Assessment of the adequacy of EN ISO 15927-4 reference years for photovoltaic systems

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ABSTRACT

The long-term performance prediction of photovoltaic systems requires representative meteorological data from a particular location. Among the numerous proposals in the field of solar energy, most of them include procedures oriented towards the generation of test reference years (TRYs). These synthetic years are composed of the concatenation of twelve actual months of the time series of meteorological measurements. Using TRYs to simulate the performance of different types of solar energy systems reduces the computational effort of the simulation and simplifies the analysis of the results. In this sense, the technical standard EN ISO 15927-4 describes a procedure for constructing a reference year suitable for evaluation of the annual heating and cooling long-term needs in buildings. In this work the adequacy of the EN ISO 15927-4 reference year for photovoltaic systems has been studied. The electricity production obtained by simulation with this TRY has been compared with that obtained by the Weather Year for Solar Systems. This latter reference year only uses the monthly thermal energy collected by the system as a selection parameter of typical months. This comparison has been performed for seven locations of United States considering two 5.6 kWp grid-connected photovoltaic systems that only differ in the solar tracking system. The suitability of the EN ISO 15927-4 reference year for the estimation of the electrical

energy generated by a PV system has been proved, showing good results in the annual and daily predictions in most of the cases studied.

KEYWORDS

test reference year; EN ISO 15927-4; PV systems

1. INTRODUCTION

The economic viability of solar energy harnessing projects using photovoltaic technology strongly depends on the capability to predict the behaviour of such systems in the long-term. In order to achieve this goal, it is necessary to have typical or representative meteorological data of the most frequent conditions at this location, which permits the simulation of the electrical energy production supplied by the system in the long-term.

Since the early seventies of the last century, the subjectivity of typicality concept has caused numerous proposals in the field of solar energy to appear. Some of them consist of the selection of meteorological data series with duration of less than one year. These are known as Short Reference Year (SRY) [1,2,3]. Also, have been developed Simulated Meteorological Years (SMYs) [4,5]. These employ stochastic models or similar to produce hourly values of long-term meteorological data that, consequently, do not contain any observed meteorological measurement.

One of the first proposals for the generation of typical years composed of real measurements was the Test Reference Year (TRY) of the National Climatic Data Center [6] that consisted of a selection of one whole year from the series of meteorological measurements. However, as pointed out by Crawley and Huang [7], this method results in a particularly mild year as it progressively excludes the years with extreme weather conditions. Because of this, most of the subsequent approaches propose the construction of a TRY in which, the resulting year of the analysis of the time series of meteorological variables, is made up by typical real months of this data set. It is, therefore, a year composed of the combination of twelve typical months that may belong to different years of the data set (January of year *i*, February of year *j* and so on). Hence, this year includes 8760 records corresponding to the concatenation of the hourly measurements of each selected real month. This is the case of the Typical Meteorological Year (TMY) of Hall et al. [8], the International Weather for Energy Calculations (IWEC) from ASHRAE [9], the Canadian Weather Year for Energy Calculations (CWEC) described in Siurna et al. [10] or the Weather Year for Solar Systems (WYSS) proposed by Gazela and Mathioulakis [11]. As shown in Bilbao et al. [12], the performance of a TRY depends on the location, so they must be calculated for each site and, in point of fact, many TRYs have been generated for several locations in the world.

Different methodologies proposed use statistical indexes in order to select the typical months that will be part of the TRY. For example, the Festa and Ratto method [13], that arises as a modification of the known as Danish method developed by Andersen et al. [14] and Lund and Eidorff [15], sets the use of the Kolmogorov-Smirnov statistics [16]. For its part, the Sandia National Laboratory method that leads to obtaining the above mentioned TMY [8] uses the Finkelstein-Schafer statistics [17] as the main selector of the candidate years to represent each typical month. In both approaches, short and long-term cumulative distribution functions of the climatic parameters are taken into consideration but with different treatments. In the second method, the selection of the candidate months is carried out by means of the classification of the weighed sum of the Finkelstein-Schafer (F_S) statistics corresponding to each climatic variable. Accordingly, a different importance can be assigned to each considered parameter. This method has been used by Pissimanis et al. [18] in the construction of a TMY for the city of Athens (Greece) and by Petrakis et al.

[19] for its construction for Nicosia (Cyprus). Subsequent variations of Sandia National Laboratory methodology that lead to obtaining the TMY2 [20] and the TMY3 [21], maintain the F_S statistics treatment although they modify the considered climatic parameters and their weighing factors. In this way, modifications of the climatic variables and weighing coefficients proposed in the original method have been suggested by other authors as Sawaqed et al. [22], Chow et al. [23] and Zang et al. [24].

Using TRYs to simulate the performance of different types of solar energy systems presents a number of advantages over the use of the whole historic data series. Probably, the most obvious is the reduction of the computational effort of the simulation [5], as well as simplifying the analysis of the results. Likewise, as pointed out in Pernigotto et al. [25], these synthetic years mitigate the effects of missing or wrong data when a historic data series is simulated. Chow et al. [23] showed that TRYs, far from being static, exhibit a dynamic behaviour that might consider the effects of the local climate changes in the meteorological variables. Consequently, these years should be reviewed periodically so as to consider this long-term influence. So much so that different meteorological data sources such as Meteonorm or the National Solar Radiation Database (NSRDB), dependent on the National Renewable Energy Laboratory (NREL), provide TMY2s and TMY3s.

In 2005 the European technical standard EN ISO15927-4 [26] proposed a method to generate a TRY based on the F_S statistic. However, unlike the above mentioned procedures, this one assigns the same weight to all climatic variables considered. This methodology is aimed at the construction of a reference year of hourly data to evaluate the annual energy demand for heating and cooling in buildings. The EN ISO15927-4 method (cited hereafter as ISO method) has been employed by Kalamees and Kurnitski [27] in a TRY generation at six locations of Estonia and by Lee et al. [28] for its construction for seven cities of South Korea. Likewise, Pernigotto et al. [25] have implemented this method in five north Italy cities in order to assess the representativeness of ISO TRY for evaluating the energy performance of buildings.

After analysing the influence of different climatic parameters on the energy demands of two sample buildings, Kalamees et al. [29] suggested a variation of the ISO method. In the original procedure dry bulb temperature, global horizontal radiation and relative humidity are considered main climatic parameters. However, in this proposal only temperature and solar radiation should be used as main variables for the selection of the three candidate months, while wind speed and relative humidity are employed as secondary parameters for the final selection of the typical month. Furthermore, the influence of the air temperature on the energy demand is emphasized by applying a seasonally dependent weighting factor. In this way, Pernigotto et al. [30] proposed two variations of the ISO method with the aim of improving its representativeness for energy building simulation. One of these is related to the final selection of the typical month. The other one assigns different weights to the climatic parameters depending on whether the final objective pursued by the TRY is the analysis of heating or cooling needs.

Despite the fact that most of the published procedures employ different meteorological variables, Gazela and Mathioulakis [11] developed a new method, so-called Weather Year for Solar Systems (WYSS), for typical weather data selection. In this procedure only the monthly thermal energy collected by the system is used as a selection parameter of typical months. Typical years thus obtained are directed towards the prediction of long-term behaviour of solar hot water systems (SHWS). Therefore, before applying this method, simulation of the behaviour of the solar system is needed in order to determine the monthly solar gain of every year of the historic data series.

Most of the literature related with the development of reference years is aimed at predicting the long-term behaviour of solar thermal systems in which there is a linear relationship between the ambient temperature and the collector performance. However, Argiriou et al. [31] in their comparison of different methods for generating typical meteorological years, between the various simulations performed, considered a PV array of 5.8 m^2, facing south with a tilt angle of 40° in Athens. This concluded that, among the seventeen TRYs produced, the three best for this PV system were the Danish method with the variable sunshine duration, the modified Festa and Ratto method and one of nine different TMYs that only differs in the weights assigned to weather variables. Nevertheless, the WYSS method and the ISO method, which were published subsequent to this work, were not assessed herein. Also, the study of the aptitude of three TRYs when predicting the long-term performance of three solar energy (thermal, passive and photovoltaic) systems in two cities of Spain was conducted by Bilbao et al. [12]. This work determined that the methods which had better results for photovoltaic systems were the Festa and Ratto modified [31] for Madrid and the Danish method for Valladolid.

The objective of the present work is to evaluate the adequacy of the reference years generated using the methodology proposed in the standard EN ISO 15927-4 to estimate the electrical energy produced by a photovoltaic power generation system in the long-term.

2. METEOROLOGICAL DATA

The meteorological data used in this study comes from the seven weather stations of the Surface Radiation Budget Network (SURFRAD) which are distributed in different climatic regions of the United States (see Figure 1). In Table I geographical features of the seven stations are shown. The meteorological data sets provided by the SURFRAD network are in accordance with the recommendations of the standard EN ISO 15927-4, namely hourly data sets with ten or more years of at least four meteorological variables (i.e. dry bulb temperature, global horizontal solar radiation, relative humidity and wind speed at a height of ten meters above the ground).

Weather data provided by SURFRAD are quality controlled by the institution itself following the procedure recommended by the Baseline Surface Radiation Network [32]. The results of the analysis of yearly missing data in the time series of each of the seven stations considered are presented in Table II. As can be seen, most of the available years show low proportions of gaps. The years with missing records of over 10% have been removed from the data set, so that, the time series of meteorological data considered finally for each station are those shown at the end of Table II. Isolated gaps or erroneous data found in the other years have been filled by simple linear interpolation.

3. METHODOLOGY

In order to evaluate the adequacy of the reference year obtained by applying the ISO method to the estimation of the energy performance of a photovoltaic system, the electrical energy production obtained after ISO TRY simulation has been compared with that achieved by the WYSS method. Among the various proposals, the WYSS has been chosen in this study as the reference year against which to compare the TRY obtained by applying the ISO method. As it is a system oriented approach, it minimizes the error in estimating the energy generated [11] because it bases the selection of the months that make up the TRY only in the monthly solar gain and not in meteorological parameters. Although this method is intended for thermal systems, in this paper it has been modified for use in photovoltaic technology. So, as described in Section 3.2, the monthly electrical energy produced by the system (EP_{ym}) has been used in order to select each typical month rather than solar gain.

The behaviour of the two TRYs has been assessed by studying the electrical output of two grid-connected 5.6 kWp photovoltaic systems which only differ in the solar tracking system (see Table III). The first, named System 1, has its modules in a fixed position with an optimal tilt angle that depends on the location. In the second one, System 2, the modules are mounted on a two-axis solar tracker that provides it with complete freedom of movement. This device allows the collector surface to be normal to the sunbeams thereby maximizing the energy captured.

Figure 2 illustrates the general procedure followed to assess the adequacy of the ISO TRYs for the estimation of the electric energy produced by a photovoltaic system. As can be seen, once both, the ISO TRY and the WYSS, are generated by the methods described below for all the studied locations (see Sections 3.1 and 3.2), the electric output provided by each of them has been obtained using PVSOL simulation software. The input weather file to the program consists of a list of 8760 hourly values of dry bulb temperature, global horizontal radiation, relative humidity and wind speed. After the definition of the technical characteristics of the installation and the simulation with each file of meteorological data, the program returns 8760 hourly values of electricity production that are exported for further analysis. Annual, monthly and daily electric production results obtained are compared with simulations carried out for each of the years of the data set using six statistical indicators suggested by Gazela and Mathioulakis [11]. The indicator F_1, obtained from Equation (1), is the root mean square difference of the yearly energy productions of the system. The indicators F_2 and F_5 (Equations 2 and 5) are the total standard error of estimates of monthly and daily energy outputs, respectively. The indicator F_3 (Equation 3) is the chi square parameter on monthly solar productions. Lastly, the indicators F_4 and F_6, which can be derived from

Equations (4) and (6), are the root mean squares of the mean energy production of the historic data series minus the productions of the TRYs on a monthly and daily basis.

- 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:

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

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

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

- Daily electric energy production:

$$F_5 = \frac{\sum_{d=1}^{365} SEE_d}{365} = \frac{1}{365}\cdot\left\{\sum_{d=1}^{365}\left[\frac{\sum_{y=1}^{j}\left(EP_{yd} - EP_{td}\right)^2}{20}\right]^{1/2}\right\} \tag{5}$$

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

3.1. The EN ISO 15927-4 method

The standard EN ISO 15927-4 [26] describes a method for constructing a reference year suitable for evaluation of the annual heating and cooling long-term needs in buildings. The procedure is designed to build a year of hourly meteorological data in which the mean value of the individual variables, its cumulative distribution function and the correlations between the different variables of each month are the closest possible to the corresponding calendar month of the historical series.

As recommended in the procedure, dry bulb temperature, global horizontal solar radiation and relative humidity are considered as main selectors of the months that make up the reference year, with the wind speed as a secondary selection parameter. Regardless of this, the possibility of using other combinations of primary and secondary parameters is included in the standard. Nevertheless, the parameters recommended have been employed in this work. The procedure, shown in Figure 3, starts conducting, for each climatic parameter *p*, where *p* is the dry bulb temperature, solar radiation and relative humidity, the following:

- Calculation of daily means from the hourly values of *p*, for each of the years of the time series.
- For each calendar month the long-term cumulative distribution function of the daily means over all the years of the data set is calculated for each parameter, by sorting all the values in increasing order and then using Equation (7).

$$\Phi(p,m,i) = \frac{K(i)}{N+1} \tag{7}$$

- For each year of the data set, the short-term cumulative distribution function of the daily means for each calendar month is calculated by sorting all the daily means for that month and that year in increasing order and then using Equation (8).

$$F(p,y,m,i) = \frac{J(i)}{n+1} \tag{8}$$

- For each calendar month the F_S statistic is then calculated for each year of the data set by using Equation (9).

$$F_S(p,y,m) = \sum_{i=1}^{n} \left| \, F(p,y,m,i) - \Phi(p,m,i) \, \right| \tag{9}$$

- For each calendar month, the individual months are then ranked from the multiyear record in order of increasing size of F_S statistic for each parameter. Then, the individual ranks of the three climate parameters are summed in order to calculate the total ranking.
- For each calendar month, for the three months with the lowest total ranking, the deviation of the monthly mean wind speed from the corresponding multi-year calendar month mean is calculated. The month with the lowest deviation in wind speed is selected as the best month to be included in the reference year.

Finally, the method proposes the use of a cubic spline with the purpose of smoothing the transition of the 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 has not been taken into consideration in this work.

When implementing the final step of the process, some coincidences in the sum of the orders of the F_S statistics of the three main variables have been found. Therefore, in certain cases, it is not possible to select the three months with the lowest ranking. Since the ISO method does not consider this, in these cases it has been introduced, as a secondary selection condition, the order of F_S statistics of the radiation variable. This ensures that, in case of a tie in the total ranking, priority is given to those months with lower order in the radiation variable. This modification of the original method is shown in Figure 3 as a dashed line.

In order to illustrate the variation proposed, an example of the selection of the candidate months of June in Bondville weather station is shown in Table IV. In this case, the third and the fourth years coincide with the lowest ranking sum of the F_S statistics, that is, 2001 and 2011. Considering the lowest order of the radiation variable, June 2001 has been selected as the third candidate month.

Continuing the above example, Table V shows the final selection of the month in response to the slightest deviation between the mean wind speed of each month and its multi-year mean wind speed.

3.2. The WYSS method

The WYSS procedure is directed towards the prediction of long-term behaviour of a SHWS. However, in this work, it has been modified with the target of predicting the electric energy provided by a photovoltaic system. The only parameter considered for the selection of the typical months is the solar gain, in this particular case, the monthly electric energy production. Thus, the first stage is obtaining the monthly production of each year of the data set by simulation. Once the monthly productions are determined, the selection process (see Figure 4) begins as described below:

- Calculation of the mean value of the electric production of each year from Equation (10).

$$\overline{EP}_m = \frac{\left(\sum_{y=1}^{j} EP_{ym} \right)}{j} \tag{10}$$

- From Equation (11), calculation of the squared difference between the monthly electricity production of *m* month of *y* year and the mean value of monthly energy output of the same month of long-term data.

$$\tau_{ym} = \left[EP_{ym} - \overline{EP}_m \right]^2 \tag{11}$$

- Designation of the month *m* of the year *y* with the minimum value of τ_{ym}. This month is considered typical and is selected for the WYSS.

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

4. RESULTS AND DISCUSSION

4.1. TRY generation

Firstly, in order to make up the WYSSs, each of the years of the data set of every weather station has been simulated with PVSOL considering each of the two photovoltaic systems established, performing a total of 218 executions. According to the procedure already described, the further processing of the results has led to the obtaining of the WYSS considering System 1 (WYSS1) and System 2 (WYSS2). Table VI shows the selected typical months for each station. Meanwhile, in Table VII the typical months, obtained after application of the ISO method, are shown.

So as to simplify the analysis of the results, in Table VIII the coincidences that have occurred in the typical months of WYSS1 and WYSS2 are illustrated for each weather station. The cases in which the typical months of WYSS1 and WYSS2 coincide are labelled with a "1" and those in which no match occurs, with a "0". It can be seen that Bondville, Penn State and Sioux Falls stations have the highest number of matches, a total of six months, while in Fort Peck and Goodwin Creek stations only three of the twelve months of the year coincide.

The analysis of the overall results by month shows that October and November have the largest number of matches whereas there are months, like May and July, in which any match is encountered. The total percentage of agreement between the WYSS1 and WYSS2 is around 40% of all months studied. It is not surprising given that both TRYs are the result of applying the same procedure to the energy generated by two photovoltaic systems that only differ in the sun-tracking system.

When analysing the number of typical months of ISO TRY matching the WYSS1 and the WYSS2 (see Table IX) it can be seen that, in both cases, the percentage of agreement of all the stations considered is just over 15%. By comparing the ISO TRY with the WYSS1 it can be seen that, at least, one month matches in all stations. The largest number of agreements is shown in Table Mountain station, in which three months coincide. Nevertheless, when carrying out this comparison with the WYSS2 it is seen that no agreement occurs for Fort Peck station while it occurs in up to four of the twelve possible cases in Sioux Falls. Also, the analysis of the results in Table IX concludes that the typical months of June, August and December of the ISO TRY does not match with those of WYSS1 and WYSS2 in any of the stations.

4.2. Electric energy productions

Having determined the months that constitute the WYSS1, the WYSS2 and ISO TRY for each weather station, each reference year has been built, obtaining a sequence 8760 hourly data of each of the four meteorological variables considered. Using the PVSOL software again, hourly electrical production of each generated TRY has been simulated for both photovoltaic systems.

In Figure 5 monthly electricity production values obtained for each of the stations after the simulation of each TRY for the System 1 are shown. Also, the mean monthly production of energy of the historical series ($\overline{EP}_m$) is represented. It can be seen how the monthly production obtained by simulating the WYSS1 coincides with the long-term mean production curve while the ISO TRY curve deviates, to a greater or lesser extent, depending on the station considered.

Figure 6 presents monthly results obtained by considering the System 2, that is, the two-axis sun tracking system. Comparing this with the Figure 5, the most significant difference observed is the higher production values obtained due to the increased solar radiation gained through the solar tracker. As in the previous situation, the electrical energy output of the WYSS2 closely fit with the average monthly production while the electric energy obtained by ISO TRY simulation departs from the long-term curve following the same pattern as in the case of System 1.

4.3. Adequacy of the EN ISO 15927:4 reference years for photovoltaic systems

The results obtained after the calculation of the six statistical indicators (Equations 1-6) for the System 1 are shown in Table X. The Table XI presents the deviations of each of the six indicators calculated for the ISO TRY with respect to the ones of the WYSS1. From the point of view of the prediction of the annual electrical production, the reference year determined by the ISO method for Sioux Falls station fits better than the WYSS1 as the F_1 parameter has a lower value. Although for Bondville, Table Montain, Fort Peck and Goodwin Creek stations the F_1 parameter calculated for the standardised reference year is greater than that determined for the WYSS1, it can be seen that the deviation of the two values is lower than 2%. However, deviations of the first parameter in the case of Penn State and Desert Rock stations have considerably higher values.

From the point of view of predicting the monthly production, assessed by F_2, F_3 and F_4 parameters, the results of Table XI evidence the worst performances of the ISO reference years regarding those obtained using the WYSS method. This seems reasonable given that the criterion for selection of typical months in the latter is to minimize the error of the monthly energy production compared to the long-term monthly electrical output.

Moreover, the total standard error of estimates on daily energy production (F_5) for the ISO TRY presents a lower value than for the WYSS1 in three of the seven weather stations analysed and in the other four has a minimal deviation. In reviewing the results of the F_6 parameter that, along with the F_5, evaluates the accuracy of the prediction of the daily energy generated by each TRY, it has been seen that, in four of the seven analysed stations, the ISO TRY presents a lower value than the WYSS1. In the remaining three stations, the calculated deviation is about 5%.

The study of the results obtained for the System 2 (see Tables XII and XIII) confirms the analysis performed for the System 1. The ISO TRY generated for Table Mountain and Sioux Falls stations predict the annual electrical production better than the WYSS2. The annual production predictions made by the ISO reference year for Bondville, Fort Peck and Goodwin Creek stations, in spite of presenting a worse result than those estimated by the WYSS2, deviate slightly. Again, the performance of the ISO TRY for Desert Rock and Penn State stations is considerably worse than the WYSS2. Concerning the prediction of the monthly production, as in the previous case, the worse behaviour of the ISO TRY regarding the WYSS2 is perceived.

The F_5 values obtained for System 2 by simulating both TRYs confirm the good behaviour of the ISO reference year in estimating the daily energy generated by a photovoltaic system. In five of the weather stations considered, the ISO TRY has a better performance than the WYSS2 and in the remaining two stations, although the performance is worse, the deviation of the F_5 indicator is negligible. Such good results are slightly worsened by those obtained for F_6. In this case, while in three of the seven stations the behaviour of the ISO TRY is better at estimating the daily energy produced, in the other stations is worse, presenting deviations below 5% except for Table Mountain in which the deviation exceeds 8%.

As noted above, considering the selection criteria of the WYSS method, it is expected that the reference year thus obtained behaves better than the ISO TRY when estimating the monthly production. However, it is noteworthy that, for both photovoltaic systems considered, the ISO TRY presents a good performance in the prediction of daily and annual production in a large number of cases studied while provides a significantly worse prediction than the WYSS for monthly outputs. This better performance in estimating daily production is due to the fact that the distribution functions of daily values are considered the ISO method and, therefore, their probability of occurrence. However, in WYSS procedure only a first order statistic is used, as is the case of the average.

It seems coherent to think that a TRY that has a good fit in the prediction of daily production should also fit well to the monthly and annual prediction. In fact, the reference year recommended to evaluate the long-term performance of a photovoltaic system should be the one that presented a better fit in the daily prediction.

In order to explain this inconsistency it is necessary to examine the expressions of the indicators used in the evaluation of the accuracy of the prediction of the two TRY studied. First, it should be remembered that the electrical output of each month and each year of the historical series is the sum of the daily power production, as shown in Equation (12).

$$EP_y = \sum_{m=1}^{12} \left(EP_{ym} \right) = \sum_{m=1}^{12} \left(\sum_{d=1}^{n} EP_{ymd} \right) \tag{12}$$

Given the above, it can be seen how the expressions that determine the statistical indicators related to the annual and monthly production (F_1-F_4) implicitly compensate the deviations that occur between the daily values of production for each year of data set and those of the reference year evaluated. That is, the positive and negative differences between the daily production of a given year (EP_{ymd}) and for the same day of the reference year (EP_{tmd}) are algebraically added, underestimating the actual error occurred. Also in Equation (11) it can be seen how the WYSS method, when selecting the months that make up the reference year, compensates the deviations between the total monthly production of the series and the average monthly production. By contrast, the indicators for the daily production do not allow the compensation of the daily deviations by squaring each difference. This is the reason why the ISO TRY, showing good results in the daily indicators, which do not compensate production deviations, may have comparatively worse results in monthly indicators, which allows this compensation. Nevertheless, the WYSS has obtained good results in the monthly indicators.

5. CONCLUSIONS

In view of the results obtained the ISO method may be recommended for assessing the long-term behaviour of photovoltaic systems. Although this method is focused on the generation of synthetic years for the evaluation of thermal loads in buildings, its suitability for the estimation of the energy generated by a PV system has been proved, showing good results in the annual and daily indicators in most of the cases studied. Also, despite the fact that this approach does not consider the effect of the autocorrelation performed in the TMY, TMY2 or TMY3 by the analysis of runs, its implementation is simpler than these.

Both reference years studied, namely the ISO TRY and the WYSS, show good, although different, skills when estimating the electrical energy produced by the photovoltaic system. However, considering the typical months that make up each of the two TRYs, it can be seen that there are few coincidences.

The WYSS procedure is easy to implement, though, requires a considerable simulation effort. In fact, this effort would go against one of the main advantages that we considered to justify the interest of using test reference years. Furthermore, it presents a potential weakness due to the compensation of deviations from daily production in the short-term compared to the long-term, which should be deeply analyzed in future work.

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 monthly 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).
$\Phi(p,m,i)$	long-term cumulative distribution function of the daily means of a month m for a climatic parameter p.
$K(i)$	rank order of the i^{th} daily value of a parameter p for a month m.
N	total number of days for a specific month over all the available years.
$F(p,y,m,i)$	short-term cumulative distribution function of the daily means for a month m of a year y for a climatic parameter p.
$J(i)$	rank order of the i^{th} value of the daily means within a month m of a year y

n	number of days for a specific month.
$F_S(p,y,m)$	Finkelstein-Schafer statistic of a month m within a year y for a climatic parameter p.

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Table I. Geographical data of the SURFRAD Network stations.

Station	Code	Latitude (ºN)	Longitude (ºW)	Elevation (m)
Bondville, Illinois	BON	40° 3' 5.58"	88° 22' 23.70"	230
Table Mountain, Boulder, Colorado	TBL	40° 7' 32.04"	105° 14' 15.94"	1689
Desert Rock, Nevada	DRA	36° 37' 13.98"	116° 1' 40.03"	1007
Fort Peck, Montana	FPK	48° 18' 28.70"	105° 6' 6.41"	634
Goodwin Creek, Missisippi	GWN	34° 15' 16.91"	89° 52' 22.46"	98
Penn. State Univ. Pennsylvania	PSU	40° 43' 12.82"	77° 55' 51.25"	376
Sioux Falls, South Dakota	SXF	43° 44' 3.52"	96° 37' 24.04"	473

Table II. Annual percentages of missing data and time series of meteorological measurements considered for each station (%).

Year	Station code						
	BON	TBL	DRA	FPK	GWN	PSU	SXF
1996	0.00	1.50	-	-	0.05	-	-
1997	3.50	1.00	-	4.00	0.00	-	-
1998	0.25	0.00	-	0.00	0.50	-	-
1999	10.25	0.00	0.00	0.25	0.25	0.00	-
2000	0.00	0.00	1.00	0.00	0.00	0.50	-
2001	0.00	0.00	0.00	4.50	0.00	0.00	-
2002	0.25	0.00	1.50	0.25	0.00	0.00	-
2003	0.00	0.00	0.00	0.25	9.75	0.00	-
2004	0.00	0.00	0.00	0.50	13.25	4.50	0.00
2005	0.50	0.00	2.00	0.00	0.00	0.00	0.25
2006	2.25	0.00	1.00	1.00	0.00	1.00	0.00
2007	0.00	0.00	0.00	0.00	1.50	5.00	0.25
2008	0.25	0.00	2.00	0.00	1.00	0.25	0.00
2009	0.75	0.25	0.00	0.00	2.25	0.75	0.00
2010	0.00	0.00	3.50	0.00	3.50	0.00	0.00
2011	0.00	0.00	0.00	0.00	3.50	0.00	0.00
2012	0.00	0.00	0.00	0.00	0.00	0.00	1.00
2013	0.00	0.25	0.00	0.00	2.25	1.00	0.25
Removed years	1999	-	-	-	2004	-	-
Period considered	96-13	96-13	99-13	97-13	96-13	99-13	04-13
Total years	17	18	15	17	17	15	10

Table III. Technical data of the PV systems.

	System 1	System 2
PV power (kWp)	5.60	5.60
Number of PV modules	56	56
Number of PV modules in series	14	14
Number of PV modules in parallel	4	4
Solar tracking system	No	Yes (2 axes)
System azimuth angle (ºS)	0	Variable
System tilt angle (º)	Optimal	Variable

Table IV. Selection of the three candidate months of June for Bondville station according to the standard EN ISO 15927-4 and the suggested modification.

Year	0Dry bulb temperature		0Global radiation		0Relative humidity	0	Total ranking	Candidate years
	F_S	Ranking	F_S	Ranking	F_S	Ranking		
1996	2.3398	11	1.0098	3	3.2228	10	24	
1997	2.1129	9	3.6301	16	6.7769	16	41	
1998	1.5927	8	3.2016	15	5.1725	15	38	
2000	2.3390	10	1.2833	6	3.7770	12	28	
2001	1.5718	6	1.4711	7	1.7596	5	18	3
2002	3.7174	15	1.2057	5	2.2030	8	28	
2003	5.3562	17	1.6336	10	2.0914	7	34	
2004	3.8943	16	0.9450	2	1.1871	3	21	
2005	3.6243	14	2.9318	14	1.8863	6	34	
2006	1.3423	3	1.6637	11	4.2779	13	27	
2007	1.5611	5	0.9092	1	2.7532	9	15	1
2008	2.7476	12	1.5750	8	3.4423	11	31	
2009	1.4862	4	1.6201	9	1.0520	2	15	2
2010	3.5609	13	1.1994	4	4.6752	14	31	
2011	1.1487	2	1.7756	12	1.6130	4	18	
2012	0.7304	1	5.3033	17	7.2368	17	35	
2013	1.5798	7	2.5914	13	1.0001	1	21	

Table V. Final selection of the typical month of June for Bondville station according to the standard EN ISO 15927-4.

Candidate years	Wind speed short-term mean (m·s^{-1})	Wind speed long-term mean (m·s^{-1})	Deviation	Typical month
2007	3.9060	4.2080	0.3020	
2009	4.2050	4.2080	0.0030	*
2001	3.8536	4.2080	0.3543	

Table VI. Generated TRYs according to WYSS method considering the System 1 and the System 2 (numbers in Table are abbreviations of the year, i.e. 2008=08).

Month	WYSS1							WYSS2						
	BON	TBL	DRA	FPK	GWN	PSU	SXF	BON	TBL	DRA	FPK	GWN	PSU	SXF
1	08	96	99	99	05	04	13	01	09	99	08	11	03	13
2	08	07	99	99	13	00	09	11	07	99	13	13	00	07
3	13	13	13	98	97	04	08	07	13	13	03	96	07	08
4	07	00	12	97	01	03	12	07	13	01	01	97	08	12
5	98	97	05	08	00	04	07	04	07	13	12	10	12	08
6	02	01	04	09	01	06	08	02	01	99	08	07	06	04
7	96	13	08	03	03	08	08	08	10	02	13	97	06	13
8	05	02	04	97	03	99	11	05	08	99	97	97	99	11
9	12	00	07	07	98	99	04	05	00	99	05	11	04	08
10	96	08	01	97	97	06	12	96	13	01	97	06	06	12
11	08	10	04	10	10	05	06	08	10	05	10	10	05	07
12	06	09	01	02	07	11	05	06	08	04	06	07	11	05

Table VII. Generated TRYs according to ISO method (numbers in Table are abbreviations of the year, i.e. 2008=08).

Month	ISO TRY						
	BON	TBL	DRA	FPK	GWN	PSU	SXF
1	00	11	06	10	08	10	13
2	01	07	08	13	08	01	07
3	11	10	03	09	05	08	08
4	07	01	04	99	03	03	09
5	10	09	08	08	08	06	04
6	09	07	03	13	08	13	13
7	10	10	08	02	03	12	07
8	01	98	09	99	06	12	09
9	03	04	08	07	11	09	08
10	96	08	12	13	07	12	08
11	02	10	05	11	10	07	12
12	03	06	09	05	09	09	10

Table VIII. Coincidences between the typical months selected according to WYSS method for System 1 (WYSS1) and System 2 (WYSS2).

Month	WYSS1 - WYSS2							
	BON	TBL	DRA	FPK	GWN	PSU	SXF	Total
1	0	0	1	0	0	0	1	2
2	0	1	1	0	1	1	0	4
3	0	1	1	0	0	0	1	3
4	1	0	0	0	0	0	1	2
5	0	0	0	0	0	0	0	0
6	1	1	0	0	0	1	0	3
7	0	0	0	0	0	0	0	0
8	1	0	0	1	0	1	1	4
9	0	1	0	0	0	0	0	1
10	1	0	1	1	0	1	1	5
11	1	1	0	1	1	1	0	5
12	1	0	0	0	1	1	1	4
Total	6	5	4	3	3	6	6	33

Table IX. Coincidences between the typical months selected according to WYSS method and the ISO method.

Month	WYSS1 – ISO TRY								WYSS2 – ISO TRY							
	BON	TBL	DRA	FPK	GWN	PSU	SXF	Total	BON	TBL	DRA	FPK	GWN	PSU	SXF	Total
1	0	0	0	0	0	0	1	1	0	0	0	0	0	0	1	1
2	0	1	0	0	0	0	0	1	0	1	0	1	0	0	1	3
3	0	0	0	0	0	0	1	1	0	0	0	0	0	0	1	1
4	1	0	0	0	0	1	0	2	1	0	0	0	0	0	0	1
5	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	1	0	1	0	0	2	0	1	0	0	0	0	0	1
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	1	0	0	0	1	0	0	0	0	1	0	1	2
10	1	1	0	0	0	0	0	2	1	0	0	0	0	0	0	1
11	0	1	0	0	1	0	0	2	0	1	1	0	1	0	0	3
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	2	3	1	2	2	1	2	13	2	3	1	1	2	0	4	13

Table X. Values of the indicators calculated for System 1.

Station	TRY	F_1	F_2	F_3	F_4	F_5	F_6
BON	ISO TRY	328.66	69.76	2.88	26.91	4.48	9.23
	WYSS1	324.01	64.39	0.09	4.60	4.48	9.34
TBL	ISO TRY	205.39	54.12	1.91	19.68	4.90	7.95
	WYSS1	203.40	50.73	0.20	6.08	4.90	7.52
DRA	ISO TRY	195.58	57.42	3.77	29.76	5.30	5.55
	WYSS1	180.55	50.24	0.15	5.28	5.30	5.76
FPK	ISO TRY	251.85	72.62	3.43	27.39	4.65	7.94
	WYSS1	250.90	67.05	0.24	8.30	4.65	8.11
GWN	ISO TRY	835.62	111.84	9.83	72.21	4.54	8.79
	WYSS1	830.14	90.78	0.04	5.02	4.54	8.75
PSU	ISO TRY	292.65	74.44	3.23	35.71	4.27	9.26
	WYSS1	256.48	66.19	0.07	5.25	4.26	8.84
SXF	ISO TRY	242.99	70.93	4.18	29.29	4.61	8.45
	WYSS1	244.01	64.74	0.57	12.02	4.61	8.68

Table XI. Relative deviations of the indicators calculated for System 1 (%).

Station	F_1	F_2	F_3	F_4	F_5	F_6
BON	-1.41	-7.70	-96.99	-82.89	-0.02	1.21
TBL	-0.97	-6.26	-89.71	-69.12	-0.02	-5.41
DRA	-7.68	-12.50	-96.04	-82.25	0.04	3.84
FPK	-0.38	-7.67	-93.01	-69.70	0.00	2.07
GWN	-0.66	-18.83	-99.60	-93.04	0.00	-0.49
PSU	-12.36	-11.08	-97.68	-85.31	-0.04	-4.52
SXF	0.42	-8.72	-86.42	-58.96	-0.07	2.70

Table XII. Values of the indicators calculated for System 2.

Station	TMY	F_1	F_2	F_3	F_4	F_5	F_6
BON	ISO TRY	498.13	101.04	2.97	40.52	5.11	13.00
	WYSS1	490.67	92.63	0.03	4.40	5.11	12.36
TBL	ISO TRY	301.28	78.67	1.98	27.38	5.63	11.42
	WYSS1	302.41	73.65	0.10	7.04	5.63	10.50
DRA	ISO TRY	282.89	86.17	3.56	43.32	6.18	8.09
	WYSS1	254.19	75.34	0.05	5.04	6.18	8.26
FPK	ISO TRY	372.44	103.55	3.76	42.74	5.36	11.51
	WYSS1	369.16	93.97	0.11	7.46	5.36	11.09
GWN	ISO TRY	947.04	141.15	9.95	91.17	5.19	12.41
	WYSS1	936.58	114.35	0.04	6.56	5.19	12.73
PSU	ISO TRY	479.29	108.23	3.54	53.19	4.84	13.21
	WYSS1	400.00	95.46	0.06	6.49	4.84	12.60
SXF	ISO TRY	346.19	98.05	3.37	42.53	5.27	11.55
	WYSS1	346.35	88.32	0.22	10.51	5.27	11.98

Table XIII. Relative deviations of the indicators calculated for System 2 (%).

Station	F_1	F_2	F_3	F_4	F_5	F_6
BON	-1.50	-8.32	-99.15	-89.13	-0.01	-4.94
TBL	0.37	-6.39	-94.93	-74.31	0.00	-8.04
DRA	-10.14	-12.56	-98.63	-88.35	0.04	2.11
FPK	-0.88	-9.25	-97.16	-82.55	0.01	-3.62
GWN	-1.10	-18.99	-99.59	-92.80	0.00	2.63
PSU	-16.54	-11.79	-98.41	-87.80	-0.08	-4.61
SXF	0.05	-9.92	-93.48	-75.30	0.00	3.72

LIST OF CAPTIONS

Figure 1. Location of SURFRAD Network stations in US.

Figure 2. General procedure for assessing the adequacy of the ISO TRYs for PV systems.

Figure 3. Procedure for obtaining the ISO TRY.

Figure 4. Procedure for obtaining the WYSS.

Figure 5. Comparison between the long-term average monthly electricity production and that obtained for each TRY considering System 1.

Figure 6. Comparison between the long-term average monthly electricity production and that obtained for each TRY considering System 2.