Multi-year and reference year weather data for building energy labelling in North Italy climates

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Abstract

Representative weather information is essential for a reliable building energy performance evaluation. Even if detailed energy analyses can be carried out considering the multi-year weather data, generally a single reference year is adopted. Thus, this artificial year has to correctly approximate the typical multi-year conditions. In this work, we investigate the representativeness of the method described in the technical standard EN ISO 15927-4:2005 for the development of reference years. Energy performance of a set of different simplified buildings is simulated for 5 North Italy locations using TRNSYS. The energy needs computed using the reference year are compared to those of a multi-year simulation. The annual variability of energy results for the studied thermal zones is investigated, paying attention to its effects on the

building envelope energy ratings according to a proposed classification. Also, those configurations more influenced by the annual weather changes are identified by means of statistical indexes. The analyses demonstrate that the representativeness of the reference year results can vary significantly in the considered locations – and, consequently, the accuracy in building energy assessment and classification can be reduced, especially for some building envelope configurations.

1.   Introduction

In many building design applications, the use of simplified calculation methods for the evaluation of the energy consumption cannot provide results detailed enough for advanced investigations. For instance, these approaches are not suitable to achieve both high energy efficiency and adequate visual and thermal comfort for the occupants. Consequently, the recourse to the detailed building energy simulation (BES) tools by professionals is becoming more and more frequent. The higher capability in calculating detailed outputs requires more complex and detailed inputs [1]. As regards the weather data, the datasets of monthly mean values used in simplified methods, such as those of dry bulb temperature, solar radiation and relative humidity in the Italian standard UNI 10349:1994 [2], are not sufficient for detailed simulation tools, which generally require at least an hourly discretization of the weather data inputs. The problem of the development of weather data for BES has been widely investigated in the literature and Barnaby and Crawley discussed and presented the main aspects, contexts and issues related to their definition [3].

We can distinguish three kinds of data for dynamic simulation [4]:

•   multi-year weather data;

•   typical or reference years;

•   representative days.

The multi-year weather data are the best solution in trend and sensitivity analyses of building performance to the variability of the weather conditions, especially if aimed at a design robust to climatic changes [5]. Typical weather data years are simply a single year of hourly data representative of the profiles recorded in a multi-year dataset. The representative days are hourly data for some average days descriptive of the typical climatic conditions (e.g., summer conditions). Simulations with typical years (or

representative days) instead of multi-year weather data lead to less information but they are less time-consuming and results are easier to manage [6, 7]. They are also preferred to mitigate the effects of missing or wrong data in the collected series. Eventually, typical years are also necessary for assessing the building energy performance under standard weather reference conditions, which are expected to be representative of the multi-year series in a given location. Some previous studies observed that the variability of buildings annual energy uses are less than 10 % in the multi-year period – between 4 % and 6 % for U.S. climates [8, 9] or 4.6 % for Hong-Kong [10]. Although the previous studies are valid only for the climatic context and buildings analysed, they indicate that a single reference year can generally be used to express the typical energy performance. The reference years have been defined in different ways in the last decades. One of the first definitions was given for 60 American localities [11]: 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 [12] recommends using the typical meteorological years (TMY), the European test reference years [3] or other typical years built according to similar procedures instead of the original TRY of 1976. In these cases the reference year is an artificial year composed of 12 months selected as the most representative in the multi-year series. One of the first definitions of the typical year was given by Hall *et al.* [13]. According to Lund [14-16] and Lund and Eidorff [17], they 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 last feature is probably one of the most important [18].

In the literature many approaches are available and there is not a single procedure accepted for the construction of a reference year [19]. Each method starts from the calculation of some statistics of the weather variables (e.g., mean dry bulb temperature, daily solar radiation) for the selection of the representative month from the collected data [13]. The relative importance of the different variables is given by weighting factors, whose selection should be made considering the final use of the reference year, for instance distinguishing sizing from energy assessment [20]. Most of the approaches are based on the Finkelstein-Schafer statistic [21], with the exception of the method by Festa and Ratto [22], which implements the Kolmogorov–Smirnov statistic. Among the methods there is no agreement on the number of weather parameters to use. For instance, as observed by Argiriou *et al.* [23], 9 weather parameters were considered in the SANDIA method [13], while 7 were considered in the "Danish method" [17, 24] and 5 were considered in the method by Festa and Ratto [22]. Moreover, there is no general agreement on the weighting factors for the weather variables and some authors remarked that they should be based also on the type of building analysed [25]. Different methods and groups of weighting factors for the determination of the reference year were compared by many authors, considering the average results of the multi-year series as benchmark. Weather statistics, solar fraction of thermal solar systems, electrical power output of PV systems, heating and cooling degree-days, energy needs or final uses were considered as indexes for the assessment of the reference years [26-28]. Analysing different climates and applications, some authors drew different conclusions. Implementing different approaches for the development of a reference year for Damascus, Syria, Skeiker and Ghani observed that the selected

typical month can vary significantly [29]. Comparing the SANDIA, the "Danish" and the Festa-Ratto methods for the evaluation of the reference years for 4 localities in Thailand, Janjai and Deeyai concluded that there is no significant difference in solar fractions and outputs of both thermal and PV solar systems [30]. In their study for the location of Subang, Malaysia, Rahman and Dewsbury recommended to weight equally the weather parameters in the calculation [31]. Studying the sensitivity of the energy production of a PV module and building energy needs in Palermo, Sicily, to the chosen method, Sorrentino *et al.* underlined that the best solution can be found using different weights for the selection of the TRY months, in particular for the building energy need evaluation [32]. Argiriou *et al.* assessed 17 different methodologies for the generation of a reference year in the climate of Athens, Greece, and stated that the optimum choice 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) [23].

In Italy, for the revision (currently in progress) of the technical standard UNI 10349:1994 reporting the weather data to use for energy calculations, the procedure described in the European technical standard EN ISO 15927-4:2005 [33] was selected. The dataset previously used in Italy was developed from weather data collected in Italian airports from 1951 till 1970 and so it is far from being representative of the current urban conditions. In order to improve the representativeness, instead of modifying previous reference years, for instance to include the urban heat island effect as done by Chan for Hong Kong [34], new data series have been collected in the urban sites by the regional environmental protection agencies (ARPAs). This choice is also coherent with the need to periodically update the weather dataset to account medium and long term climate change trends [19, 35]. Although there are some cases for which

the new data collection started 20 years ago, for many Italian localities only a limited number of years is generally available [36].

The selection method adopted for the Italian localities is based on the dry bulb temperature, the solar radiation and the relative humidity as primary variables for the determinations of a short list of eligible reference months and the wind speed as secondary variable for the final selection. No different weighting coefficients are considered for the primary variables even if the standard allows the user to build a new test reference year (TRY_{EN}) for specific purposes. The method of the technical standard has already been implemented for the evaluation of the reference years in several climates, as for instance for 7 localities in South Korea [37]. Moreover, for building energy analyses, some authors tried to identify the optimum combination of weighting factors to improve the standard procedure, such as those proposed by Kalamees *et al*. in the Finnish climate [38].

In spite of the large literature on reference years, the impact of the EN ISO 15927-4:2005 assumptions on the building energy labelling with BES tools is not deeply investigated. In the present work, the EN ISO 15927-4:2005 method adopted in Italy for the development of the new reference years based on the new data collected in urban sites is applied for some localities in the northern regions of the country. The representativeness issues are discussed both under the perspective of the weather parameters and that of the energy needs of a sample of buildings, focusing on the problem of the limited number of years available in the data series. Moreover, the variability of the building energy performances in a multi-year period are studied considering also the effects on the ratings of heating and cooling energy needs given by the reference years. By means of statistical indexes, the correlations between the envelope characteristics of the considered sample of buildings and the variability of the

weather data in the multi-year series are studied, in order to identify those

configurations sensitive to the change of the climatic conditions.

2. Methods

The analysis requires 4 main steps:

(2.1) selection and analysis of the weather data of the multi-year series,

(2.2) definition of a TRY_{EN} according to EN ISO 15927-4:2005,

(2.3) analysis of the representativeness of the TRY_{EN} by comparing:

   a) the weather variables distribution,

   b) the energy performance of a set of reference buildings calculated both with

       TRY_{EN} and multi-year weather files,

   c) The energy performance rating of the reference building set resulting from the

       previous calculations.

(2.4) sensitivity analysis of multi-year energy performance.

2.1   Selection and analysis of the weather data of the multi-year series

The data collected by the local ARPAs are available for 24 cities, capitals of each

province in 4 North Italy Regions: Emilia-Romagna, Lombardia, Trentino-Alto

Adige/Südtirol and Valle d'Aosta. Errors and outliers are generally present in the raw

weather data measurements: before using the hourly weather data in BES, the wrong

entries have to be identified and, if possible, fixed. Since the weather variables are

measured with different instruments and affected by different errors, the specific criteria

indicated in Table 1 [39] are followed for each variable to find the errors in a first

analysis, according to the recommendations of WMO Guide [40].

For single hours or a low number of consecutive hours affected by wrong data, the errors are fixed by interpolation. Wrong and missing data are replaced using linear interpolation for the temperature, the relative humidity and the wind speed when the consecutive incorrect data points are less than 6 entries, otherwise a cyclic interpolation is considered [41]. For larger periods, bias errors are corrected by properly shifting the relevant data.

2.2   Definition of a TRY_{EN} according to EN ISO 15927-4:2005

The construction of a TRY_{EN} requires mean values of the meteorological variables and, in particular, the individual frequency distributions and the cross correlations between the parameters.

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

1. calculation of the daily averages $\bar{p}$ for each primary climatic parameter p, month m and year y of the series;

2. sorting of all the $\bar{p}$ 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 ith day and N is the total number of days for a month over all the available years;

3. sorting of all the $\bar{p}$ 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:

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

where $J(i)$ is the rank order of the ith 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

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

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 month among the first 3 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 involved in the correction, it applies only to the dry bulb temperature and the relative humidity.

In accordance with the EN ISO 15927-4:2005, at least 10 years (not necessarily consecutive) should be used but the longer the period, the better. For those locations without this minimum requirement, a slightly less restrictive criterion is followed: only locations with at least 8 years in the data series, as in the chapter 14 of the ASHRAE Handbook of Fundamentals [42] and with less than 10 % of wrong/missing data for each variable and each year are considered to develop a TRY$_{EN}$.

2.3   Analysis of the representativeness of the reference year

The analysis is carried out following the steps outlined below which are aimed at studying the weather parameters, the energy results and the effects on the energy ratings for the buildings in the sample.

a   Weather variables

The ability of the TRY_{EN} to represent the whole dataset is analysed comparing monthly average values of dry bulb temperature, daily horizontal solar radiation and relative humidity. Monthly average values for these variables of the reference year are compared to the distributions of the averages in the multi-year series, which are described by maximums, minimums, first and third quartiles and medians. The closer a TRY_{EN} average variable is to the median for a given month, the better. A representativeness problem can be identified when a TRY_{EN} monthly average variable is outside the interquartile range, *IQR*.

b   Building energy performances

The representativeness of the test reference year for the North Italy climates is studied by carrying out different dynamic simulations with both TRY_{EN} and multi-year data series, according to the suggestion by Chan *et al.* [43] in assessing Hong Kong TMY. The annual energy needs (both for cooling and heating) of a set of reference buildings characterized by different insulation levels, thermal inertia, sizes and orientations of windows and kind of glazing are analysed. This allows an estimation of the sensitivity of the building energy performance to the variability of the considered climates by changing the characteristics of the building itself. In this perspective, both buildings expected to be characterized by higher heating energy demand (e.g., the poorly

insulated buildings) and buildings with higher cooling energy demand (e.g., buildings with windows with high solar heat gain coefficient) are considered.

Starting from a base thermal zone, a set of 48 different simplified thermal zones is developed in accordance with a full factorial plan. The base module consists 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 are neglected and the floor is modelled with a crawl space (i.e., without sun exposition and infrared thermal losses towards the sky dome), instead of in thermal contact with the ground, whose sensitivity and response to the variability of the external conditions are very low considering a limited number of years because of its very high thermal inertia.

All opaque components are 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 is 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, consist 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 is 20 % of the whole window area. The internal gains are assumed equal to 4 W m^{-2}, half radiative and half convective, as indicated by the EN ISO 13790:2008 [44] for residential dwellings. A constant ventilation rate of 0.3 ACH is considered, as suggested by the Italian technical specification UNI/TS 11300-1:2008 [45].

The analysed variables can be assumed to have the most relevant effects on the building envelope performance, and, with the only exception of the window orientation, each one presents a high and a low level:

- insulation thickness of the envelope components (5 cm or 15 cm of polystyrene) which gives two levels of thermal transmittance (e.g., for the vertical walls, $U = 0.45$ W m^{-2} K^{-1} and $U = 0.21$ W m^{-2} K^{-1});

- thermal inertia of the opaque elements (area specific heat capacity of the internal layer equal to 75 kJ m^{-2} K^{-1} for the timber structure and equal to 300 kJ m^{-2} K^{-1} for the concrete);

- solar heat gain coefficient (*SHGC*) of the glazing (0.35 or 0.61);

- size of the windows ($A_{win} = 14.56$ m^2 or 29.12 m^2);

- orientation of the windows (East, South or West).

The different configurations are simulated with TRNSYS, considering the following assumptions:

- the time-step is coherent with the hourly discretization of the weather data, in order to avoid the interpolations influencing the results;

- constant convection coefficients are selected, in accordance with the standard EN ISO 6946:2007 [46];

- the internal long wave radiation exchanges are considered according to the star network approach in TRNSYS;

- the heating and the cooling setpoints are imposed to 20 °C and 26 °C in accordance with the UNI/TS 11300-1:2008 prescriptions for residential buildings, but they are applied all year long, i.e. no specific heating and cooling seasons are defined.

The annual heating and cooling energy needs simulated with TRNSYS, considering both the developed reference year weather files and each one of the multi-year series, are analysed for each combination of building configuration and location. In particular, in order to discuss the representativeness problem under the energy perspective, the

TRY$_{EN}$ annual energy results are compared to the averages and to the multi-year results

for each case.

c   Building performance energy rating

The effects of the deviations between the TRY$_{EN}$ annual energy needs and those of the

multi-year series on the building energy rating are discussed in order to study this

additional aspect of a weak representativeness. The classification currently used in Italy

and defined in the National Guidelines for the Energy Labelling of Buildings [47],

based on final uses for space heating during the heating season and for the domestic hot

water production, is not followed since the analysis is focused only on the envelope and

not on the systems. A specific classification is developed coherently with the procedure

described in the technical standard EN 15217:2007 [48] for the set of buildings in the

analysis.

In the technical standard EN 15217:2007, two reference values are defined: R_r is

representative of the requirements of energy performance for new buildings while R_s is

the energy performance reached by half of the national or regional building stock. The

simulated sample of buildings is not designed to be representative of the Italian

residential building stock neither to comply with the current minimum energy

requirements. Instead, the set of buildings is aimed to assess the effect of the variability

of weather parameters in multi-year series. Moreover, the reference values have to be

defined considering the final energy uses. Thus, the standard methodology is adapted to

the purposes of this work: two separate ratings are defined in order to distinguish

heating and cooling energy needs and the reference values are chosen for each location,

according to the annual results for the sample of buildings with the TRY$_{EN}$. The

medians of the energy results are attributed to the R_s values while the first quartile Q_1 to

the R_r values. According to the Annex B of the technical standard, 7 classes are defined, as in Table 3.

As it can be seen, by associating the first quartile Q_1 to the R_r value 25 % of the building configurations belong to classes A and B which have the best energy performance. The median distinguishes the classes D and E and so half of the sample belongs to the classes E, F and G which have the worst energy performance.

Considering each of the years in the original weather data series, the energy performance of a building configuration can be either better or worse than the rating according to the TRY_{EN}. A trend of higher or lower ratings in the multi-year series with respect to the reference year can be identified if the TRY_{EN} is not representative of the original multi-year series. Moreover, the energy performances of some configurations can be more sensitive to the weather variability and both years with higher and years with lower ratings can be present. In this case the TRY_{EN} ratings can be considered representative if the number of upgrades and that of downgrades are close. In order to take into account both issues, two criteria of analysis are considered:

- Criterion A: in order to detect the trends, if the number of downgrades/upgrades is larger than or equal to half of the years in the data series for a given building configuration (e.g., 4 or 5 years), this building is accounted among those with a representativeness problem;

- Criterion B: in order to detect unbalanced behaviour for those configurations more sensitive to weather variability, if the difference between the number of downgrades and the one of upgrades is larger than or equal to 33 % of the years in the data series (e.g., around 3 years), it is accounted among those with a representativeness problem.

2.4   Sensitivity analysis of multi-year energy performances

The variability of the energy results is analysed in order to find correlations between building envelope parameters and dispersion of the results.

The annual results with the TRY_{EN} weather files are considered as a reference and the deviations between the energy needs simulated in each year and the ones of the TRY_{EN} are calculated. The deviations are analysed by means of Spearman's index. Since it is expected that some envelope properties act in reducing both the positive and negative deviations with respect to the reference year results and because of the monotonic definition of Spearman's index, the analysis is performed distinguishing positive and negative differences. The considered variables are divided into those describing the envelope characteristics and those related to the external weather conditions.

For the energy need deviations, in this analysis we assess:

- the variables descriptive of the dynamic behaviour of the opaque envelope, such as the area-weighted average periodic thermal transmittance $Y_{ie,env}$ [W m^{-2} K^{-1}], the area-weighted average time shift $\Delta t_{ie,env}$ [h], and the total internal heat capacity $k_i \cdot A_{tot}$ [kJ K^{-1}], defined in the EN ISO 13786:2007 [49];
- the area-weighted average thermal transmittance of the opaque envelope U_{env} [W m^{-2} K^{-1}];
- the solar heat gain coefficient of the glazing $SHGC$ [-];
- the glazing area A_{gl} [m^2];

In order to take into account the variability of the weather conditions, the deviations of the area-weighted *equivalent Heating/Cooling Degree Days* [K d] are calculated for both opaque and transparent envelope. In particular, the $HDD_{sol-air,env}$, $CDD_{sol-air,env}$, $HDD_{sol-air,gl}$ and $CDD_{sol-air,gl}$ are determined for each orientation considering,

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respectively, the sol-air temperature for the opaque components and the equivalent sol-air temperature for the transparent ones, according to the Eq. (4) and (5):

$$\theta_{sol\text{-}air,\ env} = \theta_e + \frac{I\alpha + h_{r,sky}(\theta_{sky} - \theta_e)}{h_{se}} \tag{4}$$

$$\theta_{sol\text{-}air,\ gl} = \theta_e + \frac{SHGC \cdot I}{U_{gl}} + \frac{h_{r,sky}(\theta_{sky} - \theta_e)}{h_{se}} \tag{5}$$

In order to have aggregated variables, area-weighted heating/cooling degree days are calculated for each year and location of the weather series and used for determining the deviations $\Delta HDD_{sol\text{-}air,env}$, $\Delta CDD_{sol\text{-}air,env}$, $\Delta HDD_{sol\text{-}air,gl}$ and $\Delta CDD_{sol\text{-}air,gl}$ with respect to the equivalent degree days of the reference year.

3.   Results

The selection procedure and the chosen criteria led to the identification of 5 cities: Aosta (with 8 available years), Bergamo (10 years), Monza (9 years), Trento (10 years) and Varese (9 years). The details of the considered years in the multi-year series and the chosen months for the test reference years are reported in Table 4.

3.1   Representativeness of the reference year

a   Weather variables

The monthly values of average dry bulb temperature, daily horizontal solar radiation and relative humidity of the different years and TRY_{EN} were calculated and compared. In Figure 1 the monthly average weather variables are showed for the location of Trento.

The red dots represent the TRY_{EN} monthly averages while the distributions of the monthly averages of the multi-year series are described by lines: the external dotted

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lines are the maximum and the minimum, the internal dotted lines the first and the third

quartiles (Q_1 and Q_3) and the continuous line the medians.

Table 5 presents the deviations between the TRY_{EN} monthly averages and the medians

of the average value distributions in the multi-year period. Those months outside the

IQR are typed in bold. As regards the average dry bulb temperatures, TRY_{EN} values are

outside IQR for 4 months for all localities with the exception of Monza, where the

critical month is only 1. Some representativeness problems are present for the global

horizontal radiation in 4 months for Aosta and Bergamo reference years, in 3 for Trento,

in 2 for Varese and only in August for Monza. For what concerns the relative humidity,

the number of cases outside IQR is generally higher: 6 for Varese and Trento, 5 for

Monza and 4 for the other cities. The identification of months with low

representativeness is important to understand discrepancies between building energy

performance calculated using TRY_{EN} and multi-year data.

b   **Building energy performances**

Figure 2 presents annual heating and cooling energy needs for each building

configuration in the sample. In the graphs, the annual energy needs simulated using a

test reference year as weather file are reported in the horizontal axis while the annual

energy needs and the averages of the multi-year series are indicated on the vertical axis.

As regards the ranges of the annual results of the buildings sample simulated with the

reference years, the heating energy needs are between 5 and 35 GJ per year (i.e.,

between 13.9 and 97.2 kWh m^{-2} yr^{-1}) while the cooling energy needs are less than 20 GJ

(i.e., 55.6 kWh m^{-2} yr^{-1}), with most of cases under 10 GJ (i.e., 27.8 kWh m^{-2} yr^{-1}). Some

differences can be found among the ranges for the different localities but they are

negligible and the ranges remain comparable. Moreover, the dispersion of the results for

the different locations and building configurations can be observed in the graphs.

Considering the standard deviations normalized with respect to the means for each combination of climate and building configuration, for the heating needs the average of the buildings sample is equal to 13.8 % for Aosta, 8.6 % for Bergamo, 8.3 % for Monza, 7.4 % for Trento and 7.1 % for Varese. As concerns the cooling needs, it is 33.4 % for Aosta, 23.1 % for Bergamo, 20.5 % for Monza, 19.5 % for Trento and 18.8 % for Varese.

A good alignment between multi-year average results and TRY_{EN} results indicates a good representativeness of the energy performance evaluated by means of the reference year with respect to the multi-year series:

- for the annual heating needs the trend deviations between the TRY_{EN} results and the averages are +1.6 % for Aosta, +7.2 % for Bergamo, -4.0 % for Monza, +4.3 % for Trento and -1.9 % for Varese;

- for the annual cooling needs the trend deviations between the TRY_{EN} results and the averages are -5.3 % for Aosta, -4.4 % for Bergamo, -7.4 % for Monza, -10.7 % for Trento and +3.8 % for Varese.

c   Energy performance rating

The horizontal lines in Figure 2 divide the different rating classes for each locality and kind of energy need: the dark green line distinguishes classes A and B, the light green B and C, the yellow line separates C and D, the orange D and E, the light red E and F and, finally, the dark red distinguishes class F from class G.

In Tables 6, 7 and 8 both heating and cooling energy ratings are analysed for the sample of buildings. In Table 6 the distributions in the different classes of the building configurations according to the TRY_{EN} weather file are reported for each climate. In the

first two classes 25 % of the building sample configurations are present but most of them are in class B for both heating and cooling need ratings. Referring to the 25 % of cases belonging to classes C and D, most of configurations are in class C for the heating need ratings and equally distributed in classes C and D for the cooling ratings. As regards the last 50 % of configurations, most of them belong to classes F and G according to the heating need ratings and to classes E and G according to the cooling need ratings.

In Table 7 and Table 8 the variation of the ratings in the different years is analysed according to the criteria described before. Looking at the first table about the heating ratings, according to the criterion A (i.e., presence of a trend) there is a marked upgrade for 37.5 % of configurations (i.e., 18 cases) in Bergamo and 22.9 % of configurations (i.e., 11 cases) in Trento while there is a downgrade for 12.5 % of buildings in Monza, 6.3 % in Varese and 4.2 % in Aosta (respectively 6, 3 and 2 cases). Analysing the results with the criterion B, the number of upgrades is significantly larger than that of the downgrades for 45.8 % of cases (i.e., 22 buildings) in Bergamo and 31.3 % (i.e., 15 buildings) in Trento, while the opposite is true for 10.4 % of configurations in Varese and 50 % in Monza (respectively, 5 and 24 buildings). As concerns the cooling ratings, an upgrade trend can be identified for 25 % of cases (i.e., 12) in Varese while a trend of downgrade can be seen for 20.8 % of buildings (i.e., 10) in Aosta and Monza, 14.6 % (i.e., 7) in Bergamo and 58.3 % (i.e., 28 buildings) in Trento. According to the criterion B, the building configurations with a number of upgrades much larger than that of downgrade are 18.8 % in Varese (i.e., 9) while more downgrades occur in 33.3 % of cases for Aosta, 18.8 % for Bergamo, 13 % for Monza and 58.3 % for Trento, respectively 16, 9, 6 and 28 cases.

3.2 Sensitivity analysis of multi-year energy performances

The Spearman's indexes were calculated in order to correlate the variability of the energy results in the multi-year period to the characteristics of the building envelopes. The indexes are reported in Figure 3.

4. Discussion

4.1 Representativeness of the reference year

a Weather variables

Analysing the weather variables in Figure 1 and in Table 5, it can be seen that the TRY_{EN} values are within the range between the first quartile Q_1 and the third quartile Q_3 in most of cases, indicating that the overall representativeness of TRY_{EN} is good, but different behaviours and levels of agreement can be observed when different months and locations are considered. In some cases the TRY_{EN} mean dry bulb temperatures are far from the median values of the multi-year period, as it can be seen in Figure 1 for Trento, for instance for February, March and November. The same is true of the daily global solar radiation of Trento for May, June and August and the relative humidity for February, March, October and December. The relative humidity, in particular, has representativeness problems for a larger number of combinations of months and locations than the dry bulb temperature and the horizontal solar radiation. Furthermore, the TRY_{EN} averages are rarely close to the medians for the three climatic parameters at the same time and the number of critical months is different for each variable and locality. In this context, the statistical properties of the data series are crucial in order to correctly develop the typical year. Even if the lengths of the collected series are

comparable for the 5 localities, it is possible to see that the results are different. For instance, considering the solar radiation, in Monza only August is critical while in Aosta and Bergamo there are 4 months outside the interquartile ranges. Data series of 10 years, as suggested in the EN ISO 15927-4:2005, may not be enough for climates with a large variability of the weather conditions year after year or in the presence of anomalous years, which can affect the TRY_{EN} selection procedure.

According to the central limit theorem, the effects of outliers can be mitigated by increasing the number of entities in the analysed sample but, until the number of collected years will not be high enough, the development of the reference year has to be optimized considering its final use. In this work we focused on the building envelope energy performance, so attention has to be paid, in particular, to the effects of temperature and solar radiation. On this respect, the relative humidity has a marginal role in the evaluation of the fictitious sky temperature in order to simulate the infrared heat flow towards the sky-dome according to the model implemented in TRNSYS [50]. Since constant ventilation rates and convective coefficients were used, the effect of the wind speed was completely neglected.

b   Building energy performances

Both for heating and cooling annual energy needs, the error provided by the TRY_{EN} weather data is in average under 10 % (Figure 2), as observed for Chinese climates by Yang *et al.* [7]. This does not represent the global error but just the effect of the inaccuracy in the modelling of the weather data and it has to be summed to the uncertainties of all other inputs and to the effects of the modelling assumptions. The general trend of the heating deviation is not the same in all locations: in Bergamo and in Trento there are overestimations of the heating energy needs while in Monza the TRY_{EN}

leads to an underestimation. This is consistent with the dry bulb temperatures in Table 5: in Bergamo the monthly averages of January, March, October and December, as well as February, March, November and December in Trento, are significantly lower than the medians while in Monza the monthly averages of February and October are higher. As concerns the annual cooling energy needs, there are underestimations in Aosta, Bergamo, Monza and, in particular, Trento. As it can be noticed in Table 5, for these localities the summer months of the reference year are generally colder than the medians and in some cases with less daily solar radiation (e.g., May and August for Trento, July and August for Monza, June and July for Bergamo and June for Aosta). While for the heating needs the discrepancies are ascribable to dry bulb temperature differences, for the cooling needs they depend on the combined effects of temperature and solar radiation.

c   Energy performance ratings

For many configurations the performances are not in the same rating class (e.g., for a colder year we can see a downgrade in the annual heating needs while for a warmer year an upgrade). Looking at the variability of the ratings in Table 7 and Table 8, some considerations about the effects of some representativeness issues can be drawn. According to both criterion A and B, we saw a trend of upgrade for a relevant number of configurations in Bergamo and in Trento in the classification of the heating energy performances. The criterion B also underlined an imbalance between the downgrades and the upgrades for the heating ratings in Monza. Analysing the cooling ratings, both criteria highlighted relevant numbers of upgrades in Varese and of downgrades in Aosta, Bergamo, Monza and, especially, Trento. The analysis about the energy ratings confirms the representativeness issues identified in the evaluations of the energy needs:

for Bergamo, Monza and Trento as concerns the heating needs and for all locations as concerns the cooling needs. Even if there is a light overestimation trend of the cooling needs in Varese (around 3 %), a significant number of cases present a trend of upgrades.

4.2   Sensitivity analysis of multi-year energy performances

The standard deviation of the energy needs simulated by using the different years in each historic series is between 7 % and 8 % for the heating needs and around 20 % for the cooling. Aosta, being affected by the anomalous year 2007, presents standard deviations more than 50 % larger than the other localities. Referring to the heating needs, the values are coherent with other studies in the literature, even if their focus was on the final energy uses and not on the energy needs. The cooling needs, instead, have a much larger variability but they are not particularly relevant for the considered climates, which are dominated by the heating demands. In Figure 3 it is possible to identify the parameters whose correlations with the variability of the energy needs are more significant. As it can be seen in graph (a), the most relevant correlations are with the deviations of the annual heating equivalent degree days and, for what concerns the envelope properties, with the opaque envelope thermal transmittance, periodic thermal transmittance and time shift. All their correlation indexes have a p-value lower than 1 % (i.e., statistically significant with respect to a 1 % significance level). Looking at the correlation indexes for the cooling needs in graph (b), the most correlated parameters are the deviations in the equivalent cooling degree days as well as the *SHGC* and area of the glazing. Also for the cooling need variability, these indexes have a p-value lower than 1 %.

From these indexes we can conclude that buildings with more efficient opaque envelopes (i.e., insulated walls, with a low periodic thermal transmittance and high time

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shift) and with a low *SHGC* of the glazing (or, generally speaking, of a control of the entering solar radiation) are more robust to the changes of the weather conditions. These results can be useful to:

- identify configurations of the existing building stock more sensitive to the weather variability and the interventions to choose not only for the reduction of the energy consumption but also to make building envelopes less sensitive to the external variability;

- give some indications about the strategies to follow in the design of new buildings robust to climate changes.

5. Conclusions

In this work the EN ISO 15927-4:2005 method for the development of test reference year has been implemented in 5 North Italy climates, considering a number of years close to the limit suggested by the technical standard itself and without attributing different weights to the weather variables. The representativeness of EN ISO 15927-4:2005 reference years has been assessed by studying both the weather files and the annual energy needs of a set of 48 simplified buildings simulated with TRNSYS. The reference year weather variables have been compared to those of the multi-year distributions, as well as the energy needs of the reference years to the averages of the whole series. Moreover, the variability of the building energy ratings with respect to the reference year ones has been studied, in order to assess the influence of the typical weather data on the energy labelling.

We observed that:

1. With a low number of years in the dataset for the development of the $TRY_{EN,}$ the representativeness - both of weather variables and energy needs, can vary significantly in the different locations.

2. The variability of the heating needs is in agreement with the results in the literature. For the cooling needs, instead, the variability is larger but it should be considered that little variations in the weather conditions can lead to large percentage differences in the analysed climates due to the low cooling energy needs.

3. If the TRY_{EN} is not very representative of the historic weather conditions, misleading information can be provided in the building energy labelling, especially for cases that are more sensitive to the weather variability.

4. The characteristics of these less robust configurations were identified: building envelopes with low insulation level and poor dynamic performances (e.g., high periodic thermal transmittance, low time shift) are more susceptible to heating needs variability and those with high *SHGC* and large glazing are more susceptible to cooling needs variability.

We can conclude that, in case of low number of recorded years in the historic weather data series and climates with large variability – such as the Italian ones, specific reference years should preferably be developed, depending on the analysis purposes:

- for the evaluation of the annual heating needs, the representativeness of the external temperature should be optimized;

- for the assessment of the cooling needs, instead, the solar radiation should be well represented.

The use of representative weather inputs will improve the accuracy of energy need evaluation and rating, especially for those configurations more sensitive to the climate variability and so more affected by errors in the reference year characterization.

Acknowledgement

Nomenclature

Symbols

α	solar absorptance (-)
Δ	parameter deviation with respect to the reference values computed by means of TRY_{EN}
θ	temperature (K)
λ	thermal conductivity (W m^{-1} K^{-1})
ρ	density (kg m^{-3})
Φ	cumulative distribution function of variable daily means within the whole historic series of the calendar months (-)
A	surface (m^2)
CDD	cooling degree days (K d)
c	specific heat (J kg^{-1} K^{-1})
EP	energy performance of the building envelope (GJ)
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 (-)
HDD	heating degree days (K d)
H	solar radiation (MJ m^{-2})
h	heat transfer surface coefficient (W m^{-2} K^{-1})
I	solar irradiance (W m^{-2})
IQR	interquartile range
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 years of the series (-)
k	areal heat capacitance of an envelope components (kJ m^{-2} K^{-1})
m	specific calendar month analyzed 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 (-)
p	weather variable used in the TRY_{EN} calculation procedure (-)
$Q_{1/3}$	first or third quartile
R	thermal resistance (m^2 K W^{-1})
R_R	maximum energy performance for new construction in a specific climate zone (GJ yr^{-1})
R_S	national or regional average of building stock heating demand (GJ yr^{-1})
RH	relative humidity (%)
s	thickness (m)
$SHGC$	solar heat gain coefficient (-)
TRY	test reference year (-)
t	time shift of the envelope components (h)
U	thermal transmittance (W m^{-2} K^{-1})

Y periodic thermal transmittance of an envelope component (W m^{-2} K^{-1})

y select year of the historical series

Subscripts

EN calculation procedure of European standard EN ISO 15927-4:2005

e external surface of the envelope or external environment

env area weighted average of a variable

fr referred to window frame

gl referred to window glazing plane

hor horizontal surface

i internal surface of the envelope

se envelope external surface

$sol\text{-}air$ referred to sol-air temperature

sky referred to sky dome

win referred to window

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Figures captions

Figure 1: (a) Average monthly temperature (b) average daily horizontal global radiation and (c) average monthly relative humidity for Trento. The red dots represent the TRY_{EN} monthly averages while the distributions of monthly averages of the multi-year series are described by lines: the external dotted lines are the maximum and the minimum, the internal dotted lines the first and the third quartiles (Q_1 and Q_3) and the continuous line the medians.

Figure 2: Heating (left) and cooling (right) energy needs: average energy needs (dark red dots) and annual results (light red dots) in the multi-year series respect to the TRY_{EN} values. The horizontal lines divide the different rating classes for each locality and energy need: the dark green line distinguishes classes A and B, the light green B and C, the yellow line separates C and D, the orange D and E, the light red E and F and, finally, the dark red distinguishes class F from class G.

Figure 3: Correlations of the building envelope characteristics and the deviations of the annual heating energy needs (a) and annual cooling energy needs (b), evaluated by means of Spearman's index.

Highlights

- The EN ISO 15927-4:2005 reference year is assessed in North Italy climates

- We compare heating and cooling needs with reference and multi-year simulations

- The representativeness of the reference year weather file is investigated

- The building envelope energy ratings are studied with a proposed classification

- We identify building envelope characteristics sensitive to weather variability

Table 1: Selection criteria for the identification of the outliers in the weather variables.

Weather variables	Selection criteria
Dry bulb temperature	o values exceeding the 50% of the 99th percentile o data with a derivative larger than ± 4 K h^{-1} o periods with constant values for more than 5 h
Horizontal global solar radiation	o values exceeding the solar constant o positive values during the night-time
Relative humidity	o values exceeding 100% or null o periods with constant values for more than 5 h (if lower than the 75th percentile)
Wind velocity	o values exceeding the 50% of the 99th percentile or negative o periods with constant values for more than 5 h (if the registered speed is larger than the anemometer minimum speed)

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: Criteria for the classification of heating and cooling energy needs (EP).

Classes	Criteria
A	$EP < 0.5 \cdot R_r$
B	$0.5 \cdot R_r \leq EP < R_r$
C	$R_r \leq EP < 0.5 \cdot (R_r + R_s)$
D	$0.5 \cdot (R_r + R_s) \leq EP < R_s$
E	$R_s \leq EP < 1.25 \cdot R_s$
F	$1.25 \cdot R_s \leq EP < 1.5 \cdot R_s$
G	$EP \geq 1.5 \cdot R_s$

Table 4: Selected months for the TRY$_{EN}$.

	Aosta	Bergamo	Monza	Trento	Varese
Number of years	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 5: Deviations between the TRY$_{EN}$ monthly averages and the monthly medians averages. In bold the months with the TRY$_{EN}$ monthly averages outside of the *IQR*.

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
$\Delta\theta_e$	Aosta	-0.14	**-1.33**	**-0.59**	**0.75**	0.30	-0.34	-0.34	0.47	-0.18	-0.48	**-0.93**	-0.01
	Bergamo	-0.43	-0.08	**-1.00**	0.14	**-2.82**	0.01	**-0.39**	-0.09	0.46	**-1.98**	0.49	-0.98
	Monza	0.16	1.43	0.31	-0.06	**-2.74**	0.47	0.00	-1.42	0.51	0.61	0.00	0.14
	Trento	-0.03	-1.41	**-1.32**	0.31	0.05	**-0.66**	**-0.79**	-0.58	-0.29	0.19	**-1.00**	-0.47
	Varese	-0.16	0.74	**0.63**	**0.40**	0.00	-0.09	**-1.67**	**1.00**	1.23	0.00	0.07	0.00
ΔH_{hor}	Aosta	0.17	0.21	**1.88**	**1.36**	0.25	-1.26	-0.02	**0.67**	0.52	**0.69**	0.03	-0.21
	Bergamo	**-0.89**	**1.07**	-0.14	0.36	0.18	-0.46	**-0.47**	-0.09	**1.05**	-0.31	0.45	-0.04
	Monza	0.00	-0.22	-0.41	-0.11	0.00	0.00	-0.94	**-1.14**	0.11	-0.79	0.20	0.00
	Trento	**-0.10**	-0.23	-0.82	0.00	**-1.47**	0.95	0.23	**-1.05**	0.15	-0.21	0.28	-0.05
	Varese	0.04	-0.17	**-0.43**	0.97	**2.08**	0.00	-0.15	-0.04	0.00	-0.56	-0.70	0.00
ΔRH	Aosta	-6.33	**4.67**	**4.31**	0.78	0.45	0.63	**4.02**	0.82	-0.89	**-3.10**	-3.24	0.70
	Bergamo	0.53	-4.62	-2.22	-0.66	-2.28	-1.69	**-3.57**	-3.31	**-8.86**	**-4.05**	**-6.76**	1.17
	Monza	**7.43**	**-8.13**	-0.99	**2.53**	3.81	-6.14	-2.42	**1.82**	0.02	**-3.03**	-0.01	0.15
	Trento	4.50	**-6.45**	**7.20**	**3.68**	-0.46	-1.74	**2.98**	-1.64	0.24	**4.84**	-1.19	**5.09**
	Varese	**-19.6**	-0.08	3.00	**12.1**	0.01	**7.97**	**4.84**	0.49	**7.34**	0.95	**5.85**	2.90

Table 6: Distributions of the sample buildings in the heating and cooling rating classes.

classes	A		B		C		D		E		F		G	
	H	C	H	C	H	C	H	C	H	C	H	C	H	C
Aosta	0%	6%	25%	19%	17%	19%	8%	6%	8%	10%	23%	13%	19%	27%
Bergamo	2%	2%	23%	23%	17%	8%	8%	17%	4%	10%	10%	10%	35%	29%
Monza	0%	0%	25%	25%	25%	13%	0%	13%	4%	23%	29%	6%	17%	21%
Trento	2%	4%	23%	21%	10%	19%	15%	6%	4%	19%	8%	6%	38%	25%
Varese	0%	0%	25%	25%	21%	13%	4%	13%	4%	23%	19%	4%	27%	23%
Average	1%	2%	24%	23%	18%	14%	7%	11%	5%	17%	18%	8%	27%	25%

Table 7: Analysis of the variation in the heating energy need ratings according to the proposed criteria.

Criteria	A		B	
	Upgrade	Downgrade	Upgrade	Downgrade
Aosta	2.1%	4.2%	6.3%	2.1%
Bergamo	37.5%	0.0%	45.8%	0.0%
Monza	0.0%	12.5%	0.0%	50.0%
Trento	22.9%	0.0%	31.3%	0.0%
Varese	0.0%	6.3%	0.0%	10.4%

Table 8: Analysis of the variation in the cooling energy need ratings according to the proposed criteria.

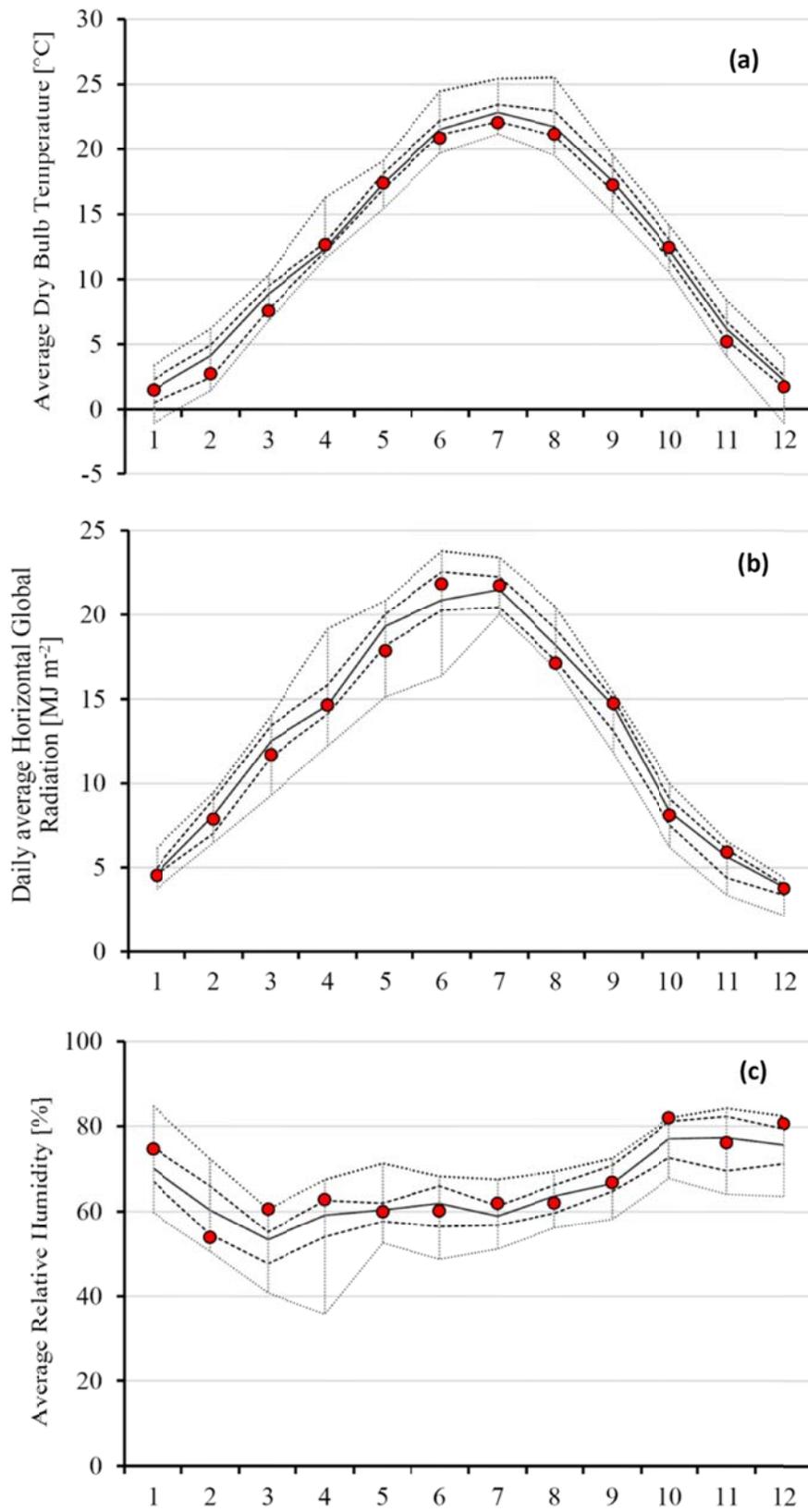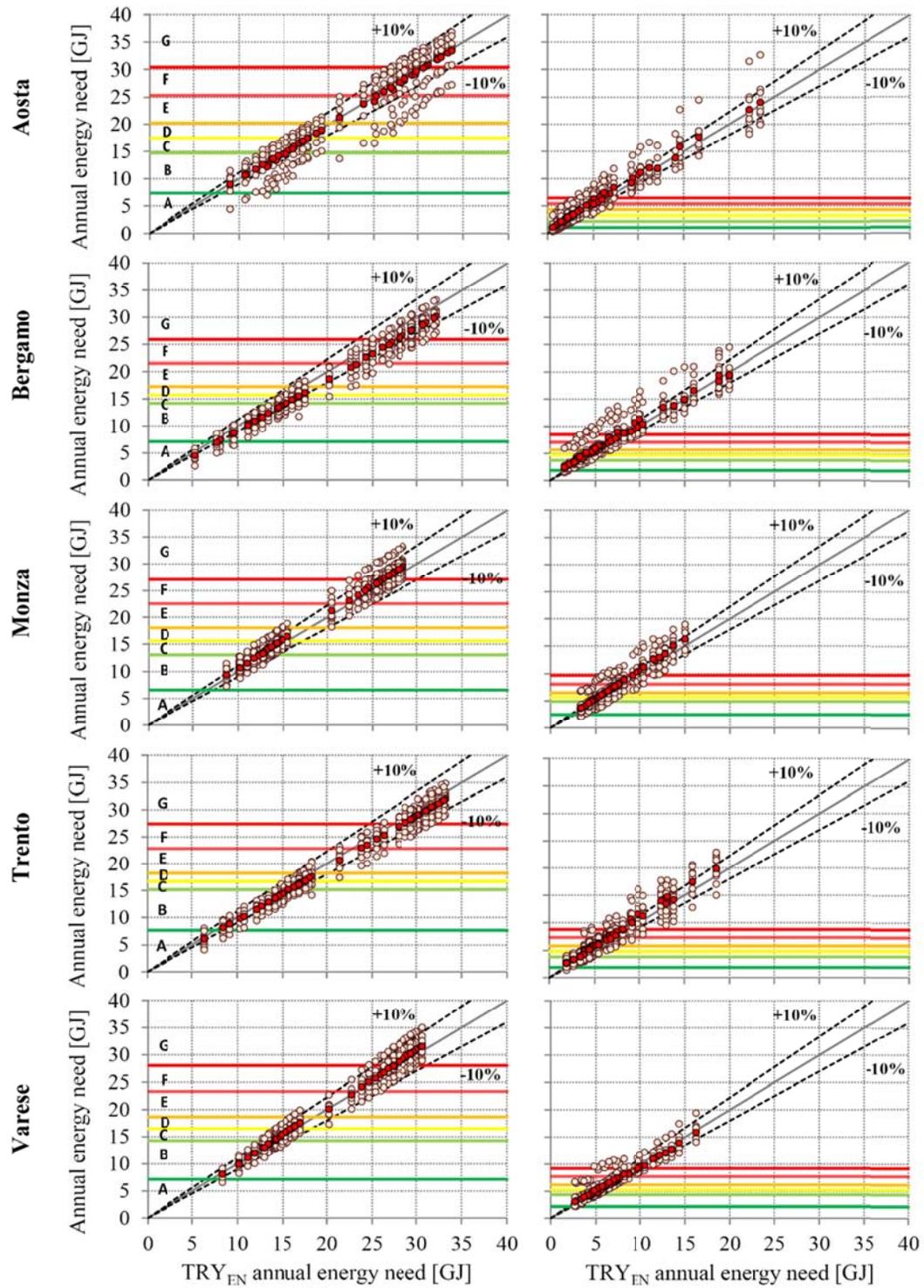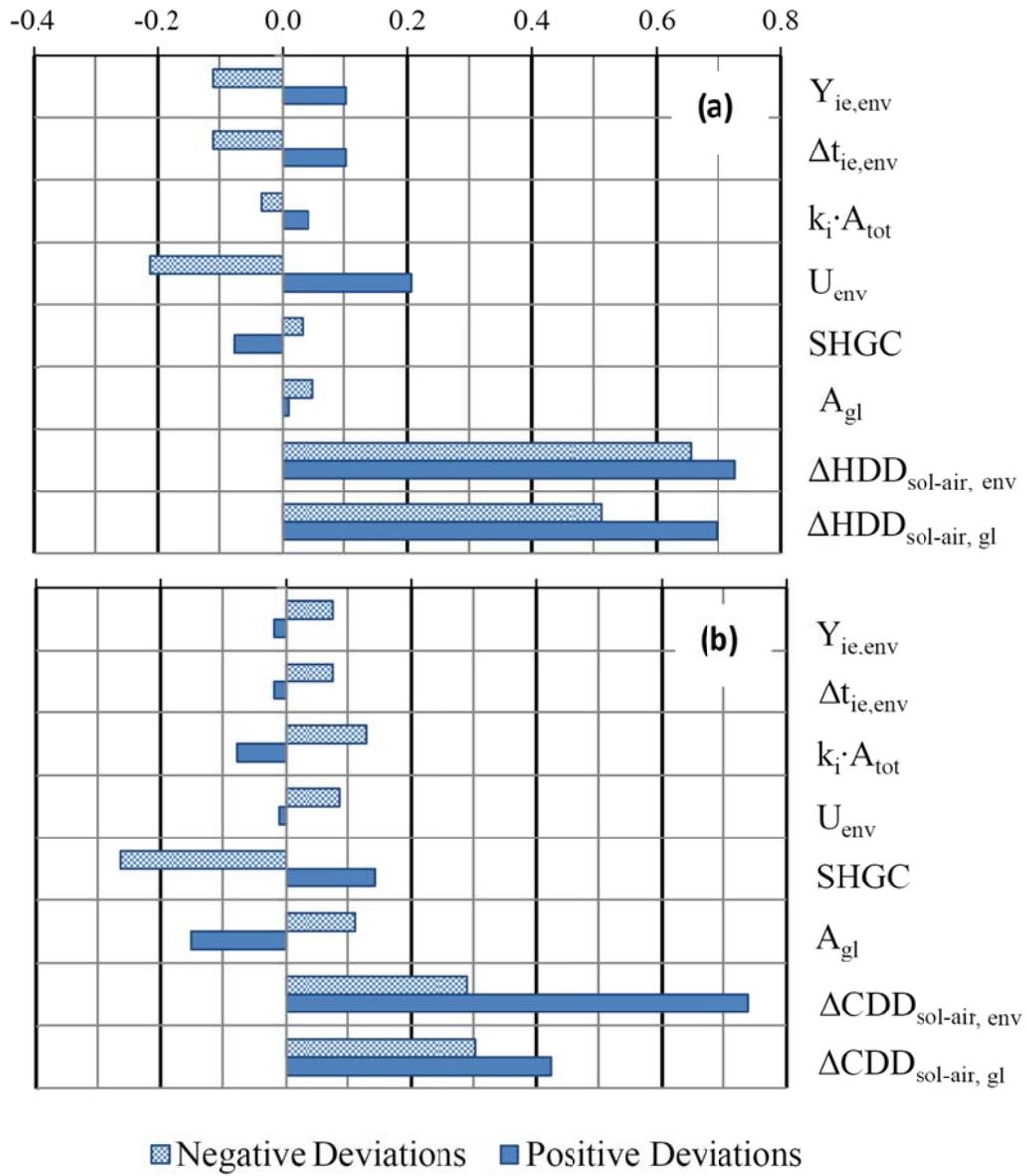| Criteria	A		B	
	Upgrade	Downgrade	Upgrade	Downgrade
Aosta	2.1%	20.8%	0.0%	33.3%
Bergamo	0.0%	14.6%	0.0%	18.8%
Monza	0.0%	20.8%	0.0%	13.0%
Trento	0.0%	58.3%	0.0%	58.3%
Varese	25.0%	0.0%	18.8%	0.0%

Figure 1

Figure 2

Figure 3

Graphical abstract

Analysis of the raw weather data of historic series
(dry bulb temperature, solar radiation, relative humidity, wind speed)

Selection of the **North Italy climates**

Development of **test reference years** according to **EN ISO 15927-4:2005**

Study of the **representativeness** of the test reference year

Weather parameters

Building energy performances

Building performance energy rating

Sensitivity analysis of multi-year energy performances