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Impact of Reference Years on the Outcome of Multi-Objective Optimization for Building Energy Refurbishment

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Abstract: There are several methods in the literature for the definition of weather data for building energy simulation and the most popular ones, such as typical meteorological years and European test reference years, are based on Finkelstein–Schafer statistics. However, even starting from the same multi-year weather data series, the developed reference years can present different levels of representativeness, which can affect the simulation outcome. In this work, we investigated to which extent the uncertainty in the determination of typical weather conditions can affect the results of building energy refurbishment when cost-optimal approach is implemented for the selection of energy efficiency measures by means of the NSGA-II genetic algorithm coupled with TRNSYS simulations. Six different reference years were determined for two north Italy climates, Trento and Monza, respectively in the Alpine and in the continental temperate regions. Four types of energy efficiency measures, related to both building envelope and HVAC system, were applied to six existing building typologies. Results showed how the choice of reference year can alter the shape of the Pareto fronts, the number of solutions included and the selection among the alternatives of the energy efficiency measures, for the entire front and, in particular, for energy and economic optima.

Keywords: EN ISO 15927-4 reference year; typical meteorological year; genetic algorithm; building energy simulation; multi-objective optimization; Finkelstein-Schafer statistics

1. Introduction

One of the main goals of building energy simulation (BES) is to characterize the response of the building system to both internal and external dynamic boundary conditions. However, meaningful transient profiles are often difficult to identify and adopt as inputs. Indeed, both occupants' behavior, on the internal side, and weather solicitation, on the external one, are intrinsically stochastic in nature [1,2]. Consequently, provided that BES goal is not to replicate reality but to allow for understanding how a building system works, it is of fundamental importance to specify representative boundary conditions. Their typical time-discretization is hourly but, in some cases, also shorter intervals are adopted.

As regard the weather input, the search for reference series to use is particularly complex, as shown in the literature [1,3]. First, the external input is multi-dimensional and weather data are collections of several weather or climatic variables recorded in meteorological stations. In particular, air temperature and humidity and solar irradiance are the quantities necessary to run simulations. Moreover, solar irradiance, which is clearly different on the various external surfaces of the building envelope, is generally expressed as global horizontal irradiance and then elaborated by means of solar models to distinguish horizontal beam and diffuse components and to project their values on the envelope surfaces, whatever their slope and azimuth. When available, diffuse horizontal irradiance and direct normal irradiance are adopted instead of the global horizontal one. Nevertheless, the number of meteorological stations in which both are actually recorded is small compared to the total ones [4]. To these three primary variables, the wind vector is commonly added, expressed as wind velocity and main wind direction. However, the representativeness of wind conditions recorded in the closest meteorological station with respect to the building site can be very low, depending on its actual local characteristics [5], and, compared to the primary variables, wind can play a minor role on the energy performance for some building typologies and climates [6]. As a whole, alternatives are possible and the number of weather variables can change, depending on the specific methodology.

Even if some authors recommend the adoption of multi-year weather input for BES [7], at the current state of the art, reference years are generally preferred [8,9]. After an initial period in which the reference year was defined as an actual year of data belonging to the multi-year series (e.g., [10]), the technical and scientific literature agreed with the need of developing reference years as artificial years to improve their representativeness [11]. Lund [12,13] and Lund and Eidorff [14] clarified that the typical or reference year should be composed by true sequences of weather recordings, with true frequencies and true correlations. This means that the artificial year has to be prepared starting from actual weather recordings, selecting the most typical ones without altering the cross-correlations among weather variables, which are described, for example, in [15]. The series are processed on a monthly basis, making the reference year simply a collection of twelve reference months for a given locality [16]. Nevertheless, ensuring a good representativeness of three or four weather variables at the same time is not easy task, especially when the historical series are short and climate affected by high variability [17]. For this reason, proper statistical techniques are adopted, such as Kolmogorov–Smirnov (e.g., as done by Festa and Ratto [18]) and Finkelstein–Schafer non-parametric tests (e.g., as done by Hall et al. [16]). The latter, in particular, has become popular in the framework of the development of reference years, both in the literature [19] and in technical standards (e.g., EN ISO 15927-4 [20]). However, those tests can be performed for one weather variable at a time and are not addressed to identify the best candidates but to isolate those months remarkably different from the long-term average trends (e.g., see the "Danish method" by Andersen et al. [21] and Lund and Eidorff [14]). This implies that synthesis of the different statistical outcome is required but the approaches commonly adopted do not take into account of statistical significance and are, to some extent, subjective [16,22] and aimed to maximize the representativeness for specific climate conditions or use of the reference weather data [23]. As a result, several alternative methods are present in the literature. At the moment, the most popular ones are those implemented for the development of TMY2 [24] and TMY3 [25] and those described in the technical standard EN ISO 15927-4:2005 [20], which are often applied with slight modifications in the different countries, as in the current Italian standard UNI 10349-1:2016 [26].

The alternative methods can lead to different results and, in particular, to different levels of accuracy with respect of the multi-year series [27,28]. This can impact in different ways on the BES outcome, as discussed by several contributions in the literature. For example, Huang [29], Skeiker [30] and Chiesa and Grosso [31] analyzed the impact on energy performance for space conditioning, Garcia and Torres [32] and Realpe et al. [33] focused on PV systems, while Bilbao et al. [34] and Sorrentino et al. [35] discussed both. In a previous work, Pernigotto et al. [17] checked the representativeness of EN ISO 15927-4 reference years for north Italy climates in terms of effect on the building energy labeling of 48 reference buildings. In a further development [27], the annual energy needs for space heating and cooling of the same set were simulated considering different reference years built starting from the same multi-year series. Again, different levels of representativeness were detected, with different performances from climate to climate, which pushed Pernigotto et al.

to propose new approaches in order to ensure a better result independently of the specific climatic conditions. The impact of the type of reference year on BES, nevertheless, is far from being comprehensively assessed.

After the publication of the European Directive 2010/31/EU [36] and the European Commission Delegated Regulation 244/2012 [37], we have been witnessed at an increasing number of research works coupling BES simulations with optimization to identify cost-optimal equivalent levels of achievable energy efficiency during building economic lifecycle, the most convenient energy efficiency measures or to define subsidization strategies for energy refurbishment (e.g., [38,39]). In many contributions, refurbishment involves more objectives, such as building economic and energy performances, and is driven by optimization algorithms, among which the family of genetic algorithms is currently the most popular [40]. Multi-objective optimization outcome can be affected by several factors, such as the adopted technique [41,42], the characteristics of BES models and, in particular, the used inputs. Focusing on this latter aspect, as a further development of a previous contribution [43], this work discusses the extent to which the different methods for the development of reference years can affect cost-optimal energy refurbishment for north Italy residential building stock. As optimization objectives, building economic performance and primary energy for space heating have been considered.

2. Methods

The following sections describe the methods implemented for the generation of the different reference years, the sample of buildings and the considered energy efficiency measures, as well as settings for building energy simulations and multi-objective optimization. The results obtained with the different reference years have been compared in terms of energy and economic results achievable through the optimized refurbishment, composition of the Pareto fronts and selection of the energy efficiency measures.

2.1. Development of Reference Years

As clarified in the introduction, there are several methodologies in the literature for the definition of typical or reference years for BES. In a previous work [27], four widespread approaches based on Finkelstein–Schafer statistics were selected and two new methods proposed. Six types of reference years were analyzed: (RY_1) EN ISO 15927-4 [20], (RY_2) Wilcox and Marion's method [25], (RY_3) the method by Pissimanis et al. [22], (RY_4) the minimum Finkelstein–Schafer statistic, (RY_5) Best rank I, and (RY_6) Best rank II. Their representativeness with respect to the multi-year weather data series was discussed both in terms of weather variables and in terms of impact on the building energy needs for space heating and cooling.

The analysis was performed studying five north Italy climates: two Alpine climates (i.e., Aosta and Trento) and three continental temperate climates of the Po Valley (i.e., Bergamo, Monza, Varese). All these climates belong to the Italian climatic zone E according to the classification established by the national laws, i.e., DPR 412/1993 [44] and 74/2013 [45], which includes almost 53% of Italian municipalities and is characterized by large heating demand. From this comparison, Trento and Monza reference years, developed starting, respectively, from 10- and 9-year series, showed the largest impact on heating needs and, for this reason, have been selected for the current analysis. In particular, for the sample of buildings considered in [17,27], in Trento the annual energy needs for space heating varied from a minimum of −9.26% to a maximum of +4.28% with respect to the multi-year averages and in Monza from −8.23% to +11.53%. For the climates studied in [27], simulation results obtained with RY_5 and RY_6 had generally a better accuracy with respect to those with multi-year series. However, none outperformed the others for all climates: for those considered in this study, the largest representativeness was registered for RY_5 and RY_6 in Trento (respectively, with +0.52% and +0.79%) and for RY_2 and RY_6 in Monza (respectively, with −0.02% and +0.7%).

Some additional details regarding the procedures for the definition of the six reference years are reported in the following paragraphs.

2.1.1. RY_1: EN ISO 15927-4 Reference Year

The European technical standard procedure can be summarized by means of the following steps.

Starting from the multi-year series, for each primary climatic parameter (i.e., dry bulb temperature, relative humidity and global horizontal solar irradiation), the daily averages p are calculated.

For each calendar month m, the daily averages p are sorted in increasing order to calculate the cumulative distribution function $\Phi(p,m,i)$ 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 the calendar month considering all available years in the series.

For each calendar month m and year y, the daily averages p are sorted in increasing order to calculate 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 given calendar month.

For each month m and year y, i.e., for each candidate, Finkelstein–Schafer statistics F_S can be calculated as:

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

Considering that the larger is the F_S value for a given month, the poorer is its representativeness, rankings are prepared for each climate parameter, with months ordered by increasing F_S values. Then, a global ranking is made by summing the positions of the candidate months in those partial rankings.

Among the top-3 candidate months, the one with the average wind speed closest to the multi-year average one is chosen for the inclusion in the reference year.

Finally, once the 12 reference months are identified, cubic spline interpolation is applied to the first and the final 8 h of dry bulb temperature and relative humidity data of each couple of subsequent months, in order to avoid discontinuities.

2.1.2. RY_2: Reference Year by Wilcox and Marion

The EN ISO 15927-4 procedure was developed starting from the methodology adopted since the late 70s for the definition of typical meteorological years TMY and, more recently, for TMY2 and TMY3. The approaches are very similar, with the main differences relying on the presence of weighting coefficients for the primary climatic variables in the preparation of the rankings and the way in which the final choice is made. In particular, TMY and TMY2 are based on the persistence criterion [16], which was modified in TMY3 definition by Wilcox and Marion [25]. This criterion is applied to daily dry bulb temperatures and solar global horizontal irradiation and considers their frequencies and run lengths (i.e., number of consecutive days with averages above or under a given percentile with respect to long-term distribution). According to Wilcox and Marion [25], the months with more runs than every other one are excluded from the global ranking but, if no candidate month remains, the selection is made by closeness to multi-year mean and median.

2.1.3. RY_3 and RY_4: Reference Years According to Pissimanis et al., and to the Minimum F_s Value

Pissimanis et al. [22] proposed a simplified approach for the final selection of the reference months, focusing only on the hourly distribution of solar global horizontal irradiation. The root mean square differences *RMSD* is calculated with respect to the multi-year hourly distribution for each candidate month. Then, all months with *RMSD* lower than a chosen value or the month with the minimum *RMSD* are identified and, in the case of more candidates for a calendar month, the one which has the minimum F_S values for dry bulb temperature and solar global horizontal irradiation is taken as reference.

Alternatively, some authors in the literature (e.g., [46–48]) chose the reference month simply taking the one with the lowest value of weighted Finkelstein–Schafer statistics.

2.1.4. RY_5 and RY_6: Best Rank I and II Reference Years

Analyzing the experiences reported in the literature, two new approaches have been proposed in [27] for the final selection of the reference months.

According to Best rank I, the last step of the EN ISO 15927-4 procedure is discarded and, simply, the candidate month at the top of the global ranking is considered in the reference year.

In Best rank II, instead, the statistical significance of F_S values is taken into account: only those months with non-significant F_S statistics are included in the partial rankings and only those shared by all primary climatic parameters included in the global one. Finally, as in the Best rank I, the candidate at the top of the ranking is included in the reference year. In the case of no candidates satisfying the requirements, some recommendations, giving priority to maximize the representativeness for dry bulb temperature and solar global horizontal irradiation, are also given in [27].

2.2. *Samples of Existing Buildings*

A sample of six existing building typologies has been defined for the refurbishment, starting from a base module oriented towards the main cardinal directions, with a square floor area of 100 m^2, chosen in agreement with the weighted average surface of the European residential buildings [49], an internal height of 3 m and a window to floor ratio equal to 0.144 (Figure 1). The compactness ratio *S*/*V* of the module has been varied by imposing adiabatic boundary conditions, aimed at characterizing adjacency to other apartments assumed at the same setpoint conditions. All modules have an adiabatic vertical wall while ceiling and floor can be either adiabatic or exposed to the external environment, depending on the specific case modeled. Intermediate flats in multi-story buildings (S/V = 0.3 m^{-1}) are characterized by both ceiling and floor as adiabatic, penthouses (S/V = 0.63 m^{-1}) only by the floor, and semi-detached houses (S/V = 0.97 m^{-1}) have no adiabatic horizontal components. Taking advantage of the findings reported in [39,50], in this study, the windows have been positioned only on the façade in front of the adiabatic wall and oriented towards east (east-oriented buildings) or south (south-oriented buildings).

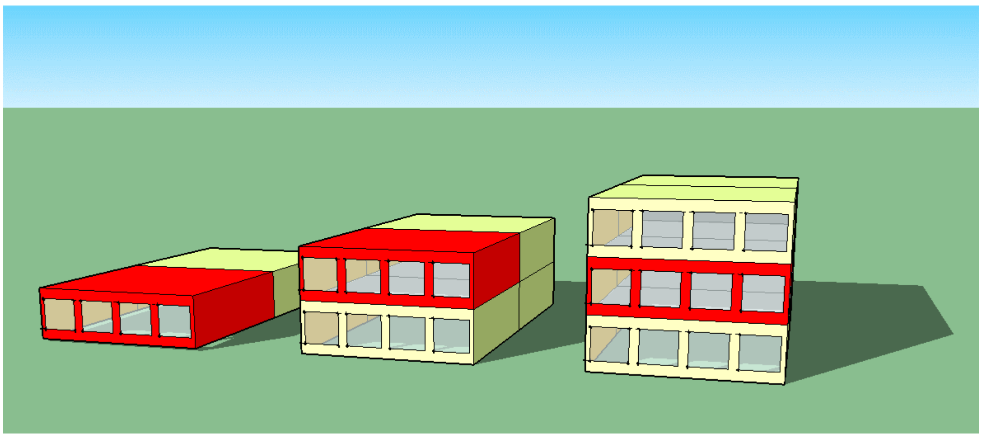

Figure 1. Existing reference buildings: intermediate flat (**Right**); penthouse (**Center**); and semi-detached house (**Left**).

As regards the thermal transmittance of opaque and transparent envelope components, the values typical of the Italian building stock built before Law 373/1976 [51], i.e., the first Italian energy saving law, have been assumed, as shown in Table 1.

Table 1. Envelope properties of the existing configurations.

Clay Block Wall			
λ = 0.25 W·m^{-1}·K^{-1}	ρ = 893 kg·m^{-3}	c = 840 J·kg^{-1}·K^{-1}	U_{wall} = 1.03 W·m^{-2}·K^{-1}
Windows (Single Glazing, S)			
U_{gl} = 5.69 W·m^{-2}·K^{-1}	U_{fr} = 3.20 W·m^{-2}·K^{-1}	A_{fr}/A_{win} = 20%	$SHGC$ = 0.81
Thermal Bridges (Calculated According to EN ISO 10211:2007 [52])			
Ψ_{corner} = 0.098 W·m^{-1}·K^{-1}	$\Psi_{int\text{-}floor}$ = 0.182 W·m^{-1}·K^{-1}	Ψ_{roof} = 0.182 W·m^{-1}·K^{-1}	Ψ_{win} = 0.06 W·m^{-1}·K^{-1}

Internal gains have been assumed as half radiative and half convective according to EN ISO 13790:2008 [53] and defined basing on the room type and the domestic occupancy schedule proposed by the Italian technical specification UNI/TS 11300-1:2014 [54]. Half of the floor area has been assumed as living rooms and the other half as bedrooms. During occupancy time, ventilation air change rate (ACH) has been set to 0.5 ACH according to the Italian Standard UNI 10339:1995 [55]. Infiltration rates, determined according to EN 12207:1999 [56] and EN 15242:2007 [57], have been imposed equal to 0.06, 0.13 and 0.2 ACH, respectively, for the intermediate flats, penthouses and semi-detached houses.

The heating system has been chosen as representative of the solution typically installed in Italian buildings built up to the 70 s and not yet renovated, i.e., a standard natural gas boiler, STD, with capacity determined according to EN 12831:2003 [58] and nominal efficiency η of 89% with respect to the fuel's lower heating value (LHV = 32.724 MJ·Sm^{-3}), coupled with radiators and ON-OFF system control operating between 20 °C and 22 °C. For each configuration, the system serves the building as a single thermal zone [53,54]. The heating season, from 15 October to 15 April for both climates, has been defined according to the laws currently in force in Italy, i.e., DPR 412/1993 [44] and 74/2013 [45].

2.3. Energy Efficiency Measures

In this section, a list of the energy efficiency measures EEMs is presented. The investment costs have been determined in [38,39] by consulting the databases of the Italian Regional Price Lists. Four main EEMs have been considered:

- Installation of an insulating layer of extruded polystyrene (λ = 0.04 W·m^{-1}·K^{-1}; ρ = 40 kg·m^{-3}; c = 1470 J·kg^{-1}·K^{-1}) on the external side of the opaque components, with thickness d_{ins} ranging from 0.01 to 0.20 m with a step of 0.01 m, changed independently for non-adiabatic walls, ceiling (only for penthouses and semi-detached houses) and floor (only for semi-detached houses). The unit investment cost of this EEM can be estimated as in the following equations for both vertical, IC_{vw}, and horizontal walls, IC_{hw}:

$$IC_{vw} = 160 \cdot d_{ins} + 38.53\ EUR \cdot \mathrm{m}^{-2} \tag{4}$$

$$IC_{hw} = 188 \cdot d_{ins} + 8.19\ EUR \cdot \mathrm{m}^{-2} \tag{5}$$

- Substitution of existing windows with new solutions characterized by aluminum frames with thermal break (U_{fr} = 1.2 W·m^{-2}·K^{-1}) and high performance glazing: DH: double glazing with high $SHGC$ (U_{gl} = 1.14 W·m^{-2} K^{-1}; $SHGC$ = 0.61; IC_{DH} = 404.33 EUR·m^{-2}); DL: double glazing with low $SHGC$ (U_{gl} = 1.10 W·m^{-2}·K^{-1}; $SHGC$ = 0.35; IC_{DL} = 439.06 EUR·m^{-2}); TH: triple glazing with high $SHGC$ (U_{gl} = 0.61 W·m^{-2}·K^{-1}; $SHGC$ = 0.58; IC_{TH} = 477.65 EUR·m^{-2}); and TL: triple glazing with low $SHGC$ (U_{gl} = 0.6 W·m^{-2}·K^{-1}; $SHGC$ = 0.34; IC_{TL} = 454.49 EUR·m^{-2}).
- Replacement of the existing standard boiler, STD, due to obsolescence with an equivalent model (IC_{STD} = 1000 EUR) or substitution with either a modulating boiler MOD (η = 96%; IC_{MOD} = 1500 EUR) or condensing boiler COND (η = 101%; IC_{COND} = 2000 EUR). Both modulating and

condensing boilers are equipped with a climatic control system in order to vary the supply temperature as a function of the external air temperature.

- Installation of a mechanical ventilation system, MVS, with heat recovery (IC_{MVS} = 6000 EUR). The system has a nominal ventilation rate of 150 $m^3\ h^{-1}$, a power capacity of 59.7 W and a nominal heat recovery efficiency of 93%. The actual efficiency of the heat recovery η_{HR} clearly depends on the difference between internal and external temperatures and has been modeled as a function of the external temperature ϑ_e [°C] starting from the technical datasheet:

$$\eta_{HR} = 0.0003 \cdot \vartheta_e^4 - 0.0116 \cdot \vartheta_e^3 + 0.1413 \cdot \vartheta_e^2 + 0.7505 \cdot \vartheta_e + 83.051 \quad [\%] \tag{6}$$

The mechanical ventilation system has been set to operate following the occupancy schedule, bypassing the heat recovery when inconvenient.

The proposed EEMs bring also some secondary improvements:

- The additional insulation layers reduce the thermal losses due to thermal bridges and, to take account of that, new linear thermal transmittances have been calculated.
- The windows replacements increase air tightness, which has been considered by halving the infiltration rates estimated for the existing buildings.
- Even though radiators have not been substituted, the adoption of a climatic control system allows for supply water temperatures lower than those under design conditions.

2.4. Building Energy Simulation and Optimization Objectives

Building energy simulations have been run with TRNSYS 17.1 [59] with hourly timestep. Windows have been modeled with LBNL Window 6.3 [60] and the linear thermal transmittances of thermal bridges calculated with LBNL THERM 6.3 [61]. TRNSYS "Type 56" has been used for multizone building modeling and "Type 869" [62,63] for the heating systems, together with "Type 2" for the ON-OFF control, "Type 3" for the calculation of the pump power consumption and "Type 31" for the estimation of distribution heat losses of pipes. As regards the climatic solicitations, Reindl et al. [64] and Perez et al. [65] models have been implemented for the calculation of the solar irradiation on the external surfaces, the fictive sky vault temperature estimated with "Type 69" and the other weather variables read directly from the reference year input. The output of each simulation has been the primary energy demand for space heating, EP_h, according to EN ISO 15217:2007 [66] which is also the first objective considered in optimization.

The other objective is economic and quantified through the Net Present Value (*NPV*), as suggested by the regulation EU 244/2012 [37]. The investment analysis is 30 years long and, besides the investment costs shown before, includes:

- annual maintenance and energy costs for natural gas and electricity, whose unit costs are equal, respectively, to 0.85 EUR Sm^{-3} and 0.25 EUR kWh_{el}^{-1}, according to AEEG [67] and value added tax equal to 10% [68];
- periodic replacement costs due to substitution of building elements; and
- the residual value of the equipment with longer lifespan according to according to EN 15459:2007 [69].

Furthermore, annual increases of energy costs equal to 2.8% and 1.7% have been assumed for natural gas and electricity, respectively [70], and all calculations performed adopting a real discount rate of 3% [37].

2.5. Multi-Objective Optimization with Genetic Algorithm

Since the two considered objectives are in trade-off, it has been possible to define a Pareto front. The calculation of the EEMs belonging to the Pareto front and the determination of the corresponding EP_h and *NPV* have been performed through a multi objective optimization based on the Elitist Non-dominated Sorting Genetic Algorithm (NSGA-II) [71], frequently chosen in the literature because of its superior performance [72]. A Matlab® fitness function has been written to launch TRNSYS simulation, read its output, calculate EP_h and *NPV* and return their values to the genetic algorithm.

The Sobol sequence coupled with a pseudo random generator [73] has been used to select the initial population as a uniform sample of 128 configurations with a reduced risk of oversampling [74,75]. Once evaluated EP_h and *NPV*, the genetic algorithm performs the Tournament Selection Without Replacement [76,77], with a fraction set to 0.5, to identify the best configurations, i.e., the "parents", whose characteristics are combined to give rise to the next generation. "Children" are a random [73] arithmetic mean of two "parents", always feasible with respect to the bounds [78]. In this work, the crossover fraction has been set to 0.8 and mutation, based on Mersenne-Twister pseudo random generator [73], to 0.2. The convergence criterion is based on a variation of the average crowding distance of 10^{-3} between two consecutive generations and the maximum number of generations is 100.

3. Results

3.1. Comparison of Reference Years

A preliminary comparison has been performed between the six reference years developed for Trento and for Monza, as shown in Figure 2 for monthly averages of dry bulb temperature, water vapor partial pressure and daily global horizontal solar irradiation calculated for the RYs and the multi-year series.

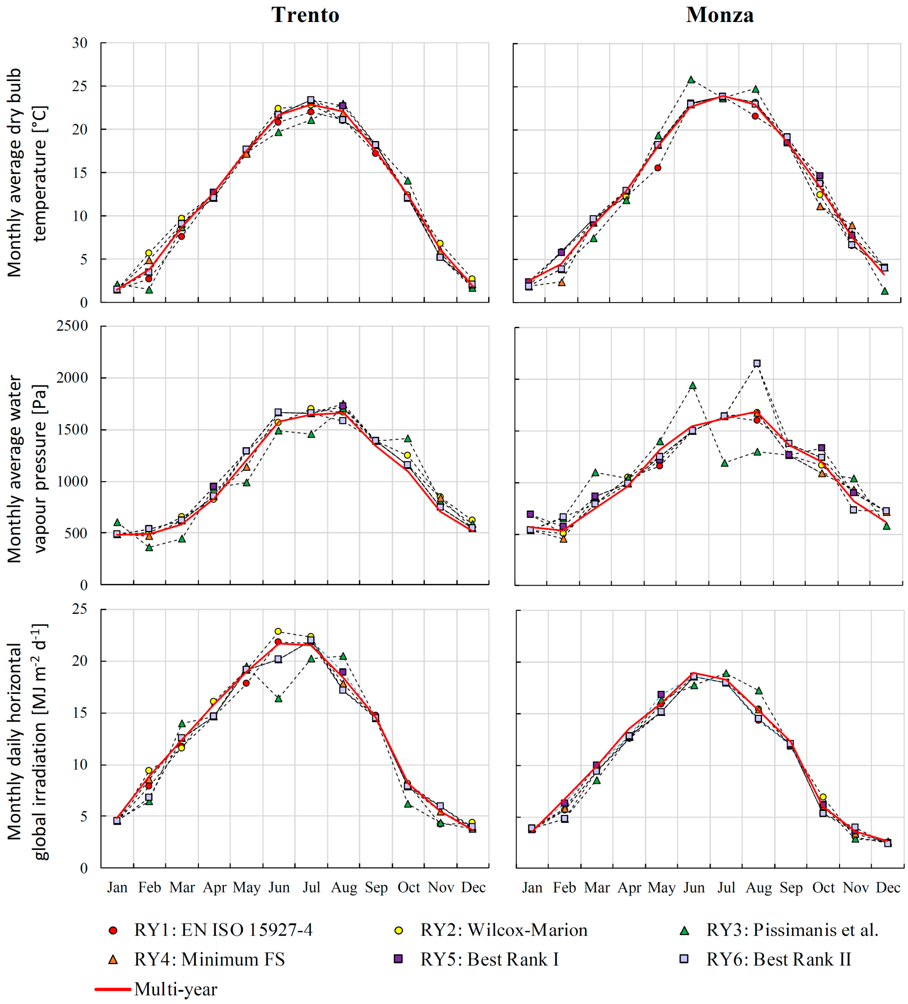

Figure 2. Monthly statistics of climatic variables (dry bulb temperature, water vapor partial pressure and global horizontal irradiation) for the six reference years and the multi-year series in Trento and Monza.

Focusing on the heating season (Table 2), it can be found that the choice of different months can bring differences in terms of Heating Degree-Days calculated with respect to a base temperature of 18 °C, HDD_{18}, and in daily average global solar irradiation on horizontal surface during the heating season, H_{sol}.

Table 2. Heating Degree-Days and daily average global solar irradiation on horizontal surface calculated for the different reference years. The minimum value is highlighted in blue and the maximum one in red.

Reference Year	Trento		Monza	
	HDD_{18} [K·d (day)]	H_{sol} [MJ·m^{-2}·d^{-1}]	HDD_{18} [K·d]	H_{sol} [MJ·m^{-2}·d^{-1}]
RY_1	2610	7.51	2232	5.62
RY_2	2330	7.65	2270	5.68
RY_3	2496	7.27	2459	5.34
RY_4	2448	7.70	2329	5.83
RY_5	2484	7.50	2139	5.93
RY_6	2504	7.49	2269	5.57

In Trento, the maximum HDD_{18} is 2610 K·d and is obtained with RY_1, i.e., the EN ISO 15927-4 reference year, while the minimum, around 11% lower, is 2330 K·d and is found with RY_2, i.e., the reference year according to Wilcox and Marion's method. However, minimum and maximum daily average horizontal global solar irradiations are found for different reference years, specifically for RY_3 and RY_4, i.e., Pissimanins et al., and minimum Finkelstein–Schafer reference years, with a deviation of about 6%.

In Monza, instead, the maximum value of HDD_{18} is, with RY_3 (Pissimanis et al.) and the minimum one with RY_5 (Best rank I), around 13% lower. As regards average daily solar irradiation, the extreme values are found for the same reference years: the coldest year, RY_3, also has the lowest H_{sol}, and the warmest one, RY_5, the largest H_{sol}. In this climate, the deviation is larger and equal to 10%.

3.2. Energy and Economic Performances of the Existing Buildings

Before discussing the outcome of the several optimizations performed, the initial conditions have been analyzed. As can be seen in Tables 3 and 4, energy and economic performances of buildings can change if simulated considering different reference years.

Table 3. EP_h [kWh·m^{-2}·a (year)$^{-1}$] and *NPV* [10^3 EUR] for east- and south-oriented existing buildings in Trento. The minimum value is highlighted in blue and the maximum one in red.

		RY_1	RY_2	RY_3	RY_4	RY_5	RY_6
East-Oriented Buildings							
Intermediate Flat	EP_h	154.2	143.2	154.6	149.6	153.3	153.3
	NPV	42.7	39.7	42.8	41.4	42.4	42.4
Penthouse	EP_h	231.9	217.6	230.8	225.3	229.3	230.1
	NPV	63.8	59.9	63.5	62	63.1	63.3
Semi-detached house	EP_h	294.7	281	292.7	288.7	292	293
	NPV	80.9	77.2	80.4	79.3	80.2	80.5
South-Oriented Buildings							
Intermediate Flat	EP_h	119.8	106.5	122.1	112.6	116.7	116.9
	NPV	33.3	29.7	33.9	31.4	32.5	32.5
Penthouse	EP_h	197.9	182	200.4	190.3	194.6	195.5
	NPV	54.6	50.2	55.2	52.5	53.7	53.9
Semi-detached house	EP_h	265	248.2	266.8	256.7	260.8	262
	NPV	72.8	68.3	73.3	70.6	71.7	72

Table 4. EP_h [kWh·m^{-2}·a^{-1}] and *NPV* [10^3 EUR] for east- and south-oriented existing buildings in Monza. The minimum value is highlighted in blue and the maximum one in red.

		RY$_1$	**RY$_2$**	**RY$_3$**	**RY$_4$**	**RY$_5$**	**RY$_6$**
East-Oriented Buildings							
Intermediate Flat	EP_h	140.4	145.6	157.8	149.5	139.0	146.8
	NPV	38.9	40.3	43.6	41.4	38.5	40.6
Penthouse	EP_h	214.1	220.6	236.1	226.0	212.4	222.5
	NPV	59.0	60.8	65.0	62.2	58.5	61.3
Semi-detached house	EP_h	274.7	282.5	298.7	288.4	272.9	283.8
	NPV	75.5	77.6	82.0	79.2	75.0	77.9
South-Oriented Buildings							
Intermediate Flat	EP_h	118.2	122.5	137.0	126.0	115.9	123.8
	NPV	32.9	34.0	38.0	35.0	32.2	34.4
Penthouse	EP_h	192.8	198.5	217.4	204.4	189.7	200.5
	NPV	53.2	54.7	59.9	56.3	52.3	55.3
Semi-detached house	EP_h	255.2	262.8	283.2	269.3	251.9	263.9
	NPV	70.2	72.2	77.8	74.0	69.3	72.5

In both localities, the largest differences are met in intermediate flats and energy and economic performances for the east-oriented cases are less sensitive to the reference year. In Trento (Table 3), the deviations range from 4% to 8% with respect to the average values for east-oriented cases and from 7% to 14% for the south-oriented ones. In Monza (Table 4), the deviations are slightly larger and range from 9% to 13% for east-oriented cases and from 11% to 17% for the south-oriented ones. The spread of the results is coherent with what observed in previous works [27]. For Trento, the minimum primary energy demand and net present value are registered with RY$_2$, coherently with the HDD_{18} in Table 2, but the maximum ones are found most frequently with RY$_3$, which has the minimum H_{sol}, except for east-oriented penthouses and semi-detached houses, for which RY$_1$, the reference year with maximum HDD_{18}, maximizes the values of EP_h and *NPV*. On the contrary, in Monza, the minimum values are registered with RY$_5$ and the maximum ones with RY$_3$, for all configurations, coherently with HDD_{18} and H_{sol} values in Table 2.

3.3. Pareto Fronts: Shapes and EEMs

After the discussion of the initial conditions for the existing building configurations in 3.2, the shape of the Pareto fronts and the number and type of EEMs is analyzed.

As regards the number of identified solutions belonging to the fronts, it can vary significantly according to the reference year used as input. For the cases with east-oriented windows in Trento, the number of identified solutions in the fronts ranges from 10 to 15, 14 to 29 and 14 to 23, respectively, for intermediate flats, penthouses and semi-detached houses. Considering the buildings with south-oriented windows in the same locality, the fronts include from 13 to 24, 43 to 53 and 15 to 33. In Monza, we can observe similar differences: from 11 to 19, 13 to 27 and 13 to 25 for east-oriented intermediate flats, penthouses and semi-detached houses, and from 17 to 29, 18 to 47 and 9 to 32 for south-oriented buildings.

3.3.1. Shapes of the Pareto Fronts

Figures 3 and 4 show the Pareto fronts for Trento and Monza, respectively. The fronts are composed by two groups of points, which correspond to the adoption of mechanical ventilation systems, on the top of EP_h-*NPV* charts, and to the choice of natural ventilation, on the bottom.

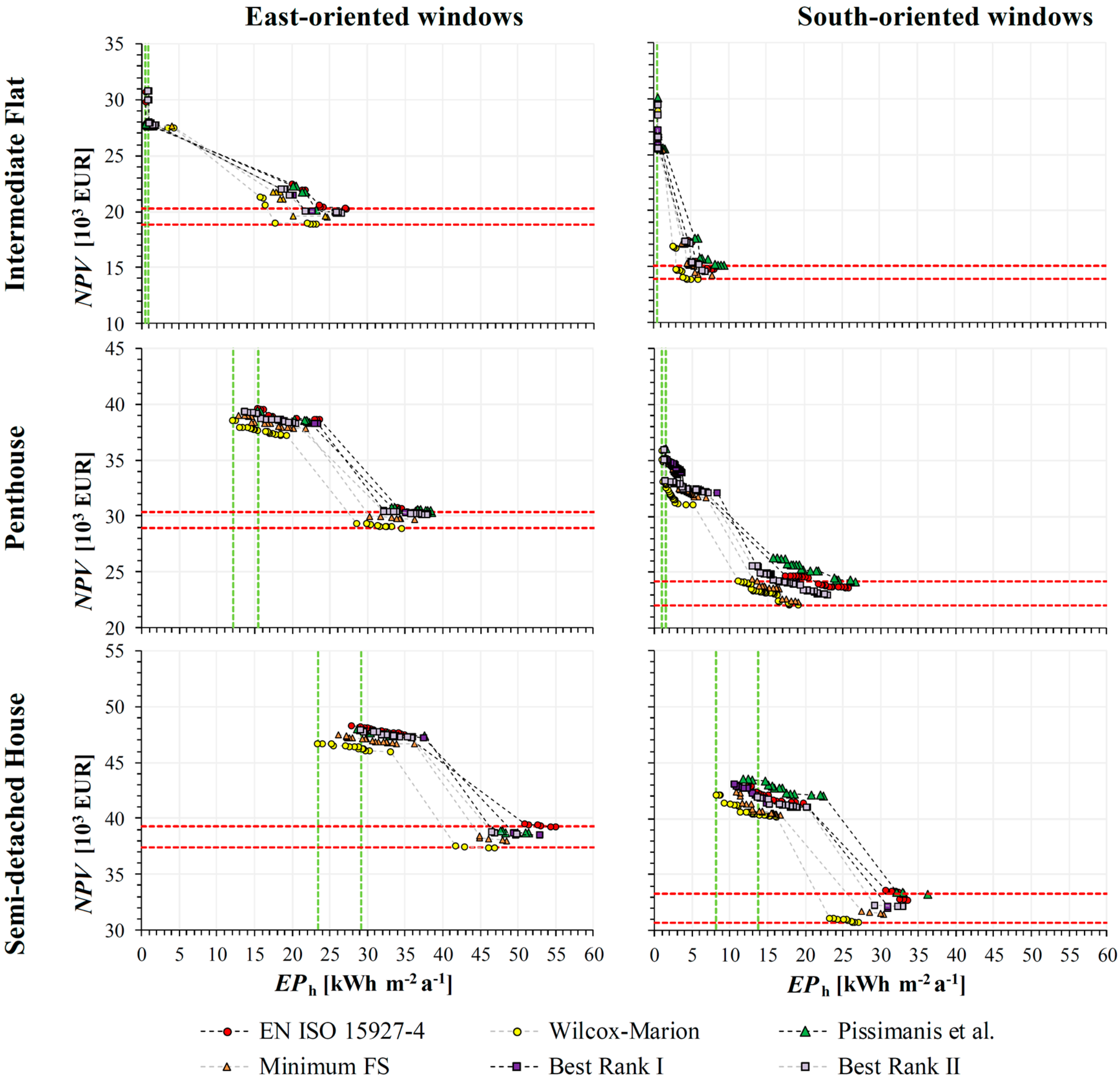

Figure 3. Pareto fronts for Trento. The horizontal red dotted lines and the vertical green dotted lines delimitate the range between best *NPV* and EP_h identified with the optimization with the six reference years.

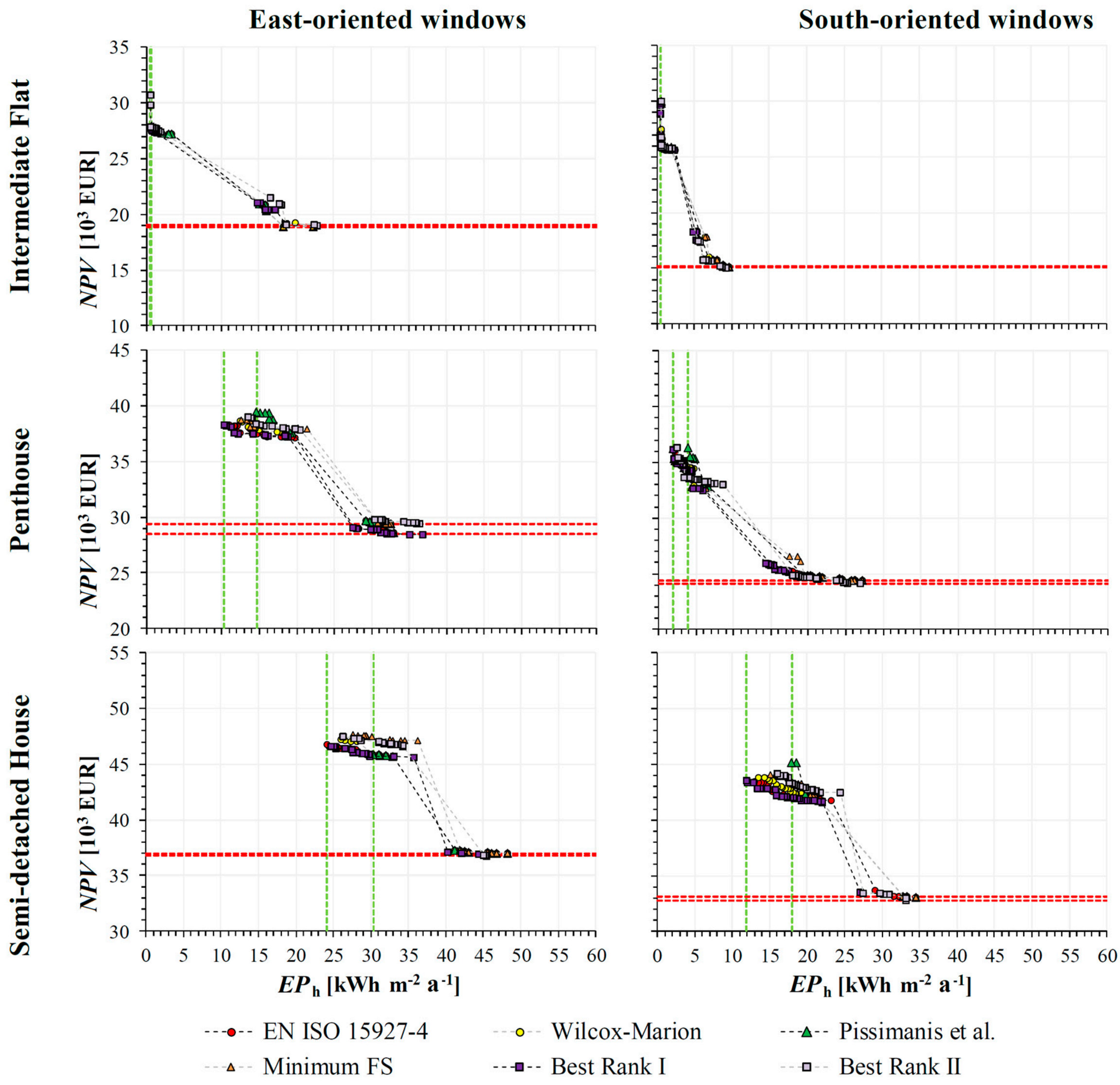

Figure 4. Pareto fronts for Monza. The horizontal red dotted lines and the vertical green dotted lines delimitate the range between best *NPV* and EP_h identified with the optimization with the six reference years.

The fronts' relative positions in the charts are shifted according to the deviations in the initial solutions. In Trento, minimum EP_h and *NPV* are achieved with RY_2 and the maximum are registered either with RY_3 (south-oriented buildings) or RY_1 (east-oriented buildings), coherently with what observed in Section 3.2. In Monza, the differences are less marked and, for solutions with natural ventilation, they are even negligible. The minimum EP_h and *NPV* are found with RY_5, coherently with the analysis of the existing buildings' performance, and the maximum ones for RY_3 and RY_6.

Furthermore, some fronts are not only shifted but also intersected: for example, south-oriented penthouses in Trento have the worst economic performances with RY_5 and RY_6 if mechanical ventilation is installed but, in the case of natural ventilation, this result is observed with RY_3.

3.3.2. EEMs in the Pareto Fronts

The different EEMs belonging to the fronts have been studied analyzing modal values and standard deviations of the thicknesses of insulation layers applied to the opaque components and the distribution functions of windows, boilers and ventilation.

The modal values and the standard deviations of insulation thicknesses have been calculated for each case and climate. In Trento, the modal values vary of maximum 2 cm, except for vertical walls' insulation in south-oriented intermediate flats, whose difference is up to 7 cm. Excluding this case, standard deviations are generally close or within 1 cm. In Monza, the largest deviations of modal values are equal to 3 cm and the standard deviations are slightly larger than 1 cm. As a whole, the impact of the RY choice on the proposed insulation thicknesses of EEMs included in the fronts is modest, with only one configuration in Trento with remarkable differences depending on the RY.

Figures 5 and 6 depict, as examples, the results for Trento. For east-oriented intermediate flats, double glazings with high *SHGC*, DH, and both kinds of triple glazings, TH and TL, are selected while only DH and TH are found in the fronts of the other east-oriented configurations. There are differences considering the various RYs for east-oriented configurations: for example, for intermediate flats, DH is not included in the fronts if optimization is run adopting RY_3, and, for semi-detached houses, either DH or TH are the most frequent EEMs in the front, respectively with RY_5 and RY_1. The deviations in the shares of DH and TH are around 40% for both building configurations. Analyzing the south-oriented cases in Trento (Figure 6), similar trends are seen for windows' substitutions, even if with different shares. The maximum deviation in frequency is only slightly larger than 20%, with the exception of semi-detached houses, where it increases to 44% and, for optimization with RY_5, TH does not belong to the front. As regards the boiler, the existing standard system is recommended to be kept only for some solutions in intermediate flats (both orientations) and penthouses (only south-oriented configurations) while more efficient alternatives are proposed for the other types of buildings. Deviations can be detected for east-oriented semi-detached houses, with modulating boilers present in the front only if RY_1, RY_2 and RY_4 are adopted. Changes of share between 30% and 35% are detected for modulating and condensing boilers in east-oriented penthouses and semi-detached houses. On the contrary, for south-oriented configurations, share deviations are slightly larger than 20%, except for the penthouses for which they are around 35%. Considering ventilation, mechanical solutions are more frequently found in penthouses and semi-detached houses but the impact of the weather data is more limited. As a whole, as far as the solutions in the Pareto fronts are considered, east-oriented penthouses and south-oriented intermediate flats are the most robust configurations to the choice of reference years for the climate of Trento.

The Pareto fronts for Monza are generally less sensitive to the weather input definition but the global trends of selected EEMs are similar to Trento. Regarding windows' substitution, maximum share deviations are larger than 20% only for south-oriented intermediate flats and east-oriented penthouses and semi-detached houses. Considering the boiler, in east-oriented configurations, the maximum share deviation is always lower than 20%, except for penthouses with 24% share deviation for modulating and condensing boilers. In south-oriented configurations, share changes are lower than 20% for intermediate flats, between 14% and 29% for penthouses and up to 49% for semi-detached houses. As concerns ventilation, the only share deviations larger than 20%, i.e., equal to 46% and 25%, are for east-oriented semi-detached houses and south-oriented penthouses, respectively. For both orientations, in Monza, intermediate flats are the configurations with the EEMs included in the Pareto fronts more robust to the reference year input.

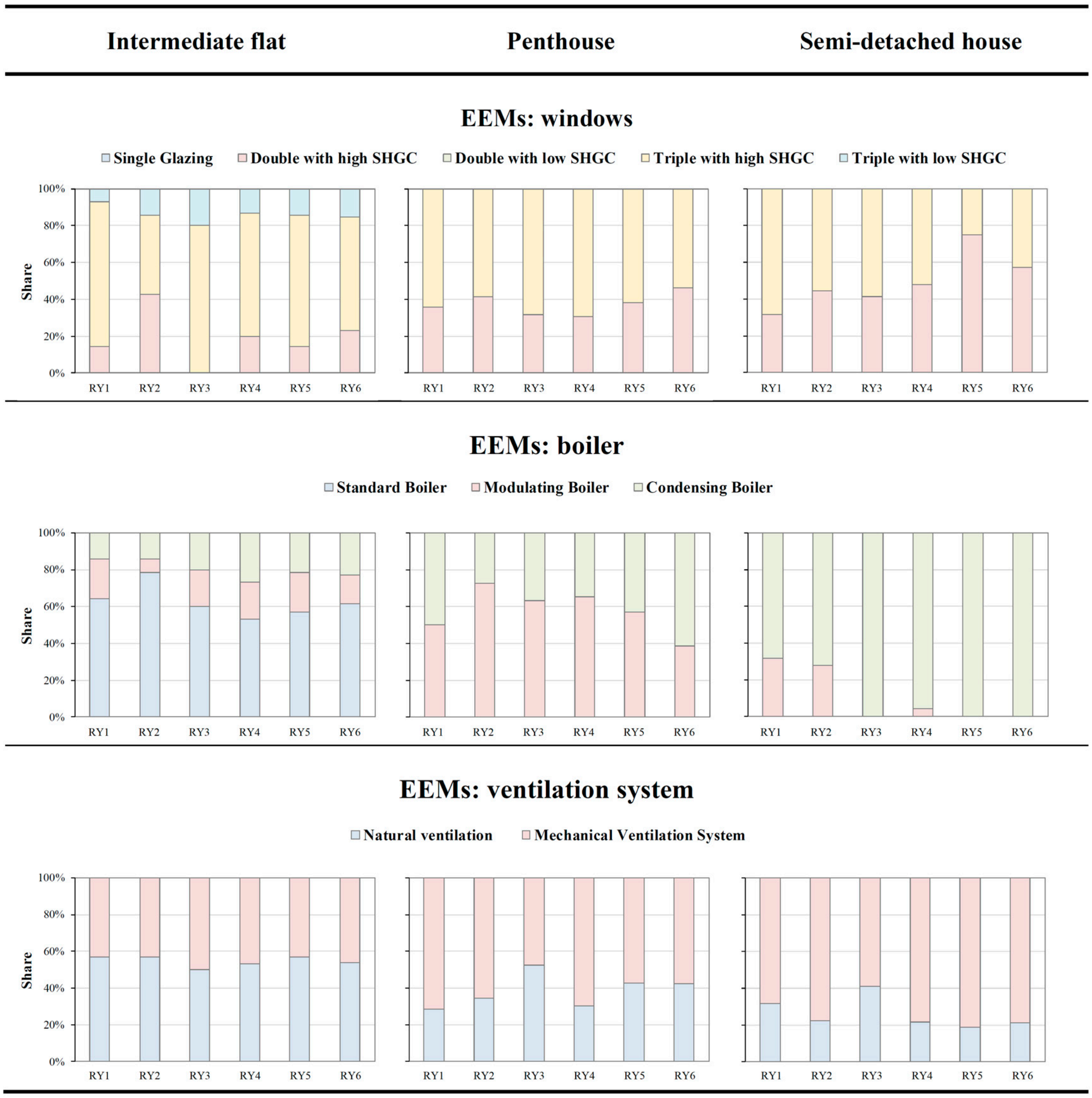

Figure 5. Shares of the different alternative energy efficiency measures belonging to the Pareto fronts for east-oriented buildings in Trento.

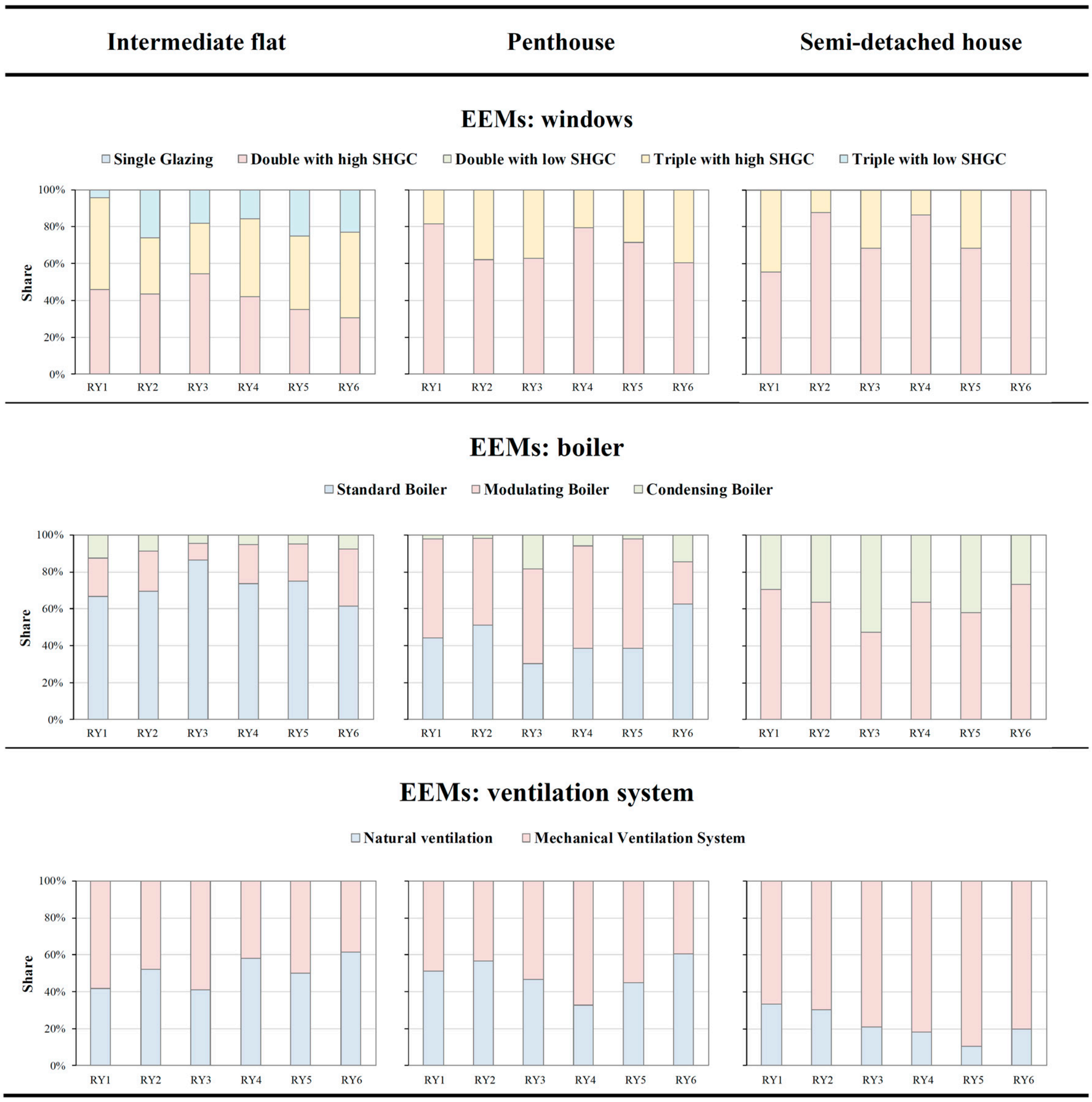

Figure 6. Shares of the different alternative energy efficiency measures belonging to the Pareto fronts for south-oriented buildings in Trento.

3.4. Economic and Energy Optimal Solutions

This last analysis focuses on two specific points belonging to the fronts, i.e., the one maximizing the cost objective (cost optimum) and the one maximizing the energy one (energy optimum). After an evaluation of which EEMs are selected for those points, their economic and energy performances are discussed.

3.4.1. EEMs for Economic and Energy Optima

Tables 5 and 6 report, as examples, the EEMs optima for the different building configurations in Trento. Considering the cost optima, the impact of RY on the insulation thicknesses is limited to 2 cm in many configurations, except for example for the south-oriented intermediate flat, for which 14 cm are recommended for the vertical walls' insulation with RY_4 and 18 cm with RY_5 and RY_6. All RYs lead to the same results for south-oriented buildings in terms of window, boiler and ventilation preferences. For those east-oriented, instead, the recommendations are different: for example, RY_3 leads to the selection of TH glazings for intermediate flats while DH are preferred in all other cases, RY_1 and RY_2 lead to the recommendation of a modulating boiler (instead of a condensing one), respectively for the penthouse and the semi-detached house. Considering energy optima, the variability of insulation thicknesses is very limited (i.e., 1 cm) for the east-oriented configurations and, in particular, null for the intermediate flat, while for the south-oriented configurations we can detect both large sensitivity (e.g., up to 5 cm difference for walls' insulation of the intermediate flat, 4 cm of difference for floor's insulation for semi-detached houses) and null sensitivity (i.e., for the penthouse). Penthouses have the same results, independently of RY, in terms of window, boiler and ventilation preferences. For intermediate flats, windows and boiler selections are affected by RYs while for south-oriented semi-detached houses, this is true only for the windows.

Table 5. Cost optima for Trento. As regards windows, S (in dark blue) indicates single glazing, DH (red) double glazing with high *SHGC*, DL (green) double glazing with low *SHGC*, TH (yellow) triple glazing with high *SHGC*, TL (light blue) double glazing with low *SHGC*; as regards boiler, STD (blue) indicates standard boiler, MOD (red) modulating boiler, COND (green) condensing boiler; ventilation is distinguished by natural (NAT in blue) or provided by mechanical ventilation system (MVS in red).

	East Orientation						**South Orientation**					
	RY_1	**RY_2**	**RY_3**	**RY_4**	**RY_5**	**RY_6**	**RY_1**	**RY_2**	**RY_3**	**RY_4**	**RY_5**	**RY_6**
Intermediate Flat												
Insulation thickness [cm]												
Wall	19	17	18	19	19	18	17	15	17	14	18	18
Roof	-	-	-	-	-	-	-	-	-	-	-	-
Floor	-	-	-	-	-	-	-	-	-	-	-	-
Windows	DH	DH	TH	DH	DH	DH	DH	DH	DH	DH	DH	DH
Boiler	STD	STD	STD	STD	STD	STD	STD	STD	STD	STD	STD	STD
Ventilation	NAT	NAT	NAT	NAT	NAT	NAT	NAT	NAT	NAT	NAT	NAT	NAT
Penthouse												
Insulation thickness [cm]												
Wall	18	18	17	17	17	17	17	16	18	17	17	17
Roof	17	19	17	17	17	17	15	17	16	18	16	16
Floor	-	-	-	-	-	-	-	-	-	-	-	-
Windows	DH	DH	DH	DH	DH	DH	DH	DH	DH	DH	DH	DH
Boiler	COND	MOD	COND	COND	COND	COND	STD	STD	STD	STD	STD	STD
Ventilation	NAT	NAT	NAT	NAT	NAT	NAT	NAT	NAT	NAT	NAT	NAT	NAT
Semi-Detached House												
Insulation thickness [cm]												
Wall	19	18	17	18	16	18	17	18	17	17	17	17
Roof	19	17	18	18	17	18	18	16	18	17	17	17
Floor	18	18	18	18	17	19	17	17	16	16	18	16
Windows	DH	DH	DH	DH	DH	DH	DH	DH	DH	DH	DH	DH
Boiler	MOD	COND	COND	COND	COND	COND	MOD	MOD	MOD	MOD	MOD	MOD
Ventilation	NAT	NAT	NAT	NAT	NAT	NAT	NAT	NAT	NAT	NAT	NAT	NAT

Table 6. Energy optima for Trento. As regards windows, S (in dark blue) indicates single glazing, DH (red) double glazing with high *SHGC*, DL (green) double glazing with low *SHGC*, TH (yellow) triple glazing with high *SHGC*, TL (light blue) double glazing with low *SHGC*; as regards boiler, STD (blue) indicates standard boiler, MOD (red) modulating boiler, COND (green) condensing boiler; ventilation is distinguished by natural (NAT in blue) or provided by mechanical ventilation system (MVS in red).

	East Orientation						**South Orientation**					
	RY_1	**RY_2**	**RY_3**	**RY_4**	**RY_5**	**RY_6**	**RY_1**	**RY_2**	**RY_3**	**RY_4**	**RY_5**	**RY_6**
Intermediate Flat												
Insulation thickness [cm]												
Wall	20	20	20	20	20	20	13	16	18	13	14	13
Roof	-	-	-	-	-	-	-	-	-	-	-	-
Floor	-	-	-	-	-	-	-	-	-	-	-	-
Windows	TH	TH	TH	TH	TH	TH	TH	TL	TL	TL	TL	TL
Boiler	COND	STD	STD	COND	COND	COND	COND	COND	COND	COND	COND	COND
Ventilation	MVS	MVS	MVS	MVS	MVS	MVS	MVS	MVS	MVS	MVS	MVS	MVS
Penthouse												
Insulation thickness [cm]												
Wall	20	19	19	19	19	20	20	20	20	20	20	20
Roof	19	19	19	20	20	20	20	20	20	20	20	20
Floor	-	-	-	-	-	-	-	-	-	-	-	-
Windows	TH	TH	TH	TH	TH	TH	TH	TH	TH	TH	TH	TH
Boiler	COND	COND	COND	COND	COND	COND	COND	COND	COND	COND	COND	COND

Ventilation	MVS	MVS	MVS	MVS	MVS	MVS	MVS	MVS	MVS	MVS	MVS	MVS
Semi-Detached House												
	Insulation thickness [cm]											
Wall	20	19	18	19	18	18	19	19	19	18	18	18
Roof	20	19	19	19	19	19	19	19	19	17	19	19
Floor	20	20	20	20	19	19	18	18	20	18	20	16
Windows	TH	TH	TH	TH	TH	TH	TH	TH	TH	TH	TH	DH
Boiler	COND	COND	COND	COND	COND	COND	COND	COND	COND	COND	COND	COND
Ventilation	MVS	MVS	MVS	MVS	MVS	MVS	MVS	MVS	MVS	MVS	MVS	MVS

In Monza, EEMs follow trends similar to those observed for Trento. As concerns the cost-optima, however, the deviations among the outcome of the different optimizations are more limited. Indeed, the choice of reference year always affects the insulation thicknesses in terms of 2 cm and only for some configurations, such as penthouses and semi-detached houses. In particular, with RY_5 and RY_6, proposed thicknesses are generally different from those obtained with the other reference years. Furthermore, the EEMs regarding windows, boiler and ventilation are affected only for the type of boiler in the east-oriented penthouse and south-oriented semi-detached houses, for which modulating boiler is preferred to the condensing one when, respectively, RY_5 and RY_6 are adopted. Considering the energy optima, besides the choice of the optimal insulation thickness, TH, condensing boiler and mechanical ventilation system are always recommended, except for the south-oriented intermediate flat, for which TL glazings are proposed, as in Trento. The reference year has no impact on the ventilation system and affects slightly window and boiler selection: for example, for east-oriented semi-detached houses, RY_3 leads to a selection of DH, for east-oriented intermediate flats the output with the same reference year includes no substitution of the boiler and, similarly, for south-oriented penthouses the output with RY_2 includes the adoption of a modulating boiler instead of a condensing one.

As observed, the impact of reference years on the selected EEMs in cost and energy optima are slightly different for the two localities, with Trento presenting a larger sensitivity. Besides the insulation thickness, which is particularly affected in Trento in south-oriented intermediate flats, proposed windows and boiler can be influenced by the reference weather file while the type of ventilation is not.

3.4.2. Performances of Economic and Energy Optima

Considering the differences in the best EP_h in Trento, as shown in Figure 3, all reference years lead to EP_h lower than 1 kWh·m^{-2}·a^{-1} for all intermediate flats, between 12 and 16 kWh·m^{-2}·a^{-1} and 1 and 2 kWh·m^{-2}·a^{-1}, respectively for east- and south-oriented penthouses, and between 23 and 30 kWh·m^{-2}·a^{-1} and 8 and 14 kWh·m^{-2}·a^{-1}, respectively, for east and south oriented semi-detached houses. In Monza, as in Figure 4, the reference years lead to EP_h lower than 1 kWh·m^{-2}·a^{-1} for all intermediate flats, between 10 and 15 kWh·m^{-2}·a^{-1} and 2 and 5 kWh·m^{-2}·a^{-1} for penthouses, respectively east- and south-oriented, and between 24 and 31 kWh·m^{-2}·a^{-1} and between 11 and 18 kWh·m^{-2}·a^{-1} for semi-detached houses, respectively east- and south-oriented.

Regarding *NPV*, in Trento we have between 18,000 and 21,000 EUR and 13,000 and 16,000 EUR, respectively, for east- and south-oriented intermediate flats, between 28,000 and 31,000 EUR and 22,000 and 25,000 EUR, respectively, for east- and south-oriented penthouses, and between 37,000 and 40,000 EUR and 30,000 and 34,000 EUR, respectively, for east- and south-oriented semi-detached houses. In Monza, the deviations are more limited: around 19,000 and around 15,000 EUR for intermediate flats, between 28,000 and 30,000 EUR and around 24,000 EUR for penthouses, and around 37,000 EUR and between 32,000 and 34,000 EUR for semi-detached houses, for east- and south-oriented configurations, respectively.

In both climates, the absolute deviations for the optima are similar or lower than those for the existing buildings' performances, even if their relative impact is much larger. For example, for south-oriented semi-detached houses in Trento, the variability of EP_h is more than 75% between the energy performances simulated with RY_2 and RY_3. Similarly, for the same configurations, economic performances can change of more than 13%.

4. Discussion and Conclusions

In this work, the impact of the weather data on the outcome of multi-objective optimization has been analyzed in the context of building energy refurbishment. The study focused on two north Italy climates, i.e., Trento and Monza, respectively, with an Alpine and a continental temperate climate, for which different reference years were developed starting from the multi-year weather data series. The methodologies for the reference year definition were chosen according to the current state of the art and technical standards. In particular, the work considered as references the European standard EN ISO 15927-4:2005, the Wilcox-Marion method for TMY3 generation, two approaches frequently found in the literature, i.e., the Pissimanis et al., and the minimum Finkelstein–Schafer methods, and two approaches proposed by Pernigotto et al. in previous works, i.e., Best rank I and II methods. The six reference years were used as input for TRNSYS simulations of the primary energy uses for space heating for six building typologies, with features representative of the existing Italian residential stock built before the first energy efficiency laws during the 70 s. Four main energy efficiency measures were designed with respect to opaque envelope insulation, windows replacement, boiler substitution and adoption of a mechanical ventilation system. The NSGA-II genetic algorithm was implemented to optimize the mix of measures for each building configuration and reference year, in order to minimize both net present value of the refurbishment investment and the primary energy for space heating.

The following findings can be drawn:

- Analyzing the developed reference years, different values of Heating Degree-Days and daily average global solar irradiation on horizontal surface during the heating season can be observed. For the first one, the largest deviations are 11% and 13%, while, for the latter, they are 6% and 10%, respectively, for Trento and Monza.
- The deviations in the weather data impact differently on the energy and economic performances of the existing buildings: indeed, while for east-oriented configurations, the difference ranges are between 4% and 8% and between 9% and 13%, respectively in Trento and in Monza, for the south-oriented ones, they are shifted towards larger values (i.e., from 7% to 14% and from 11% to 17%). This suggests various sensitivities to the climatic solicitation and a role of the building's features on the propagation of the uncertainty from weather data. In particular, the largest differences are met for the performances of the existing intermediate flats.
- Analyzing the Pareto fronts obtained through genetic algorithm multi-objective optimization, it is possible to see that they are not simply shifted according to the performance deviations of the considered existing buildings but also intersected. This is related to types of ventilation system, either natural or mechanical one, which lead to different shapes of Pareto fronts according to the selected reference year. Looking at the alternative solutions belonging to the Pareto fronts, it can be observed that their number varies significantly, and, in some cases, variations are also equal to 100%.
  - Studying the energy efficiency measures of the solutions belonging to the Pareto fronts, it is possible to conclude that, in most of configurations, the impact of the reference years on the recommended insulation thicknesses for the envelope opaque components is modest and generally lower than 2 or 3 cm, respectively, for Trento and Monza modal values. An exception is found for the insulation of vertical walls in south-oriented intermediate flats in Trento, ranging from 13 to 20 cm of polystyrene. The impact is more relevant considering the other efficiency measures. Indeed, the shares of occurrence of specific alternatives of windows, boilers and ventilation systems, change with the reference years and, for some configurations and weather data, they are not even included among the solutions belonging to the Pareto front. Considering these three energy efficiency measures, in Trento, east-oriented penthouses and south-oriented intermediate flats are the most robust configurations while, in Monza, this is true for intermediate flats, independently of the orientation.
- Focusing on the solutions in the Pareto fronts maximizing either economic or energy objectives, it can be seen that the impact of reference years on the selected energy efficiency measures are slightly different for the two localities, with Trento presenting a larger sensitivity despite of the

lower variability of performances of the existing building configurations. Besides the insulation thickness in Trento, which is particularly affected in south-oriented intermediate flats as mentioned above, proposed windows and boiler can be influenced as well while this does not occur for the type of ventilation system. The absolute deviations in terms of primary energy for space heating and net present value for the optima are similar or lower than those for the existing buildings' performances for both localities, even if their relative impact is larger. The largest deviations are within 4000 EUR for the net present values and 7 $kWh{\cdot}m^{-2}{\cdot}a^{-1}$ for the space heating energy uses.

In conclusion, it was observed that the procedure adopted for the definition of reference years for building energy simulations affects the outcome of cost-optimal energy refurbishment. In particular, some solutions can be excluded from the Pareto fronts and different mix of energy efficiency measures can be proposed. Different levels of energy and economic efficiency can be estimated for the refurbishment investment, introducing an uncertainty which can be significant if the target is the renovation of the existing building into a nearly zero energy building. Consequently, reference years should be carefully selected or developed considering their actual representativeness, especially when cost-optimal energy refurbishment is adopted by policy makers to define new requirements or energy goals for the building stock. In particular, the reference years with the largest representativeness with respect to the multi-year series should be primarily identified for each locality and used as input for cost-optimal energy refurbishment.

Finally, in this research, only two objectives were studied, and focus was put on those Italian climates characterized by larger heating demand. Uncertainty may increase by adding more goals, e.g., thermal comfort, and including more energy uses in primary energy calculation, e.g., those for space cooling and lighting, as is expected in further developments involving some Mediterranean locations.

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Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

Symbols

A	Area (m^2)
ACH	Air change (h^{-1})
BES	Building energy simulation
c	Specific heat capacity ($J{\cdot}kg^{-1}{\cdot}K^{-1}$)
COND	Condensing boiler
d	Thickness (m)
DH	Double glazing with high *SHGC*
DL	Double glazing with low *SHGC*
EEM	Energy efficiency measure
EP_h	Primary energy demand for space heating ($kWh{\cdot}m^{-2}{\cdot}a^{-1}$)
F/*Φ*	Cumulative distribution functions
F_S	Finkelstein–Schafer statistics
H	Daily horizontal global solar irradiation ($MJ{\cdot}m^{-2}{\cdot}d^{-1}$)
HDD_{18}	Heating degree-days with base temperature equal to 18 °C (K·d)
HVAC	Heating ventilation and air-conditioning
i	Day
IC	Investment cost (EUR m^{-2} if referred to the envelope, EUR if referred to the system)
J/*K*	Rank order functions
LHV	Lower heating value ($MJ{\cdot}Sm^{-3}$)

m	Month
MOD	Modulating boiler
MVS	Mechanical ventilation system
n	Number of days of a calendar month
N	Total number of days of a calendar month in the multi-year series
NPV	Net present value (EUR)
p	Daily average of a weather parameter
PV	Photovoltaic
$RMSD$	Root-mean square difference
RY	Reference year
S	Single glazing
$SHGC$	Solar heat gain coefficient
STD	Standard natural gas boiler
S/V	Building compactness ratio
TH	Triple glazing with high $SHGC$
TL	Triple glazing with low $SHGC$
TMY	Typical meteorological year
U	Thermal transmittance ($W \cdot m^{-2} \cdot K^{-1}$)
y	Year
Greek	
η	Nominal efficiency
ϑ_e	External temperature (°C)
λ	Thermal conductivity ($W\ m^{-1} \cdot K^{-1}$)
ρ	Density ($kg \cdot m^{-3}$)
Ψ	Linear thermal transmittance ($W \cdot m^{-1} \cdot K^{-1}$)
Subscripts	
corner	Referred to corner thermal bridges
HR	Referred to heat recovery
hw	Referred to horizontal wall
ins	Referred to insulation layer
int-floor	Referred to thermal bridges due to intermediate floor and walls
fr	Referred to the window frame
gl	Referred to the glazing
roof	Referred to roof thermal bridges
sol	Solar
vw	Referred to vertical wall
wall	Referred to the opaque components
win	Referred to the window

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