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Analysis and Improvement of the Representativeness of EN ISO 15927-4 Reference Years for Building Energy Simulation

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Representativeness of weather inputs is crucial to limit the global uncertainty of building energy simulation (BES) results. The length of the starting multi-year weather data series and the methodology used for the typical month selection largely influence the results of the reference year development process. In this work, we investigate two possible modifications to the EN ISO 15927-4:2005 procedure aimed at improving the representativeness of reference year heating and cooling needs. The first modification maintains the reference years independent of their final use while the second one leads to the development of specific weather files for heating or cooling analyses by introducing weighting coefficients for the different weather parameters. The study is performed for 5 North Italy localities with 10 or less years in the dataset and for a sample of 48 simplified buildings. Both proposed modifications brought improvements to the representativeness of the reference year results.

Keywords: test reference year, EN ISO 15927-4:2005, building energy simulation

1. Introduction

The use of detailed building energy simulation (BES) tools by professionals is becoming more and more common. The higher capabilities in calculating detailed outputs - such as heating and cooling sub-hourly loads profiles and indoor thermal hygrometric and visual comfort, imply more complex and detailed inputs (Attia *et al.* 2012). As regards the weather data input, issues related to the development of weather data for BES have been widely investigated in the literature and Barnaby and Crawley (2011) discussed and presented the main aspects, contexts and problems related to their definition.

According to Keeble (1990), we can distinguish three kinds of data for BES: the multi-year weather data, the typical or reference years and the representative days. The most used in dynamic simulations is the typical year, which is simply a single year of hourly weather data representative of the typical profiles recorded in a multi-year dataset. The use of the typical year brings different advantages since it can be considered a reasonable “substitute for the real long term weather in the thermal simulations” (Aguiar, Camelo and Gonçalves 1999) and it has generally “a better match to the long term performance than any single year of data” (Freeman 1979).

The typical or reference years have been derived in different ways in the last decades. One of the first definitions was given for 60 American localities (National Climatic Data Center 1976): the test reference year TRY was an actual year selected using a process where years in the period 1948-1975 with extremely high or low mean dry bulb temperatures were progressively eliminated until only one year remained. Crawley (1998) discouraged the use of the original TRY of 1976 and suggested using artificial years such as the typical meteorological years (TMY) or other typical years built according to similar procedures, as the European test reference years (Barnaby and Crawley 2011). This has also been confirmed, for instance, by Chan *et al.* (2006) and Chow *et al.* (2006) in their studies for the climate of Hong Kong. The typical meteorological year and the European reference year are composed of 12 months selected as the most representative over the multi-year series. One of the first definitions of the selection procedure for the generation of the typical year was given by Hall *et al.* (1978) for the TMY and it is based on the Finkelstein-Schafer statistic (Finkelstein and Schafer 1971). According to Lund (1991, 1995) and Lund and Eidorff (1981), the typical or reference years have to be characterized by:

- *true frequencies* (i.e., the reference year should be a good approximation of the mean values derived from a long period of measurements);
- *true sequences* (i.e., the weather situations must follow each other in a similar manner to the recorded data);

- *true correlations* (i.e., the weather data are cross-correlated variables).

The main issue with this kind of artificial reference years is related to the risk of the selection of a wrong candidate for a given calendar month, affecting the typicality of the weather file (Adelard *et al.* 2000). To face this problem, many different approaches have been developed. After the TMY according to the SANDIA method (Hall *et al.* 1978), changes to the procedure and to the datasets of historic years led to TMY2 (Marion and Urban 1995) and TMY3 (Wilcox and Marion 2008). The SANDIA and similar methods have been implemented for the generation of reference years for a number of localities, considering many weather variables (Kalogirou 2003; Lee, Yoo and Levermore 2010; Oko and Ogoloma 2011) or just one (Bulut 2004; Zhou, Wu and Yan 2006). Other methodologies prefer different statistical indexes or approach of analysis for the assessment of the typicality of the different candidates for each calendar month: for instance, the "Danish" method (Andersen *et al.* 1986; Lund and Eidorff 1981) is based on some criteria aimed at excluding the worst candidates and selecting those characterized by typical values and variations of the weather parameters and the Festa-Ratto method (Festa and Ratto 1993) uses the Kolmogorov-Smirnov statistic, which is similar to the Finkelstein-Schafer one.

Since there are several alternatives for the generation of a reference year, many authors - for instance Huang (1998), Levermore and Doylend (2002), Skeiker (2007) and Sorrentino *et al.* (2012), made some comparisons in order to assess the capabilities of the different methods and identify the best solutions. Generally, the evaluation involves the analysis of weather statistics, solar fraction of thermal solar systems, electrical power output of PV systems, heating and cooling degree-days, energy needs or final uses (Bilbao *et al.* 2004; Freeman 1979; Gansler, Klein and Beckman 1994). Analysing different climates and applications, some authors drew different conclusions since the best method depends on the considered energy system - e.g., building or thermal solar system, and on the focus of the analysis - e.g., heating or cooling demand, solar system output (Argiriou *et al.* 1999).

In Italy, the procedure based on the Finkelstein-Schafer statistic described in the European technical standard EN ISO 15927-4:2005 (European Committee for Standardization 2005) was selected for the revision (currently in progress) of the technical standard UNI 10349:1994 (Ente Nazionale Italiano di Normazione 1994) which reports the weather data to use for energy calculations. The dataset previously used in Italy to develop reference weather data considered the measurements collected in Italian airports from 1951 till 1970 and so, since it is far from being representative of the current urban conditions, a new weather data collection has started. Although there are some cases for which the new proposed datasets contain almost 20 years, for many Italian localities only a limited number of years is generally available (Baggio *et al.* 2010).

In some previous works ([names deleted to maintain the integrity of the review process] 2013; [names deleted to maintain the integrity of the review process] under review), we developed reference years according to the EN ISO 15927-4:2005 method for 5 North Italy localities and compared the annual energy needs and peak loads of a set of 48 simplified buildings evaluated by means of these weather files to the averages of the multi-year series involved in the reference years development. We observed that few years in the historic weather data series can lead to a poor representativeness of the generated reference year and, therefore, also the one of BES results decreases. Moreover, the effects on the building envelope energy rating were investigated, allowing us to conclude that, even following the prescriptions of the technical standards about the minimum number of 10 years, a good representativeness of the building energy performance cannot be taken for granted.

In this work two possible modifications to the technical standard procedure are proposed and discussed in order to improve the representativeness of the reference years for locations characterized by climates with a large variability and limited years in the historic weather data series. For the assessment of the modifications, we compare the annual energy needs simulated with the new reference years to the multi-year averages of each one of the same 48 buildings considered in the previous works ([names deleted to maintain the integrity of the review process] 2013; [names deleted to maintain the integrity of the review process] under review). We investigate both changes to the final selection steps and the introduction of weights to consider the relative importance of the different weather variables in the reference year generation. While the first improvement is aimed at developing general purpose weather files – which can be used, for instance, for occupants' comfort assessment, study of indoor condition in intermediate seasons, etc., the second one is tailored for the evaluation of heating or cooling annual energy needs and, in particular, it is expected to be used to assess heating and cooling energy for the building energy rating.

2. Methods

The construction of a reference year requires evaluations of mean values, individual frequency distributions and cross correlations of the meteorological variables, which can be analysed according to the different approaches of the literature. The choice of which parameters can be used to describe the weather conditions, their number and relative importance are some elements of disagreement among the different methods. At large, each methodology can be distinguished into two parts: the first part is aimed at identifying a group of most representative candidates for each calendar month while the second part is related to the selection of the best one for the development of the reference year. The first steps generally involve the calculation of some statistical indexes, such as the Kolmogorov–Smirnov statistic (Festa and Ratto 1993) and the Finkelstein-Schafer statistic (Hall *et al.* 1978), as remarked in the introduction. The second step is somehow more subjective (Hall *et al.* 1978; Pissimanis *et al.* 1988) and so some authors preferred to adopt different selection criteria.

2.1 The EN ISO 15927-4:2005 reference year

A reference year in accordance with the technical standard EN ISO 15927-4:2005, TRY_{EN}, can be built following the steps described below:

(1) calculation of the daily averages $\overline{p}$ of a set of primary climatic parameter *p* (i.e., dry bulb temperature, horizontal global solar radiation and relative humidity as suggested by the technical standard), month *m* and year *y* of the series;

(2) sorting of all the $\overline{p}$ for a specific month *m* of all the available years in increasing order and calculating the cumulative distribution function $\Phi(p, m, i)$ for each parameter and i^{th} day as:

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

where $K(i)$ is the rank order of the i^{th} day and N is the total number of days for a month over all the available years;

(3) sorting of all the $\overline{p}$ for a specific month *m* and year *y* in increasing order and calculating the cumulative distribution function $F(p, y, m, i)$ for each parameter and i^{th} day, as:

$$F(p,y,m,i) = \frac{J(i)}{n+1} \quad (2)$$

where *J(i)* is the rank order of the i^{th} day and *n* is the number of days for a specific month;

(4) calculation of the statistics by Finkelstein-Schafer for each month *m* and year *y* as:

$$F_S(p,y,m) = \sum_{i=1}^{n} \left| F(p,y,m,i) - \Phi(p,m,i) \right| \quad (3)$$

(5) sorting of the months for increasing values of F_S for each parameter, calculating the ranks for each month and parameter and summing them in order to calculate the total ranking;

(6) for each calendar month, among the first 3 candidate months with the lowest ranking sum, calculate the absolute deviation between the mean wind speed of the month *m* of the year *y* and the multi-year mean wind speed: the month with the lowest deviation can be chosen for a TRY_{EN}.

The final 8 hours of a month and the first 8 hours of the next month have to be smoothed by means of a cubic spline interpolation in order to avoid discontinuities. Since the adjustment involves night-time hours and wind speed is generally not corrected, it applies only to the dry bulb temperature and the relative humidity. The technical standard does not prescribe the use of different weights for the weather parameters but the user is free to adopt also a different set of variables.

2.2 Other approaches for the final selection of the reference months

As seen in the previous paragraph, according to the EN ISO 15927-4:2005 the final selection (i.e., step 6) is driven by the wind speed, which is considered a secondary parameter. The role of this variable in the reference year development has been criticized since the first works. Lund (1974), for instance, observed that, since the wind presents large local variability, a selection based on the wind speed or direction is unsuitable. Hall *et al.* (1978) suggested to develop typical wind years (TWY) separately. Marion and Urban (1995) remarked that both TMY and TMY2 are not suitable for the analysis of wind energy conversion systems and, even if wind speed is involved in the definition of the candidate months, its relative weight is small. In the definition of TMY2 and TMY3, the weights for the weather parameters describing the wind are also decreased with respect to TMY (Wilcox and Marion 2008). Moreover, Guan, Yang and Bell (2007) observed that the wind is weakly dependent on the dry bulb temperature with respect to the correlations between the other 3 meteorological variables. In the literature, different approaches can be found for the final selection but, among the most used, for instance, for the development of TMY and TMY2 (Hall *et al.* 1978), TMY3 (Wilcox and Marion 2008) and the one proposed by Pissimanis *et al.* (1988), no one involves the wind variables.

2.2.1 TMY and TMY2 method for the final month selection

Both TMY and TMY2 are based on the *persistence* approach by Hall *et al.* (1978). The starting multi-year weather data series have around 27 years for the TMY and 30 for the TMY2.The TMY considers 9 parameters for the identification part (i.e. minimum, mean and maximum daily dry bulb temperature, minimum, mean and maximum daily dew point, mean and maximum daily wind velocity and daily global horizontal radiation). In the TMY2 the weather quantities are 10 since the direct solar radiation has been added. In both approaches the weather variables have different relative importance in the selection process but the used weights are slightly different. Similarly to the EN ISO 15927-4:2005 method, the first part of the procedure is based on the Finkelstein-Schafer statistics but it leads to the calculation of a weighted index for each calendar month, which is used for listing the best 5 candidate years with the lowest values for the statistical index.

The 5 candidates are ranked with respect to their closeness to the long-term mean and median and the *persistence* of mean dry bulb temperature and daily global horizontal radiation are evaluated, by calculating:

- for the daily mean dry bulb temperature, the frequency and run length (i.e., number of consecutive days with averages above or under a given percentile) above the 67th percentile (i.e., the consecutive warm days) and below the 33rd percentile (i.e., the consecutive cool days) with respect to long term distribution;
- for the global horizontal radiation, the frequency and run length below the 33rd percentile (i.e., consecutive low radiation days) with respect to long term distribution.

The month with the longest run, the one with the highest number of runs and the one with zero runs are excluded. The highest ranked candidate month that meets the *persistence* criterion is selected.

2.2.2 TMY3 method for the final month selection

The TMY3 development follows the same approach of TMY and TMY2 for the first part of the procedure and the main changes are related to the second part. Since 15 instead of around 30 years have been used for TMY3 development, it has been observed that the *persistence* criterion is not always suitable for the final selection for shorter historic data series and in some cases none of the candidates complies with the prescriptions. Wilcox and Marion (2008) proposed some changes to the *persistence* criterion:

- a candidate is eliminated just if it has more runs than every other one;
- if all candidates for a given calendar month are excluded according to the modified *persistence* criterion, then the criterion is ignored and the final selection is based only on closeness to the long-term mean and median.

2.2.3 Method for the final month selection by Pissimanis et al.

Pissimanis *et al.* (1988) proposed a different final selection procedure based mainly on the solar radiation. This method has been adopted, often with some modifications, by a number of authors for the development of typical meteorological years (Argiriou *et al.* 1999; Bilbao *et al.* 2004; Gazela and Mathioulakis 2001; Janjai and Deeyai 2009; Kalogirou 2003; Petrakis, Lykoudis and Kassomenos 1996; Skeiker 2004; Zang, Xu and Bian 2012).

The procedure prescribes:

- the calculation of the root mean square differences (*RMSD*) between the hourly distributions of global horizontal radiation and the long term hourly distribution for each of the candidate months:

$$RMSD = \sqrt{\sum_{i=1}^{N} \frac{\left(p_i - \overline{p}_i\right)^2}{N}} \tag{4}$$

- a first criterion of selection based on the *RMSD*, which is, for example, the identification of all candidates with a *RMSD* lower than a given value or the selection of the minimum value;
- in case of more candidates for a calendar month, the selection is based on the minimum values of the Finkelstein-Schafer statistics of the horizontal global radiation and dry bulb temperature.

2.2.4 *Criterion of the minimum Finkelstein-Schafer statistic*

The approaches described in the previous paragraphs are marginally based on the statistics used in the first part of the development of the reference years: the Finkelstein-Schafer statistic is considered only in the final selection method by Pissimanis *et al.* (1988) but as secondary criterion. Some authors (Fagbenle 1995; Lee, Yoo and Levermore 2010; Yang, Lam and Liu 2007) used a simplified final step by selecting the candidate with the lowest value of weighted Finkelstein-Schafer statistics. In particular, commenting on the *persistence* approach, Yang, Lam and Liu (2007) underlined that "there was no evidence that it would necessarily produce useful information relating to building energy performance".

2.2.5 *Proposed criteria of the best rank and possible modifications to step 5*

Considering the methodology proposed by the technical standard EN ISO 15927-4:2005, which is not based on the calculation of an average Finkelstein-Schafer statistic, a criterion similar to the minimum F_S statistic (*Best rank I*) can be defined, prescribing the selection of the candidate with the best rank after step 5 and neglecting the comparison with the wind speed.

Studying the different methods based on the Finkelstein-Schafer statistics, it can be observed that the statistical significance of F_S values is not investigated. Ordering the candidates according to their F_S values for each weather parameter, it is supposed to reduce the chance of selection of a year with a statistically significant F_S value for a given month and particular weather variable (i.e., a candidate non-representative of the long-term series for a given weather variable in a specific calendar month) . This is not generally assured, especially when the historic series has a limited number of years: for instance, considering a temperature ranking with just the first candidate with a low and non-significant F_S value, if this candidate is not among the top ranks of the global ranking, a month non-representative for the dry bulb temperature can be selected. In the Finkelstein-Schafer test, like all statistical tests, the choice of a proper significance level α can depend on many aspects: a higher α value can easily lead to reject the *null hypothesis* (which is, in this context, that every candidate is a good approximation of the long term distribution for a given calendar month), accept the *alternative hypothesis* (e.g., there is at least one month which is not a good approximation of the long term distribution for a given calendar month) and thus to be more selective in the choice of the representative month, excluding a larger number of candidates. From the statistical point of view a high α value can lead to a type I error (*false positive error*) – the exclusion of a candidate which could be actually a representative month. From the operative point of view, by erasing many candidates it makes more difficult to build the global ranking and to perform the final choice because failing just a test for a single weather variable means to be erased from the list. Finkelstein and Schafer (1971) reported many critical values for F_S, according to the size of the sample and the most common significance level but they are not generally used for the reference year development, wasting the real potential of this statistics.

We propose some modifications to step 5 to fully exploit the significance of the F_S statistics of the different candidates in order to exclude those which are significantly non-representative for a weather parameter, in particular for the dry bulb temperature and the solar radiation because of their primary role in the energy need calculation. The relative humidity is less relevant in energy need calculation but in some models implemented in BES codes, it is considered for the elaboration of the external environment conditions, such as the diffuse component of the horizontal solar radiation (Reindl, Beckman and Duffie 1990) and the fictive sky temperature (Martin and Berdahl 1984). Taking into account the issues discussed before, we suggest a significant level of 1%. This means that the probability of making a false positive error is equal to 1%. The proposed procedure of this criterion (*Best rank II*) is the following:

(1) For each weather parameter (i.e., dry bulb temperature, solar radiation, relative humidity) the candidate months are ranked according to their F_S values for each calendar month like step 5 but only those with statistically non-significant F_S statistics are considered (i.e., only the candidates which are not identified as statistically different from the rest of the sample).

(2) For each calendar month the candidates which are shared by the three weather parameters are selected and used to build a global ranking.

(3) The candidate with the first position is selected to be the representative month.

If there are no candidates common to the three weather parameters, the priority is to find those common to the dry bulb temperature and the solar radiation rankings. In case of multiple candidates, their F_S values for the relative humidity – all of them clearly significant in this case, are analysed and the one with the minimum significant F_S is chosen. In this way, similarly to the approach of the "Danish" method (Lund and Eidorff 1981), a representative month for temperature and solar radiation is selected paying attention to have the best among the significant F_S for relative humidity. If there are no candidates in common for the dry bulb temperature and the solar radiation, we consider the complete rankings, including the candidates with the significant F_S value, and select the month with the minimum F_S values for both parameters.

2.3 The use of weighting coefficients for the weather parameters

Weighting coefficients for the weather parameters have been largely employed in the methodologies described in the literature and many considerations were done about the proper definition of them. The choice of the weights was often based on the expected influence of a given variable on the building energy needs or other applications (e.g., the evaluation of the outputs of photovoltaic or thermal solar systems). The introduction of weights for the different weather parameters implies that the typicality of certain weather statistics is sacrificed for the typicality in others and this is due to the fact that often “no month in the period of record adequately represents the long term in more than one or two statistics" (Freeman 1979). Some authors (Rahman and Dewsbury 2007) suggested to use the same weights for each weather parameter and to avoid weighting strategies if not necessary. However, many authors consider the use of weights important for the development of specific reference years according to the different applications, as observed by Yang and Lu (2004).

For what concerns the energy needs, a large importance has been attributed to the solar radiation, whose normalized weight is 0.5 according to Hall *et al.* (1978) and Marion and Urban (1995) - 0.25 to the global horizontal radiation and 0.25 to the direct normal radiation, and 0.4 according to Siurna, D’Andrea and Hollands (1984) and Thevenard and Brunger (2002) but not all researchers agree. As reported by Zhang, Huang and Lang (2002), the study by Matsuo *et al.* (1974) indicated that a weight of 0.5 for the solar radiation is too large for building energy analyses. The weights of the temperature statistics are generally very low if compared to the solar radiation ones, 0.17 and 0.2 in the TMY (Hall *et al.* 1978) and in the TMY2/TMY3 (Marion and Urban 1995; Wilcox and Marion 2008), with the exception of the CWEC (Siurna, D’Andrea and Hollands 1984) and the IWEC (Thevenard and Brunger 2002), where the same weight of the solar radiation (i.e., 0.4) is considered. Su *et al.* (2009) investigated the problem of optimizing the weights and observed that “the selection of these differing parameter weights is based largely on practical considerations rather than rigorous objective criteria”. Moreover, the optimum combination of weights for reference years for BES depends on the characteristics of the analysed building (Adelard *et al.* 2000; Hensen 1999; Kershaw, Eames and Coley 2010; Su *et al.* 2009) and the reference year should contain a variety of weather situations allowing the assessment of the energy performance of each building independently of its characteristics (Lund 1975). After an extensive analysis of 3600 combinations of weights for the locations of New York and Bejing, Su *et al.* (2009) observed that there are no relevant changes in the selection of the typical months and the variability of the chosen temperatures and solar radiation monthly values are less than 10%. This does not mean a good representativeness on the building energy perspective. As underlined in a previous work ([names deleted to maintain the integrity of the review process] under review), an uncertainty of 10% on BES annual energy results ascribable to the weather input has to be combined with all other uncertainties, consequently the representativeness of the simulated results can be poor. van der Bruggen (1977) observed that if the target is an accuracy within 5% with respect to a 10-year period, it is not possible to have a single reference year both for heating and cooling analyses and two separate reference years have to be developed. Similarly, Kalamees *et al.* (2012) observed that the relative importance of the weather parameters are different in winter, summer or in intermediate seasons and, even if they did not distinguished a reference year for heating and cooling needs analyses, they used different weighting coefficients in each season.

In each method, the weights are used for the calculation of a mean Finkelstein-Schafer statistics for each month, which is then used for the ranking and the selection of the representative ones. This step leads to the loss of the statistical significance and meaning of the index because a statistical multi-varied analysis is not simply the composition of analyses on single parameters or attributes, especially if there are cross correlations. In the literature, the weather parameters are analysed singularly and put together in a second step which is characterized, in addition, by an arbitrary choice of the relative importance of the different parameters. This approach of analysis is not strictly correct from a statistical point of view and introduces inaccuracy in the generated reference year, as observed by David *et al.* (2010). An exact and robust approach should take into account the different weather quantities – which are the attributes describing each candidate month, since the beginning for the elaboration of global statistical indexes and the evaluation of their significance. Alternatively, if it is not possible to determine a global statistical index, at least the statistics should not be weighed but used to develop rankings for the considered variables. The EN ISO 15927-4:2005 is consistent with this line of reasoning and the final ranking is built by considering the position of each candidate in the rankings of one single weather parameter. Just at this point, the user could choose to attribute a relative importance to the parameters involved and so influencing the composition of the global ranking.

However, even if we suggest a different use of the weighting coefficients, the choice of their values and combinations is still an unsolved issue and, together with the final selection criteria, it is the main focus of our research.

2.4 Approach of analysis

In this work we research how the EN ISO 15927-4:2005 could be improved by modifying the procedure to determine reference years, which allow representative building energy results, even with a limited number of available years in the historic data series. In order to pursue this goal, some changes to the last steps of the procedure are analysed and discussed. For each location, the developed reference years are used as weather files for simulating the annual energy needs – both heating and cooling, of the sample of 48 buildings developed in the previous parts ([names deleted to maintain the integrity of the review process] 2013; [names deleted to maintain the integrity of the review process] under review). The energy results of each building are compared to averages over the whole historic series calculated in the previous works ([names deleted to maintain the integrity of the review process] 2013; [names deleted to maintain the integrity of the review process] under review). The two approaches – change of the final selection procedure and introduction of weighting coefficients, are studied separately since they pursue distinct goals: while the first one is addressed to the development of a general purpose reference year, the second one is for the development of specific reference years for building heating or cooling needs analyses.

2.4.1 Localities and building configurations

In some previous works ([names deleted to maintain the integrity of the review process] 2013; [names deleted to maintain the integrity of the review process] under review), we analysed the raw weather data and focused on 5 localities in northern Italy: Aosta, Bergamo, Monza, Trento and Varese. The selection took into account the presence of errors and outliers in the dry bulb temperature, relative humidity, horizontal solar radiation and wind speed profiles of multi-year historic series, according to the criteria specified by Antonacci and Todeschini (2013), coherently with the WMO suggestions (2008). The found outliers and errors were corrected by interpolation as in Prada (2012). The technical standard procedure was applied and the months reported in (Table 1) were selected in the reference years.

Both multi-year and reference year weather data profiles were used to evaluate the energy performance, in terms of annual heating and cooling energy needs, of the sample of buildings developed in ([names deleted to maintain the integrity of the review process] under review). The set of reference buildings is characterized by different insulation levels, thermal inertia, sizes and orientations of windows and kind of glazing and it presents both configurations expected to have higher heating demands (e.g., the poorly insulated buildings) and configurations with higher cooling energy demand (e.g., buildings with windows with high solar heat gain coefficient). It has been specifically adopted since sets of reference buildings have not yet identified for the selected locations.

As a whole, 48 different simplified thermal zones were developed, modifying a base model according to a full factorial plan. The base case consisted of a single, square thermal zone with an area of 100 m^2 and a height of 3 m with the façades facing the main cardinal directions. Thermal bridges were neglected and the floor was modelled with a crawl space (i.e., without sun exposition and infrared thermal losses towards the sky dome). All opaque components were modelled as a two-layer structure with insulation on the external side and a massive layer (timber or concrete) with a thermal resistance around 0.8 m^2 K W^{-1}. The solar absorptance was 0.3 for both sides of the vertical walls and for the internal side of the roof, 0.6 for the external side of the roof and the internal side of the floor and 0 for the external side of the floor. The thermal properties of the considered materials are reported in (Table 2).

The windows, positioned all on the same façade, consisted of a double-pane glazing (U_{gl} = 1.1 W m^{-2} K^{-1}) with a timber frame (U_{fr} = 1.2 W m^{-2} K^{-1}) whose area was 20% of the whole window area. The internal gains were assumed equal to 4 W m^{-2}, half radiative and half convective, as indicated by the EN ISO 13790:2008 (European Committee for Standardization 2008) for residential dwellings. An average constant ventilation rate of 0.3 ACH was considered, as suggested by the Italian technical specification UNI/TS 11300-1:2008 (Ente Nazionale Italiano di Normazione 2008). The variables analysed in the factorial plan are reported in (Table 3): with the only exception of the window orientation, each one presents a high and a low level. As seen in the sensitivity analyses ([names deleted to maintain the integrity of the review process] under review), these envelope characteristics have the most relevant effects on the building envelope performance.

The different configurations were simulated by means of TRNSYS, considering the following assumptions:

- an hourly time-step, such as the discretization of the weather data;
- constant convection coefficients, in accordance with the standard EN ISO 6946:2007 (European Committee for Standardization 2007);
- the TRNSYS star network approach for internal long wave radiation exchanges;
- heating and cooling setpoints respectively of 20 °C and 26 °C, in accordance with the UNI/TS 11300-1:2008 prescriptions for residential buildings, but applied all year long without specifying heating and cooling seasons.

2.4.2 Final selection modifications to the EN ISO 15927-4:2005 procedure

The methods described in paragraphs 2.2.1 - 2.2.4 and those proposed in 2.2.5 are implemented in place of the original final selection part of the technical standard in order to find the one able to provide the best results in terms of representativeness of annual heating and cooling energy needs.

2.4.3 Introduction of weights to the EN ISO 15927-4:2005 procedure

In this part, the effects of the introduction of weighting coefficients in the EN ISO 15927-4:2005 procedure is considered and the optimum combinations for each location identified, distinguishing those optimizing the annual heating needs and those optimizing the annual cooling needs. Differently from the prevalent approach in the literature, we consider weights not for the calculation of average F_S indexes but for the determination of the global ranking and, thus, we weigh the ranks of the single weather variables and not the Finkelstein-Schafer statistics. We consider normalized weights for the three primary weather parameters indicated by the technical standard (i.e., dry bulb temperature, relative humidity, global horizontal radiation) with a discretization step of 0.1, giving a total of 66 possible combinations.

According to the literature, it is expected that each building configuration has its best combination of weights. The research of the optimum solutions is pursued analysing separately heating and cooling annual energy needs. Thus, we identify the weights minimizing the sum of the deviations between the reference year results and the averages of the multi-year annual heating needs and the ones minimizing the deviations for the annual cooling needs. The chosen objective function considers differently the absolute deviations of each building case according to its long term average annual energy need:

$$O.F. = \frac{\sum_{i=1}^{48} \left| Q_i - \overline{Q}_i \right| \cdot \overline{Q}_i}{\sum_{i=1}^{48} \overline{Q}_i} \qquad (5)$$

This specific objective function allows to select among the most representative candidates for each calendar month those which give annual energy needs as close as possible to the multi-year averages. Like all approaches based on the weighting coefficients, it does not mean that every month has the best possible month in the data series. Moreover, since the aim is to optimize the heating needs (with the $TRY_{EN,\,H}$) or the cooling needs (with the $TRY_{EN,\,C}$), it follows that the months with higher heating demand for the first ones and those with higher cooling demand for the second ones have a larger impact on the optimum weights. Thus, for the chosen objective function their representativeness is more important than the other months. Finally, the optimum weighting coefficients are closely related to the final selection criterion to a certain extent, therefore, the combination of weights that is supposed to be the most relevant from the physical perspective is not necessary the best one.

Considering all these aspects, the adoption of weights for the different weather parameters addresses to a specific use of the developed reference years and this is clearly strengthened by the choice of their optimization as a function of the annual heating (for the $TRY_{EN, H}$) or cooling energy needs (for the $TRY_{EN, C}$).

2.4.3.1 Correlation between objective function, sample of buildings and optimum combination of weights

The proposed objective function weighs differently the contributions of the buildings in the sample. For each case the deviation between the reference year annual energy need and the multi-year average is multiplied by the multi-year average. Thus, the configurations with larger energy needs assume larger importance. In order to study the effects of objective function and sample of buildings and the representativeness of those buildings with lower energy needs, the proposed method is applied to subsamples of the whole sample of 48 buildings.

In the previous works ([names deleted to maintain the integrity of the review process] 2013; [names deleted to maintain the integrity of the review process] under review), sensitivity analyses allow us to underline that the average thermal transmittance of the dispersing opaque components is the envelope characteristic more correlated with the annual variability of the heating energy needs while the glazings *SHGC*, and with a lower magnitude, their area to the annual variability of the cooling energy needs. These variables are used to divide the whole sample into subsamples:

- for the heating need analysis, the whole sample is split into two subsamples according to the insulation level of the opaque envelope (H_1: cases with high insulation and H_2: cases with low insulation);

- for the cooling need analysis, two subsamples are identified according to glazings *SHGC* (C_1: cases with low *SHGC* and C_2: cases with high *SHGC*).

H_1 and C_1 include the building configurations with lower annual energy needs while H_2 and C_2 the ones with higher energy demands, respectively for heating and cooling. For each subsample $TRY_{EN, H}$ and $TRY_{EN, C}$ are built and used in TRNSYS simulations.

2.4.3.2 Role of the historic weather data series on the optimum combination of weights

In the proposed criterion for the final selection in paragraph 2.2.5, *Best rank II*, the statistical properties of the historic weather data series are discussed: For each candidate, the role of each weather variable in the selection of the reference month is taken into account by means of the statistical significance of the Finkelstein-Schafer statistic. In order to study the effects of the statistical properties of the historic weather data series also on the modified EN ISO 15927-4:2005 method with weighting coefficients, we implement this method changing the composition of the starting multi-year series. Each series is considered and one or more years are randomly eliminated in order to develop new shorter series, as reported in (Table 4). The minimum number of years is fixed to 5.

The multi-year annual energy need averages are recalculated for each building and used also as benchmark for the assessment of the reference year representativeness.

3 Results

3.1 Final selection modifications to the EN ISO 15927-4:2005 procedure

The results of the different tested approaches for the final selection of the reference months are reported in this paragraph. (Table 5) shows the comparison in term of correspondences of the selected reference months with respect to the EN ISO 15927-

4:2005. As it can be observed, the best rank criteria are closer to the technical standard selection. Confirming what already observed in the literature, the Hall *et al.* method does not allow the selection for one or more calendar months in all analysed locations. For this reason, this method has been excluded from the following energy comparisons.

The effects of the selection procedure on the estimation of the energy needs have been compared by using two different indexes: the trend deviations and the standard deviations of the sample buildings with respect to the trend line (Table 6). The trend deviation represents the percentage difference between the average annual energy needs over the multi-year period and the TRY_{EN} results. A negative value means an underestimation while a positive one an overestimation of the energy needs given by the use of the reference year. In addition, the standard deviation gives information about the spread of the results around the trend line; keeping the perspective of the effect on building energy ratings of the previous work ([names deleted to maintain the integrity of the review process] under review), the standard deviations are expressed in kilowatt per hour per square meter. A good representativeness is underlined by small absolute trend deviations and standard deviations. Moreover, a significant improvement can be registered if there are smaller deviations for both heating and cooling annual energy needs. In order to analyse more easily the trend deviations, they are also reported in (Figure 1).

3.2 Introduction of weights to the EN ISO 15927-4:2005 procedure

The comparison between the different annual heating and cooling energy needs of the sample of buildings simulated with the 66 different TRY_{EN} and the long term averages are represented in (Figure 2). The optimum combinations of weights for $TRY_{EN, H}$ for heating need calculation and the ones for $TRY_{EN, C}$ for cooling need calculation are reported for each location in (Table 7) and the respective annual energy needs are highlighted with dots in (Figure 2). The trend deviations with respect to the annual mean energy needs and the standard deviations with respect to the trend line are reported in (Table 8). The trend deviations of the original EN ISO 15927-4:2005 procedure are drawn also in (Figure 2) by means of red dotted lines.

3.2.1 Correlation between objective function, sample of buildings and optimum combination of weights

The optimum combinations of weights are reported for each subsample in (Table 9). The trend deviations found when single reference years are used and those calculated when specific reference years are developed for each subsample are showed and compared to those of the whole sample in (Figure 3).

3.2.2 Role of the historic weather data series on the optimum combination of weights

The optimum combinations of weights, both for heating and for cooling calculations, are reported in (Table 10). In (Figure 4) the trend deviations of the annual energy needs simulated with the TRY_{EN} determined according to the EN ISO 15927-4:2005 and those simulated with the reference years with weighting coefficients, $TRY_{EN,\,H}$ and $TRY_{EN,\,C}$, are compared.

4. Discussion

4.1 Final selection modifications to the EN ISO 15927-4:2005 procedure

The analysis of the final selection criteria allows to confirm some aspects already observed in the literature, such as that, with a limited number of years in the historic series, the algorithm adopted in the development of TMY and TMY2 can lead to reject all candidates. As regards the standard deviations, the values are within 1 kWh

m^{-2} yr^{-1} for most of the localities and the methods and, thus, the main element of comparison among the different approaches consists of the trend deviations.

Improvements in both trend and the standard deviations for annual heating and cooling energy needs are registered for 4 locations with the *best rank II* approach, 3 locations with the minimum F_S value, just one location according to the procedure by Wilcox and Marion and the *best rank I* approach and no one with Pissimanis *et al.* method. Considering separately heating and cooling needs:

- for the heating needs, the best approaches are still the *best rank II* and the minimum F_S (improvements for 5 and 4 localities, respectively), followed by Wilcox and Marion's method and the *best rank I* (for 2 localities);
- for the cooling needs, the best approaches are the minimum F_S and both best rank methods (improvements for 3 localities), followed by Wilcox and Marion's method (for 2 localities).

As it can be seen in (Table 6) and (Figure 1), the best improvements are achieved for the heating energy needs. The most efficient algorithm is the *best rank II* method but also the minimum Finkelstein-Schafer statistics and the *best rank I* approaches give good performance. For the considered cases and localities, Pissimanis *et al.* method gives the worst results, confirming that a selection mainly based on the solar radiation can be suitable for the development of reference years for solar system analyses but not for BES.

4.2 Introduction of weights to the EN ISO 15927-4:2005 procedure

Considering the 66 combinations of weights, we can distinguish three main possible categories for the examined locations:

a) Changing weights is unimportant, since for more than 70% of combinations the selected candidate is the same, like June in Trento (Figure 5a);
b) Changing weights allows the identification of two main possible candidates, like July in Trento (Figure 5b);
c) Changing weights is highly effective since there are at least three possible selections, depending on the chosen weights, like October in Trento (Figure 5c).

The higher is the number of months characterized by an important role of the weights, the larger the relevance of their choice on the final selection. For Aosta 9 months belong to category *a* while for the other localities the relative majority is in category *c* (5 for Bergamo, 6 for Monza and Varese and 7 for Trento).

Looking at (Figure 2), it is possible to analyse the effects of the combinations of weights on the agreement between the annual energy needs simulated with the reference year and the average of the long term simulations. As regards the heating needs, all TRY_{EN} weather files give results within 10% with respect to the multi-year values. For Aosta, Bergamo and Trento the deviations are more limited and for Varese most of the developed reference years lead to underestimations of the annual heating needs. For what concerns the cooling needs, for Aosta, Bergamo and Trento the results are well under 10% of deviation while for Monza and Varese there are many reference years which lead to larger overestimation or underestimation with respect to the long term averages. In particular, in Monza many combinations of weights lead to underestimation while, in Varese, to overestimation. In comparison to the heating needs, the cooling ones have a larger variability among the different building cases. The analysis on weighting coefficients shows that the behaviour is not the same for all locations and it depends also on the property of the historic series of weather data. Moreover, both the deviations and their trends are correlated to the characteristics of the considered buildings.

Analysing the optimum combinations of weights of (Table 7), many remarks can be drawn. The weights for the development of the TRY_{EN} for heating needs and those for the cooling needs are different for all localities. This strengthens the hypothesis that the development of two different reference years for BES is needed, at least when the available historic series are short. Secondly, the weights change from one locality to another and, in particular, they can be very different. The best reference years for heating needs $TRY_{EN, H}$ have small weights (i.e., 0.1 or 0.2) for the solar radiation for Aosta, Bergamo and Monza while for Trento and Varese the weighting coefficients are very high (i.e., 0.7 and 0.8). Furthermore, for these last two localities, the weight of the temperature is very low, being 0.2 for Trento and even 0 for Varese, which means that the temperature ranking has no role in the final steps. Looking for other combinations of weights giving annual heating needs close to multi-year averages for Varese, we can find (0.0, 0.9, 0.1), (0.0, 1.0, 0.0), (0.1, 0.9, 0.0), (0.2, 0.8, 0.0), where the first weight is for the temperature, the second for the solar radiation and the last for the relative humidity. In all cases the solar radiation has a high relative importance. For Trento, instead, the sub-optimal combinations have temperature weights from 0.4 to 0.6. The best reference years for cooling needs $TRY_{EN, C}$ have weights of 0.6 for the solar radiation for Bergamo, Trento and Varese, 0.4 for Aosta and null for Monza. For this last locality, the other sub-optimal combinations making results close to the best one, for instance (0.4, 0.4, 0.2), (0.4, 0.1, 0.5), (0.4, 0.6, 0.0), are dominated by the dry bulb temperature, which is always 0.4. For Aosta and Varese, the $TRY_{EN, C}$ are calculated by attributing a null weight to the temperature. In Aosta the second best option is (0.1, 0.3, 0.6) but the next ones have high weights for the dry bulb temperature and null or almost null weight for the solar radiation. In Varese the 10 combinations of weights giving the best cooling need agreement with the long term averages are characterized by a low weight for the temperature and weights from 0.4 to 0.6 for the solar radiation. As a whole, a general trend common to the five locations cannot be identified. Moreover, it should be remembered that the reference years giving the best correspondences with the long-term averages are not necessary composed only by the best months but they could have also different sub-optimal months whose summed energy demands are closer to the long term annual ones. In addition to that and to the remarks of paragraph 2.4.3, coherently with what observed in (Figure 2), the optimum combinations are also strongly influenced by the statistical properties of the weather data collected in the historic series and the statistical properties of the whole series.

Analysing the results of (Table 8), we can see that there are significant improvements with respect to the EN ISO 15927-4:2005 procedure without weights, both for the trend and for the standard deviations. As regards the heating energy needs for all locations the trend deviations are within 0.5% while for the cooling energy needs they are within 1% with the exception of Trento, whose value is +1.33%. Considering the standard deviations, they are generally less or close to 0.5 kWh m^{-2} yr^{-1}.

Even if generalizable rules for the attribution of the weights to the weather variables have not been found, we tried to look for the best solutions considering all localities together. Similarly to the approach for making the global ranking in the last steps of the technical standard, we ranked the weights for each city and developed a global rank for the heating needs and another for the cooling ones. The best combination of weights for the heating needs is (1.0, 0.0, 0.0) while the one for the cooling needs is (0.3, 0.3, 0.4). It is interesting to notice that for the heating needs, the best ranks are occupied by combinations which give high importance to the dry bulb temperature while for the cooling needs there is not a clear trend. The results are reported in (Table 11), as well as the original EN ISO 15927-4:2005 ones. As a whole, the results for the heating needs are generally improved: the trend deviations are slightly larger just for Aosta and Varese and the standard deviations for Aosta, Trento and Varese. Considering the cooling needs, since the weights are almost equal, there are no large differences from the original procedure: some improvements are for Aosta, Bergamo and Trento and worsening for Monza and Varese. While for the cooling needs no general behaviour can be found, some improvements can be achieved with respect to the original method for the heating needs by giving higher importance to the dry bulb temperature.

4.2.1 Correlation between objective function, sample of buildings and optimum combination of weights

For the subsamples with higher energy demands, the weights are the same as those of the whole sample, as it can be noticed in (Table 9). As expected, this is a consequence of the chosen objective function, which weighs the absolute deviation by the multi-year average energy need for each building configuration in order to minimize the sum of the absolute deviations. Other objective functions, e.g., aimed at minimizing the average relative deviations, could lead to different optimum combinations of weights, both for the whole set and for the subsamples.

As it can be seen in (Figure 3), the use of reference years for each subsample leads to improvements for the subsets characterized by lower annual energy needs (H_1 and C_1) but the effects on the whole sample are limited. Nevertheless, these results underline the applicability of the methodology by basing on different samples of buildings, encouraging the definition of set of reference buildings to be used for each locality.

4.2.2 Role of the historic weather data series on the optimum combination of weights

In (Table 10) it can be noticed that changing the number and the years in the historic weather series, also the optimum combinations change but in different ways for the 5 locations. There are no clear correlations between the lengths of the multi-year series and the optimum weighting coefficients and this means that the composition of the series is more influencing of the included number of years.

The introduction of weights led to significant improvement in the agreement between the annual energy needs calculated with a reference year and the averages of the corresponding multi-year series, as seen in (Figure 4). Furthermore, the reduction of the length of the historic series does not imply an increase of the trend deviations but just the possibility of having larger values, depending on the statistical properties of the series – and so on the years included, both for the standard and the modified TRY_{EN} development method.

5 Conclusions

In this work we analysed the main issues of the procedure described by the European technical standard EN ISO 15927-4:2005 and proposed some changes in order to improve the representativeness of BES results when reference years are developed according this standard method, especially starting from a limited number of years of collected weather data. We observed that:

(1) As regards the final selection criteria, some findings already described in the literature are confirmed, as for instance that the *persistence* method described in the procedures for the development of TMY and TMY2 weather files is inapplicable for short historic series of weather data. Considering the approaches most frequently implemented in the literature by those methods based on the

Finkelstein-Schafer statistic, the one giving the best performances for both annual heating and cooling energy needs, prescribes the selection of the candidates with the minimum F_S average value.

(2) Drawing on the final selection method based on the minimum F_S value and considering that the EN ISO 15927-4:2005 does not prescribe the calculation of average Finkelstein-Schafer statistics, as well as different criticisms in the literature about averaging a statistical index and on the actual importance of the wind speed in the identification of the best candidates, we proposed two additional final selection steps. The first one (*Best rank I*) simply considers as reference month the one with the best rank in the global ranking while the second one (*Best rank II*) introduces also some criteria regarding the definition of the global ranking based on the statistical significance of F_S values for each variable. Both proposed methods give better results with respect to the original standard solution. In particular, *Best rank II* brings to trend deviations within 2% for the annual heating needs and within 5% for the annual cooling needs compared to the long term energy results.

(3) Differently from the modifications to the final selection steps, which leave the development of reference years independent of their application (general purpose reference years), we investigated the introduction of weights for the improvement of the representativeness of BES results. Since this means that the generated reference year is tailored for a specific use, we distinguished the TRY_{EN} for heating need analyses from the TRY_{EN} for cooling need studies. The weighting coefficients have not been used for the calculation of an average statistical index but for the definition of the global ranking attributing a different weight to the rankings of the different weather parameters. It has not been

possible to identify a common combination of weights for the 5 considered localities, suggesting that the optimum is a function of the properties of each historic weather data series, the climatic characteristics of the locality, the sample of buildings and the methodology followed for the typical month selection. In particular, further developments of this study should consider different sample of buildings (or the definition of a suitable one), which are representative for each specific location.

(4) As a whole, the separate reference years for heating and cooling need give good performance in terms of representativeness of the energy results with respect to the long term averages and they are better than those obtained with the non-weighting approaches. The $TRY_{EN, H}$ bring to trend deviations lower than 0.5% while the $TRY_{EN, C}$ have trend deviations within 1% for all localities with the exception of Trento (whose trend error is +1.33%). The proposed procedure has been implemented also for subsamples of the whole set of buildings considered in this work and for shorter historic weather data series: in both assessments the modified EN ISO 15927-4:2005 procedure with weighting coefficients gave better results than the standard one. Moreover, the proposed methods resulted applicable independently of the number of years and the chosen sample of buildings. Further developments of this study are likely to consider the performance of these weather files, specifically optimized for the energy calculations, on different outputs of interest in BES, such as the indoor thermal-hygrometric comfort for the occupants, in order to evaluate also different objective functions.

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Nomenclature

Symbols

α	statistical significance level (-)
θ	temperature (K)
κ	areal heat capacitance of an envelope component (kJ m^{-2} K^{-1})
λ	thermal conductivity (W m^{-1} K^{-1})
ρ	density (kg m^{-3})
σ	standard deviation with respect to the trend line (kWh m^{-2} yr^{-1})
Φ	cumulative distribution function of variable daily means within the whole historical series of the calendar months (-)
A	surface (m^2)
c	specific heat (J kg^{-1} K^{-1})
F	cumulative distribution function of variable daily means within the whole days of the calendar month of a specific year (-)
F_S	Finkelstein-Schafer statistics (-)
I	solar irradiance (W m^{-2})
J	rank order of variable daily means within the month of a specific year (-)
K	rank order of variable daily means for a calendar month within all the years of the series (-)
m	specific calendar month analysed in the TRY_{EN} calculation procedure (-)
N	total number of days for a specific calendar month within the whole historic series (-)
n	number of days for a specific calendar month (-)
$O.F.$	objective function (-)
p	weather variable used in the TRY_{EN} calculation procedure (-)
Q	annual energy need (GJ)
R	thermal resistance (m^2 K W^{-1})
RH	relative humidity (%)
s	thickness (m)
$SHGC$	solar heat gain coefficient (-)
TRY	test reference year (-)
U	thermal transmittance (W m^{-2} K^{-1})
y	select year of the historical series (-)

Subscripts

C	cooling
EN	calculation procedure of European standard 15927-4
fr	referred to window frame
gl	referred to window glazing plane
H	heating
i	internal surface of the envelope

win referred to window area

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Table 1. Selected months for the TRY_{EN}.

	Aosta	**Bergamo**	**Monza**	**Trento**	**Varese**
Number of years in the sample	8	10	9	10	9
Years	2000-2005; 2007-2008	1998-2005; 2007-2008	1999-2007	1996-1998; 2002-2008	1997-2000; 2003; 2005-2008
January	2001	2004	2003	1998	2003
February	2005	2008	2002	1996	2000
March	2000	2005	2007	2004	2007
April	2000	2004	2002	2004	2006
May	2001	2004	2004	2006	2007
June	2001	2004	2005	2004	1998
July	2002	2004	2005	2004	1997
August	2002	2004	2007	2005	1998
September	2004	2003	2004	2008	2006
October	2003	2003	2000	2005	1999
November	2000	2004	2004	2005	1997
December	2004	1999	2004	2008	2008

Table 2. Materials thermal properties.

Property	**Timber**	**Concrete**	**Insulation**
Thermal conductivity λ [W m^{-1} K^{-1}]	0.13	0.37	0.04
Specific heat capacity c [J kg^{-1} K^{-1}]	1880	840	1470
Density ρ [kg m^{-3}]	399	1190	40
Thickness s [m]	0.10	0.30	0.05/0.15
Thermal resistance R [m^2 K W^{-1}]	0.77	0.81	1.25/3.75

Table 3. Variables of the full factorial plan.

Variable	Description of the alternatives
Insulation of the opaque envelope	a. 5 cm of polystyrene - $U = 0.45$ W m^{-2} K^{-1} b. 15 cm of polystyrene - $U = 0.21$ W m^{-2} K^{-1}
Thermal inertia of the opaque envelope	a. timber structure - $\kappa_i =$ 75 kJ m^{-2} K^{-1} b. concrete structure - $\kappa_i =$ 300 kJ m^{-2} K^{-1}
Solar heat gain coefficient of the glazing	a. $SHGC = 0.35$ b. $SHGC = 0.61$
Size of the windows	a. $A_{win} = 14.56$ m^2 b. $A_{win} = 29.12$ m^2
Orientation of the windows	a. East b. South c. West

Table 4. New samples of historic weather data series.

Number of years	Aosta	Bergamo	Monza	Trento	Varese
10	n.a.	1998-2005, 2007, 2008	n.a.	1996-1998, 2002-2008	n.a.
9	n.a.	1998-2002, 2004, 2005, 2007, 2008	1999-2007	1996, 1997, 2002-2008	1997-2000, 2003, 2005-2008
8	2000-2005, 2007, 2008	1998, 2000-2003, 2005, 2007, 2008	1999-2004, 2006, 2007	1996, 1997, 2002, 2004-2008	1998-2000, 2003, 2005-2008
7	2000-2005, 2007	1998, 1999, 2001, 2002, 2005, 2007, 2008	2000-2003, 2005-2007	1996, 1997, 2002-2006	1997, 1998, 2000, 2005-2008
6	2000, 2001, 2003, 2004, 2007, 2008	1998, 1999, 2001, 2002, 2004, 2008	1999, 2000, 2003, 2004, 2006, 2007	1996-1997, 2002, 2003, 2007, 2008	1997, 1999, 2000, 2003, 2005, 2006
5	2000, 2003-2005, 2007	2000, 2001, 2005, 2007, 2008	2000, 2001, 2004, 2005, 2007	1997, 2003-2006	1997, 1998, 2000, 2005, 2006

Table 5. Correspondences in the chosen months according to the different approaches with respect to the original EN ISO 15927-4:2005 procedure.

		Aosta	**Bergamo**	**Monza**	**Trento**	**Varese**
Hall *et al.*	Same choices	4	2	3	2	2
	No one selected	*1*	*2*	*3*	*2*	*1*
Wilcox - Marion		5	0	5	1	3
Pissimanis *et al.*		1	1	0	2	1
Minimum F_S		1	2	4	2	3
Best rank I		6	4	5	2	3
Best rank II		3	3	5	2	3

Table 6. Trend and standard deviations with respect to the trend line. In bold those cases with an improvement with respect to the EN ISO 15927-4:2005.

Location	Final selection method	Heating needs		Cooling needs	
		Trend deviation	***σ*** [kWh m^{-2} yr^{-1}]	**Trend deviation**	***σ*** [kWh m^{-2} yr^{-1}]
Aosta	*EN ISO 15927-4*	*1.64%*	*0.67*	*-5.35%*	*0.76*
	Wilcox – Marion	**-1.31%**	**0.60**	-9.63%	1.16
	Pissimanis *et al.*	4.18%	0.89	6.09%	0.89
	Minimum F_S	**-1.07%**	**0.46**	-5.68%	0.68
	Best rank I	2.04%	0.95	**-2.99%**	**0.53**
	Best rank II	**-1.58%**	**0.63**	**-3.74%**	**0.46**
Bergamo	*EN ISO 15927-4*	*7.21%*	*1.25*	*-4.39%*	*0.98*
	Wilcox – Marion	-8.22%	1.15	7.17%	0.69
	Pissimanis *et al.*	**-1.64%**	**0.51**	5.25%	0.43
	Minimum F_S	**-0.72%**	**0.30**	**-3.27%**	**0.54**
	Best rank I	**1.55%**	**0.44**	-7.55%	0.63
	Best rank II	**-1.09%**	**0.39**	-4.98%	0.81
Monza	*EN ISO 15927-4*	*-3.95%*	*0.48*	*-7.37%*	*0.67*
	Wilcox - Marion	**-0.02%**	**0.15**	**2.46%**	**0.30**
	Pissimanis *et al.*	11.53%	1.59	16.30%	0.82
	Minimum F_S	**3.25%**	**0.46**	**2.97%**	**0.35**
	Best rank I	-8.23%	1.27	**1.74%**	**0.29**
	Best rank II	**0.70%**	**0.33**	**3.51%**	**0.39**
Trento	*EN ISO 15927-4*	*4.28%*	*0.88*	*-10.71%*	*1.02*
	Wilcox – Marion	-9.26%	1.38	**1.79%**	**0.56**
	Pissimanis *et al.*	3.09%	1.50	-13.10%	1.15
	Minimum F_S	**-3.11%**	**0.60**	**0.04%**	**0.33**
	Best rank I	**0.52%**	**0.34**	**7.09%**	**0.87**
	Best rank II	**0.79%**	**0.32**	**-1.24%**	**0.44**
Varese	*EN ISO 15927-4*	*-1.91%*	*0.69*	*3.75%*	*0.64*
	Wilcox – Marion	-3.20%	0.58	11.32%	1.00
	Pissimanis *et al.*	2.03%	0.98	-3.78%	0.61
	Minimum F_S	-2.54%	0.80	9.43%	0.97
	Best rank I	-2.87%	0.52	3.61%	0.68
	Best rank II	**-0.13%**	**0.34**	3.55%	0.66

Table 7. Optimum weights for the TRY_{EN} for heating need calculation and those for the TRY_{EN} for cooling need calculation.

Location	**Heating needs**			**Cooling needs**		
	θ	***I***	***RH***	***θ***	***I***	***RH***
Aosta	0.4	0.1	0.5	0.0	0.4	0.6
Bergamo	0.5	0.1	0.4	0.1	0.6	0.3
Monza	0.6	0.2	0.2	0.4	0.0	0.6
Trento	0.2	0.7	0.1	0.4	0.6	0.0
Varese	0.0	0.8	0.2	0.0	0.6	0.4

Table 8. Trend and standard deviations with respect to the trend line: comparison between the original method and the one modified by introducing optimum weighting coefficients.

Location	Heating needs				Cooling needs			
	Original method		Modified method		Original method		Modified method	
	Trend deviation	***σ*** [kWh m^{-2} yr^{-1}]	**Trend deviation**	***σ*** [kWh m^{-2} yr^{-1}]	**Trend deviation**	***σ*** [kWh m^{-2} yr^{-1}]	**Trend deviation**	***σ*** [kWh m^{-2} yr^{-1}]
Aosta	1.64%	0.67	0.22%	0.52	-5.35%	0.76	-0.02%	0.53
Bergamo	7.21%	1.25	0.27%	0.26	-4.39%	0.98	-0.65%	0.54
Monza	-3.95%	0.48	-0.13%	0.25	-7.37%	0.67	-0.95%	0.33
Trento	4.28%	0.88	-0.45%	0.47	-10.71%	1.02	1.33%	0.44
Varese	-1.91%	0.69	0.07%	0.22	3.75%	0.64	-0.50%	0.40

Table 9. Optimum combinations of weights of the sub-samples compared to those of the whole sample for the reference years for heating need calculation (on the top) and for cooling need calculation (on the bottom).

	$TRY_{EN, H}$								
Location	**Sample H_1**			**Sample H_2**			**Whole sample**		
	θ	***I***	***RH***	***θ***	***I***	***RH***	***θ***	***I***	***RH***
Aosta	0.3	0.3	0.4	0.4	0.1	0.5	0.4	0.1	0.5
Bergamo	0.5	0.4	0.1	0.5	0.1	0.4	0.5	0.1	0.4
Monza	0.0	0.5	0.5	0.6	0.2	0.2	0.6	0.2	0.2
Trento	0.6	0.2	0.2	0.2	0.7	0.1	0.2	0.7	0.1
Varese	0.0	0.8	0.2	0.0	0.8	0.2	0.0	0.8	0.2
	$TRY_{EN, C}$								
Location	**Sample C_1**			**Sample C_2**			**Whole sample**		
	θ	***I***	***RH***	***θ***	***I***	***RH***	***θ***	***I***	***RH***
Aosta	0.0	0.4	0.6	0.0	0.4	0.6	0.0	0.4	0.6
Bergamo	0.3	0.0	0.7	0.1	0.6	0.3	0.1	0.6	0.3
Monza	0.4	0.4	0.2	0.4	0.0	0.6	0.4	0.0	0.6
Trento	0.4	0.2	0.4	0.4	0.6	0.0	0.4	0.6	0.0
Varese	0.4	0.4	0.2	0.0	0.6	0.4	0.0	0.6	0.4

Table 10. Optimum weighting coefficients for the new samples of historic weather data series: the first coefficient is related to the dry bulb temperature, the second to the solar irradiance and the last one to the relative humidity. The combinations on the top of each cell are for the calculation of $TRY_{EN, H}$ – optimized for the heating need calculation, while those on the bottom are for the calculation of $TRY_{EN, C}$ – optimized for the heating need calculation.

Number of years	**Aosta**	**Bergamo**	**Monza**	**Trento**	**Varese**
10	n.a.	(0.5, 0.1, 0.4) (0.1, 0.6, 0.3)	n.a.	(0.2, 0.7, 0.1) (0.4, 0.6, 0)	n.a.
9	n.a.	(0.5, 0, 0.5) (0, 0.7, 0.3)	(0.6, 0.2, 0.2) (0.4, 0, 0.6)	(0, 0.5, 0.5) (0, 0.5, 0.5)	(0, 0.8, 0.2) (0, 0.6, 0.4)
8	(0.4, 0.1, 0.5) (0, 0.4, 0.6)	(0, 0.8, 0.2) (0.4, 0.2, 0.4)	(0, 0.4, 0.6) (0.8, 0.1, 0.1)	(0.5, 0.3, 0.2) (0.5, 0.5, 0)	(0.6, 0.1, 0.3) (0.5, 0.1, 0.4)
7	(0.8, 0, 0.2) (0.8, 0, 0.2)	(0.5, 0.3, 0.2) (0, 0.7, 0.3)	(0.5, 0.1, 0.4) (0.3, 0.2, 0.5)	(0.3, 0.7, 0) (0.3, 0.7, 0)	(0.4, 0.6, 0) (0.3, 0.6, 0.1)
6	(0.4, 0, 0.6) (0.4, 0.1, 0.5)	(0.5, 0.3, 0.2) (0.4, 0.5, 0.1)	(0.3, 0, 0.7) (0.7, 0.2, 0.1)	(0.5, 0.4, 0.1) (0.7, 0.2, 0.1)	(0, 0.5, 0.5) (0, 0, 1)
5	(0, 0.4, 0.6) (0.4, 0.4, 0.2)	(0.2, 0.4, 0.4) (0.5, 0.2, 0.3)	(0.4, 0, 0.6) (0.4, 0, 0.6)	(0.6, 0.2, 0.2) (0, 0.5, 0.5)	(0, 0.6, 0.4) (0.6, 0, 0.4)

Table 11. Trend and standard deviations with respect to the trend line: comparison between the original method and the one modified by introducing weighting coefficients: (1, 0, 0) for the heating need calculation and (0.3, 0.3, 0.4) for the cooling need calculation.

Location	**Heating needs**				**Cooling needs**			
	Original method		**Modified method**		**Original method**		**Modified method**	
	Trend deviation	***σ*** [kWh m^{-2} yr^{-1}]	**Trend deviation**	***σ*** [kWh m^{-2} yr^{-1}]	**Trend deviation**	***σ*** [kWh m^{-2} yr^{-1}]	**Trend deviation**	***σ*** [kWh m^{-2} yr^{-1}]
Aosta	1.64%	0.67	-2.42%	0.78	-5.35%	0.76	-5.26%	0.76
Bergamo	7.21%	1.25	0.88%	0.38	-4.39%	0.98	-1.68%	0.66
Monza	-3.95%	0.48	-0.36%	0.20	-7.37%	0.67	-10.99%	0.71
Trento	4.28%	0.88	-2.52%	0.93	-10.71%	1.02	-5.37%	0.69
Varese	-1.91%	0.69	-2.52%	0.80	3.75%	0.64	4.00%	0.67

List of figures captions

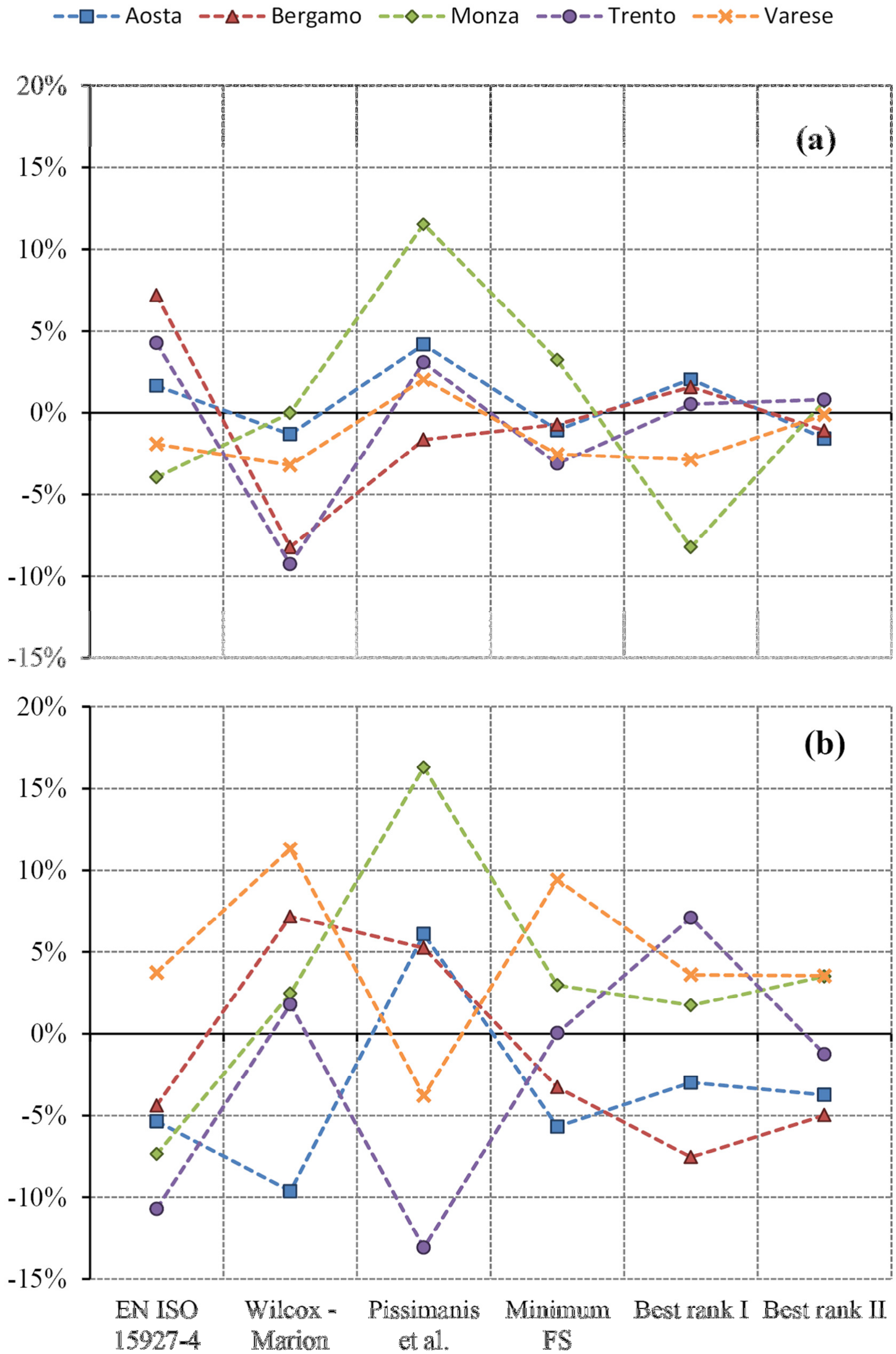
Figure 1. Trend deviations of the different final selection procedures for the annual heating energy needs (a) and the annual cooling energy needs (b).

Figure 2. Comparison between the average annual heating (left) and cooling (right) energy needs for the sample of buildings and those simulated considering the TRY_{EN} developed with the 66 combination of weights (green bars). The dots represent the annual energy needs simulated with the reference years developed with the modified EN ISO 15927-4:2005 with the optimum combination of weights for the whole set of buildings and the dotted red lines the trend lines of the original standard method.

Figure 3. Annual heating (on the top) and cooling energy need trend deviations (on the bottom) for the 5 locations, considering single reference years for the whole sample of buildings and for the subsamples (on the left) and separate reference years for the subsamples (on the right).

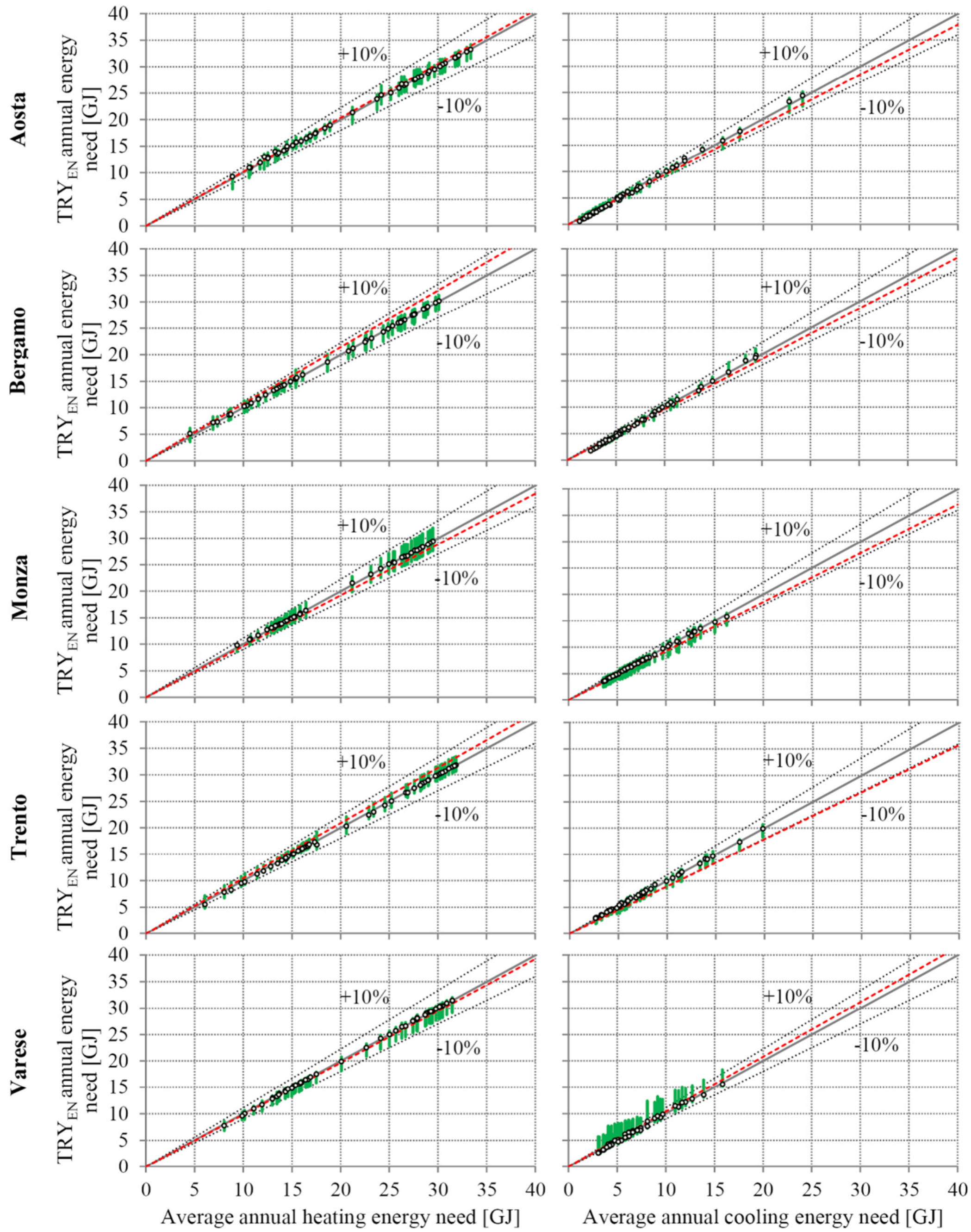
Figure 4. Annual heating and cooling energy need trend deviations for the whole set of buildings and for the 5 locations with respect to the corresponding multi-year averages of the different historic weather data series. Trend deviations with the standard EN ISO 15927-4:2005 method on the left and with the modified approach with optimized weights on the right.

Figure 5. Examples of the different impacts of the combinations of weights for Trento: less (June), medium (July) or highly effective (October). The upper vertex of each triangle represents the combination (1, 0, 0), the lower vertex on the left (0, 0, 1) and on the right (0, 1, 0).



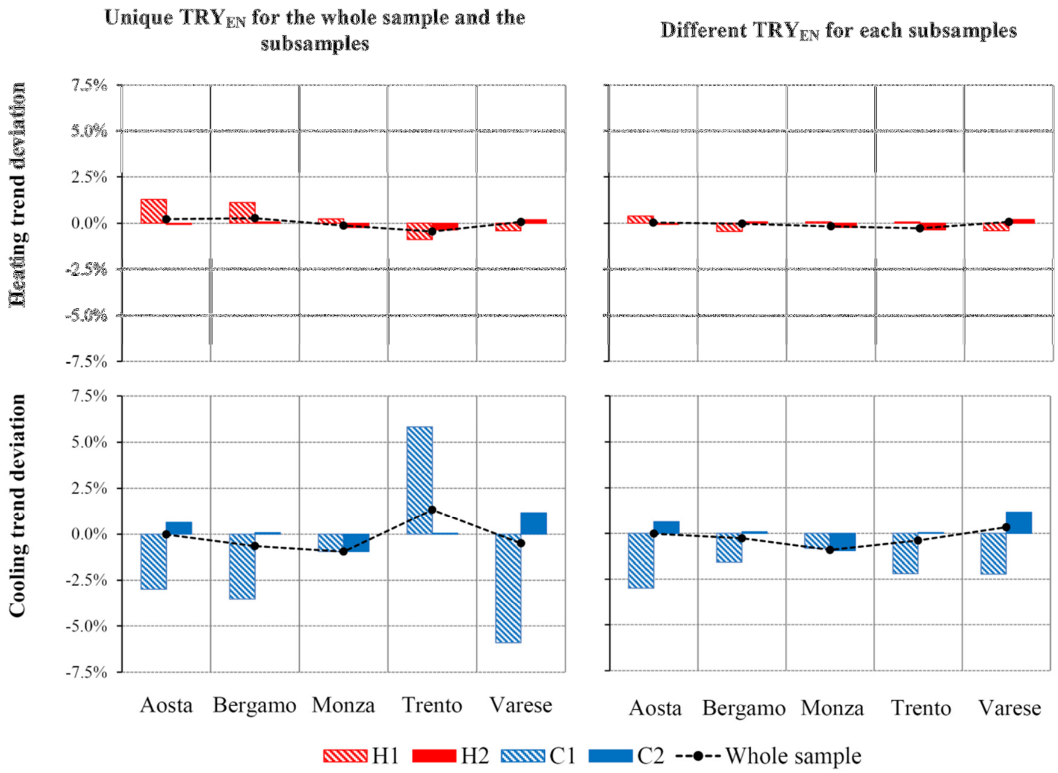
Aosta
Bergamo
Monza
Trento
Varese
20%
15%
10%
5%
0%
-5%
-10%
-15%
(a)
(b)
EN ISO 15927-4
Wilcox - Marion
Pissimanis et al.
Minimum FS
Best rank I
Best rank II

Figure 1



Aosta
Bergamo
Monza
Trento
Varese
TRY$_{EN}$ annual energy need [GJ]
+10%
-10%
Average annual heating energy need [GJ]
Average annual cooling energy need [GJ]

Figure 2



Unique TRY$_{EN}$ for the whole sample and the subsamples
Different TRY$_{EN}$ for each subsamples
Heating trend deviation
Cooling trend deviation
7.5%
5.0%
2.5%
0.0%
-2.5%
-5.0%
-7.5%
Aosta
Bergamo
Monza
Trento
Varese
H1
H2
C1
C2
Whole sample

Figure 3

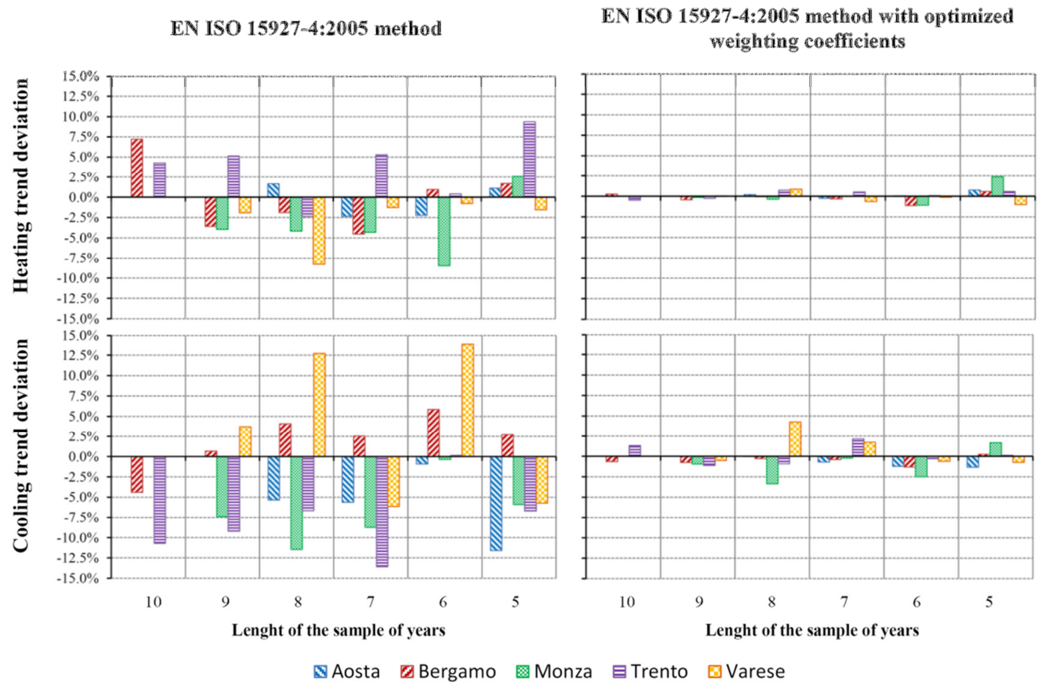
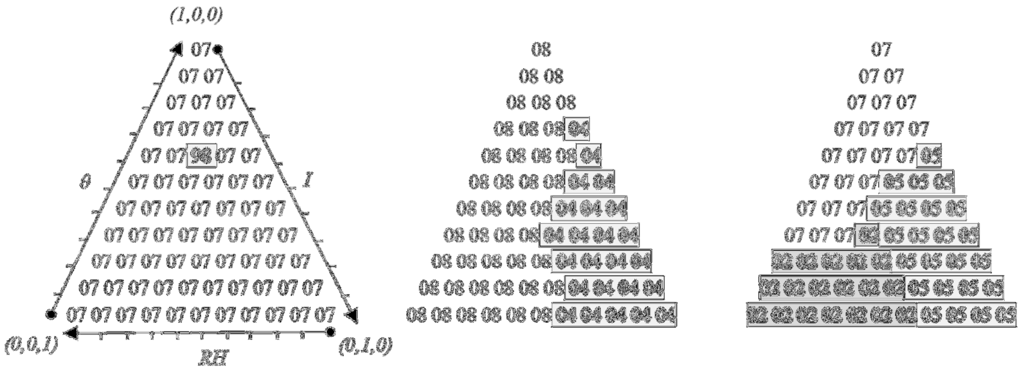

EN ISO 15927-4:2005 method
EN ISO 15927-4:2005 method with optimized weighting coefficients
Heating trend deviation
Cooling trend deviation
15.0%
12.5%
10.0%
7.5%
5.0%
2.5%
0.0%
-2.5%
-5.0%
-7.5%
-10.0%
-12.5%
-15.0%
10
9
8
7
6
5
Lenght of the sample of years
Aosta
Bergamo
Monza
Trento
Varese

Figure 4



a) - June b) - July c) - October

Figure 5