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A STUDY OF THE EFFECT OF WEIGHTING INDICES FOR THE DEVELOPMENT OF TMY USED FOR BUILDING SIMULATION

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ABSTRACT

Nowadays thermal, environmental performance of buildings and systems are investigated mainly through building simulation software. The prediction of the building performance requires an updated long-term weather database by the generation of a comprehensive database, so-called Typical Meteorological Year (TMY). However, the majority of methods and studies on the generation of TMY are employing the default weighting indices, resulting in a gap of basis of assigned factor for meteorological parameters. In essence, this paper investigates the impact of weighting factor and climatological variables, on the implementation of TMY in particular simulation studies. A statistical analysis has been carried out, and the results show that for solar applications, the TMY mainly driven by the global radiation, demonstrate the best performance. Similarly, for the simulation case of a wind turbine, the best performance achieved by the TMY, based on the wind profile. The cooling and heating mode of a building are better described by the weather data set that is influenced from all the meteorological parameters. Thereby, on enhancing the precision and accuracy of results at building simulation analysis, the weighting factors of the environmental parameters must be driven by the intended use of the weather file.

INTRODUCTION

Building simulation is routinely applied for energy and environmental performance assessments of buildings. One of the key requirements for building simulation is an updated long-term weather database, representative of the climate of the area under investigation. Various approaches are available for the generation of typical weather data; most notable one is the Typical Meteorological Year (TMY), which has found worldwide acceptance as a practical method. TMY is produced by aggregating typical meteorological months (TMM) from a multi-year database of observed weather parameters (e.g. temperature, humidity, wind speed and direction, solar radiation, rainfall, etc.) at a suitable time-step, typically hourly resolution.

Currently, there are different methods to generate a TMY data series. Their main difference is the statistical approach to identify the selection of the most typical data for the construction of the TMY, as well as the weather indicators, accuracy and complexity of each method (Argiriou et al. 1999). Some of the most recent methods are the Sandia method, the Danish method, the Festa-Ratto method, the Miquel-Bilbao method which is based on weather meteorological data and not on solar radiation, Crow method and Gazela-Mathioulakis method. Extensive comparison between these methods has been carried out (Ebrahimpour and Maerefat 2010; Skeiker 2007; Argiriou et al. 1999; Janjai and Deeyai 2009) and the results demonstrated that the majority of the methods have a similar performance. However, the Sandia method is the most widespread approach for the generation of TMY due to its simplicity (Janjai and Deeyai 2009).

Recent reviews of the weighting indices of Sandia method, has identified that the most of the methods are using the highest weighting index for solar radiation. Hall et al. stated that the indices are influenced by the intended use of TMY (I.J Hall et al. 1978). However, in the most cases the generation of TMY is based on the default weighting indices. This has resulted in discrepancy over selecting appropriate weighting indices for building simulation. Thus, this paper aims to investigate the impacts of the weighting indices during the generation of a TMY and as a result, the performance of building simulation.

Throughout the study there will be a development of TMYs with different indices for numerous climatological parameters. Such TMYs will be used for the simulation analysis of particular cases such as solar thermal application, wind turbine and heating/cooling mode of a residential building. The findings will be compared to the long term (LT) average and 2012 actual data (AD) weather files in order to investigate the effect of weighting indices for different environmental variables.

TMY SELECTION PROCEDURE

The Sandia method is an empirical approach where a TMY is composited by 12 calendar months (Ebrahimpour and Maerefat 2010). The generation of the meteorological data file lies upon the statistical analysis of several weather parameters and their weighting factors. At the initial state, Hall et al. used 13 parameters from a 23 years period (I.J Hall et al. 1978). These were the maximum, minimum, mean and ranges of dry bulb and dew point temperature, wind velocity and total daily solar radiation. Thereafter, authors generated TMYs, based on different climatic variables and weighting factors, as shown in the Table 1.

The generation of the TMY will depend upon the maximum, minimum and mean of dry bulb temperature, relative humidity, maximum and mean wind velocity and the total daily solar radiation (9 weather indices).

The procedure is consisted by two sub-processes. The first is the selection of the five candidate years, founded on the FS statistics. This approach adopted by the majority of the modified Sandia method. The latter is the final selection of TMM, driven by the persistence structure of the five candidate months. At the default Sandia version, Hall et al. evaluated persistence of weather parameters by determining the frequency and run length above and below of fixed percentiles (I.J Hall et al. 1978). However, given the significant number of studies adopted the Pissimanis method (Skeiker 2007; De Miguel and Bilbao 2005; Janjai and Deeyai 2009; Argiriou et al. 1999; Skeiker and Ghani 2009), the current study will be based on its application. The method is based on simpler and intuitive formulas for the selection of TMM (Skeiker 2007).

Additionally, it is crucial to highlight the manipulation of erroneous and missing data. According to Levermore and Parkinson (Levermore and Parkinson 2006), a fraction of 15% of erroneous data is acceptable for the generation of TMY. In addition, if there are gaps in data for a period of 1 to 6 hours, the linear and polynomial interpolation will applied, as proposed by Chen and Claridge (Chen and Claridge 2000). Essentially, twelve typical months will concatenated to form a typical meteorological year. In all TMYs, the transition from one month to next month has smoothed, using the linear interpolation of the real values for ± 5 hours.

Selection of five candidate months

The selection of the five candidate years involves the examination of the closeness to the long-term database. The procedure repeated in a similar manner for all calendar months. For this study, the long-term database is composited by data from the recent decade (2001-2011).

The closeness of each year to the long term is examined by the comparison of the short and long-term cumulative distribution function (CDF) through the Finkelstein-Schafer (FS) statistics. In a given month, the daily averages referred to as *"short term"*. When these averaged for the whole period of database then they called *"long term"*. The short and long term cumulative distribution function (CDF) of weather index (i.e. temperature) is determined by a monotonic increasing function $CDF_{(x)}$, when a number n, of observations of the weather variable x

Table 1 Weather parameters and assigned weather indices

Indices		Studies				
		(I.J Hall et al. 1978; Skeiker and Ghani 2009; Skeiker 2007)	(Sawaqed, Zurigat, and Al-Hinai 2005)	(Petrakis et al. 1998; Kalogirou 2003)	(Marion and Urban 1995)	(Chan et al. 2006)
Temperature	Max	1/24	1/22	1/32	1/20	1/20
	Min	1/24	1/22	1/32	1/20	1/20
	Mean	1/12	1/22	1/16	1/10	3/10
	Range	-	1/22	1/32	-	-
Humidity/ Dew point temperature	Max	1/24	1/22	1/32	1/20	2.5/100
	Min	1/24	1/22	1/32	1/20	2.5/100
	Mean	1/12	1/22	1/16	1/10	1/20
	Range	-	1/22	1/32	-	-
Wind velocity	Max	1/12	1/22	1/32	1/20	1/20
	Min	-	-	1/32	-	-
	Mean	1/12	1/22	1/16	1/20	1/20
	Range	-	1/22	1/32	-	-
Wind direction	Mean	-	-	1/32	-	-
Solar Radiation	Global	1/2	1/2	1/4	1/4	2/5
	Direct beam	-	-	1/4	1/4	-

are available and have been sorted into an ascending order $x_1, x_2, \ldots, x_n$. Equation 1 expresses the CDF.

$$CFD\ (x) = \begin{cases} 0 & for\ x < x_1 \\ \frac{(i-0.5)}{n} & for\ x_i \leq x < x_{i+1} \\ 1 & for\ x \geq x_n \end{cases} \qquad (1)$$

The following Equation 2 calculates the FS statistics between the short and long term CDF for a given month:

$$FS_x(y,m) = \frac{1}{N}\sum_{i=1}^{N}\left|CDF_m(x_i) - CDF_{y,m}(x_i)\right| \qquad (2)$$

where $FS_x(y, m)$ is FS (y, m) statistics for each weather index x (y-year and m-month); CDF_m is the long-term and $CDF_{y,m}$ is the short term (for the year y) cumulative distribution function of the weather index x for month m and N is the number of daily reading of the month (i.e. February N=28).

Finally, the five candidate years for each month selected with respect to the smallest score of the Weighted Sum (WS). The WS is the aggregation of FS statistics of the nine climatic indices that multiplied by their assigned weighting factor.

$$WS(y,m) = \frac{1}{M}\sum_{x=1}^{M} WF_x FS_x(y,m) \qquad (3)$$

, where WS(y, m) is the weighted sum for the month m in the year y, WF_x is the weighting factor for the x_{th} weather index and M is the number of the meteorological indices.

Final selection of TMM

The final selection of the typical meteorological months (TMM) carried out by the examination of the persistence structure of the five candidate years.

According to the aforementioned, the Pissimanis method applied, which founded on a simpler method to examine the persistence of mean daily values of weather variables by the utilization of RMSD (Pissimanis et al. 1988):

$$RMSD = \left(\frac{1}{n}\sum_{i=1}^{n} d_i^2\right)^{0.5} \qquad (4)$$

, where n is number of data (i.e. 8760 for a year) and d_i is the difference between the hourly values and the hourly long-term average values of global radiation. Afterwards, a variation of this method was introduced, where a composite score S is calculated by the Equation 5 and the month with the highest score is selected.

$$S_x(y,m) = \frac{\min_{i=1,\ldots,20}(RMSD_x(i,m))}{RMSD_x(y,m)} \qquad (5)$$

METHODOLOGY

The paper aims to examine the impact of the weighting factor and hence, the importance of meteorological parameters during the implementation of a TMY data files in a simulation environmental analysis. In essence, the methodology, adopted for the particular study, involves the generation of TMY data files and a statistical analysis of the different weather data sets for several simulation applications.

Weather data selection

In the present study, the hourly weather data for the period 2001-2012, have been acquired from the meteorological station of Paphos National Airport, which is situated at the south-west coastal region, 34°72’ N 32°48’ E, of Cyprus (MetDep 2012). However, due to a lack of global radiation data for the period 2001-2004, additional databases employed, providing a comprehensive data for the TMY development (NOAA 2013; SolarGIS 2012). For shorter periods of erroneous and missing data, the linear and polynomial interpolation applied.

The environmental variables, for the construction of the TMYs, are the dry bulb temperature, dew-point temperature, relative humidity, wind speed, wind direction and global horizontal radiation.

Global radiation

For the generation of typical meteorological year, the values of hourly extra-terrestrial (I_o), direct normal (I_{bn}) and diffuse horizontal (I_d) radiation, estimated according to the Duffie and Beckman method 1982 (Duffie and Beckman 1982), as is presented below:

Initially, the procedure requires some mandatory parameters of the solar geometry. Thus, the declination angle of the sun, δ, and (degrees) is defined by:

$$\delta = 23{,}45.\sin\left(360.\frac{284+D}{365}\right) \qquad (6)$$

, where D is the calendar day of the year (1-365).

Here, φ is the latitude of the location (degrees) and ω is the hourly angle of the sun (deg). At 12:00 midday the value of ω is zero, with the morning being negative and afternoon being positive, where for each hour the value is changed by 15° (i.e. at 10:00 ω=-30°).

Moreover, the θ_z is the solar zenith angle calculated by Duffie and Beckman:

$$\cos\theta_z = \cos\varphi\,.\cos\delta\,.\cos\omega + \sin\varphi\,.\sin\delta \qquad (7)$$

Hence, by the calculation of solar parameters, the hourly solar radiation variables can be estimated from the following equations. The extra-terrestrial horizontal radiation (kJ/m^2) given as:

$$I_o = \left(\frac{12.3600.I_{sc}}{\pi}\right).E_o.\left[\cos\varphi\,.\cos\delta\,.\left(\sin\omega_2 - \sin\omega_1\right)\right] + \left(\frac{2\pi(\omega_2-\omega_1).\sin\varphi.\sin\delta}{360}\right) \qquad (8)$$

, where: the solar constant, I_{sc}=1367 Wm^{-2} and the eccentricity correction factor, E_O=1+0,033.cos (360.D/365). The clearness index, k_t, defined as the ratio of the hourly horizontal radiation on horizontal surface to the hourly horizontal extraterrestrial radiation,

$$k_t = {}^{I}/_{I_o} \qquad (9)$$

The hourly diffuse solar radiation, I_d, estimated by the equation 10.

$$k_d = {}^{I_d}/_{I} = \begin{cases} 1\text{-}0.249k_t & k_t<0.35 \\ 1.557\text{-}1.84k_t & 0.35<k_t<0.75 \\ 0.17 & k_t>0.75 \end{cases} \qquad (10)$$

, while the direct normal radiation calculated as follows:

$$\mathrm{n} \quad \frac{-}{\mathrm{os}\,\theta} \qquad (11)$$

TMY data sets

The study will focus on a parametric analysis, and thus, four sets generated from the period of 2001-2011. Particularly, the weighting index for all parameters nullified, except the one that will describe the selection of the TMY. The indexing shown in the Table 2. As a result, the impact of each meteorological parameter will be examined in comparison to the LT and AD. Moreover, the TMY_d is constructed with regards to the default weather indices by (I.J Hall et al. 1978), acting as a reference database to the study.

Preliminary results are presented in the Table 3.

Table 3 Typical meteorological months (TMM)

	TMY_d	TMY_g	TMY_{db}	TMY_{rh}	TMY_{ws}
1	2011	2011	2011	2008	2001
2	2008	2007	2011	2008	2002
3	2008	2006	2011	2007	2001
4	2009	2009	2008	2007	2009
5	2008	2002	2002	2002	2008
6	2008	2003	2011	2003	2006
7	2011	2005	2001	2008	2011
8	2007	2011	2004	2004	2007
9	2011	2011	2010	2007	2001
10	2007	2008	2001	2008	2007
11	2003	2003	2007	2010	2008
12	2005	2005	2011	2006	2008

It can be noticed, that regarding to the applied importance on a particular meteorological parameter, the selected typical months (TMM) vary considerably.

The variations of dry bulb temperature and horizontal radiation are presented. Figure 1 shows the comparison of the monthly long mean measured temperature and TMYs series. Similarly, the evolution of monthly mean horizontal irradiance and TMYs are shown in Figure 2. From the Figures 1 and 2, it can be seen that the TMYs have approximately similar average monthly values over the long-term period.

Table 2 Weighting factor of environmental parameters

		Weighting Indices				
Parameter		Default[1] (TMY_d)	TMY_g	TMY_{db}	TMY_{rh}	TMY_{ws}
Temperature	Mean	0.08	0	0.5	0	0
	Max	0.04	0	0.25	0	0
	Min	0.04	0	0.25	0	0
Relative Humidity	Mean	0.08	0	0	0.5	0
	Max	0.04	0	0	0.25	0
	Min	0.04	0	0	0.25	0
Wind Speed	Mean	0.08	0	0	0	0.5
	Max	0.08	0	0	0	0.25
	Min	0	0	0	0	0.25
Global Radiation		**0.50**	1	0	0	0
Focus on			Global Radiation	Dry bulb temperature	Relative humidity	Wind Speed

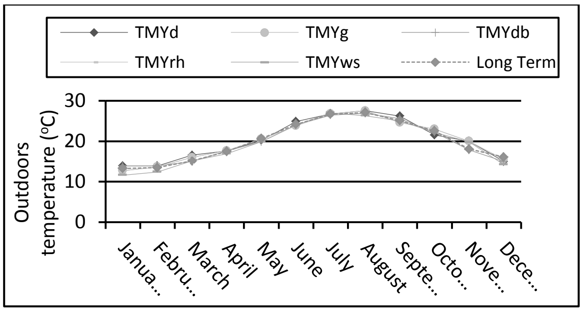

Figure 1 Monthly average dry bulb temperature

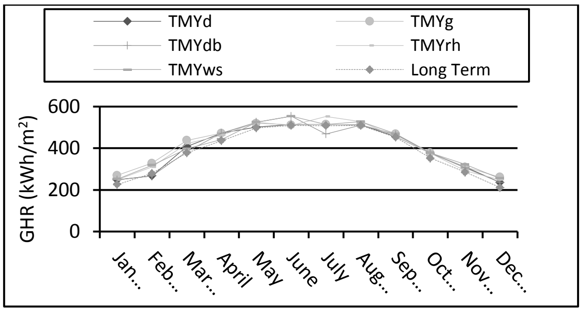

Figure 2 Monthly global horizontal radiation

Simulation applications

The investigation of TMY's performance in simulation environment, was examined by the implementation of a residential solar thermal system, a wind turbine generator and heating/cooling mode analysis of a typical dwelling in Cyprus. The same parameters of each simulation used for all weather data sets. The analysis was carried out using EnergyPlus software.

As a starting point, a domestic flat plate solar collector designed to serve the residential demands for domestic hot water, in conjunction with an electrical heater.

The collector consisted of two solar plates with a gross area 2.96 m^2. In the Figure 3, the daily heat production is presented for 3 arbitrary days in January, April and July.

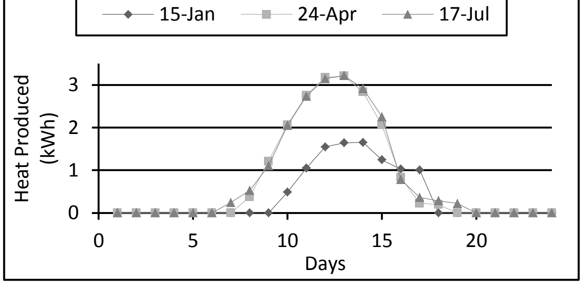

Figure 3 Daily heat production (Long term data set)

Thereby, the heat production by the integration of each TMY set will be evaluated against the long term and actual data of the year 2012.

Similarly, a wind turbine examined in the perspective of energy production. For the particular simulation case, the result will be the electricity generation (kWh) and will be assessed in a similar manner as the solar collector case stud. In the Table 4, the characteristics of a horizontal axis turbine are shown, as referred by (Bergey 2012).

Table 4 Wind turbine characteristics

Characteristic		Units
Rated rotor speed	84.07	rev/min
Rotor diameter	2.5	m
Overall height	5	m
Number of blades	3	-
Rated power	1.0	kW
Rated wind speed	11.6	m/s
Cut in wind speed	2.5	m/s
Cut out wind speed	30	m/s
Maximum tip speed ratio	5	-

Moreover, the seasonal heating and cooling mode for a typical residential building examined. A simple single zone dwelling, with 200 m^2 of total floor area designed according to (CYSTAT 2010). The properties of the elements of the construction are presented in Table 5.

Table 5 Properties of building envelope

Structural Element	U value (W/m^2.K)
Exterior Walls	1.389
Floor	2.47
Roof	1.8
Glazing	1.960

The parameter that are investigated through the study is the energy required by the heating and cooling loads, to maintain the indoor temperature at 21 °C and 25 °C, for the period of November-March and April-October, respectively.

Statistical analysis

The TMY performance obtained by the simulation procedure, are evaluated according to the long-term average and actual data of 2012. As a result, through the analysis, the impact of weighting index are revealed in the perspective of typicality for a particular period (i.e. 2001-2011 periods) and the capability to predict future years.

Thereby, the evaluation assessment is contacted through a statistical analysis, based on the modified Pearson coefficient of determination, so-called adjusted-R^2 and the root mean square error (RMSE). The application of each coefficient is mainly based on the extent of impact by the presence of outliers.

In the case of cooling mode and solar collector, the adjusted-R^2 employed, with a confidence level of 95%. The adjusted-R^2 compensates the additional variables in the model, enhancing the accuracy of the analysis, on the contrary to the simple R^2 (Mark and Jolley 2010). A closer value to 1.0 indicates a strong correlation between the compared data sets.

However, for the heating mode case, the simple regression analysis is not sufficient to describe the model. Due to this fact, the robust regression applied to estimate the adjusted-R^2 to eliminate the impact of outliers (Witten and Frank 2000).

Furthermore, the unpredictable seasonal wind profile contributes to the implementation of the root mean square error (RMSE) for the assessment of turbine performance. Lower values of RMSE indicate smaller offset between the compared data set.

RESULTS AND DISCUSSION

In this section, the results from the evaluation of the TMYs performance against the long term and 2012 data are presented. The outcome is based on the aforementioned simulation cases.

As can be seen from the Figures 4-7, the cooling mode and solar collector cases are following a linear trend. The application of simple linear regression will be sufficient to evaluate the TMYs.

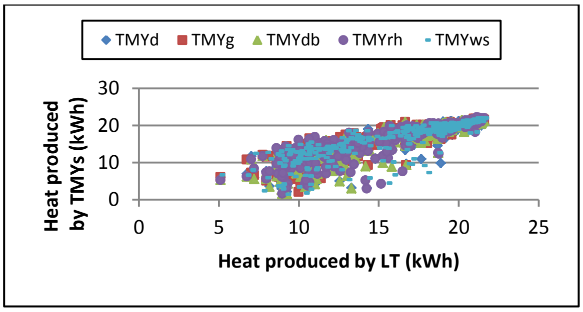

Figure 4 Heat production against LT

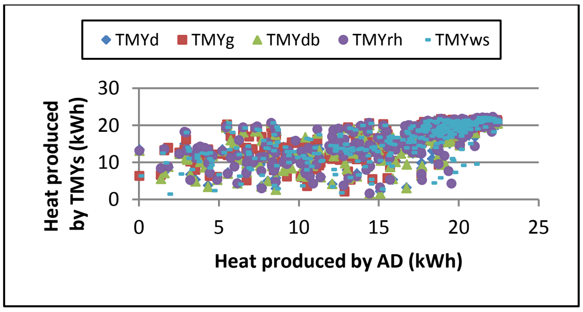

Figure 5 Heat production against AD

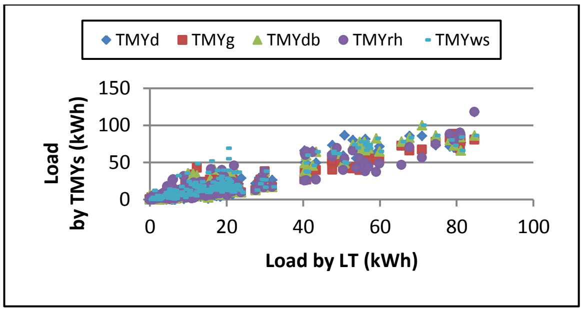

Figure 6 Cooling load against LT

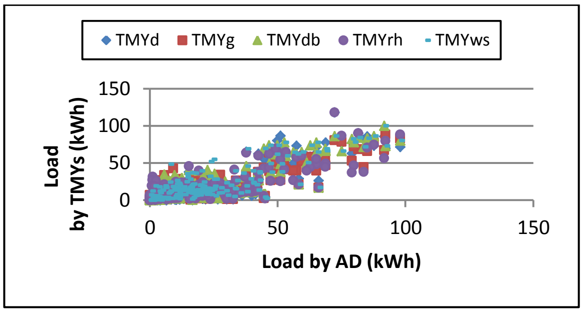

Figure 7 Cooling load against LT

In contradiction, for the heating mode and wind turbine simulation the adoption of an alternative approach is mandatory, due to the existence of outliers that distort the linearity of the model. A possible cause is the lack of seasonality of the winter period and the difficulty to forecast the wind profile.

Climate in Cyprus is characterized by summer dominant. Thereby, the winter period is not as constant as summer season. This shown in Table 6, where the frequency of standard deviation for the dry bulb temperature hourly values is estimated for winter and summer period during 2001-2011.

Table 6 Frequency of standard deviation in winter and summer period in Cyprus

Standard Deviation	Summer	Winter
0-1	538	4
1.01-2	1478	215
2.01-3	142	722
3.01-4	2	593
4.01-5	0	495
5.01-8	0	131

As it can be seen, the standard deviation during the winter period reaches up to 8, where during summer goes up to 4 with the frequency concentrates between 1-3. As a result, the presence of outlier values leads to the distortion of the results. In essence, the adjusted-R^2 calculated by robust fitting using the case of heating mode. Figures 8-9 show the results for the heating mode.

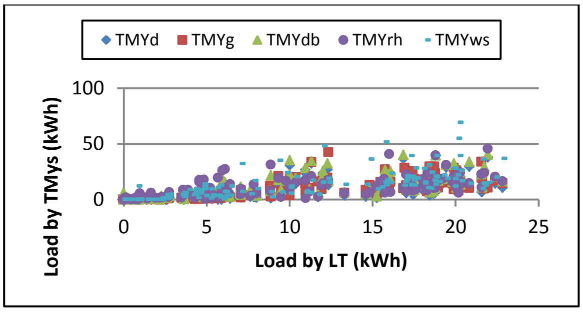

Figure 8 Heating load against LT

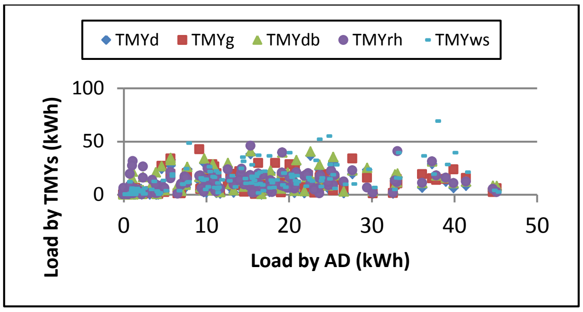

Figure 9 Heating load against AD

Analogously, the effect of large-scale mechanisms such as the difference of temperature, pressure and local surface characteristics contribute to the difficulty of estimating wind profile between years (Sfetsos 2000). The TMYs present similar seasonal profile, but the hourly magnitude and direction of wind varies considerably. Thereby, the deviation from the long term and actual data of 2012 estimated by the RMSE.

From Tables 7-8, it is noticed that the performance of all TMYs data series are relatively similar, which is revealed by the composition method. During the concatenation of the months to form the data sets, the selected months are the most typical, resulting to the approximately similar performance.

However, distinguish can be made with the cases that have the best fit with the long term. The TMYs driven mainly by global radiation and wind speed have the best performance, for the solar collector and wind turbine, accordingly. Now, in the perspective of heating and cooling mode of a residential building, the TMY_d presents the best performance. As it is above mentioned, the generation of TMY_d is mainly driven by global radiation, but it is also influenced by the rest meteorological parameters, resulted to the expected performance on the calculation of building loads.

As it can be seen in the Table 8, the scene remains the same through the comparison of the TMYs against the AD. The best performance is also presented by the same TMYs, as described before.

According to the aforementioned, the impact of weighting factor in the generation of TMY data series is driven by the simulation case that the TMY will be applied as a weather input. For the investigation of specific renewable applications such as solar collector and wind turbine, an attention must be given to the weather parameters that are directly related to the applications i.e. global radiation and wind profile.

Table 7 Performance of TMYs according to LT

Data Set	Solar collector	Cooling mode	Heating mode	Wind Turbine
	Adjusted-R^2			RMSE
TMYd	0.7692	**0.9265**	**0.8878**	0.455
TMYg	**0.8132**	0.902	0.87	0.464
TMYdb	0.7831	0.923	0.83	0.427
TMYrh	0.7456	0.9156	0.69	0.447
TMYws	0.7183	0.914	0.85	**0.401**

Table 8 Performance of TMYs with regards to AD

Data Set	Solar collector	Cooling mode	Heating mode	Wind Turbine
	Adjusted-R^2			RMSE
TMYd	0.51	**0.886**	**0.747**	0.830
TMYg	**0.526**	0.809	0.722	0.860
TMYdb	0.5212	0.88	0.5745	0.831
TMYrh	0.446	0.862	0.3558	0.857
TMYws	0.4607	0.87	0.7102	**0.795**

On the contrary, when the simulations examine the performance of a building under the heating and cooling mode, the emphasis must given in all meteorological variables, as the demand for heating or cooling is driven by the conjunction of the most weather parameters.

Moreover, the application of a TMY for a given location must examine with the perspective of the climate characteristics. As highlighted in the study, the cooling load evaluated by the use of the linear regression, while the heating load and the wind turbine require the implementation of the robust regression and RMSE to estimate the performance of TMYs against the long term and actual future data.

CONCLUSION

The study attempted to reveal the impact of the weighting factor and hence, the importance of the meteorological parameters on the generation of a TMY data set for use on building simulation.

Initially, in the section on generating TMYs, it presented that the backbone (TMM) of a TMY data set can significantly varied due to the assigned factor of the climatological variables. For instance, the TMY_{rh} has one similar TMM with TMY_d, while the TMY_g has five months, presenting the importance of the global radiation on the default data set.

Now, on the perspective of the simulation studies, the outcome highlights the Hall's statement regarding to the intended application of a TMY data file and thus, the assigned weighting factor for the meteorological variable. Overall, the performance of the TMYs was similar for the majority of the simulation cases. However, slightly better performance occurred by particular data sets. For example, at the solar collector case, the highest adjusted R^2, was given by the TMY_g. Similarly, at the comparison of TMYs for the electricity generated by a wind turbine, the TMY_{ws} demonstrated the best performance. In addition, the significance of all meteorological parameters presented on the heating and cooling mode, where the TMY_d described better the long-term and actual data sets.

In the statistical context, the performance difference is relatively small. However, by using an appropriate weather file the accuracy of the simulation analysis may be enhanced. For instance, at the calibration stage of a simulation analysis, the errors revealed by the weather file will be eliminated, resulting to a validated simulation model.

Consequently, the procedure to assign weighting factors will be wise to driven by the intended application of the TMY and thus, the enhancement of the accuracy in the building simulation studies.

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