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Comparison of methodologies for TMY generation using 10 years data for Damascus, Syria

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Abstract

The generation of a typical meteorological year (TMY) is of great importance for calculations concerning many applications in the field of thermal engineering. The need of an accurate TMY for simulations has been well recognized over the years. Various methods for deriving TMYs have been developed, but their final results can be significantly different. In this paper, the major methodologies reported in the literature were applied to 10 year hourly measurements of weather data from Damascus, Syria. The TMYs obtained were evaluated according to their impact on the typical Syrian building's thermal system in order to decide which method should be recommended for generating typical meteorological years and for predicting the performance of thermal systems in buildings. Based on simulation results for seasonally, monthly and daily building thermal loads, three widely used statistical estimators, namely, root mean square difference RMSD, total standard error SEE and chi square χ^2 were calculated to assess the performance of each TMY. The findings showed that the TMY giving the closest performance to the average performance of the building's thermal system as predicted using the 10 year weather data is the one generated by using the modified Sandia method. This method gives sufficiently accurate results compared with the other methods reported in the literature.

Keywords: Thermal engineering; TMY; Methods; Meteorological variables

1. Introduction

Modern simulation software for the performance prediction of solar and building energy systems requires an updated and more comprehensive climatological and solar database. Such database is very important for calculation of energy efficiency and must be representative of the area of interest. A representative database for a year duration is known as a typical meteorological year (TMY), a term mainly used in the USA, or a test reference year (TRY) or a design reference year (DRY), terms mainly used in Europe. TMY, TRY or DRY consists of individual months of meteorological data sets selected from different years over the available data period, which is called a long term measured data series.

The question of "typicality" appears to have been sidestepped by most users of solar and building energy simulations. Some have selected weather, which appears to them to be typical of an appropriate portion of a year. The others have selected a year, which appears to be typical from several years of solar radiation data and some investigators have run long periods of observational data in an attempt to simulate typical weather for a calculation. The best answer to the question of typicality thus far appears to be that taken by the solar group at the University of Wisconsin [1,2]. This group has selected each month of a typical year from some 10 years of data on the basis that the month selected had the same mean radiation as the mean for that month calculated from the entire 10 years of data. Nevertheless, even this approach leaves unanswered the question whether the sequence of days within the month selected is typical.

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Several methods for generating typical data have been developed, and typical meteorological year methodologies have been proposed, Refs. [2–19] by the date of publication. The primary objective of these methods is to select single years or single months from a multi-year database, preserving a statistical correspondence. This means that the occurrence and the persistence of the weather should be as similar as possible in the TMY to all available years. These different TMY methodologies have been developed with selection criteria based on solar radiation or on solar radiation together with other meteorological variables. Yet the aforementioned methods often seem rather convoluted and complex when put into use. For description of and performance comparison between different methods for generating TMYs the reader is referred to Argiriou and Lykoudis [20] and Julia et al. [21].

Methodologies known as typical meteorological year use a modified version of Hall et al. [4], whereas test reference year (TRY) methodologies use different algorithms and month selection criteria according to other authors. However, all of them share the common feature that they use real meteorological and radiation measured data values to build a single year of data, while the design reference year (DRY) method proposes to use data adjusted to give a monthly cumulative distribution like the cumulative distribution of these months in the original multi-year data set. Apart from these methodologies, computer time limitations, which were determinant in the past, led to the development of methodologies referred to as short reference years (SRYs). These are collections of typical meteorological data covering only some days of each month.

The literature review conducted within the framework of this work shows that one of the most common methodologies for generating a TMY is the one proposed by Hall et al. using the Filkenstein–Schafer (FS) statistical method [22], “Sandia method”. The other methodologies cited above for generating a TMY use a modified version of Hall et al. This method is an empirical approach that selects individual months from different years from the period of record. The selection criteria were based on 13 meteorological parameters. These parameters are the daily mean, maximum and minimum values and ranges of temperature, dew point and wind velocity and the daily values of global solar radiation. However, 4 of the 13 parameters are considered to be less effective and, therefore, are given zero weight. These variables are the ranges of daily dry bulb temperature, wet bulb temperature and wind speed, and daily minimum wind speed. Moreover, it finds the typical meteorological month (TMM), which would seem to include the following sensible properties:

- The meteorological measures of the TMM, i.e. temperature, relative humidity, wind and solar radiation should have frequency distributions, which are “close” to the long term distributions.
- The sequences of the daily measures of the TMM should in some sense be “like” the sequences often registered at a given location.
- The relationships among the different measures of the TMM should be “like” the relationships observed in nature.

Except for a few changes to the weighting criteria, which account for the relative importance of the solar radiation and meteorological elements, there has been no change in the original methodology and it has been adopted by different countries: for example, by date of publication, for Canadian Cities [23], Athens [8], Egypt [24], 239 meteorological stations of USA [10], Ibadan, Nigeria [25], Hong Kong [26], Nicosia,Cyprus [12], main Turkish cities [27], Bangkok [28], main Chinese cities [31], Nicosia, Cyprous [32,40], Istanbul, Turkey [33], Damascus, Syria [34], Taiwan [35], southeastern Anatolia, Turkey [36,37], Oman [38] and Hong Kong [39].

Recently, ASHRAE has started an international project to develop TMY data throughout the world, the international weather year for energy calculations (IWEC) [29,30]. Most recently, using the Sandia method, Kalogirou developed TMYs for the city of Nicosia, Cyprus. The study of Kalogirou included additional variables such as illuminance, visibility, precipitation and snow fall data [18].

The objective of the present work is to select and implement TMY generating methodologies using long term hourly measured meteorological and global solar radiation data and to evaluate the TMYs by comparing the performance of building thermal systems in the Damascus province. The performance of a building's thermal system was evaluated with the TMYs and the long term average measured meteorological data series. The results were compared to decide which method could be recommended as the best for the Syrian region.

Damascus is located in the southwestern corner of Syria and covers 18100 km^2 of built up area. About 3.5 million people live and work in the area. It has a pleasant and varied Mediterranean climate with four distinct seasons. Average temperatures in the summer, winter, spring and autumn are 32 °C, 10 °C, 22 °C and 22 °C, respectively. The time zone for November through February is GMT + 2 h and for March through October is GMT + 3 h.

The meteorological and global solar radiation data that were used in this work are from the measurements of meteorological stations in Damascus International Airport and in the Kharabo site and cover a period of 10 years (1981–1990). The Damascus International Airport Station is located at 36°30′ east longitude, 33°24′ north latitude and at an elevation of 608 m above sea level. The Kharabo station is located at 36°28′ east longitude, 33°30′ north latitude and at an elevation of 620 m above sea level. A variety of routine meteorological data as well as irradiance data have been collected for a great number of years and archived in the database of the Meteorology Department.

The importance of this paper is that no similar work has previously been done in this area using so much recorded meteorological measured data. The results of it are the first TMY generation and evaluation in the region, which is essential for developing solar energy use and to facilitate performance comparison of different energy systems in Syria with low computational time.

The theoretical basis of the selected TMY generation methodologies, the database, the performance of thermal building system with different TMYs and the comparison results are given in the following sections, and specific details can be seen at the corresponding reference.

2. Description of methodologies for TMY generation

A TMY provides a standard for hourly data for some meteorological parameters for a period of one year, representing climatic conditions considered to be typical over a long time period. The different TMY methodologies have been developed with selection criteria based on solar radiation or on solar radiation together with other meteorological variables. Among the different TMY generation methods available in the literature, six were selected for analysis and validation. These are: the Sandia National Laboratories method and its modification by Pissimanis et al., the Danish method, the Festa and Ratto method, the Crow "Weather Year for Energy Calculations" method, the Miquel and Bilbao method and the Gazela and Mathioulakis method. For comparison purposes, a TMY was also generated using simple averaging over the available period. The criteria for having chosen these particular methods were the following:

- They are frequently used in practice;
- They employ quite different approaches to generating the TMY;
- The full availability of the algorithms and numerical parameters;
- The quality of the results reported by the original authors.

The modification of the original Sandia National Laboratories method by Marion and Urban, known as the TMY2 method [11], could not be applied due to the lack of some meteorological parameters required by this method.

In all the generated TMYs, the transition from one month to another was smoothed. Smoothing was performed by substituting the real values of the last 3 h of the leading month and the first 3 h of the following month with values obtained by linear interpolation, unless both months were coming from the same year.

2.1. Sandia National Laboratories method (modified Sandia method)

This method was initially developed by Hall et al. [4]. The TMY is created by concatenating twelve TMM to form a complete year. It is an empirical methodology for selecting individual months from different years over the available period. The original selection process of the 12 typical months consists of three steps:

Step 1. For each month of the calendar year, 5 months are selected having the smallest weighted sum of the Filkenstein–Schafer (FS) statistics of nine daily indices, namely maximum, minimum and mean air temperature ($T_{\max}, T_{\min}, \overline{T}$) and relative humidity ($\mathrm{RH}_{\max}, \mathrm{RH}_{\min}, \overline{\mathrm{RH}}$), maximum and mean wind speed ($W_{\max}, \overline{W}$) and daily global radiation (G). The weighted sum (WS) of the FS statistic is calculated according to

$$\mathrm{FS}_x(y,m) = \frac{1}{N}\sum_{i=1}^{N}|\mathrm{CDF}_m(x_i) - \mathrm{CDF}_{y,m}(x_i)| \tag{1}$$

$$\mathrm{WS}(y,m) = \frac{1}{M}\sum_{x=1}^{M}\mathrm{WF}_x \cdot \mathrm{FS}_x(y,m) \tag{2}$$

$$\sum_{x=1}^{M}\mathrm{WF}_x = 1 \tag{3}$$

where CDF_m is the long term (10 years) and $\mathrm{CDF}_{y,m}$ is the short term (for the year y) cumulative distribution function of the daily index x for month m and the WF_x are the weighting factors, one for each daily index. N is the number of bins and M is the number of considered meteorological parameters in the study. In order to calculate the CDFs for each parameter, the data are grouped under a number of bins, and the CDFs are calculated by counting the cases under the same bin. According to the FS statistic, if a number N of observations of a variable x is available and have been sorted into an increasing order $x_1, x_2, \ldots, x_n$, the CDF of this variable is given by a function $S_N(x)$, which is defined as follows:

$$S_N(x) = \begin{cases} 0 & \text{for } x < x_1 \\ (i-0.5)/N & \text{for } x_i \leqslant x < x_{i+1} \\ 1 & \text{for } x \geqslant x_N \end{cases} \tag{4}$$

From its definition, $S_N(x)$ is a monotonically increasing step function with steps of sizes $1/N$ occurring at x_i and is bounded by 0 and 1.

Step 2. The five candidate months are ranked on the basis of the closeness of the month to the long term mean and median. Relative differences are calculated between the mean and median air temperature and global radiation of each specific month and the respective mean and medians over the 10 year time series. The maximum of the four relative differences is assigned to the month.

Step 3. The persistence of air temperature and global radiation is evaluated by determining the frequency (number of occurrences) and run length (number of consecutive days) above and below fixed long term percentiles. The upper limit for the air temperature is set to be the 67th while the lower limit is set to the 33rd long term percentiles. For global radiation, only a lower limit, the 33rd long term percentile, is used. The month with the longest run, the

Table 1
Weighting factors used with the Sandia National Laboratories method

References	$T_{\max}$	$T_{\min}$	$\overline{T}$	$\mathrm{RH}_{\max}$	$\mathrm{RH}_{\min}$	$\overline{\mathrm{RH}}$	$W_{\max}$	$\overline{W}$	G
[4,8]	0.04	0.04	0.08	0.04	0.04	0.08	0.08	0.08	0.50
[20]	0.05	0.05	0.10	0.05	0.05	0.10	0.05	0.05	0.50
[7,23]	0.05	0.05	0.30	0.02	0.02	0.05	0.05	0.05	0.40

month with the most runs and the month with zero runs are excluded. The highest ranking month that remains, according to the (step 2) step above, is selected to be part of the TMY.

The weighting factors used in the first step are selected according to existing experience on the influence of the meteorological parameters used on the simulated application. Three sets of weighting factors, all oriented towards energy simulation applications were used, as shown in Table 1.

These weighting factors express the importance of the impact of the particular meteorological parameter, to which each one of them is assigned, on the behavior of a solar energy conversion system or building.

Furthermore, a variation of the original method was introduced, in order to take into account all the meteorological parameters involved. In the second selection step, instead of using the maximum relative differences for air temperature and horizontal global radiation, the sum of the mean and median relative differences for all four meteorological parameters involved was used. In addition, for the third selection step, the sum of the longest runs and the sum of runs, calculated over the four meteorological parameters, are used. The month with the greatest sum of the longest runs and the greatest sum of runs are rejected, as well as the months with zero runs, for any of the meteorological parameters.

One more variation of the original Sandia method was used. It is pretty much the same as the first variation, but instead of sums, it uses weighted sums. The weighting factor of each meteorological parameter is the sum of the respective weighting factors presented in Table 1.

Finally, instead of the second and third selection steps, Pissimanis introduced a simpler selection process using the root mean square difference RMSD [8]:

$$\mathrm{RMSD} = \left(\frac{1}{n}\sum_{i=1}^{n} d_i^2\right)^{1/2} \tag{5}$$

where n is the number of data pairs and d_i is the difference between the hourly global radiation values with respect to the hourly long term mean global radiation values. The RMSD is used as the primary selection criterion, while the global radiation and air temperature FS statistics are secondary selection criteria. Moreover, a variation of Pissimanis' method was introduced, using for each month, m, and for each parameter, x, a score, S_x, calculated over all the available years, as follows:

$$S_x(y,m) = \frac{\min\limits_{i=1\ldots10}(\mathrm{RMSD}_x(i,m))}{\mathrm{RMSD}_x(y,m)} \tag{6}$$

The maximum score, which is equal to unity, is assigned to the month with the minimum RMSD. A composite score calculated as the weighted sum of the scores of the four meteorological parameters used, namely air temperature, relative humidity, wind speed and global radiation, is calculated, and the month with the highest score is selected. The weighting factor of each meteorological parameter is the sum of the respective weighting factors presented in Table 1.

The modified Sandia method for generating the TMY is widely applied. Hourly weather data for the location of interest should be available, and this is not always possible.

The basic TMY concept of the Sandia method was also expanded by Lam et al. [41]. The assessment on the persistence and run structure, as suggested in the previous paragraphs, was not followed. Apart from the FS statistics, another non-parametric test statistics, known as the Kolmogrov–Smirnov (KS) two sample statistics was also used. While the FS statistics is based on the magnitude of the CDF difference, the KS statistics is based on the maximum deviation and is defined as follows:

$$\mathrm{KS} = \max|\delta_i| \tag{7}$$

To simplify the process in the final selection, the year with the lowest weighted sum average of the test statistics (FS and KS statistics) was selected as the TMM.

2.2. Danish method

This method was developed by Lund [10]. A three step procedure was used in order to select the months that will be included in the TMY:

Step 1. The first step is a climatological qualification of each candidate month compared with the available data series. It consists of a primary flagging of the candidate months using the following daily parameters: average temperature, maximum temperature, relative humidity, wind speed, pressure, sunshine duration and global radiation. If the mean value of the parameter for each candidate month differs more than one standard deviation from the long term mean of the respective month, the month scores zero, otherwise the month scores one. The final score of each month is the sum of the scores and takes a maximum value equal to 7, since there are 7 parameters involved.

Step 2. In the second step, assuming that the observations of a meteorological parameter are the results of a stochastic process; the respective seasonal variations have to be eliminated. Therefore, the daily meteorological parameters are converted into daily residuals with respect to smoothed daily long term trend values obtained by Fourier analysis:

$$Y(y,m,d) = x(y,m,d) - \mu_x(m,d) \tag{8}$$

where $Y(y,m,d)$ is the residual of parameter $x(y,m,d)$ for the year y, month m and day d with respect to the smoothed daily mean $\mu_x(m,d)$, as calculated over the available years. For each individual month, the absolute values of the standardized mean, $f_\mu(y,m)$ and the standardized standard deviation, $f_\sigma(y,m)$ of the residuals obtained by Eq. (8) are calculated:

$$f_\mu(y,m) = \left|\frac{\mu_Y(y,m) - \mu_{\mu_Y}(y)}{\sigma_{\mu_Y}(y)}\right| \tag{9}$$

$$f_\sigma(y,m) = \left|\frac{\sigma_Y(y,m) - \mu_{\sigma_Y}(y)}{\sigma_{\sigma_Y}(y)}\right| \tag{10}$$

where $\mu_Y(y,m)$ is the monthly mean and $\sigma_Y(y,m)$ is the respective standard deviation of the residuals $Y(y,m,d)$, for the year y and month m. $\mu_{\mu_Y}(y)$ and $\sigma_{\mu_Y}(y)$ are the mean and standard deviation of the $\mu_Y(y,m)$ parameters for year y, and $\mu_{\sigma_Y}(y)$, $\sigma_{\sigma_Y}(y)$ are the mean and standard deviation of the $\sigma_Y(y,m)$ parameters for the year y. Thus, each individual month is characterized by two values for each meteorological parameter considered. The parameters used in this step are: daily average temperature, daily maximum temperature, daily sum of global radiation and daily sunshine duration, and the later two alternatively, so each individual month was characterized by six values in total.

Step 3. The third step of the selection procedure assigns the maximum of the aforementioned three standardized means and three standardized standard deviations, $f_{\max}(y,m)$, to the candidate month:

$$f_{\max}(y,m) = \max\{f_\mu(y,m,j), f_\sigma(y,m,j) | 1 \leqslant j \leqslant 3\} \tag{11}$$

where (y,m,j) denotes the respective standardized mean or standard deviation for year y, month m and meteorological parameter j. The candidate months are sorted in ascending order of the $f_{\max}(y,m)$ value, and the first three are selected as priority candidate months.

From the three priority candidate months obtained from steps (2) and (3) of the selection procedure, the month with the highest score in step (1) is selected for the TMY.

2.3. Festa–Ratto method

The method was proposed by Festa and Ratto [9]. This is a modification of the Danish method and requires a rather complicated statistical treatment of the data. Typical months are selected according to the deviations of short term values from long term values of some chosen meteorological parameters, named x, which are considered to influence simulated system performance. These deviations are estimated by three standardized magnitudes X, z and Z.

Step 1. The meteorological parameters are converted into standardized residuals with respect to the smoothed long term trend basis (X parameters):

$$X(y,m,d) = \frac{x(y,m,d) - \mu_x(m,d)}{\sigma_x(m,d)} \tag{12}$$

where $X(y,m,d)$ is the standardized residual of parameter $x(y,m,d)$, for the year y, month m and day d, with respect to the smoothed mean and standard deviation, $\mu_x(m,d)$ and $\sigma_x(m,d)$, respectively, are as calculated over the available years.

Step 2. The first order products of the standardized residuals are calculated and converted into first order products' standardized residuals with respect to the smoothed long term trend, again on a daily basis (Z parameters):

$$z(y,m,d) = X(y,m,d) \cdot X(y,m,d+1) \tag{13}$$

$$Z(y,m,d) = \frac{z(y,m,d) - \mu_z(m,d)}{\sigma_z(m,d)} \tag{14}$$

where $Z(y,m,d)$ is the standardized residual of the first order product parameter $z(y,m,d)$, for the year y, month m and day d, with respect to the smoothed mean and standard deviation, $\mu_z(m,d)$ and $\sigma_z(m,d)$, respectively, as calculated over the available years.

Step 3. For each X and Z parameter, the average, standard deviation and cumulative distribution of each individual month are calculated (short term parameters). Then, the corresponding parameters are calculated for each month but for the entire available period (long term parameters). The distances between the short and long term means, d_{av}, and standard deviations d_{sd}, as well as the Kolmogorov–Smirnov parameter, d_{KS} are calculated for each X and Z parameter and each individual month. Then, a composite distance is calculated according to

$$d(y,m,j) = (1-a-b)\cdot d_{\text{KS}}(y,m,j) + a\cdot d_{\text{av}}(y,m,j) + b\cdot d_{\text{sd}}(y,m,j) \tag{15}$$

where $a \cong b \cong 0.1$ and $d(y,m,j)$ denotes the respective distance for year y, month m and X or Z parameter j. Thus, using daily maximum and mean air temperature, mean relative humidity and wind speed and daily sum of global radiation, 10 distances are calculated for each candidate month.

The original procedure uses a minmax approach, assigning the maximum of the ten distances to the candidate month and selecting the month with the minimum assigned distance:

$$d_{\min,\max}(y,m,1) = \min\{d_{\max}(y,m,j), 1 \leqslant j \leqslant 10\} \tag{16}$$

The minmax approach ensures that the selected month will have both typical mean values and variations for all the considered meteorological parameters. This approach treats all meteorological parameters on an equal importance basis for the final selection.

2.4. Crow method

This method was initially proposed by Crow [5] and was called the Weather Year for Energy Calculations (WYEC).

Although 12 representative months are selected to form a complete year like the Sandia, Danish or the Festa–Ratto methods, there is a major difference. After the initial selection, individual days or hours are adjusted. Replacing some hourly or daily values leads the monthly mean values to come closer to the respective long term values.

It should be noted that the monthly mean temperatures of the *N* years are obtained by averaging *N* maximum and *N* minimum measurements.

The initial selection of the months based on dry bulb temperature values is focused on the 1 or 2 'historical' months with the closest proximity to those of the N year period. The difference between the final adjusted months and multi-year normal temperature ranges is between ±0.3 °C. Going on, an adjustment in the solar radiation values becomes necessary. The original hourly solar radiation data for each selected month is modified until the monthly mean values come within one tenth of the monthly standard deviation as developed from the long term data.

This process for deriving a TMY is fairly manageable and undemandable, though its original objective was for building energy analysis. By adjusting certain values for two meteorological variables – mean monthly temperature and global radiation – these then become almost identical to those of the long term data. Yet, this takes place at the expense of the 'historical' data because chronological series are modified. Moreover, wind velocity is neglected at any stage of the selection process.

2.5. Miquel–Bilbao method

All methodologies reviewed require available solar radiation data, which is a drawback because the number of solar data series is limited in some regions and countries all over the world. Miquel and Bilbao developed a method for TMY generation based on meteorological weather data and not on solar radiation, which could be estimated afterwards from temperature using different methods and models [19]. These methods could be applied in places with long data series of air temperature, relative humidity and wind velocity. This proposed method of TMY generation will fill the gap in many places where solar radiation data are not available.

The Miquel–Bilbao method elaborates an approximate TMY data series that is based on meteorological data of the three mentioned variables. The horizontal solar radiation values are obtained from the temperature values of this approximate TMY, and finally, generated solar radiation values are included in the approximate TMY and, as a consequence a TMY is completed for its validation.

The general structure of this method to elaborate TMYs is composed by the following steps:

Step 1. Elaboration of an approximate TMY with meteorological data. A modification implemented by Argiriou and Lykoudis [20], which was based on the method proposed by Festa and Ratto [9] has been used to generate an approximate TMY, where data of temperature, relative humidity and wind velocity are considered. The daily measured values of the meteorological variables were converted into standardized residuals with respect to the smoothed long term trend (*X* variables). The monthly average values, the standard deviations and the cumulative frequency distribution were evaluated and compared with the corresponding values obtained for the whole available period (long term measured data series). The complete selection method is described in Ref. [20], and the implemented variation is to assign to each candidate month a weighted sum of the distances instead of the maximum distance.

Step 2. Estimation of monthly average daily horizontal global solar irradiation. After the generation of the approximate TMY, a mathematical model was used to estimate monthly average solar irradiation from hourly temperature values [19]. In this model, monthly average temperature, T_m, monthly average hourly temperatures T_{hm} and monthly average daily clearness index K_m are related.

Step 3. Estimation of daily values of horizontal global solar irradiation. Two models could be used in order to evaluate the daily horizontal solar irradiation. In the first model, daily solar irradiation values are fitted by means of a Fourier series, taking into account that the Fourier coefficients have been obtained from the monthly average daily solar irradiation values. In the second model used, the parameters modeled were the daily clearness indices, and from them, a monthly series of daily horizontal global solar irradiation values could be obtained.

Step 4. Estimation of hourly values of horizontal global solar irradiation. In this step, synthetic daily sequences of the hourly clearness indices are generated from the daily ones.

Step 5. Inclusion of solar radiation values into the approximate TMY. The hourly solar radiation values generated in the previous step were included in the approximate TMY.

2.6. Gazela–Mathioulakis method

All the aforementioned methods for TMY generation aim to represent the weather pattern at a particular location. Special care is given to choosing months where weather sequences and persistence maintain correspondence to long term data. The selection criterion for typical months is based mostly on mathematical and statistical methods.

This method was proposed by Gazela and Mathioulakis [16] and was called the weather year for solar systems (WYSS). It is proposed for determining typical one year weather data from multi-year records for evaluation of solar energy systems. This one year weather data is composed of a concatenation of 12 months individually selected from a multi-year database. This set consists of 8760 hourly values of the three meteorological parameters: global solar radiation, ambient temperature and wind velocity. In cases in which hourly meteorological values are not obtainable, the WYSS can also be applied with daily or mean daily values. The criterion for the selection is the minimization of error in the monthly solar gain prediction of the system. Thus, the primary difference of this method from the previously mentioned ones is that it is system oriented. In this way, the term TMY receives a specified orientation, a bit different from the one it already has. This is due to the combination of climatological conditions, weather sequences and system characteristics that affect its behavior.

A two step procedure was used in order to select the months that will be included in the TMY:

Step 1. In the first step, the monthly solar gain of the solar hot water system (SHWS) is calculated by simulation methods for all the available years, N (i.e. $\mathrm{SG}_{y,m}$ for $y = 1, 2, \ldots, N$ and $m = 1, 2, \ldots, 12$).

Step 2. In the second step, the typical months are selected according to the following procedure:

- Calculation of the mean value of the solar gains of all the N years:

$$\overline{\mathrm{SG}}_m = \frac{\sum_{y=1}^{N} \mathrm{SG}_{y,m}}{N} \tag{17}$$

- Calculation of the N values

$$E_{y,m} = [\mathrm{SG}_{y,m} - \overline{\mathrm{SG}}_m]^2 \tag{18}$$

- Designation of the month m of year y in which $E_{y,m}$ is minimum. This month m is considered typical and is selected for the TMY.

2.7. Average meteorological year

Average meteorological years were also developed, containing hourly values, each one of them being the average of the N corresponding hourly values from the N year data set.

3. Initial processing of the meteorological data

For generating the TMY, a 10 year time series of hourly values has been used. The meteorological parameters used are: air dry bulb temperature, relative humidity, wind velocity and global solar radiation intensity. These data have been collected and published by the Department of Meteorology in Damascus. The Department of Meteorology agreed to provide the available data. They supplied us with hourly weather data from the meteorological stations in Damascus International Airport and in Kharabo. The main criterion for the selection of stations was the completeness of the data and the period covered.

To complete the data, missing and atypical data were replaced by estimated values. These values were generated by an interpolation method, based on the corresponding parameter values for the day on which the missing data occurred. Interpolations were performed for a maximum of six consecutive missing values.

Special means were employed to maintain serially complete files of the data when long segments (more than 6 h) of missing meteorological data were found. The majority of these situations occurred at stations that were not operated during the evening or on weekends, but in some instances, a station would be shut down for several weeks or even longer. These segments were subdivided into two categories: 6–47 h gaps and 48 h to one-year gaps. For gaps 6–47 h in length, data from adjacent time periods (e.g. beginning at 06:00 and ending at 23:00) were selected to fill the gap. These segments of data were adjusted to match the end point values of the gap. For gaps of 48 h to one year, data from other years for the same time periods were selected to fill the gap. The selection was based on finding a year for which the data before and after the period of the gap had the best match with data before and after the actual gap. The best match was determined by characterizing three time slices for several days adjacent to the actual gap and comparing them to a corresponding period of time in the candidate years.

For quality control, all parameters were checked against empirical upper and lower bounds (solar radiation >0 during night, temperature >50 °C, dew point >dry bulb and so on). As well, they were checked for high between hours deviations (more than 3 °C for temperature, 30% for relative humidity and so on) against the hand written archives. Some corrections were deemed necessary.

4. Building's thermal system and TMYs performance

The selection of the best method to evaluate TMYs in a geographical area is based on the comparison of typical energy system performance simulations. For this reason, in the evaluation and comparison of all the aforementioned methods, a typical building's thermal system is considered. The aim was to survey and validate the TMYs generated against the long term measured meteorological data series. Finally, the most appropriate generation method was recommended for the Syrian region, and the TMY data base was also recommended for the Damascus province.

Using the methods described above, the TMYs were generated from the Damascus (Syria) meteorological data series. The typical months or years that emerge, following the already described methods, are shown in Table 2.

From Table 2, it can be easily seen that, according to the applied procedure, the selected typical months vary significantly. Even between the Danish method and its modification by Festa and Ratto, only 7 months are characterized as typical for both procedures. Moreover, between the Festa–Ratto method and its modification by Miquel and Bilbao, only 6 months are characterized as typical for both procedures. For instance, between the Sandia method (the modified version by Pissimanis) and the Danish method, or the Sandia method and the Festa–Ratto method, only 4 or 5 months, respectively, are the same. Between the Sandia method and that of Crow, only 2 months are the same. Between the Sandia method and the Gazela–Mathioulakis

Table 2
The years in which the selected typical months belong to, according to the applied method

Month	Method					
	Modified Sandia	Danish	Festa–Ratto	Crow	Miquel–Bilbao	Gazela–Mathioulakis
January	1984	1983	1983	1981	1990	1990
February	1981	1982	1982	1984	1985	1981
March	1990	1988	1985	1983	1985	1984
April	1987	1989	1981	1987	1981	1984
May	1987	1987	1987	1982	1981	1990
June	1987	1987	1987	1982	1987	1988
July	1990	1990	1990	1988	1990	1982
August	1989	1989	1989	1985	1989	1986
September	1988	1984	1984	1989	1984	1983
October	1982	1983	1982	1986	1990	1987
November	1985	1988	1986	1990	1985	1981
December	1983	1986	1981	1983	1986	1990

method or the Gazela–Mathioulakis method and the Miquel–Bilbao method, only 1 month is the same.

The mean monthly and mean hourly values of some chosen meteorological parameters were obtained, and graphical evolutions were plotted. Fig. 1 shows the comparison of the mean monthly values of global solar radiation intensity for the long term measured and TMYs data series. Similar plots for the air dry bulb temperature are given in Fig. 2. Also, in Figs. 3–5, the mean hourly values of global solar radiation intensity for three representative months, January for winter (November, December, January and February), July for Summer (June, July, August and September) and April for the transient seasons (March, April, May and October) are presented for the TMYs data series and for the long term measurements. Similar plots for the air dry bulb temperature are given in Figs. 6–8.

From Figs. 3–8, it can be seen that the daily values of global solar radiation and air dry bulb temperature for the years chosen as the TMYs are quite normally distrib-

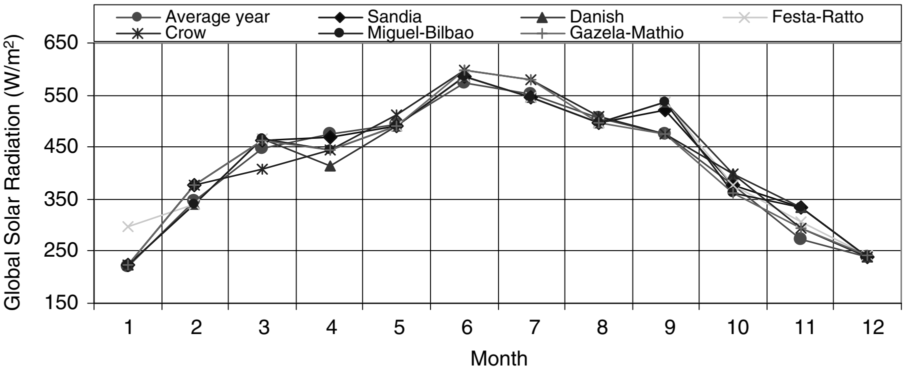

Fig. 1. Annual variations of monthly mean hourly values of global solar radiation for the selected TMYs and for the whole period of 10 years.

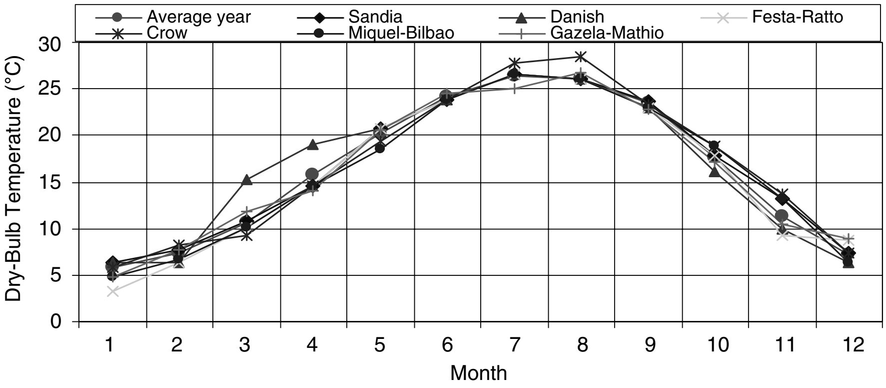

Fig. 2. Annual variations of monthly mean hourly values of air dry bulb temperature for the selected TMYs and for the whole period of 10 years.

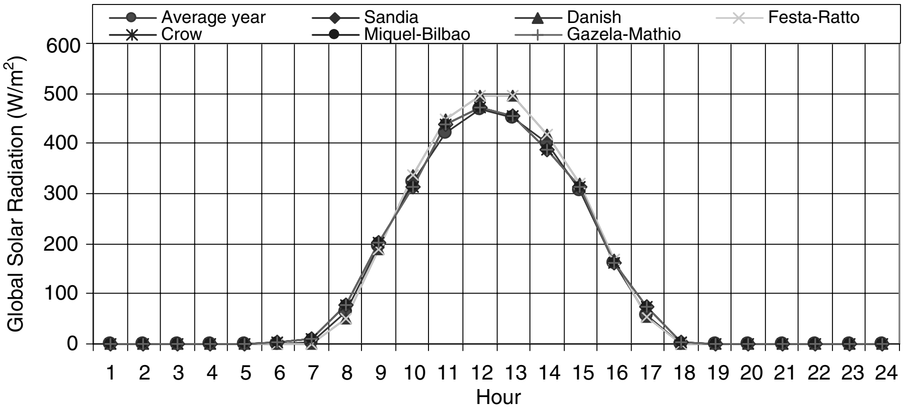

Fig. 3. Monthly variations of hourly mean values of global solar radiation for the selected TMYs and for the whole period of 10 years, for January.

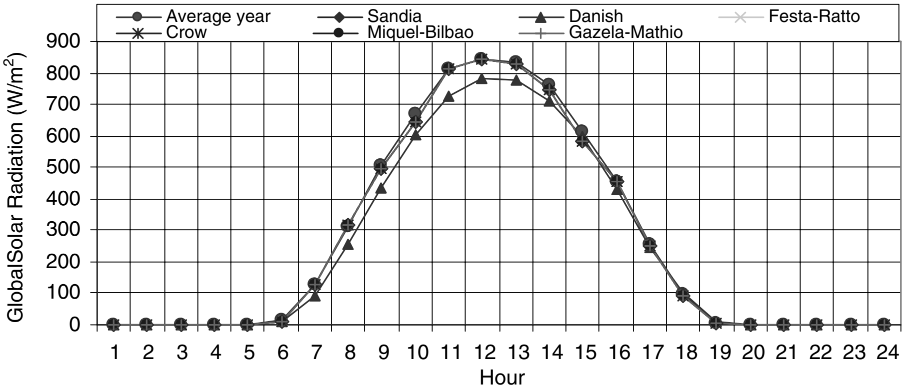

Fig. 4. As in Fig. 3 but for April.

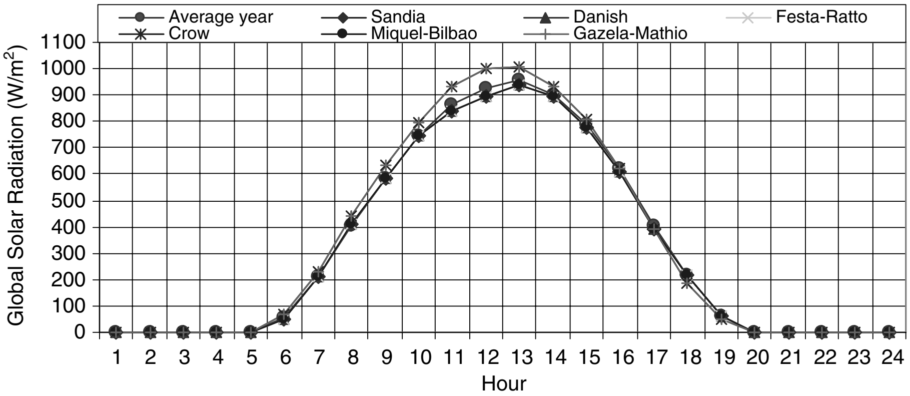

Fig. 5. As in Fig. 3 but for July.

uted with respect to the corresponding mean monthly values. It can be noticed from the above figures that the Sandia values are similar to the long term ones for all months, and the maximum variation of global solar radiation and air dry bulb temperature appears in the transient seasons.

To get some idea about the effects of meteorological data from different TMYs and to assess how close the monthly and annual building's thermal load predicted from the developed TMYs would be to that predicted from the long term measured data, a series of computer simulations was performed. The analyses were performed using the CLIMA computer program [42].

The CLIMA computer program is a scientific tool for studying, planning and calculating various buildings (thermal systems), where unusual planning or operating conditions are requested to be taken into account. It was organized to calculate, for an optionally determined period within the year, using the hourly weather data for each of the predetermined physical parameters. In the CLIMA, the dynamic analysis of heat transfer in buildings is conducted according to the adopted mathematical model by using a one hour time increment. As a starting point for calculation of the non-stationary heat transfer in a building, the ‘‘room thermal balance method’’ was adopted. It was

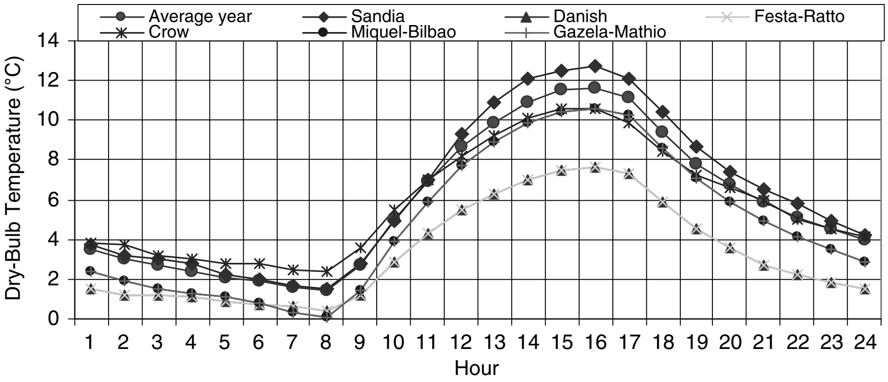

Fig. 6. Monthly variations of hourly mean values of air dry bulb temperature for the selected TMYs and for the whole period of 10 years, for January.

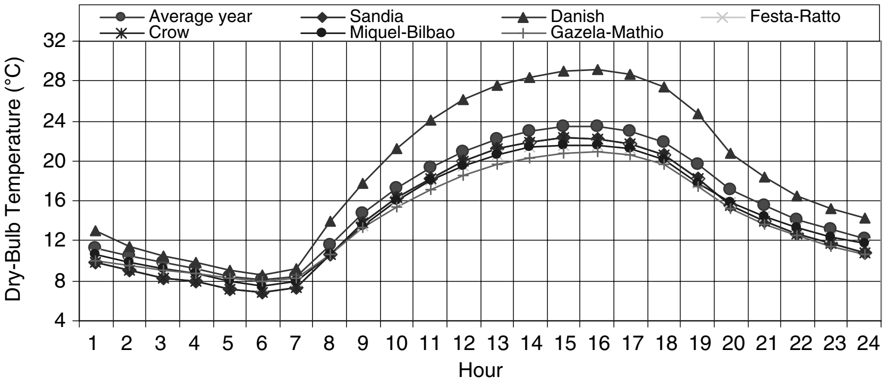

Fig. 7. As in Fig. 6 but for April.

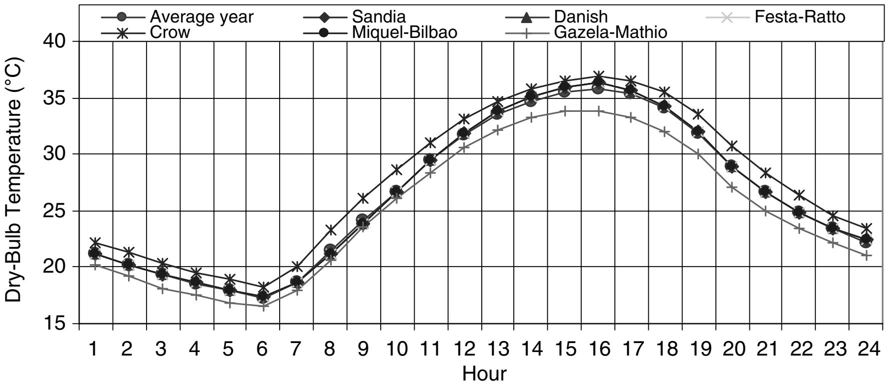

Fig. 8. As in Fig. 6 but for July.

organized for use according to the working conditions (holidays and time of starting/stopping of heating/or refrigeration) and weather seasons (months of winter and summer) in Syria. The computer program was provided with the TMYs Databases, which were generated in a previous stage of this work.

The CLIMA computer program was used to calculate the air temperature and heat loss in an enclosure within a building (Syrian typical domestic dwelling). The building consists of four floors; the studied enclosure is located on the second floor. The spaces above and under the enclosure are conditioned. The outer dimensions of the enclosure are 3 m × 8.5 m × 8.5 m, with a ground plan area of $72.3\ \mathrm{m}^2$. Each outer wall has a single glazed window with an area of $4.5\ \mathrm{m}^2$.

Following the described instructions in the CLIMA user's guide, input data of the enclosure were recorded in a relevant separate file. The recorded input data are:

- characteristics of the building,
- building location, orientation and external shading,
- indoor design conditions,

- proposed schedule of lighting, occupants, internal equipment, appliances and processes that would contribute to the internal thermal load. Occupation of the enclosure from 6:00 through 22:00 h was considered, assuming a thermostat set point of 21 °C and 26 °C during winter and summer, respectively.

Compositions of the ceiling, walls and floor were described, taking into account the systematization of layers starting from the inside towards the outside. The physical properties of the building materials used in the Damascus zone were adopted. January is adopted in the analysis as a representative month for the winter season and the 21st as its representative day. The temperature distribution in January is characteristic of an extremely cold month compared with the temperature distribution in November, December and February. Furthermore, the 21st of each month is representative of the conditions on average cloudless days.

Fig. 9 illustrates the average of the 10 year monthly thermal load, from October to April and the respective monthly thermal load for typical months as calculated by the simulating enclosure. It seems from Fig. 9 that the monthly thermal load of the enclosure depends on the procedure through which the TMY has been derived. Actually, the relative difference between monthly thermal loads estimated according to the applied procedure could be more than 50% in October. Notice that the averaged thermal load almost coincides with the one calculated by implementing the Sandia method. Thermal loads estimated by applying the Festa–Ratto method and the Crow method differ significantly for December and January. However, the Sandia and the Miquel–Bilbao method, as well as the Gazela–Mathioulakis method, offer fairly accurate results with respect to the average of the 10 year long term prediction.

In order to decide which method should be recommended for generating the TMY for the geographical zone of interest and for predicting the performance of the building's thermal system, evaluation of the procedures for TMY generation was conducted. The evaluation was made by comparing the thermal load of each year on seasonally, monthly and daily bases to the equivalent values of 'typical' data. The comparison was made by calculating six selected indicators. The point was to ascertain the behavior of the building's thermal system itself when the real data of the 10 year period are applied and also to check its behavior when typical years are in use. The first indicator is the root mean square difference, RMSD1, of the seasonal thermal load of the enclosure. It quantifies the deviation between the seasonally delivered heating load for each of the 10 years and the typical year. The second RMSD2 and third RMSD3 indicators are the root mean squares of the 10 year mean heating load minus the heating loads of the TMY on a monthly and daily basis. The fourth SEEm and fifth SEEd indicators are the total standard error of estimates of the monthly and daily heating loads, respectively. They represent the error between heating load when historical data and TMY data were applied. Finally, the sixth indicator is the chi square χ^2 parameter on the monthly heating load. This indicator is of particular interest because the sample means deviation $\sigma_{\bar{\phi}_m}$ operates as a weighting factor when the accuracy of the method is assessed. Actually, the χ^2 function provides evidence about the relation between the deviation of the TMY from historical data and the consistency (dispersion) of these data. Analytically, the equations used to estimate these indicators are

$$\mathrm{RMSD1} = \left[\frac{\sum_{y=1}^{10}(\phi_y - \phi_t)^2}{10}\right]^{1/2} \tag{19}$$

$$\mathrm{RMSD2} = \left[\frac{\sum_{m=1}^{7}(\bar{\phi}_m - \phi_{t_m})^2}{7}\right]^{1/2} \tag{20}$$

$$\mathrm{RMSD3} = \left[\frac{\sum_{d=1}^{210}(\bar{\phi}_d - \phi_{t_d})^2}{210}\right]^{1/2} \tag{21}$$

$$\mathrm{SEEm} = \frac{1}{7}\left\{\sum_{m=1}^{7}\left[\frac{\sum_{y=1}^{10}(\phi_{y_m} - \phi_{t_m})^2}{10}\right]^{1/2}\right\} \tag{22}$$

$$\mathrm{SEEd} = \frac{1}{210}\left\{\sum_{d=1}^{210}\left[\frac{\sum_{y=1}^{10}(\phi_{y_d} - \phi_{t_d})^2}{10}\right]^{1/2}\right\} \tag{23}$$

$$\chi^2 = \sum_{m=1}^{7}\left[\frac{\bar{\phi}_m - \phi_{t_m}}{\sigma_{\bar{\phi}_m}}\right]^2 \tag{24}$$

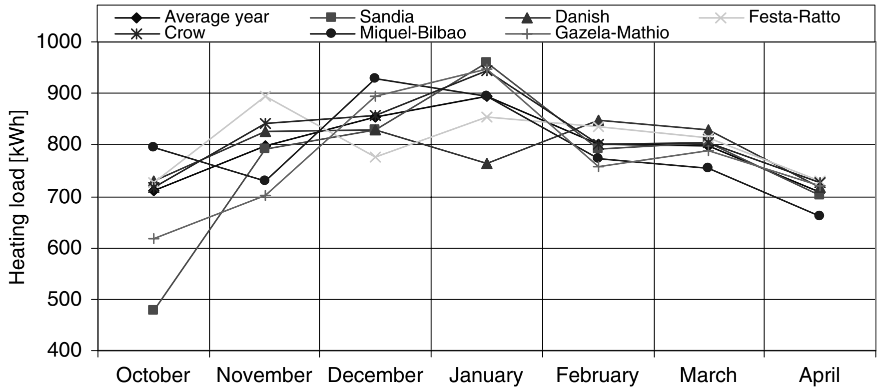

Fig. 9. Monthly heating load [kW h] from October to April for all the applied procedures for the considered typical enclosure.

Table 3
The values of the indicators, calculated for the considered typical domestic dwelling

Method	RMSD1 (kW h)	RMSD2 (kW h)	RMSD3 (kW h)	SEEm (kW h)	SEEd (kW h)	χ^2
Sandia	250	26.2	0.8	32.7	0.9	1.5
Danish	1229	55.3	1.9	42.7	1.7	7.9
Festa–Ratto	527	51.2	1.8	42.4	1.3	7.1
Crow	686	97.5	3.2	52.7	2.3	12.5
Miquel–Bilbao	443	44.0	1.7	52.3	1.3	5.1
Gazela–Mathioulakis	625	86.6	3.5	43.6	1.5	8.1

The symbols used in the above equations ϕ and $\bar{\phi}$ denote the heating load and the mean value of the heating load for the considered enclosure, respectively, on a typically t, yearly y, monthly m and daily d basis. Moreover, the $\sigma_{\bar{\phi}_m}$ denote the standard deviation of the sample means of monthly heating load of the m month. The values of the six indicators, as calculated for the considered enclosure, are presented in Table 3.

In Table 3 it is noted that the Danish method introduces a larger deviation than that in its modified versions, the Festa–Ratto method and that of Miquel–Bilbao method, while the Crow method introduces a slightly larger deviation than that in the Gazela–Mathioulakis method. As seen in Table 3, the deviation of the Sandia method is less than that of the methods mentioned above. The Sandia results in a notably lower error in the estimation of the long term thermal load. When the Sandia method is applied, the monthly/daily standard error of estimates is lower for all months. SEEm/SEEd acquire greater values for all months, when the Crow method is implemented. Lower values of χ^2 are observed when the Sandia and Miquel–Bilbao methods are implemented. The value of χ^2 when the Gazela–Mathioulakis method is applied is slightly larger than that in the Danish method and that of the Festa–Ratto method.

After comparing the results, the Sandia and Miquel–Bilbao methods could be recommended since they yield the lowest RMSD values and reproduce the performance index values extraordinarily well when they are compared with the long term measured meteorological data series.

5. Conclusions

Six methods to generate typical meteorological years from available long term measured meteorological data series have been selected, summarized, performed and implemented using the meteorological data measured at two meteorological stations, one in the Damascus International Airport and the other in the Kharabo site. The main differences between the TMY generation methods are that the Danish method and its modified versions, the Festa–Ratto method and the Miquel–Bilbao method, used standardized meteorological variables, and the modified Sandia method used solar radiation together with other meteorological measured data values for final selection of the typical months. Meanwhile, the primary difference of the Gazela–Mathioulakis method from the aforementioned ones is that it is system oriented.

The six TMYs obtained were evaluated according to their impact on the typical Syrian building's thermal system in order to decide which method should be recommended for generating typical meteorological years and for predicting the performance of thermal systems in buildings. Three widely used statistical estimators, namely, root mean square difference, RMSD, total standard error, SEE, and chi square, χ^2, were worked out to assess the performance of each TMY.

The findings showed that the TMY giving the closest performance to the average performance of the building's thermal system as predicted using the 10 year weather data is the one generated by using the modified Sandia method. This method gives sufficiently accurate results compared with the other mentioned methods that are currently also in extensive use, such as the Festa–Ratto and Miquel–Bilbao methods. It is believed that this method can be applied to other locations with similar building developments and climates.

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