions respectively for the three indicators. The worst results are obtained from TRY$_{\text{ISOd}}$, TRY$_{\text{FRMm}}$ and TRY$_{\text{FRPm}}$.

**Table 6.** Values of the $F_2$ indicator (total standard error of estimates of monthly energy outputs in kWh) for each TRY and station (the ranked order of each value is shown in brackets).

| TRY | Station Code | | | | | | | | | | | | | | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | BON | | DRA | | FPK | | GWN | | PSU | | SXF | | TBL | | |
| WYSSm | 62.97 | (1) | 46.59 | (1) | 64.61 | (2) | 70.38 | (1) | 63.78 | (1) | 63.74 | (1) | 48.63 | (1) | (8) |
| WYSSd | 63.51 | (2) | 46.80 | (2) | 64.61 | (1) | 70.67 | (2) | 63.99 | (2) | 64.18 | (2) | 48.68 | (2) | (13) |
| TGYm | 64.00 | (3) | 48.84 | (3) | 67.92 | (4) | 72.61 | (3) | 66.24 | (3) | 67.20 | (3) | 53.52 | (5) | (24) |
| FRPd | 71.24 | (7) | 50.69 | (6) | 67.49 | (3) | 73.02 | (4) | 66.55 | (4) | 76.92 | (10) | 50.40 | (3) | (37) |
| ISOm | 67.73 | (6) | 49.09 | (4) | 68.03 | (5) | 75.11 | (6) | 72.56 | (9) | 73.73 | (7) | 52.76 | (4) | (41) |
| TDYm | 67.58 | (5) | 51.87 | (7) | 77.08 | (7) | 75.35 | (7) | 67.39 | (5) | 71.96 | (4) | 58.36 | (7) | (42) |
| TMY3m | 66.53 | (4) | 50.54 | (5) | 81.40 | (10) | 74.46 | (5) | 67.92 | (7) | 74.99 | (9) | 53.99 | (6) | (46) |
| TMY3d | 72.90 | (9) | 62.08 | (8) | 84.84 | (11) | 80.76 | (8) | 67.86 | (6) | 74.64 | (8) | 60.62 | (8) | (58) |
| TDYd | 79.57 | (11) | 70.84 | (11) | 77.54 | (8) | 84.35 | (10) | 73.02 | (10) | 72.42 | (5) | 63.26 | (9) | (64) |
| TGYd | 74.44 | (10) | 75.51 | (12) | 76.89 | (6) | 86.55 | (11) | 75.85 | (11) | 73.57 | (6) | 67.45 | (10) | (66) |
| FRMd | 72.06 | (8) | 67.89 | (9) | 79.15 | (9) | 83.88 | (9) | 69.06 | (8) | 105.05 | (12) | 69.80 | (11) | (66) |
| FRMm | 86.17 | (12) | 69.73 | (10) | 94.40 | (12) | 138.60 | (12) | 97.82 | (12) | 101.69 | (11) | 73.29 | (12) | (81) |
| FRPm | 109.09 | (13) | 96.50 | (14) | 118.11 | (13) | 160.75 | (14) | 117.42 | (14) | 121.60 | (13) | 90.78 | (13) | (94) |
| ISOd | 123.15 | (14) | 89.78 | (13) | 134.52 | (14) | 141.44 | (13) | 113.39 | (13) | 125.42 | (14) | 116.85 | (14) | (95) |

**Table 7.** Values of the $F_3$ indicator (chi square parameter of monthly solar production) for each TRY and station (the ranked order of each value is shown in brackets).

| TRY | Station Code | | | | | | | | | | | | | | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | BON | | DRA | | FPK | | GWN | | PSU | | SXF | | TBL | | |
| WYSSm | 0.08 | (1) | 0.07 | (1) | 0.08 | (1) | 0.06 | (1) | 0.08 | (1) | 0.14 | (1) | 0.08 | (1) | (7) |
| WYSSd | 0.27 | (2) | 0.22 | (2) | 0.10 | (2) | 0.17 | (2) | 0.17 | (2) | 0.28 | (2) | 0.11 | (2) | (14) |
| TGYm | 0.55 | (3) | 1.20 | (3) | 1.27 | (3) | 0.93 | (3) | 1.29 | (3) | 1.63 | (3) | 2.88 | (5) | (23) |
| FRPd | 3.36 | (7) | 2.93 | (6) | 1.48 | (4) | 1.20 | (4) | 1.32 | (4) | 5.74 | (7) | 1.40 | (3) | (35) |
| TDYm | 2.03 | (5) | 3.46 | (7) | 4.83 | (6) | 1.94 | (6) | 1.71 | (6) | 3.43 | (4) | 5.98 | (7) | (41) |
| ISOm | 2.23 | (6) | 1.46 | (4) | 1.55 | (5) | 1.98 | (7) | 3.72 | (9) | 5.23 | (6) | 2.39 | (4) | (41) |
| TMY3m | 1.45 | (4) | 2.60 | (5) | 8.13 | (10) | 1.79 | (5) | 2.20 | (7) | 4.68 | (5) | 2.92 | (6) | (42) |
| TMY3d | 4.19 | (9) | 12.03 | (8) | 11.91 | (11) | 5.03 | (8) | 1.68 | (5) | 7.30 | (10) | 6.80 | (8) | (59) |
| FRMd | 4.02 | (8) | 15.44 | (9) | 6.32 | (7) | 5.15 | (9) | 2.23 | (8) | 24.11 | (12) | 14.67 | (11) | (64) |
| TDYd | 8.69 | (11) | 16.88 | (11) | 7.70 | (9) | 6.39 | (10) | 4.57 | (10) | 6.02 | (8) | 8.10 | (9) | (68) |
| TGYd | 5.83 | (10) | 22.13 | (12) | 7.22 | (8) | 7.84 | (11) | 6.99 | (11) | 6.39 | (9) | 10.73 | (10) | (71) |
| FRMm | 13.05 | (12) | 16.53 | (10) | 16.84 | (12) | 38.01 | (13) | 22.75 | (12) | 20.31 | (11) | 17.92 | (12) | (82) |
| ISOd | 44.19 | (14) | 36.60 | (13) | 45.28 | (14) | 36.54 | (12) | 29.05 | (13) | 44.69 | (14) | 55.55 | (14) | (94) |
| FRPm | 26.18 | (13) | 45.48 | (14) | 29.91 | (13) | 49.07 | (14) | 33.95 | (14) | 30.39 | (13) | 33.02 | (13) | (94) |

**Table 8.** Values of the $F_4$ indicator (root mean square of the mean energy production of the historic data series minus TRY monthly production in kWh) for each TRY and station (the ranked order of each value is shown in brackets).

| TRY | Station Code | | | | | | | | | | | | | | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | BON | | DRA | | FPK | | GWN | | PSU | | SXF | | TBL | | |
| WYSSm | 4.54 | (1) | 4.53 | (1) | 5.51 | (2) | 4.18 | (1) | 5.44 | (1) | 7.04 | (1) | 4.30 | (1) | (8) |
| WYSSd | 9.57 | (2) | 5.77 | (2) | 4.98 | (1) | 7.37 | (2) | 7.36 | (2) | 10.53 | (2) | 4.63 | (2) | (13) |
| TGYm | 11.62 | (3) | 16.34 | (3) | 22.85 | (5) | 18.25 | (3) | 18.01 | (3) | 23.48 | (3) | 23.17 | (5) | (25) |
| FRPd | 35.27 | (7) | 19.98 | (5) | 19.45 | (3) | 18.50 | (4) | 19.22 | (4) | 45.60 | (10) | 12.65 | (3) | (36) |
| ISOm | 25.71 | (6) | 16.73 | (4) | 21.76 | (4) | 25.77 | (6) | 37.24 | (10) | 38.85 | (7) | 20.72 | (4) | (41) |
| TMY3m | 22.98 | (4) | 21.99 | (6) | 50.71 | (9) | 23.66 | (5) | 22.57 | (6) | 43.76 | (9) | 24.23 | (6) | (45) |
| TDYm | 25.03 | (5) | 23.08 | (7) | 51.34 | (10) | 28.58 | (7) | 22.20 | (5) | 37.58 | (6) | 34.92 | (7) | (47) |
| TMY3d | 38.21 | (9) | 40.80 | (8) | 54.72 | (11) | 39.50 | (8) | 24.42 | (7) | 40.28 | (8) | 38.79 | (8) | (59) |
| TDYd | 48.68 | (11) | 54.60 | (10) | 42.58 | (7) | 46.66 | (9) | 35.66 | (9) | 33.83 | (4) | 42.31 | (9) | (59) |
| TGYd | 39.81 | (10) | 60.03 | (12) | 41.29 | (6) | 50.06 | (11) | 40.46 | (11) | 37.39 | (5) | 48.29 | (10) | (65) |
| FRMd | 37.18 | (8) | 51.10 | (9) | 48.27 | (8) | 48.96 | (10) | 27.59 | (8) | 89.33 | (12) | 55.10 | (11) | (66) |
| FRMm | 65.80 | (12) | 59.54 | (11) | 79.19 | (12) | 133.29 | (13) | 81.79 | (12) | 88.27 | (11) | 59.48 | (12) | (83) |
| ISOd | 109.17 | (14) | 79.04 | (13) | 119.52 | (14) | 129.06 | (12) | 97.31 | (13) | 112.28 | (14) | 109.87 | (14) | (94) |
| FRPm | 98.84 | (13) | 87.62 | (14) | 111.55 | (13) | 181.84 | (14) | 104.03 | (14) | 109.70 | (13) | 79.32 | (13) | (94) |

Regarding the $F_5$ and $F_6$ indicators (total standard error of estimates of daily energy outputs and root mean square of the mean energy production of the historic data series minus TRY daily production respectively), the reference year that better predicts the daily electricity production in the long term is TRY$_{\text{WYSSd}}$ for all of the locations (see Table 9 and Table 10). With a slightly higher score, it is followed in descending order by TRY$_{\text{TGYd}}$, TRY$_{\text{TDYd}}$ and TRY$_{\text{FRPd}}$. That is, although the first position is occupied by a TRY obtained by analyzing the electrical output of the PV system, TRYs based on the analysis of only the global horizontal irradiance (TRY$_{\text{TGYd}}$) and direct normal irradiance (TRY$_{\text{FRPd}}$) rank second and third in the overall rating. It can be seen that the seven TRYs composed of typical days perform better in estimating daily energy production patterns than their monthly versions. TRYs obtained from the original Festa-Ratto method generate the worst overall results.

**Table 9.** Values of the $F_5$ indicator (total standard error of estimates of daily energy outputs in kWh) for each TRY and station (the ranked order of each value is shown in brackets).

| TRY | Station Code | | | | | | | | | | | | | | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | BON | | DRA | | FPK | | GWN | | PSU | | SXF | | TBL | | |
| WYSSd | 9.24 | (1) | 5.25 | (1) | 8.07 | (1) | 8.77 | (1) | 9.22 | (1) | 8.99 | (1) | 7.73 | (1) | (7) |
| TGYd | 9.61 | (2) | 5.65 | (2) | 8.44 | (2) | 9.22 | (2) | 9.72 | (2) | 9.46 | (2) | 8.11 | (3) | (15) |
| TDYd | 9.93 | (4) | 5.67 | (3) | 8.80 | (4) | 9.41 | (3) | 9.95 | (4) | 9.71 | (3) | 8.30 | (4) | (25) |
| FRPd | 9.87 | (3) | 6.49 | (7) | 8.45 | (3) | 9.47 | (4) | 9.82 | (3) | 11.70 | (7) | 8.00 | (2) | (29) |
| TMY3d | 10.70 | (5) | 5.86 | (4) | 9.36 | (5) | 9.95 | (5) | 10.59 | (5) | 10.47 | (5) | 8.91 | (5) | (34) |
| ISOd | 10.73 | (6) | 6.02 | (6) | 9.60 | (7) | 10.40 | (6) | 10.80 | (6) | 10.43 | (4) | 9.04 | (6) | (41) |
| FRMd | 10.97 | (7) | 5.99 | (5) | 9.47 | (6) | 10.57 | (7) | 10.83 | (7) | 10.81 | (6) | 9.22 | (7) | (45) |
| WYSSm | 12.55 | (10) | 6.87 | (11) | 11.05 | (13) | 11.48 | (8) | 12.43 | (9) | 11.78 | (9) | 10.27 | (9) | (69) |
| TMY3m | 12.52 | (9) | 6.97 | (12) | 10.98 | (12) | 11.77 | (9) | 12.48 | (12) | 11.77 | (8) | 10.28 | (10) | (72) |
| TDYm | 12.45 | (8) | 6.85 | (10) | 10.96 | (11) | 11.89 | (12) | 12.46 | (11) | 11.99 | (12) | 10.07 | (8) | (72) |
| ISOm | 12.59 | (11) | 6.82 | (8) | 10.81 | (9) | 11.86 | (11) | 12.66 | (13) | 11.97 | (10) | 10.46 | (12) | (74) |
| TGYm | 12.67 | (12) | 6.84 | (9) | 10.75 | (8) | 11.78 | (10) | 12.45 | (10) | 12.09 | (13) | 10.52 | (13) | (75) |
| FRMm | 12.91 | (14) | 7.36 | (13) | 10.89 | (10) | 12.24 | (13) | 12.68 | (14) | 11.97 | (11) | 10.36 | (11) | (86) |
| FRPm | 12.85 | (13) | 7.57 | (14) | 11.48 | (14) | 12.75 | (14) | 12.42 | (8) | 12.59 | (14) | 10.55 | (14) | (91) |

**Table 10.** Values of the $F_6$ indicator (root mean square of the mean energy production of the historic data series minus TRY daily production in kWh) for each TRY and station (the ranked order of each value is shown in brackets).

| TRY | Station Code | | | | | | | | | | | | | | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | BON | | DRA | | FPK | | GWN | | PSU | | SXF | | TBL | | |
| WYSSd | 1.46 | (1) | 0.87 | (1) | 1.04 | (1) | 1.33 | (1) | 1.37 | (1) | 1.98 | (1) | 0.89 | (1) | (7) |
| TGYd | 3.05 | (2) | 2.36 | (2) | 2.71 | (2) | 3.32 | (2) | 3.47 | (2) | 3.68 | (2) | 2.68 | (3) | (15) |
| TDYd | 4.07 | (4) | 2.46 | (3) | 3.79 | (4) | 3.90 | (3) | 4.10 | (4) | 4.39 | (3) | 3.33 | (4) | (25) |
| FRPd | 3.95 | (3) | 4.67 | (7) | 2.81 | (3) | 4.15 | (4) | 3.82 | (3) | 8.46 | (7) | 2.32 | (2) | (29) |
| TMY3d | 6.00 | (6) | 3.11 | (4) | 5.10 | (5) | 5.39 | (5) | 5.72 | (5) | 6.18 | (5) | 4.85 | (5) | (35) |
| ISOd | 5.96 | (5) | 3.42 | (6) | 5.57 | (7) | 6.27 | (6) | 6.24 | (7) | 6.03 | (4) | 5.02 | (6) | (41) |
| FRMd | 6.40 | (7) | 3.30 | (5) | 5.33 | (6) | 6.50 | (7) | 6.19 | (6) | 6.77 | (6) | 5.43 | (7) | (44) |
| WYSSm | 9.24 | (10) | 5.61 | (9) | 8.40 | (13) | 8.29 | (8) | 9.12 | (11) | 8.58 | (9) | 7.49 | (9) | (69) |
| TDYm | 9.07 | (8) | 5.68 | (11) | 8.12 | (10) | 8.92 | (11) | 9.11 | (10) | 8.92 | (12) | 7.09 | (8) | (70) |
| TMY3m | 9.20 | (9) | 5.75 | (12) | 8.35 | (12) | 8.68 | (9) | 9.16 | (12) | 8.52 | (8) | 7.52 | (10) | (72) |
| TGYm | 9.45 | (12) | 5.62 | (10) | 7.87 | (9) | 8.73 | (10) | 9.10 | (9) | 9.01 | (13) | 7.98 | (13) | (76) |
| ISOm | 9.38 | (11) | 5.52 | (8) | 7.84 | (8) | 8.96 | (12) | 9.45 | (14) | 8.82 | (11) | 7.83 | (12) | (76) |
| FRMm | 9.84 | (14) | 6.70 | (13) | 8.13 | (11) | 9.54 | (13) | 9.40 | (13) | 8.78 | (10) | 7.71 | (11) | (85) |
| FRPm | 9.62 | (13) | 6.91 | (14) | 9.15 | (14) | 10.22 | (14) | 9.04 | (8) | 9.79 | (14) | 8.08 | (14) | (91) |

The results obtained after calculating the $F_7$ and $F_8$ indicators are presented in Table 11 and Table 12. It should be remembered that the $F_7$ indicator corresponds to the total standard error of estimates of hourly energy outputs and while the $F_8$ indicator is the root mean square of the mean hourly energy production of the historic data series minus hourly TRY production. As is apparent from the tables, TRY$_{\mathrm{WYSSd}}$ performs best for five of the seven locations studied. However, for Desert Rock and Table Mountain, this reference year is surpassed by TRY$_{\mathrm{TGYd}}$, which ranks second for the rest of the stations. TRY$_{\mathrm{TDYd}}$ and TRY$_{\mathrm{ISOd}}$ are ranked third and fourth, respectively. As was found to be the case for daily indicators, TRYs consisting of typical days show the slightest errors in the estimation of hourly production in the long term. Of the seven reference years compounded by typical months, those obtained from the Festa-Ratto method are the worst in all cases.

**Table 11.** Values of the $F_7$ indicator (total standard error of estimates of hourly energy outputs in kWh) for each TRY and station (the ranked order of each value is shown in brackets).

| TRY | Station Code | | | | | | | | | | | | | | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | BON | | DRA | | FPK | | GWN | | PSU | | SXF | | TBL | | |
| WYSSd | 0.511 | (1) | 0.313 | (4) | 0.485 | (1) | 0.483 | (1) | 0.529 | (1) | 0.505 | (1) | 0.511 | (2) | (11) |
| TGYd | 0.522 | (2) | 0.302 | (1) | 0.491 | (2) | 0.493 | (2) | 0.545 | (2) | 0.515 | (2) | 0.508 | (1) | (12) |
| TDYd | 0.530 | (3) | 0.310 | (3) | 0.503 | (3) | 0.499 | (3) | 0.549 | (3) | 0.523 | (3) | 0.517 | (4) | (22) |
| ISOd | 0.540 | (4) | 0.308 | (2) | 0.504 | (4) | 0.517 | (5) | 0.560 | (5) | 0.531 | (4) | 0.514 | (3) | (27) |
| TMY3d | 0.551 | (5) | 0.313 | (5) | 0.511 | (5) | 0.512 | (4) | 0.558 | (4) | 0.542 | (5) | 0.528 | (5) | (33) |
| FRMd | 0.560 | (7) | 0.317 | (6) | 0.515 | (6) | 0.534 | (7) | 0.570 | (6) | 0.549 | (6) | 0.534 | (6) | (44) |
| FRPd | 0.559 | (6) | 0.345 | (7) | 0.523 | (7) | 0.533 | (6) | 0.575 | (7) | 0.575 | (9) | 0.539 | (7) | (49) |
| WYSSm | 0.597 | (8) | 0.354 | (11) | 0.553 | (12) | 0.554 | (8) | 0.607 | (9) | 0.573 | (8) | 0.561 | (10) | (66) |
| TMY3m | 0.598 | (9) | 0.354 | (12) | 0.556 | (13) | 0.564 | (9) | 0.611 | (12) | 0.571 | (7) | 0.559 | (9) | (71) |
| TDYm | 0.599 | (10) | 0.352 | (9) | 0.549 | (11) | 0.572 | (12) | 0.610 | (10) | 0.580 | (11) | 0.550 | (8) | (71) |
| ISOm | 0.599 | (11) | 0.347 | (8) | 0.542 | (8) | 0.569 | (11) | 0.617 | (14) | 0.580 | (10) | 0.565 | (13) | (75) |
| TGYm | 0.604 | (12) | 0.352 | (10) | 0.545 | (9) | 0.566 | (10) | 0.611 | (11) | 0.585 | (13) | 0.564 | (11) | (76) |
| FRMm | 0.610 | (14) | 0.372 | (13) | 0.548 | (10) | 0.579 | (13) | 0.615 | (13) | 0.581 | (12) | 0.564 | (12) | (87) |
| FRPm | 0.606 | (13) | 0.380 | (14) | 0.570 | (14) | 0.593 | (14) | 0.607 | (8) | 0.603 | (14) | 0.568 | (14) | (91) |

**Table 12.** Values of the $F_8$ indicator (root mean square of the mean hourly energy production of the historic data series minus hourly TRY production in kWh) for each TRY and station (the ranked order of each value is shown in brackets).

| TRY | Station Code | | | | | | | | | | | | | | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | BON | | DRA | | FPK | | GWN | | PSU | | SXF | | TBL | | |
| WYSSd | 0.458 | (1) | 0.304 | (4) | 0.474 | (1) | 0.430 | (1) | 0.494 | (1) | 0.476 | (1) | 0.520 | (2) | (11) |
| TGYd | 0.502 | (2) | 0.261 | (1) | 0.494 | (2) | 0.468 | (2) | 0.548 | (2) | 0.510 | (2) | 0.514 | (1) | (12) |
| TDYd | 0.528 | (3) | 0.294 | (2) | 0.534 | (3) | 0.489 | (3) | 0.565 | (3) | 0.539 | (3) | 0.545 | (4) | (21) |
| ISOd | 0.561 | (4) | 0.294 | (3) | 0.541 | (4) | 0.556 | (5) | 0.604 | (5) | 0.566 | (4) | 0.532 | (3) | (28) |
| TMY3d | 0.597 | (5) | 0.319 | (5) | 0.564 | (5) | 0.540 | (4) | 0.595 | (4) | 0.601 | (5) | 0.585 | (5) | (33) |
| FRMd | 0.619 | (7) | 0.330 | (6) | 0.576 | (6) | 0.607 | (7) | 0.631 | (6) | 0.617 | (6) | 0.604 | (6) | (44) |
| FRPd | 0.611 | (6) | 0.444 | (7) | 0.590 | (7) | 0.596 | (6) | 0.636 | (7) | 0.698 | (9) | 0.608 | (7) | (49) |
| WYSSm | 0.727 | (8) | 0.479 | (11) | 0.688 | (12) | 0.669 | (8) | 0.735 | (9) | 0.697 | (8) | 0.682 | (10) | (66) |
| TMY3m | 0.730 | (9) | 0.488 | (12) | 0.701 | (13) | 0.691 | (9) | 0.745 | (12) | 0.692 | (7) | 0.675 | (9) | (71) |
| TDYm | 0.733 | (10) | 0.473 | (9) | 0.676 | (10) | 0.711 | (12) | 0.740 | (11) | 0.712 | (11) | 0.651 | (8) | (71) |
| TGYm | 0.746 | (12) | 0.477 | (10) | 0.662 | (9) | 0.699 | (10) | 0.739 | (10) | 0.723 | (13) | 0.688 | (11) | (75) |
| ISOm | 0.736 | (11) | 0.463 | (8) | 0.659 | (8) | 0.708 | (11) | 0.760 | (14) | 0.716 | (12) | 0.692 | (13) | (77) |
| FRMm | 0.765 | (14) | 0.549 | (13) | 0.681 | (11) | 0.738 | (13) | 0.751 | (13) | 0.709 | (10) | 0.690 | (12) | (86) |
| FRPm | 0.751 | (13) | 0.562 | (14) | 0.741 | (14) | 0.773 | (14) | 0.728 | (8) | 0.773 | (14) | 0.703 | (14) | (91) |

The $F_G$ parameter defined in Equation (20) was used to evaluate the overall performance of the TRYs. This is the weighted average of ranked orders obtained from the eight statistical indicators calculated for each reference year. Under this weighting, the same importance is given to the annual rank order, to the average of the three monthly orders, to the average of the two daily orders and to the average of the two hourly orders. The results obtained for the various combinations of TRYs and locations are presented in Table 13. The last column of this table shows the average value of $F_G$ obtained for each TRY based on all of the SURFRAD stations.

$$F_G = F_1 + (F_2 + F_3 + F_4)/3 + (F_5 + F_6)/2 + (F_7 + F_8)/2 \tag{20}$$

The results show that TRY$_{\mathrm{WYSSd}}$ performs well, achieving the lowest overall score for all of the stations. It is followed by TRY$_{\mathrm{TGYd}}$, TRY$_{\mathrm{WYSSm}}$, and TRY$_{\mathrm{FRPd}}$ which rank second, third and forth with very close global scores. However, when the overall results analysis is restricted to the reference years obtained from the analysis of meteorological variables, it can be seen how TRY$_{\mathrm{TGYd}}$ performs best, followed by TRY$_{\mathrm{TDYd}}$ and

$TRY_{TMY3d}$. Precisely the methodology for obtaining both TGY and TDY is based on a single variable (global horizontal irradiance and direct normal irradiance respectively).

**Table 13.** Values of $F_G$ (overall performance of each TRY) obtained by the TRYs for each station and total score.

| TRY | Station code | | | | | | | Total |
|---|---|---|---|---|---|---|---|---|
| | BON | DRA | FPK | GWN | PSU | SXF | TBL | |
| WYSSd | 9.00 | 11.00 | 4.33 | 8.00 | 6.00 | 7.00 | 6.00 | 7.33 |
| TGYd | 16.00 | 28.00 | 22.67 | 17.00 | 20.00 | 20.67 | 27.00 | 21.62 |
| WYSSm | 20.00 | 23.00 | 28.67 | 18.00 | 24.00 | 19.00 | 23.00 | 22.24 |
| FRPd | 26.00 | 25.67 | 17.33 | 21.00 | 25.00 | 33.00 | 16.00 | 23.43 |
| TDYd | 31.00 | 28.17 | 25.00 | 26.67 | 22.67 | 20.67 | 28.00 | 26.02 |
| TMY3d | 27.50 | 26.00 | 30.00 | 27.00 | 27.00 | 22.67 | 28.00 | 26.88 |
| TGYm | 33.00 | 27.50 | 28.50 | 29.00 | 33.00 | 34.00 | 37.00 | 31.71 |
| TDYm | 30.00 | 29.50 | 33.67 | 35.17 | 27.33 | 34.67 | 32.00 | 31.76 |
| ISOm | 32.00 | 27.00 | 24.17 | 31.83 | 43.83 | 30.17 | 34.00 | 31.86 |
| FRMd | 33.00 | 31.00 | 33.00 | 35.33 | 23.50 | 37.00 | 36.00 | 32.69 |
| TMY3m | 25.00 | 31.33 | 40.67 | 31.00 | 38.67 | 33.67 | 32.00 | 33.19 |
| ISOd | 37.50 | 35.50 | 39.00 | 37.33 | 38.50 | 36.00 | 37.00 | 37.26 |
| FRMm | 52.00 | 44.33 | 41.00 | 47.67 | 51.50 | 38.50 | 37.00 | 44.57 |
| FRPm | 48.00 | 52.00 | 52.00 | 55.00 | 39.00 | 53.00 | 47.00 | 49.43 |

It should be noted that under the overall classification, the modified version of the TRYs proposed in this work performs better than their original monthly-based versions. Conversely, the TRY generated following the EN ISO 15927-4 original procedure obtained better results than that generated from the proposed adjustment for the selection of typical days. This was found for six of the seven stations.

In all instances, the highest $F_G$ values were obtained from the two TRYs generated according to the original Festa-Ratto method, i.e., by concatenating twelve typical real months. Paradoxically, for all of the stations except for Penn. State (PSU), the Festa-Ratto reference year obtained from the production variable achieves worse scores than that generated from meteorological variables.

For a better appreciation of the results, Fig. 7 illustrates overall $F_G$ values obtained when considering all of the stations. $F_G$ values of the various TRYs were ordered from lowest to highest. Thus, the lower the value of $F_G$, the better the global performance becomes. Bars for daily reference years are shown in dark gray, while light gray bars correspond to TRYs composed of typical months.

## 5. CONCLUSIONS

In this paper, the effects of the temporal downscaling of typical periods that integrate three different TRYs on performance in the evaluation of the long-term behavior of PV systems have been analyzed. The following modified versions of six methods for the generation of TRYs have been proposed for selecting typical days rather than typical months: the Festa-Ratto TRY, WYSS, ISO TRY, TMY3, TDY and TGY. Consequently, these new TRYs are composed of a concatenation of 365 typical days.

The behavior of the TRYs obtained through the modified procedures has been compared to that constructed following the original procedure based on meteorological data recorded from the seven SURFRAD stations (USA). While the ISO, TMY3, TDY and TGY methods are based on the analysis of series of meteorological data, the procedure for obtaining the WYSS employs solar system production. The Festa-Ratto procedure, however, allows for the use of both meteorological and production variables. Thus, for each location, 7 daily TRYs and 7 monthly TRYs have been generated.

The results obtained from this work confirm that the timescale reduction proposed significantly improve for most locations the overall behavior of $TRY_{FR}$, $TRY_{WYSS}$, $TRY_{TMY3}$, $TRY_{TGY}$ and $TRY_{TDY}$ when estimating the electricity production of a PV system over the long term considering the hourly, daily, monthly and annual situations. In the particular case of $TRY_{FR}$, improvements are detected regardless of whether meteorological or system production values are used. However, the modification of the ISO method for the selection of typical days leads to a worsening of global results with respect to the monthly version of the procedure.

When analyzing the results obtained in different time scales it is observed that, in an annual and monthly scenario, TRYs composed of typical months outperform those obtained by the modifications proposed in this work for the selection of typical days, except in the case of the Festa-Ratto method. Conversely, the daily versions of the different reference years present a better behavior than the monthly TRYs on a daily and hourly scale. Therefore, it is not possible to state categorically that in all cases a temporal downscaling of typical moments translates into an improvement of TRY performance.

The results presented in Table 5 to Table 12 provide users with some guidance in selecting the most appropriate TRY for estimating the long-term performance of a PV system, according to their needs and motivations. It was found that the $TRY_{WYSSd}$, a production-based reference year, achieved the best overall performance when all time scales were considered. However, if a user wishes to avoid the use of a multi-year simulation, then the $TRY_{TGYd}$ method, the daily version of the TGY method proposed by NREL, would be recommended to evaluate the long-term performance of a PV system for all timescales.

Finally, one aspect that was not addressed in this study was the issue of solar tracking. This study focused solely on the choice of a TRY for a fixed tilt PV system. One might hypothesize that a different choice of TRY might occur when estimating the long-term performance of tracking-based systems. In particular, one might expect that a TDY may outperform a TGY for tracking based systems, given the higher dependence on direct normal irradiance for tracking based systems in comparison to fixed tilt systems. This issue should be explored in future work.

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