Long term evaluation of building energy performance: comparison of the test reference year and historical data series in the North Italian climates

Giovanni Pernigotto – University of Padova, Vicenza, Italy & Eindhoven University of Technology, Eindhoven, The Netherlands
Gianluca Antonacci – CISMA Srl, Bolzano, Italy
Paolo Baggio – University of Trento, Trento, Italy
Andrea Gasparella – Free University of Bozen-Bolzano, Bolzano, Italy
Jan Hensen – Eindhoven University of Technology, Eindhoven, The Netherlands

Abstract

The pursuit of better energy performance of buildings led to the recourse to more detailed instruments of analysis, requiring more complex and detailed inputs, such as the hourly weather data. In this work, the representativeness of the *test reference year* (TRY$_{EN}$) weather data, recently developed in Italy in accordance with the procedure proposed by EN ISO 15927-4:2005, has been studied evaluating the energy performance – energy needs and peak loads – of a set of different simplified reference buildings by means of TRNSYS simulation code, using both the TRY$_{EN}$ and the TRY$_{EN}$ source multi-year collected weather series for 5 north Italian locations.

The results have been analysed by means of both descriptive and inferential statistics. The variability of energy performance has also been correlated with the envelope characteristics, in order to estimate a sensitivity of the different buildings to the weather data variability.

1. Introduction

In many design applications, the use of simplified calculation methods, such as the quasi-steady state method proposed by the EN ISO 13790:2008 (CEN, 2008) for the evaluation of a building energy consumption, cannot provide results detailed enough to allow advanced investigations aimed at achieving both a high energy efficiency and an adequate occupants' visual and thermal comfort. This fact is making recourse to the detailed dynamic simulation tools by professionals more and more frequent.

The higher capability in calculating detailed outputs by simulations codes requires more complex and detailed inputs. As regards the weather data, while in simplified methods the user needs only a dataset of monthly mean values of dry bulb temperature, solar radiation and relative humidity, like the ones in the Italian Standard UNI 10349:1994 (UNI, 1994), in simulation tools the weather data inputs generally require at least an hourly discretization.

We can distinguish three kinds of data for dynamic simulation (Keeble, 1990): the multi-year weather data, the typical year and the representative days. The multi-year weather data are the best solution, in case of trend and sensitivity analyses of the building performance to the variability of the weather solicitations, aimed at a design which is robust to climatic changes (Struck *et al.*, 2009). Complete multi-year series, with low measurement errors and a good representativeness, are available for a limited number of localities in Italy, since the local environmental protection agencies (ARPA) have started to collect weather data in the urban areas only 20 years ago, in the best cases (Baggio *et al.*, 2010).

The use of typical years instead of multi-year weather data leads to a loss of information but is required to mitigate the impact of missing and wrong data and to provide a single standard weather condition for assessing the energy performance of a building in a particular location. One of the first definitions of typical reference years (TRY) was given by Lund (1974 and 1991) and Lund and Eidorff (1980): the reference years have to be characterized by *true frequencies* (i.e., the

TRY 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) and *true correlations* (i.e., the weather data are cross-correlated variables). The last feature is probably one of the most important, as also noted by Guan (2009).

Different approaches are available in the literature for the construction of a TRY but each one starts from the calculation of some weather parameters (e.g., daily solar radiation) for the selection of the representative month from the collected data, as suggested by Hall *et al.* (1978).

In accordance with Harriman *et al.* (1999), the choice of the main variables should be made with the perspective of the final use of the TRY, distinguishing the sizing and the energy assessment. Moreover, Hensen (1999) remarked that a proper statistical weighting for the primary parameters should be used, based on the type of building which will be analysed.

In Italy, the procedure selected for developing the new TRY_{EN} starting from ARPA's data is the one described in the European technical Standard EN ISO 15927-4:2005 (CEN, 2005). Its selection method is based on the dry bulb temperature, the solar radiation and the relative humidity as primary variables and the wind speed as secondary one.

In this work, the representativeness of the test reference year has been studied by carrying out different dynamic simulations with both TRY_{EN} and multi-year data series and analysing the annual energy needs and peak loads (both 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. In addition, the sensitivity of the different building envelope characteristics to the variability of 5 north Italian climates has been evaluated.

2. Methods

2.1 Analysis and selection of the weather data

The raw data were available for the capital cities of each province in four north Italian Regions: Emilia-Romagna, Lombardia, Trentino-Alto Adige/Südtirol and Valle d'Aosta. They have been first analysed in order to identify the outliers, according to the following criteria:

- *horizontal global solar radiation*: the values exceeding the solar constant or positive during the night-time;
- *dry bulb temperature*:
  - the values exceeding 50% of the 99th percentile;
  - the data with a derivative larger than ± 4 K h^{-1};
  - periods with constant values for more than 5 h;
- *relative humidity:*
  - the values exceeding 100% or null;
  - periods with constant values for more than 5 h (if lower than the 75th percentile);
- *wind velocity:*
  - the values exceeding 50% of the 99th percentile or negative;
  - periods with constant values for more than 5 h (if the registered speed is larger than the anemometer's minimum speed).

Known bias errors have been corrected.

In order to follow as closely as possible the prescription by the EN ISO 15927-4:2005, which recommends having at least 10 years for the development of a TRY_{EN}, only locations with at least 8 years in the data series and with less than 10% of wrong/missing data for each variable and each year were considered. Wrong and/or missing data have been replaced using the linear interpolation for the temperature, the relative humidity and the wind speed when the consecutive data to correct were less than 6, otherwise a cyclic interpolation has been considered (Prada, 2012).

The selection procedure led to identify 5 cities:

Aosta (with 8 years available), Bergamo (10 years), Monza (9 years), Trento (10 years) and Varese (9 years).

2.2 TRY_{EN} calculation

For each location, a TRY_{EN} has been built in accordance with the EN ISO 15927-4:2005 procedure 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 calculation the cumulative distribution function *Φ(p, m, i)* for each parameter and ith day as:

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

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 ith day, as

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

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

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

5. sorting of the months for increasing values of *Fs* 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 deviation between the mean wind speed of the month *m* of the year *y* and the mean multi-year 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 one are smoothed by means of a cubic spline interpolation in order to avoid discontinuities.

2.3 Set of reference buildings

A sample of 48 different simplified thermal zones has been developed in accordance with a full factorial plan.

The base module consists in single thermal zone with 100 m^2 of squared floor, 3 m of internal height and the façades oriented towards the main cardinal directions. The thermal bridges have been neglected and the floor has been modelled as on a ventilated cave (i.e., without sun exposition and infrared thermal losses towards the sky dome), instead of in touch 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 the opaque components have been modelled with a two-layer structure with insulation on the external side and a massive layer on the internal one, 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 material are shown in Table 1. The windows are positioned all on the same façade and consist in a double-pane glazing (U_{gl} = 1.1 W m^{-2} K^{-1}) and in a timber frame (U_f = 1.2 W m^{-2} K^{-1}), whose area is 20% of the whole window area. The internal gains have been assumed equal to 4 W m^{-2}, half radiative and half convective, as indicated by the EN ISO 13790:2008 for residential dwellings. The ventilation has a constant rate of 0.3 ACH, as suggested by the Italian technical Specification UNI/TS 11300-1:2008 (UNI, 2008).

The considered variables are the most relevant building envelope parameters and, with the exception of the window orientation, each one presents a high and a low level:

- the insulation level of the envelope components (5 cm or 15 cm of polystyrene) in order to have 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});
- the 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);
- the solar heat gain coefficient of the glazing (equal to 0.608 or 0.352);
- size of the windows (14.56 m^2 or 29.12 m^2);
- the orientations of the windows (East, South or West).

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]	0.1	0.3	0.05/0.15
Thermal resistance R [m^2 K W^{-1}]	0.77	0.81	1.25/3.75

Table 1 – Properties of the opaque components

The different cases have been simulated with TRNSYS, considering the following assumptions:

- the timestep is coherent with the hourly discretization of the weather data, in order to avoid interpolation strategy influencing, in particular, the peak load results;
- constant convection coefficients have been selected in accordance with the Standard EN ISO 6946:2007 (CEN, 2007);
- the long wave radiation exchanges are considered according to the star network approach by TRNSYS;
- the heating and the cooling set-point have been fixed 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 heating and cooling seasons have been defined.

3. Results and discussion

3.1 Average monthly data

The monthly values of average dry bulb temperature, daily horizontal solar radiation and relative humidity of the different years and TRY$_{EN}$ have been calculated and compared, as in Figure 1 for the location of Trento.

Generally, the TRY$_{EN}$ monthly value is within the range between Q_1 and Q_3 but it is rarely close with the median for the three climatic parameters at the same time. This is a consequence of the statistical method proposed by EN ISO 15927-4:2005 for the selection of each month, which tries to minimize the sum of the differences of the three parameters together.

3.2 Annual energy needs and peak loads

In Figure 2 the results for the energy needs of 48 thermal zones of the sample have been represented for the analysed localities. For the heating energy needs, the average values are generally within the ±10% range, which means that the error provided by the TRY$_{EN}$ weather data respect to the average of multi-year real data is under 10%.

In the five locations, the general trend of the deviation is not the same:

- in Bergamo and in Trento the TRY$_{EN}$ weather files lead to overestimations of the heating energy needs with respect of average over the multi-year series;
- in Monza the TRY$_{EN}$ weather file shows an underestimation;
- in Aosta and in Varese there is a good agreement between results simulated with the TRY$_{EN}$ file and average values on the multi-year series.

Also for the cooling energy needs, the differences between the TRY$_{EN}$ results and the averages on the multi-year series are generally within ±10%:

- by using the TRY$_{EN}$ weather data, in Aosta, Bergamo, Monza and, in particular, Trent

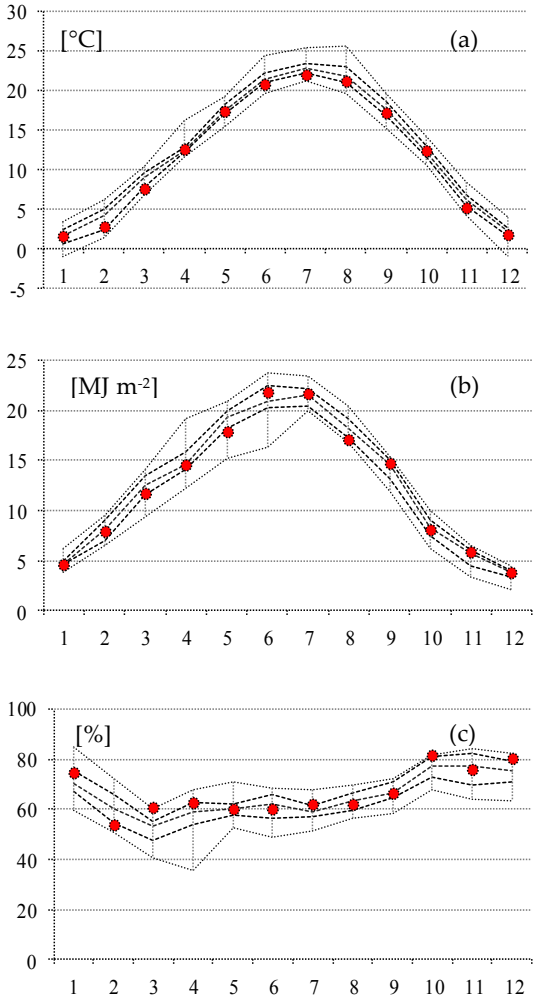

Fig. 1 – (a) Average monthly temperature (b) average daily horizontal global radiation and (c) average monthly relative humidity for Trento. The red dots represent the TRY_{EN} monthly values, the external dotted lines represent the maximum and the minimum for the multi-year series, the internal dotted lines the first and the third quartile (Q_1 and Q_3), while the continuous line is the median.

- there are underestimations of the cooling needs;
- in Varese a slight overestimation is registered.

The peak loads are represented in Figure 3. For the heating peak loads, the deviations between the TRY_{EN} results and the averages over the multi-year series are within a range of 10%:

- for all locations except Bergamo the TRY_{EN} weather file causes a slight underestimation, which is more marked for Trento;
- in Bergamo there is an overestimation by the TRY_{EN} weather file.

Also for the cooling peak loads, the results are generally within the ±10% range but the deviations present a larger variability. The TRY_{EN} weather file causes an underestimation for Aosta while for the other locations there is a good agreement.

Both for the energy needs and the peak loads, for the heating analysis the results are well aligned while for the cooling one a certain variability can be observed, demonstrating that the considered buildings present different responses to the use of a TRY_{EN} weather file instead of the multi-years data.

3.3 Statistical analysis

In order to study the variability of the energy performance and its correlation with the building envelope characteristics, the results with the TRY_{EN} weather files have been considered as a benchmark and the deviations between the energy needs and peak loads simulated in each year and the ones of the TRY_{EN} have been calculated. The deviations have been analysed by means of Pearson's correlation index, distinguishing the positive and the negative differences because of the linear definition of the index. The considered variables have been distinguished into the ones describing the envelope characteristics and the ones describing the external solicitation.

For the energy need deviations, the considered variables are:

- the variables aimed at describing the dynamic behaviour of the opaque envelope, such as $Y_{ie,env}$ [W m^{-2} K^{-1}], the area-weighted average periodic thermal transmittance, $\Delta t_{ie,env}$ [h], the area-weighted average time shift, and $k_i \cdot A_{tot}$ [kJ K^{-1}], the total internal heat capacity;
- U_{env} [W m^{-2} K^{-1}], the area-weighted average thermal transmittance of the opaque envelope;
- *SHGC* [-], the solar heat gain coefficient of the glazing;
- A_{gl} [m^2], the glazing area;
- the deviation between the area-weighted *Heating/Cooling Degree Days* [K d] calculated using a particular year and the ones of the TRY_{EN} (both for the opaque envelope and for the transparent one).

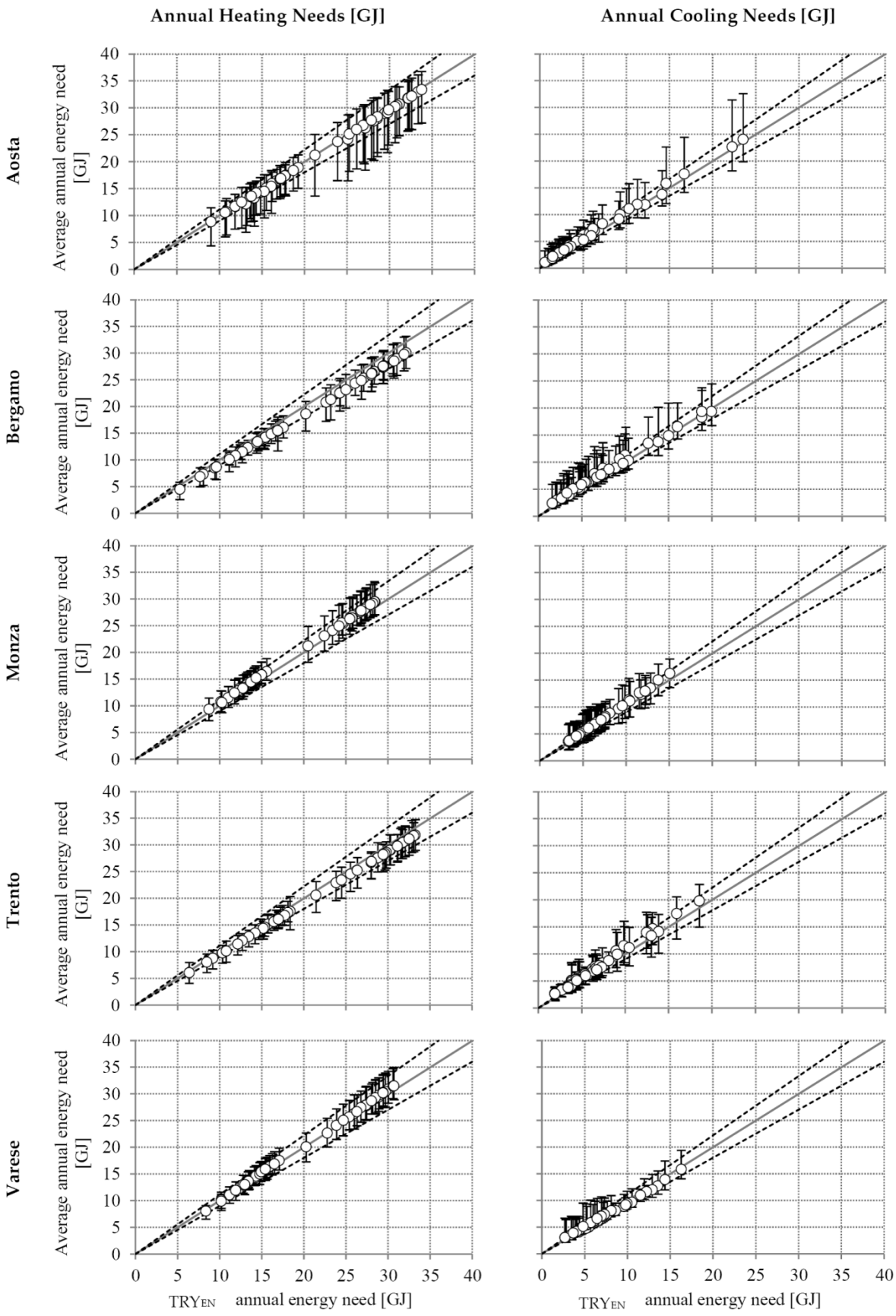

Fig. 2 – Heating and cooling energy needs: the dots are the average energy needs for the considered 10 years, the bars represent the maximum and the minimum in the multi-year series and the dotted lines a deviation of ±10% respect of the TRY_{EN} values

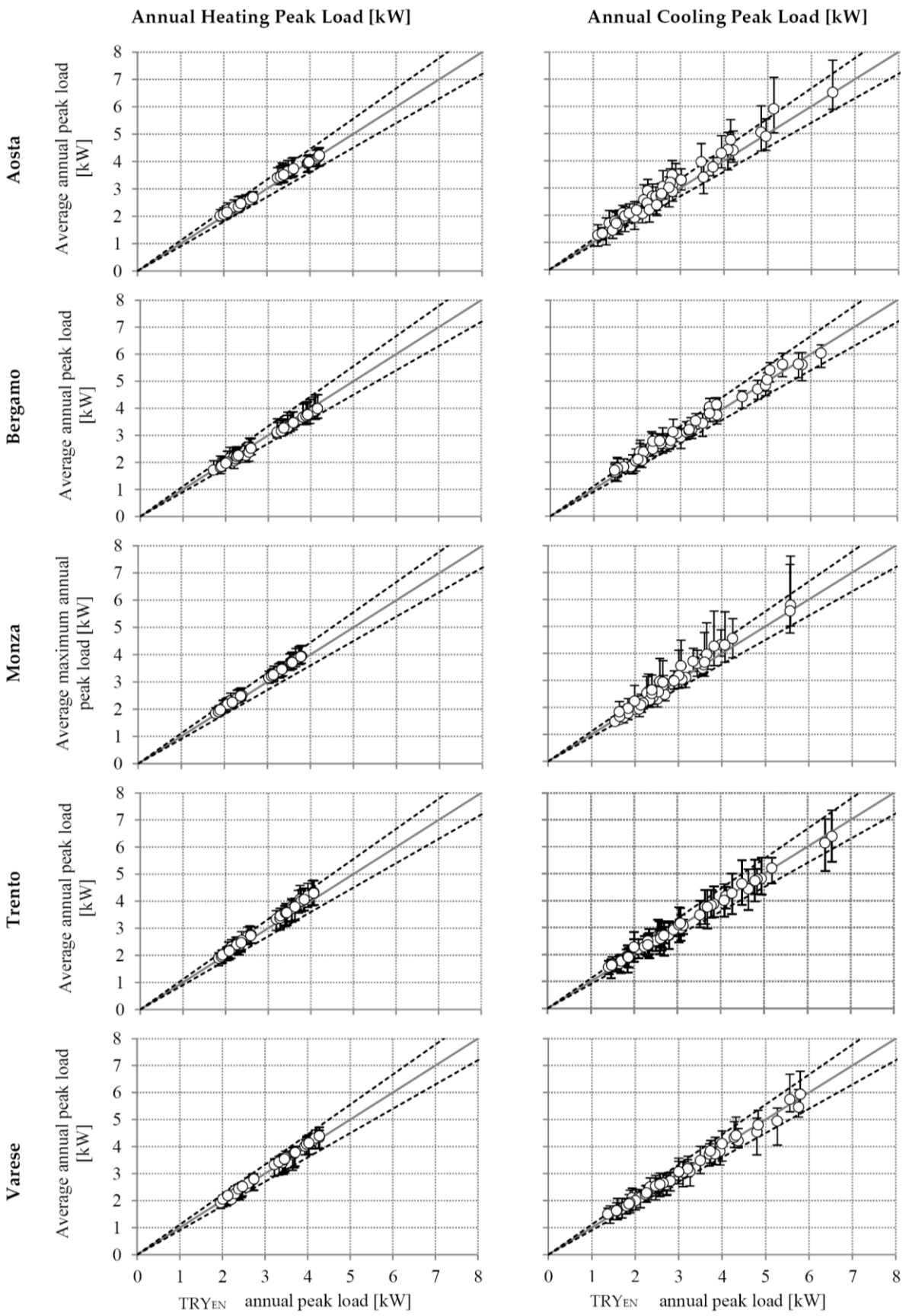

Fig. 3 – Heating and cooling peak loads: the dots are the average energy needs for the considered 10 years, the bars represent the maximum and the minimum in the multi-year series and the dotted lines a deviation of ±10% respect of the TRY_{EN} value

The HDD_{env}, CDD_{env}, HDD_{gl} and CDD_{gl} have been calculated for each orientation considering respectively the sol-air temperature for the opaque components and the equivalent sol-air temperature for the transparent components, according to the Eq. 4 and 5 (Gasparella *et al.*, 2011):

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

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

Area-weighted heating/cooling degree days have then been calculated per each year and used for determining the deviations ΔHDD_{env}, ΔCDD_{env}, ΔHDD_{gl} and ΔCDD_{gl}.

For the peak load deviations, the variables are the same, with the exception of the ones describing the variability of the external solicitation:

- $\Delta\theta_{min}$ [°C], the deviation between the minimum annual external temperature for a considered year and the one for the TRY_{EN} has been used instead of ΔHDD_{env} and ΔHDD_{gl};
- ΔH_{hor} [MJ m^{-2}], the deviation between the total horizontal solar radiation per square meter and $\Delta\hat{H}_{2dd}$ [MJ m^{-2}], the deviation between the annual peak of the 2-days cumulated solar radiation incident on the windows for a considered year and the one for the TRY_{EN}, instead of ΔCDD_{env} and ΔCDD_{gl}.

The indexes for the energy needs deviation have been represented in Figure 4 and the ones for the peak loads in Figure 5. The most influencing parameter on the variability of the heating energy needs is, as expected, the deviation of the heating degree days. In the reduction of the variability, an important role belongs to the characteristics of the opaque components (limiting U, $Y_{ie,env}$ and $\Delta t_{ie,env}$ the variability of the energy needs is reduced). For the cooling deviations, the most influencing parameter, besides the deviation of the cooling degree days, is the solar heat gain coefficient. Also the glazing area appears to have a light correlation for the positive deviations. For the heating peak loads the most influencing parameter on the variability is the deviation of the minimum external temperature. The opaque components are the most correlated with the variability of the peak deviations, both on the steady and dynamic point of view. For the cooling peak loads, the variables chosen for describing the external forcing solicitation are not able to fully justify the variability by themselves. With the exception of the glazing area, the correlations appear very weak, suggesting that interactions between the different characteristics (dynamics of the opaque components and entering solar radiation through the glazings) could be pursued to reduce the variability of the cooling peak loads.

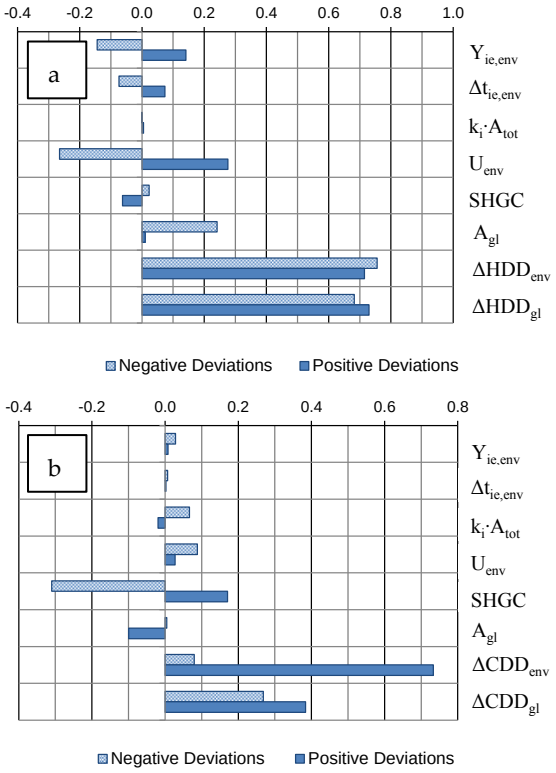

Fig. 4 – Pearson's indexes for (a) the heating needs deviations and (b) for the cooling needs deviations

4. Conclusion

In this work the TRY_{EN} weather files have been compared with the multi-year series of the data collected in 5 north Italian locations, analysing the annual energy needs and the peak loads of a set of reference buildings. Analysing the monthly average temperatures, solar radiation and humidity it can be noticed that the correspondence with the TRY_{EN} values and the averages is not good

for the three parameters at the same time. That

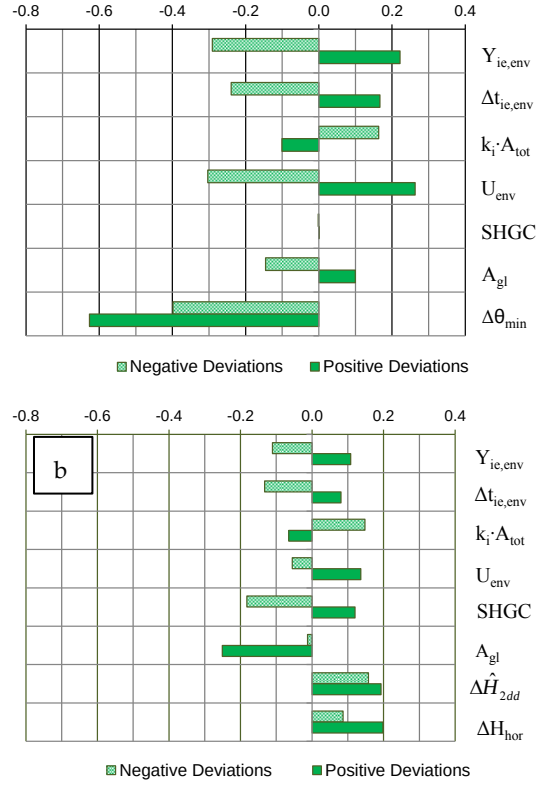

Fig. 5 – Pearson's indexes for (a) the heating peak loads deviations and (b) for the cooling ones

suggests a possible change of the Standard procedure by introducing weighting coefficients, in order to develop different TRY_{EN} to use for specific purposes, as already underlined in literature. The mean of the results of the multi-year series are within a 10% deviation from the TRY_{EN} results but in some cases (Trento and Bergamo) the TRY_{EN} overestimates/underestimates.

The correlations between the building envelope characteristics and the variability of the energy performances in a multi-year analysis have been also considered. The thermal transmittance and also the dynamic parameters can be considered for reducing the variability of the heating energy needs and peak loads. The solar heat gain coefficients and the window size are correlated with the cooling energy needs and peak loads (and, so, generally speaking, the reduction of the entering solar radiation can limit the variability of the cooling energy performance).

5. Nomenclature

Symbols

A	area (m²)
c	specific heat capacity (J kg^{-1} K^{-1})
CDD	cooling degree-days (K d)
F,Φ	cumulative distribution functions (-)
Fs	Finkelstein-Schafer's statistics (-)
H	solar global radiation (MJ m^{-2})
HDD	heating degree-days (K d)
I	solar global irradiance (W m^{-2})
J, K	rank order (-)
k	internal heat capacity (kJ m^{-2} K^{-1})
Q	quartile (-)
R	thermal resistance (m² K W^{-1})
s	thickness (m)
SHGC	Solar Heat Gain Coefficient (-)
U	thermal transmittance (W m^{-2} K^{-1})
Y_{ie}	periodic transmittance (W m^{-2} K^{-1})
α	solar absorptance (-)
Δt_{ie}	time-shift (h)
λ	thermal conductivity (W m^{-1} K^{-1})
ρ	density (kg m^{-3})
θ	temperature (K)

Subscripts/Superscripts

2dd	2-day cumulated
e	external
env	referred to the opaque envelope
f	referred to the frame
gl	referred to the glazings
hor	horizontal
i	internal
r	radiative
s	surface
sky	referred to the sky-dome
sol-air	referred to the sol-air temperature
tot	total

References

Baggio P., Corrado V., Murano G., and Riva G. 2010. Definizione degli anni tipo climatici delle province del Nord Italia. La Termotecnica, 61 (9).

European Committee for Standardization (CEN). 2005. EN ISO 15927-4:2005 Hygrothermal performance of buildings - Calculation and

presentation of climatic data - Part 4: Hourly data for assessing the annual energy use for heating and cooling. Brussels. Belgium.

Gasparella A., Pernigotto G., Cappelletti F., Romagnoni P., Baggio P. 2011. Analysis and modelling of window and glazing systems energy performance for a well insulated residential building. Energy & Building, 43(4).

Guan L. 2009. Preparation of future weather data to study the impact of climate change on buildings. Building & Environment, 44(4).

Hall I., Prairie R., Anferson H. and Boes E. 1978. Generation of a typical meteorological year for 26 SOLMET stations. Technical Report SAND - 78- 1601, Sandia Lab., Albuquerque, U.S.

Harriman L.G., Colliver D.G. and Quinn H.K. 1999. New weather data for energy calculations. ASHRAE Transactions, 41(3).

Hensen J. 1999. Simulation of building energy and indoor environmental quality - some weather data issues. Proc. Int. Workshop on Climate data and their applications in engineering. Prague.

Keeble E. 1990. Availability of UK climatic data for use in simulation. BEPAC Technical Note 1, Building Research Establishment.

Lund H. 1974. The reference year a set of climate data for environmental engineering. In 2nd Symposium on the use of computers for environmental engineering. Paris, France.

Lund H. 1991. The design reference year. In 3rd IBPSA Conference. Nice, France.

Lund H. and Eidorff S. 1980. Selection methods for a production of test reference year. Technical Report ES DK - 248-7., Copenhagen, Denmark.

Prada A. 2012. Energy performance of buildings: modeling of dynamic summer behavior. Ph.D. Thesis, University of Trento, Trento.

Struck C., de Wilde P., Evers J. E. J., Hensen J. and Plokker W. 2009. On selecting weather data sets to estimate a building design's robustness to climate variations. Proc of the 11th IBPSA Building Simulation Conference. Glasgow, U.K.