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Elements Of The Determination Of The Monthly Average Daily Power Per Area And Of The Primary Solar Energy For The Availability Of Electricity On The Grid

A methodology based on local meteorological variables

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***Abstract*—The objective of this work is to highlight and define the procedure for the determination of a solar typical year of a certain locality that contains meteorological data that does not necessarily contemplate the global radiation. The basic methodology takes advantage of the system developed in 1978 in Sandia National Laboratories - used in several regions of the planet, but with fewer variables than the original method and reduced time period. The variables used were daily insolation, mean compensated temperature and relative humidity, with measured data from 2007 to 2013 of a meteorological station in São Paulo. As a result, we obtain the procedure for the determination of the average daily power per area per month based on the local meteorological variables. The solar typical year determined is applied to determine the average daily power per area, in each month of the year. In the case study, during a typical year, power ranges from 0.5 to 1.6 kilowatt per square meter, consistent with the average value of 1 kilowatt per square meter used by designers in photovoltaic solar systems projects. It is concluded that the proposed method is more consistent to determine the potential of energy generation from the solar source than the use of values used generically without considering local particularities, since the method uses meteorological data specific to a given region.**

Keywords—solar energy generation; solar radiation; meteorological data; monthly average radiation per day

I. INTRODUCTION

In Brazil, the share of solar energy in the energy matrix tends to grow. According to data from the National Electricity Agency [7], in January 2016 the country had 21,336kW of installed capacity in photovoltaic projects in operation and 1,142,975kW of power granted to enterprises with uninitiated construction. These figures indicate that the growth in the use of photovoltaic solar energy in the coming years in Brazil will be accentuated.

In this context, understanding how variations in the availability of the solar energy resource and other meteorological data occur is important for the evaluation of projects, planning and operation of generation plants from the solar source. The measurement of solar radiation to determine the potential of electric power generation is important not only for calculating the economic feasibility of building solar projects, but also for signing contracts for the purchase and sale of electricity, for example.

However, the measurement of solar radiation presents peculiarities in relation to other energy sources. One is, for example, the variation of energy availability during daylight hours, months of the year and even between different years. Regarding annual variation, the National Renewable Energy Laboratory [3] considers that long-term data may be representative of the climate for recording periods of at least 30 years. By convention, this range is considered sufficient to indicate long-term climate trends and to filter short-terms annual fluctuations and anomalies.

In Brazil, the Energy Research Company determines, for purposes of electric power generation, the minimum term of one year of global radiation measurements must be performed, for projects without radiation concentration technology: as from 2016, a minimum of one year of measurement of horizontal global irradiance at the site of the project; and for projects with radiation concentration technology: as from 2016, a minimum of one year of measurement of normal direct irradiation at the site of the project and, as from 2018, a minimum of three years of this measurement.

Measurement of horizontal global radiation requires investments in the acquisition of calibrated sensors and specialized manpower for equipment maintenance and measured dates treatment, for at least 12 months to comply with Brazilian regulations. For projects undergoing economic feasibility studies, such investments may not be justified due to the risk of measurements indicate unattractive return rates.

Thus, the use of methods to determine the potential of electric power generation from correlations with other variables available in meteorological stations can be used to determine initial estimates of electric power generation. A consolidated method, published in the specialized literature, is the Typical Meteorological Year (TMY).

The TMY is a set of hourly values of solar radiation and weather elements for a period of one year of data. Its purpose covers simulations of solar energy conversion systems and energy efficiency of buildings to facilitate comparisons between different types of systems, performance settings and locations.

The first Typical Meteorological Year (TMY) was developed at Sandia National Laboratories, by Hall et al. [2], with data from 1952 to 1975, of 248 weather stations in different US locations, provided by a database called SOLMET (Solar Radiation Surface Meteorological Observations). The method involved the choice of a characteristic month of the climatology of a given location, for each of the 12 months of the year, between 30 years of data collected consecutively. The meteorological variables used were dry bulb temperature, dew point temperature, total daily global radiation and wind speed.

The TMY is decomposed into selected 12 typical months, being called Typical Meteorological Months (TMMs). The TMM is built on its similarity of individual cumulative frequency distributions to the selected data elements. Long-term distributions are determined for each month using data for the entire registration period. Each TMM is concatenated sequentially, essentially unmodified, to form a single year, with full serial data recording.

The TMY data show the natural diurnal and seasonal variations and represent a year of typical local climatic conditions, which are considered typical over a longer historical period, representing climatic conditions that could occur in a given location. It allows applying knowledge of local climatology to energy systems.

A second TMY was published in 1994 with more accurate data than the first TMY; from 1961 to 1990, collected in 239 meteorological stations of the National Solar Radiation Data Base - NSRDB [4]. In 2007 the information set was updated for the period from 1991 to 2005, with data from 1,020 meteorological stations, originating the third TMY.

In Brazil, there are fewer stations that measure solar radiation than in the USA, and the few that do exist do not have available historical data for 30 years, there are no historical series of meteorological data available to determine a TMY with the same methodology applied by the Sandia National Laboratories or NREL. Given the scarcity of land measurements, the natural path is the consolidation of estimates made with adapted methodologies.

Argiriou [1] adapted the method with a 20-year time series to determine a typical Solar Year of Greece.

Luiz et al. [9] applied a methodology to determine a TMY for the city of Florianópolis, with hourly meteorological data from 2000 to 2010 based on the method of Sandia National Laboratories. The methodology was adapted to allow the determination of the typical 12 months of the year from the availability of data from a local solarimetric station field with the longest historical dataset at the time, in Brazil.

In the literature, it is possible to find studies performed in other localities that use adaptations of the Sandia method, such as those performed by Argiriou [1] and Luiz et al. [9]. However, the studies present the formulation without detailing the algorithms used, since the amount of data to be worked is very large. For example, for each magnitude, it is necessary to systematize annual data recorded from hourly, minute to minute or even second to second.

A. *Objective*

The objective of this work is to define a methodology for the determination of a Solar Typical Year – (STY) to estimate the potential of electric or thermal power generation from the solar energy source, based on the TMY elaboration process.

In order to differentiate from the original method, instead of denominating TMY, this work denominated the Solar Typical Year - STY the application of the method of obtaining the TMY, with smaller number of meteorological variables and period of analysis different from 30 years.

STY applies the TMY procedures and follows its fundamentals, and can be used anywhere, with historical series of meteorological data available in Brazil, for estimating the annual potential of electric or thermal energy generation with the solar source.

II. Method

In this work, the fundamentals and procedures of the method proposed by Hall et al. [2] are presented to understand the proceedings for obtaining a TMY. For that, a shorter period and smaller amount of quantities were used, with data available from a meteorological station of a locality of the state of Sao Paulo.

To understand the method, an interpretation of the mathematical formulas is presented at each step of the TMY procedure.

Another difference between the TMY and the STY is that the TMY considers the global radiation as one of the analysis variables, and the STY may or may not consider the global radiation. This adaptation is made because in Brazil there are more meteorological stations that do not measure the global radiation than those that monitor it.

The last step of STY determination is to estimate the overall twelve-month typical twelve-month radiation from daily sunshine data to be applied to meteorological stations that do not have global radiation measurement instruments. For stations that rely on such meters, just suppress this last step of inference.

III. Fundamentals of the Typical Meteorological Year (TMY)

Firstly, in order to prepare the STY, it is necessary to understand the TMY's fundamentals to use with the historical series of available meteorological data.

The TMY methodology uses the Cumulative Distribution Function (CDF), which in statistics is used to fully describe the distribution of a real-valued random variable X or the probability that X will take a value less than or equal to X.

The CDF (FDA) used in the TMY is presented in Equation 1.

$$FDA(x) = \begin{cases} 0, & for \quad x < x_i \\ (i-0.5)/n, & for \quad x_i \le x < x_{i+1} \\ 1, & for \quad x \ge x_n \end{cases} \qquad (1)$$

Where,

FDA (x): cumulative distribution function of a meteorological variable x

i: number classification order (i = 1,2, ..., n-1)

n: total number of elements

The statistical method to evaluate the similarity of each month of a specific year, with the dataset of the whole period, is that of Finkelstein-Schafer (FS). Mathematically, the method is based on the absolute difference between the two FDAs of the month in question and for the same month of each year, according to Equation 2.

$$FS_x(a,m) = \frac{1}{N}\sum_{j=1}^{N}\left|FDA_m(x_j) - FDA_{a,m}(x_j)\right| \qquad (2)$$

At where,

m: month

a: year

x: weather variable.

n: number of FDA points used which, according to the Finkelstein-Schafer

(FS) statistic is calculated by Equation 2.

j: number classification order (j = 1,2, ..., n-1)

$FS_x(a, m)$: Finkelstein-Schafer function of the meteorological variable x, month m of year a.

FDA_m: cumulative distribution functions of the month m of all years.

$FDA_{a,m}$: cumulative distribution function of month m of year a.

FS compares a short-term database with a long-term basis, that is, compares the data of a meteorological variable of a specific month with the same month of all years of the data period considered. For example, it compares the January sunshine data for a given year with the sunshine data for all months of January for several years.

Next, a Weighted Sum (WS) is calculated by assigning weights to each FS function, according to Equation 3.

$$SP(a,m) = \frac{1}{M}\sum_{i=1}^{M} FP_x \cdot FS_x(a,m) \qquad (3)$$

At where,

SP (a, m): weighted sum (WS) in year a and month m.

M: number of meteorological variables.

FP_x: weighting factor of variable x.

SP considers several meteorological variables with the attribution of weights, according to the importance of each variable, to obtain TMY. For example, assuming that the insolation variable is more important than the average daily temperature variable in obtaining the global radiation, the weight of the insolation-related variable should be higher than the temperature.

For each month, the lowest values of the WS of all years represent the candidate years to represent the TMY. The methodology defines that during the 30-year period, for each of the twelve months of the year, the five years with the lowest WS values, define the candidate months to compose the TMY.

The interpretation of the smallest values is related to the smaller variation in relation to the average, which is intuitively related to the idea of the standard deviation. For example, in a hypothetical case where all meteorological variables are constant, in all months of all years, the WS will be null, what means, every month will be typical, since they are the same. In practice, hardly a month will present a zero WS, but the closer to zero, the more typical the month is. Conversely, the higher the value of the WS, the less typical the month is.

The last step is to eliminate months that present atypical data, called consecutive persistence analysis.

The consecutive persistence analysis is performed by counting occurrence of consecutive days outside the limits defined by lower and / or higher percentiles. For example, for a particular meteorological variable, it is checked whether each daily value falls below and / or above lower and / or higher percentiles. Then, the number of consecutive days that occur below and / or the defined percentiles are counted. The months with the highest number of consecutive atypical days, what means, below and / or above the percentiles, should be eliminated from the TMY.

The TMY will then be composed of data from one of the five candidate months, defined in the calculation step of the WS, choosing the one closest to zero that does not coincide with a month in which any of the meteorological variables were atypical in the Consecutive persistence analysis.

IV. Determination of the Typical Annual Year (STY)

Due to the purpose of familiarization with the method of obtaining the TMY and considering the availability of meteorological data available for the city of São Paulo, values were used between 2007-2013, of the Meteorological Database for Teaching and Research (BDMEP), of the National Institute of Meteorological Research [8].

The meteorological variables chosen to form the STY were based on the work as in [1], who considered the daily insulation, the average temperature and the relative humidity of the air. Thus, the meteorological variables available at the Mirante de Santana station (23.5 ° South / 46.61 ° West), in the city of Sao Paulo, at 792.06m altitude, which do not include solar radiation data, were:

• Total heat stroke[1] (Figure 1);

• Average compensated air temperature[2] (Figure 2); and

• Relative air humidity (Figure 3).

The results of the application of Equation 2 and Equation 3 generate FS statistics for each of the three meteorological variables. As an example, Table 1 presents the FS values obtained for daily insolation between 2010 and 2013. The values in bold correspond to the lowest values of each month of the year in the analyzed period. For example, the month of January 2013 is in bold because, between all the months of January, 2007 to 2013 (see the full table in the Appendix), it presents the lowest, indicating that the January 2013 data are those that are closer to the months of January of the other years.

TABLE I. FINKELSTEIN-SCHAFER (FS) STATISTIC OF DAILY INSOLATION

Month	2010	2011	*2012*	*2013*
Jan.	0,04400	0,04311	0,06452	0,02884
Feb.	0,10141	0,05453	0,05724	0,05996
Mar.	0,02646	0,14509	0,09365	0,11461
Apr.	0,04841	0,04603	0,06619	0,06794
May.	0,85253	1,03687	1,56682	0,91705
Jun.	0,09282	0,06134	0,17866	0,15431
Jul.	0,02661	0,04207	0,03731	0,08131
Aug.	0,05352	0,07239	0,10495	0,06585
Sept.	0,12349	0,06984	0,11968	**0,04730**
Oct.	0,05366	0,06362	0,09068	**0,02824**
Nov.	0,05333	0,12635	0,04381	0,08238
Dez.	0,08161	0,06125	**0,03642**	0,13245

[1] It is called total heat stroke, in meteorology, the number of hours that sunlight reaches the surface of the Earth without cloud interference. It is measured through a semi-sphere of quartz, which is exposed to the sun on a photosensitive paper.

[2] Average compensate air temperature TMC = (T9 + 2xT_{21} + T_n + T_x) / 5, where T_9 is the temperature reading at 9:00, T_{21} is the reading at 21:00, T_n is the minimum daily temperature and T_x is the maximum temperature.

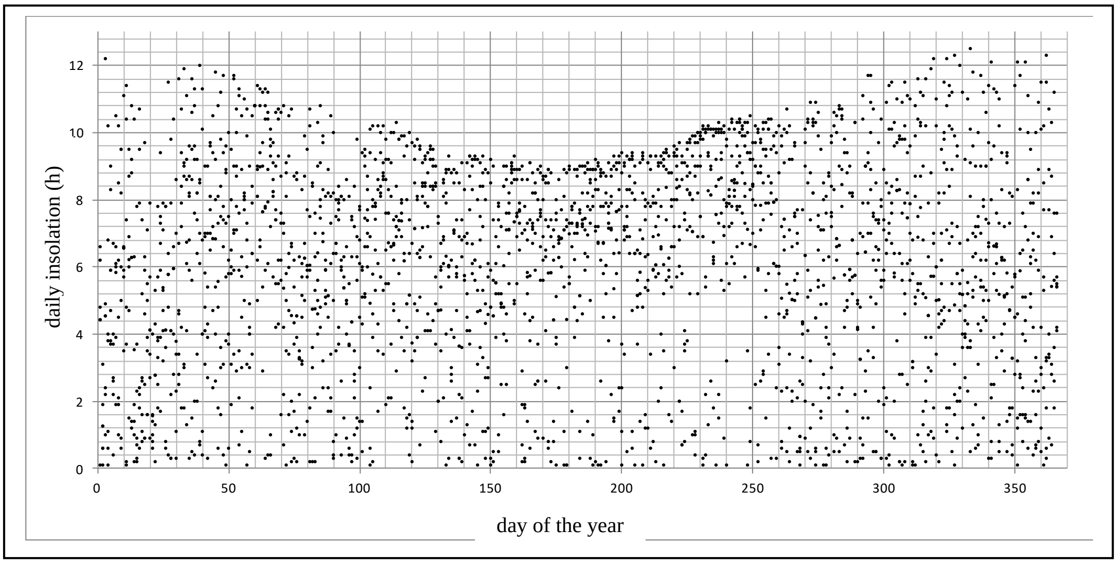

Fig. 1. *Daily sunshine data measured, from 2007 to 2013, in the city of São Paulo.*

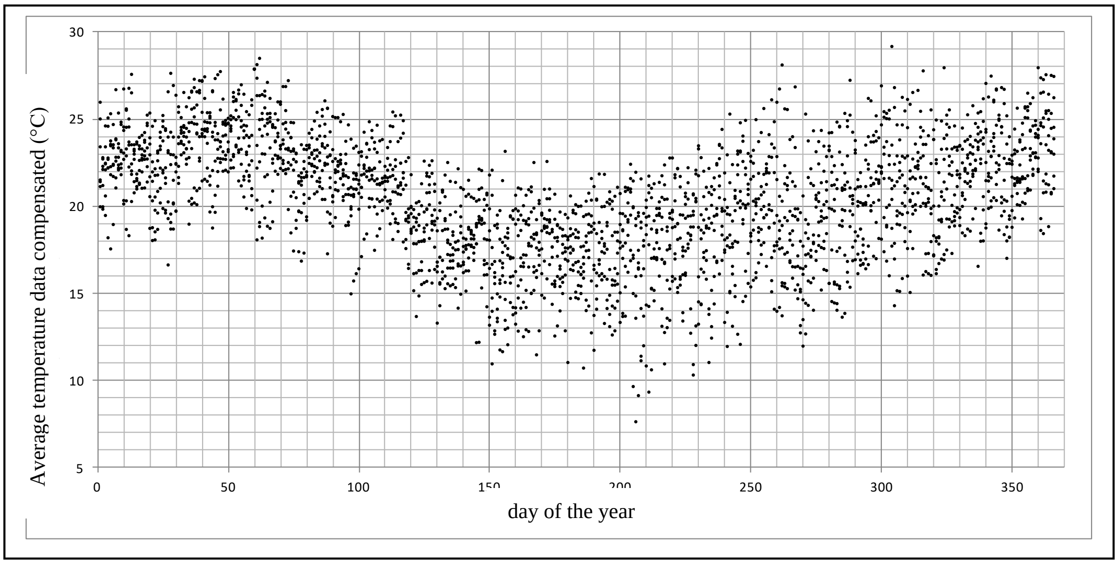

Fig. 2. *Average temperature data compensated, from 2007 to 2013, in the city of São Paulo.*

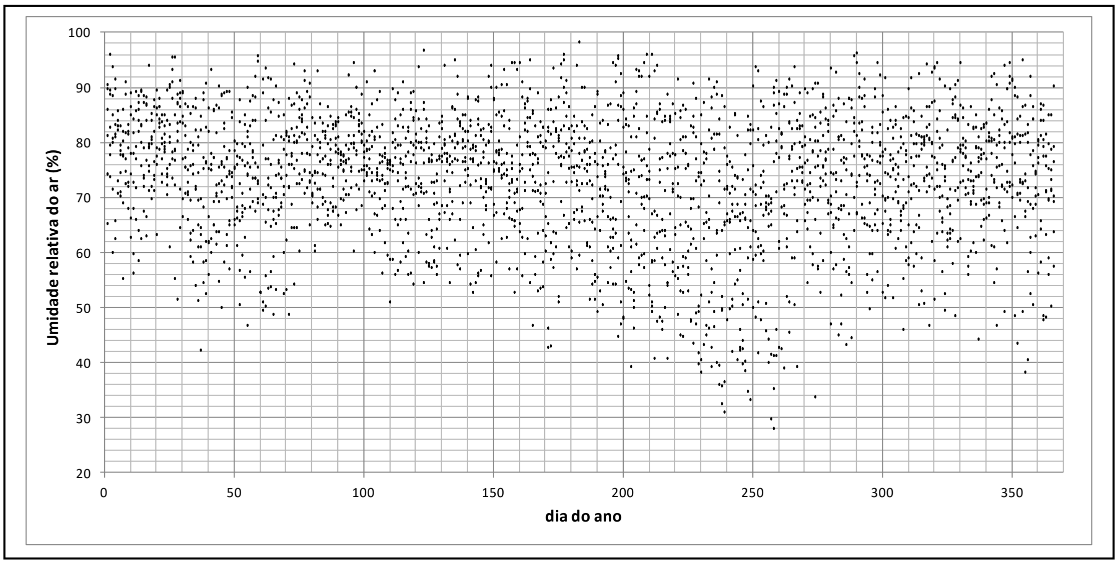

Fig. 3. *Relative air humidity, from 2007 to 2013, in the city of São Paulo.*

The next step consists in determining the weights to be applied for each meteorological variable, defining Weighting Factor (WF) values.

The adopted FPs (WF) were based on [1] with the following values:

• FP insolation = 0,6

• FP temperature = 0,2

• FP relative humidity = 0,2

In the TMY methodology, the WF is determined by the criterion of consistency from the point of view of who applies the methodology. Different weights can be applied, leading to different results, but this is not the purpose of this study.

Finally, equation 3 is applied with the WF defined for determination of the Weighted Sum (WS), reaching the values of Table 2.

TABLE II. WEIGHTED SUM OF FS STATISTICS (BOLD NUMBERS REPRESENT STY CANDIDATE MONTHS)

Month	2010	2011	*2012*	*2013*
Jan.	**0,0203**	0,0367	**0,0217**	**0,0146**
Feb.	0,0355	**0,0222**	**0,0161**	**0,0193**
Mar.	**0,0181**	0,0477	**0,0203**	-
Apr.	**0,0145**	0,0213	**0,0204**	-
May.	**0,4608**	0,6049	**0,4584**	-
Jun.	**0,0309**	**0,0221**	**0,0242**	0,0316
Jul.	**0,0204**	**0,0154**	**0,0199**	**0,0231**
Aug.	**0,0176**	**0,0177**	0,0377	-
Sept.	**0,0166**	**0,0244**	**0,0212**	-
Oct.	**0,0235**	**0,0207**	0,0340	-
Nov.	**0,0127**	**0,0264**	**0,0106**	**0,0267**
Dec.	**0,0159**	**0,0212**	**0,0270**	**0,0324**

Source: prepared by the authors

In the last column, referring to the year 2013, we observe the occurrence of some months without data. The TMY method determines that when there are months with ten consecutive daily data zeroed for any weather variable, one should simply disregard such months as if they did not exist.

The method determines the choice of 5 months, for each year, with lower values, candidates to compose the TMY. The values in bold correspond to the five lowest values of each month of the year in the analyzed period. For example, the month of January 2013 is in bold because, between all the months of January, from 2007 to 2013, it presents the lowest value. The lower the value is, the data for this month are the ones that are closest to the same months of the other years.

After determination of the weighted sum, the occurrence of atypical months should be analyzed through the analysis called consecutive persistence.

The criteria for defining the limits of consecutive persistence are not part of the objective of this work for the study case, the limits of consecutive persistence used were:

• Average temperature compensated: below 33% or above 67%

• Heat stroke: below 33%

• Relative air humidity: below 33% or above 67%

Table 3 shows an example of consecutive persistence for the compensated average temperature variable. The values represent the number of consecutive days in a given month that presented temperatures below 33% or above 67% of the other measured temperatures. The largest numbers, representing the largest sequences in a month, were highlighted in bold for later deletion.

TABLE III. CONSISTENT PERSISTENCE OF THE COMPENSATED MEAN TEMPERATURE BELOW THE PERCENTILE OF 33% OR ABOVE 67%

Month	2010	2011	*2012*	*2013*
Jan.	4	8	7	**12**
Feb.	9	8	7	8
Mar.	7	9	7	9
Apr.	9	11	6	**30**
May.	7	4	4	**28**
Jun.	9	9	4	8
Jul.	8	6	**17**	8
Aug.	6	7	3	**8**
Sept.	10	5	7	6
Oct.	6	8	7	6
Nov.	**14**	8	6	8
Dec.	4	6	5	6

Source: prepared by the authors

The same procedure is performed with the other variables applying specific limits. Tables with consecutive persistence values are presented in the Appendix.

The last step, to choose the months that will compose the ATS, consists in the elimination of the months with smaller weighted sum that coincide with the months of greater persistence consecutive. This eliminates the months that had one of the atypical meteorological variables.

Table 4 shows the years whose months were chosen to compose the STY. In this way, the STY will be composed, for each meteorological variable, by data from January 2007, February 2012, March 2008, and so on, through December 2007.

TABLE IV. MONTHS OF THE CANDIDATE YEARS FOR THE COMPOSITION OF THE SOLAR TYPICALYEAR

Month	Year
Jan.	2007
Feb.	2012
Mar.	2008
Apr.	2010
May.	2007
Jun.	2009
Jul.	2007
Aug.	2007
Sept.	2010
Oct.	2008
Nov.	2012
Dec.	2007

Source: prepared by the authors

The STY differs from the average values because, while the average refers exclusively to a certain quantity, the STY considers other relevant quantities occurring in the period.

V. PROCEDURE OF THE ENGERGY GENERATION ESTIMATE WITH THE STY

STY application is the estimation of the potential of electric power generation with photovoltaic panels or of thermal energy generation for water heating.

For a photovoltaic system, it is necessary to know the components of direct and diffuse incident solar radiation during the year, in a plane with any orientation. When there is only data on global radiation, correlations can be made to obtain the components of direct and diffuse radiation. As in [1]:

> "*The correlations obtained depend on the time scale and can be of the linear, polynomial or exponential type. For the daily scales the most well-known correlations are those proposed by Lu and Jordan (1960), and Collares-Pereira and Rabl (1979). For time scales the best known are those proposed by Erbs (1982), and Dal Pal and Escobedo (2012).*"

However, such methodologies cannot always be applied, because in some cases global radiation data of the monthly average are available, without the daily data. In these cases, the monthly insolation data can be used by applying equation (4) with the monthly sunshine data, determined for the STY.

$$Power[W/m^2] = \frac{I_{Global}[kWh/m^2/day]}{Insolation[h/day]} \quad (4)$$

The values of the insolation correspond to the values made available by the database of [8] according to Table 4. For example, the value of the insolation of January corresponds insolation of January of 2007, of February corresponds to the month of February of 2012 and so on.

TABLE V. MONTHLY SOLAR POWER CALCULATED BY THE STY

month	Mean daily heat stroke determined by ATS [h]	Average Global Radiation (Wh/m^2) per day	Power rating
Jan.	4.1	6,413.7	1.6
Feb.	7.0	5,534.4	0.8
Mar.	6.0	5,229.9	0.9
Apr.	5.8	5,222.4	0.9
May.	6.0	4,378.4	0.7
Jun.	6.1	3,425.6	0.6
Jul.	6.4	3,600.9	0.6
Aug.	7.6	4,174.2	0.5
Sept.	6.3	4,737.6	0.8
Oct.	5.6	6,264.3	1.1
Nov.	6.0	6,014.5	1.0
Dec.	5.8	5,866.6	1.0

Source: prepared by the authors

To calculate the average daily potency of each month, the data of global radiation of the Brazilian Atlas of Solar Energy (2006) were used.

The results of the application of STY monthly insolation data, with the mean global radiation value of São Paulo, are presented in Table 5.

It can be seen from Table 5 that the average power per area ranges from 0.5 to 1.6 KW/m2, which is consistent with values used in practice of 1.0 KW/m2.

This value is used as a reference for the design of solar photovoltaic systems under the name of Full Sun Hours (FSH), as explained in [11]:

> "*In the estimations of electricity production, it is useful to ignore the effects of irradiance variation at each instant and to consider the totality of the electric power converted at hourly intervals. As there is a strong linearity between energy production and hourly irradiation, this concept can be extended, generating a very convenient way to express the cumulative value of solar energy over a day: the number of Full Sun Hours (FSH). This magnitude reflects the number of hours in which the solar irradiance should remain constant and equal to 1KW/m2 (1,000 W/m2), so that the resulting energy is equivalent to the energy available by the Sun at the site in question, accumulated over a given day.*"

The STY was used, together with data from [10], to determine the global radiation power per area for a particular region of São Paulo, in each month of the year.

One advantage of using STY is that instead of using the same value for all months of the year of 1.0 kW/m^2, for example; it would be possible to use estimated values for each month of the year, based on measurements of Meteorological data, where the data were collected.

VI. Conlusions

It can be stated that the goal of understanding the methodology of TMY elaboration was reached by proposing a simplified methodology for the determination of a Solar Typical Year - STY.

The STY is a simplification of the method for obtaining the TMY, which instead of considering nine variables, with thirty years of data collected; it is used with fewer variables in a shorter period.

In this work, for the purpose of understanding the method proposed on [2], daily insolation, mean compensated temperature and relative air humidity were used for seven consecutive years. However, other meteorological variables could be used over periods of more than seven years according to the availability of meteorological station data.

It can be concluded that the use of the STY implies determining the potential of electric or thermal energy generation for a specific region, in a more consistent way, since it allows local meteorological data to be used instead of using valid values for any regions such as The Full Sun Hours.

From the understanding of the TMY, and with data more comprehensive than those available for the accomplishment of this work, it is possible to obtain an STY with more meteorological variables.

If more data are available on variables such as global, direct and diffuse radiation, in addition to other meteorological variables, in longer periods, the methodology for determining a STY, initiated in this work, can be developed with data consistency and accuracy analysis for consolidation of a methodology applicable to local conditions.

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