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Planned energy-efficient retrofitting of a residential building in Italy

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Abstract

The planned energy-efficient retrofitting of a residential building in Bologna, North-Center Italy is presented. The building is a detached house with an unheated basement, three floors with 2 apartments each, and an unheated attic. The total heated floor area is 281.9 m^2. The external wall is made of solid brick masonry and most windows are single glazed; no thermal insulation is present. Space heating is supplied by a gas boiler and radiators in the rooms. DHW is supplied by single-apartment electric boilers in 5 apartments and by a gas boiler in one apartment. Lighting is obtained by incandescent lamps.

The proposed retrofitting includes: external thermal insulation of the vertical walls by calcium silicate hydrates and loft insulation by mineral wool; replacement of windows; installation of a multifunction air-to-water heat pump for heating, cooling and DHW; replacement of the radiators by new heat exchangers; LED lighting; installation of PV panels. The building has been simulated by TRNSYS 17, and the heat pump has been simulated by own MATLAB codes. The retrofitting will reduce the total annual use of primary energy (excluding appliances) from 332.5 to 44.8 kWh/m^2, and will yield an important improvement of thermal comfort.

Keywords: Energy retrofitting; Residential building; Multifunction heat pump; PV panels; Hourly simulation

Introduction

The economic growth of the 20th century has been based on a progressive increase of the world annual use of fossil fuels. The world annual use of primary energy is still increasing, and fossil fuels represent even now the most important source of primary energy, as shown in Fig. 1, which illustrates the world annual use of primary energy by source from 1980 to 2011, according to EIA (US Energy Information Administration) (http://www.eia.gov/cfapps/ipdbproject/IEDIndex3.cfm#). In 2011, 86 % of the world primary energy use is due to oil, carbon and gas. The fossil-fuel-based development has caused two important problems: the reserves of oil and natural gas are decreasing and the emission of carbon dioxide and of other greenhouse gases is causing a climate change (https://www.ipcc.ch/report/ar5/wg1/). As a consequence, all the industrialized and developing countries and, most of all, the European Union, are struggling to shift the economic growth towards a sustainable development, based on two main pillars: the increase of energy efficiency and the use of renewable energy sources. The energy policy of the European Union already obtained some success: the annual use of primary energy of the Union is slightly decreasing from 2006, as shown in Fig. 2. The figure illustrates the use of primary energy of the European Union by sector from 1990 to 2012, according to Eurostat (European Commission portal for statistics) (http://ec.europa.eu/eurostat/data/database); it reveals that the fractions of energy use in the residential sector and in the service sector are quite relevant. The fractions of primary-energy use in sectors for 2012 are better evidenced in Fig. 3, where it is shown that the sum of the fractions which refer to the residential sector and to the service sector, i.e., the total fraction due mainly to building operation, is 39.7 %. As a consequence, an important step towards the reduction of the use of fossil fuels in Europe would be the enhancement of the energy efficiency of buildings.

According to an official document of the European Commission (http://www.ectp.org/cws/params/ectp/download_files/36D2981v1_Eeb_cPPP_Roadmap_under.pdf), buildings use 40 % of the total EU energy consumption and generate

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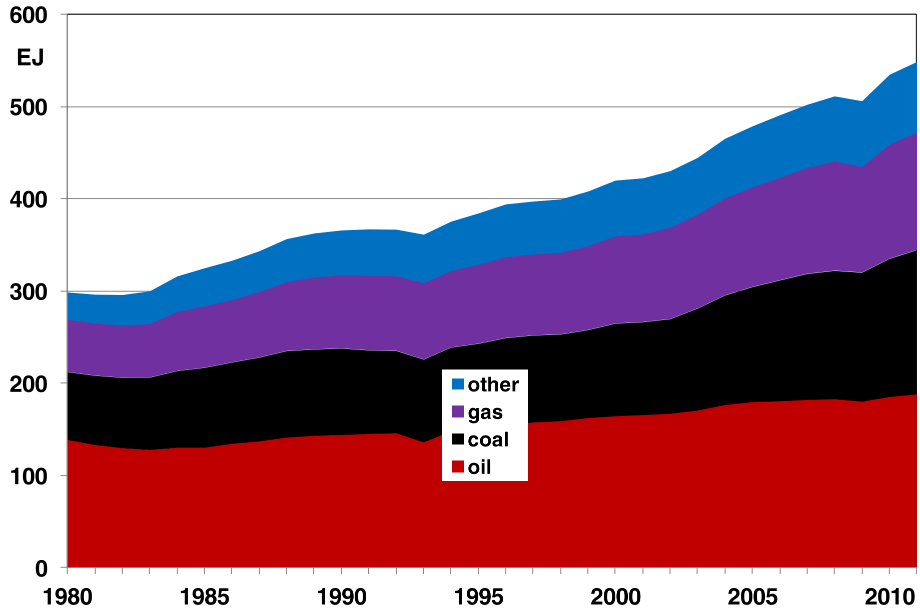

Fig. 1 World annual use of primary energy by source from 1980 to 2011, according to EIA

36 % of greenhouse gases in Europe. The construction sector is expected to reduce its CO_2 emissions by at least 80 % and its energy consumption by as much as 50 % by 2050. Since the replacement rate of the existing stock is very small (1–2 % per year), the energy retrofitting of existing buildings should play an important role to reach this goal.

A wide research activity on the techniques for energy retrofitting of buildings has been performed in the last decades. Some studies have concerned the optimization of thermal insulation (Ucar and Balo 2009; Yu et al. 2009; Daouas 2011; Cuce et al. 2014), others the improvement of the plant efficiency (Bizzarri and Morini 2006; Zhao et al. 2008, 2009; Chan et al. 2010; Terlizzese and Zanchini 2011; Brignoli et al. 2013; Liu et al. 2013; Naldi et al. 2014), others the energy-saving potential (Balaras et al. 2000; Amstalden et al. 2007; Ascione et al. 2011; Chidiac et al. 2011a, b; Dall'O' and Sarto 2013; Shahrokni et al. 2014), others again the effects of solar chimneys, permeable coverings, cool roofs and green roofs (Afonso and Oliveira 2000; Orosa and Oliveira

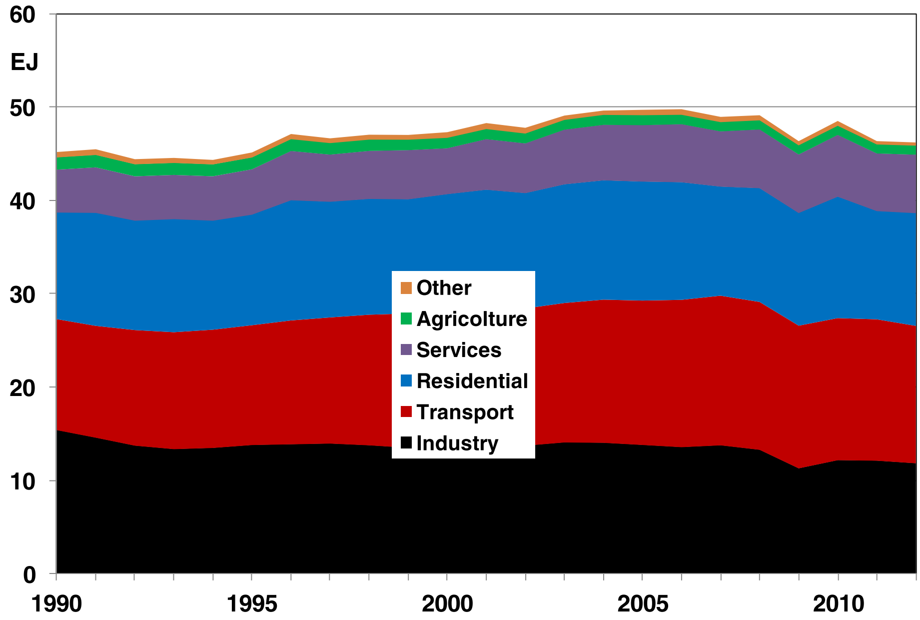

Fig. 2 Annual use of primary energy by sector in Europe, from 1990 to 2012, according to Eurostat

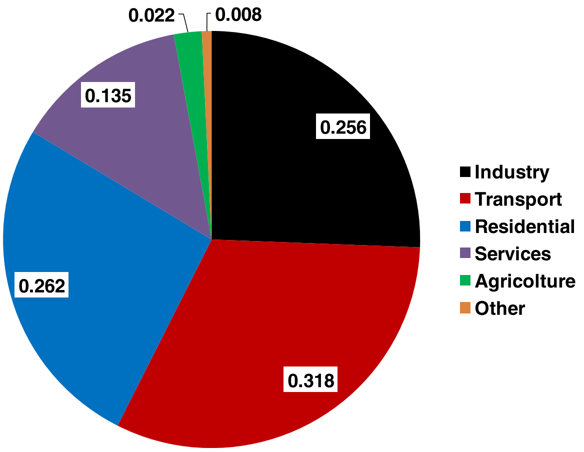

Fig. 3 Fractions of primary energy use in main sectors in Europe, in 2012, according to Eurostat

2009; Pisello et al. 2013; Santamouris et al. 2011; Santamouris 2014).

Ucar and Balo (Ucar and Balo 2009) determined the optimum insulation thickness of external walls for four cities with different climatic conditions in Turkey, with reference to Foamboard, extruded polystyrene and fiberglass as insulation materials. Yu et al. (Yu et al. 2009) studied the optimization of the insulation thicknesses of expanded polystyrene, extruded polystyrene, foamed polyurethane, perlite, and foamed polyvinyl chloride, for a typical residential wall in China. Daouas (Daouas 2011) evaluated, by an analytical method based on Complex Finite Fourier Transform, the optimum insulation thickness, the energy saving and the payback period for a typical wall structure in Tunisia, in the presence of both cooling and heating loads. Cuce et al. (Cuce et al. 2014) analyzed the optimum thermal insulation thickness of aerogel and its environmental impacts for the climatic conditions of Nottingham, UK.

Bizzarri and Morini (Bizzarri and Morini 2006) evaluated the reduction in pollutant emissions obtainable by installing new hybrid plats in hospitals. Several hybrid schemes were investigated and compared: phosphoric acid fuel cells, solar thermal systems and PV solar systems. Zhao et al. (Zhao et al. 2008) designed and numerically studied a novel dew point air conditioning system, and Zhao et al. (Zhao et al. 2009) investigated the feasibility of this system in several China regions. Chan et al. (Chan et al. 2010) pointed out advantages and limitations of passive solar heating and cooling technologies and suggested research guidelines to improve the economic feasibility of these techniques. Terlizzese and Zanchini (Terlizzese and Zanchini 2011) studied, through an economic and an exergy analysis, the feasibility of alternative plants for a zero carbon building complex in Italy. Brignoli, Cecchinato, and Zilio (Brignoli et al. 2013) performed an experimental investigation on air-to-water heat pumps, and compared a multiport aluminum flat-tube heat exchanger to a round-tube finned one. Liu et al. (Liu et al. 2013) studied a new kind of heat pump system, which utilizes gray water as heat source and sink for heating and cooling of residential buildings. Naldi et al. (Naldi et al. 2014) developed a MATLAB code for the choice of the optimal balance-point temperature of air-to-water heat pumps for heating.

Balaras (Balaras et al. 2000) audited 8 apartment buildings, located in three climatic zones of Greece, and showed that a considerable energy saving in heating, air conditioning, DHW production and lighting can be obtained by proper retrofit actions. Amstalden et al. (Amstalden et al. 2007) investigated the profitability of energy-efficient retrofit investments in the Swiss residential building sector from the house owner's perspective. Ascione, de Rossi and Vanoli (Ascione et al. 2011), through a dynamic simulation code experimentally calibrated, analyzed the effectiveness of several energy retrofit solutions for a historical building in Italy. Chidiac et.al. developed a methodology, based on the simulation code EnergyPlus, to determine the energy saving potential in the Canadian office building stock (Chidiac et al. 2011a); they also analyzed the effectiveness of single and multiple energy retrofit measures on the energy consumption of office buildings (Chidiac et al. 2011b). Dall'O' and Sarto (Dall'O' and Sarto 2013) investigated the technical end economic potential for increasing energy efficiency of 49 school

Fig. 4 Street views of the house: Northeast side (left) and Southwest side (right)

Fig. 5 3-D models of the house: Northeast and Northwest sides (left); Southwest and Southeast sides (right)

building complexes in Lombardia (Northern Italy). Shahrokni et al. (Shahrokni et al. 2014) evaluated the energy efficiency potential in Stockholm, and showed that the retrofitting of the building stock to current building codes would reduce heating energy use in the city by one third.

Afonso and Oliveira (Afonso and Oliveira 2000) studied numerically and experimentally the increase in ventilation rate obtainable by solar chimneys. Orosa and Oliveira (Orosa and Oliveira 2009) investigated the effects of indoor permeable coverings on thermal comfort and energy saving in several office buildings in Spain. Pisello, Santamouris and Cotana (Pisello et al. 2013) analyzed the coupled passive–active effect produced by a cool roof on industrial-office building located in Rome. Santamouris, Synnefa and Karlessi (Santamouris et al. 2011) and Santamouris (Santamouris 2014) presented review papers on the positive effects obtainable by advanced cool materials and green roofs.

The EU-funded Project HERB (Holistic Energy-efficient Retrofitting of residential Buildings) started in October 2012, and aims to develop innovative technologies for the energy retrofitting of buildings and to perform demonstrations of holistic energy-efficient retrofitting of residential buildings in seven European Countries: United Kingdom, Italy, Portugal, Greece, Spain, Switzerland and Netherlands. In Italy, the demonstration concerns a residential building located in Bologna, North-Center Italy, a detached social house with 6 apartments owned by the Municipality of the city, with a total heated floor area of 281.9 m^2. The external

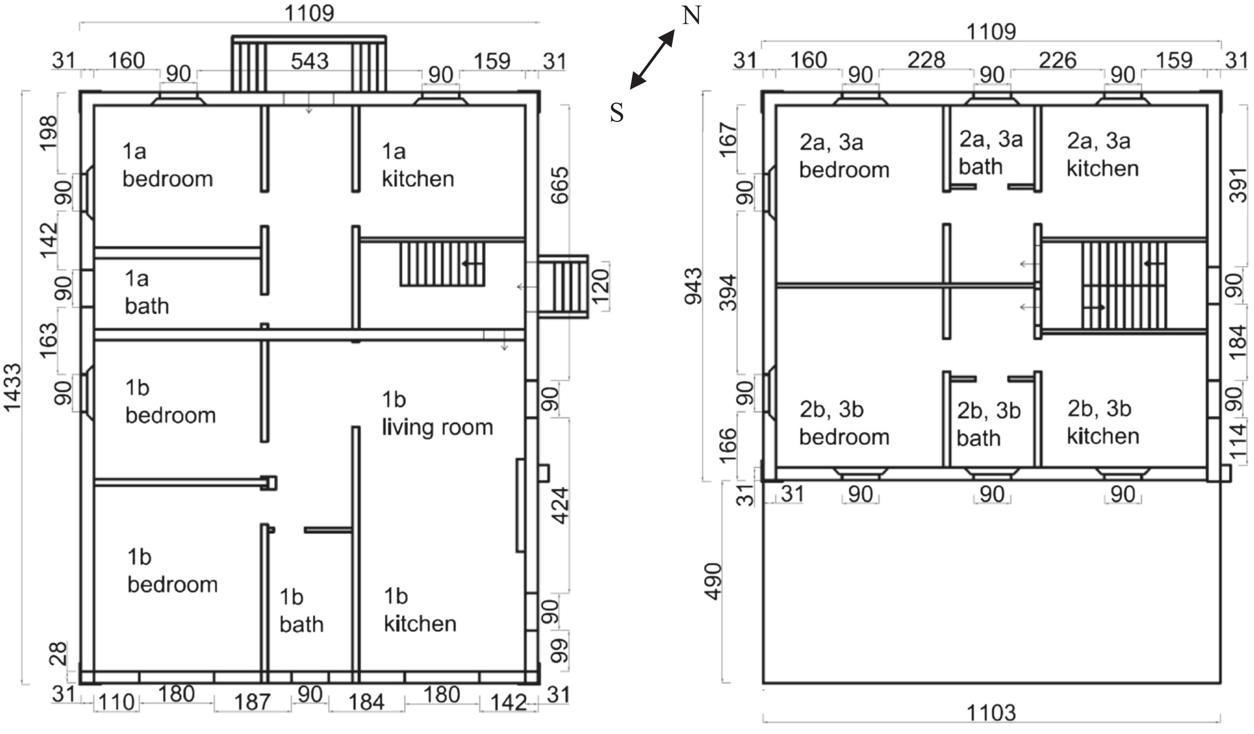

Fig. 6 Plans of the apartments: first floor on the left; second and third floor on the right

Table 1 Main properties of the opaque enclosure elements, in the present state

Element	Description	s [m]	U [W/(m^2K)]
Vertical wall	Internal plaster, solid brick masonry, external plaster	0.31	1.797
Floor on basement	Tiles, subfloor, floor brick and concrete, plaster	0.26	1.476
Floor on ground	Tiles, subfloor, floor brick and concrete	0.25	1.845
Terrace floor	Plaster, floor brick and concrete, subfloor, tiles	0.26	1.476
Loft floor	Internal plaster, floor brick and concrete	0.09	2.903
Roof	Internal plaster, floor brick and concrete	0.21	2.279

wall is made of solid bricks and is uninsulated; most windows are single glazed. Space heating is supplied by means of a gas boiler and radiators in the rooms, while DHW is supplied by single-apartment electric boilers in 5 apartments and by a gas boiler in one apartment. Lighting is obtained by incandescent lamps. With reference to the TRNSYS typical meteorological year, the annual use of primary energy for heating, DHW and lighting is 332.5 kWh/m^2 and the annual emission of CO_2 is 92.5 kg/m^2. The efficiency targets of the retrofitting, prescribed in the HERB DoW, are a reduction of at least 80 % in the use of primary energy, a reduction of at least 60 % in the CO_2 emission, an annual use of primary energy less than 50 kWh/m^2, excluding appliances. The proposed retrofitting includes: external thermal insulation of the vertical walls by a 16 cm layer of calcium silicate hydrates; insulation of loft and floors towards unheated or external spaces by mineral wool; replacement of windows; installation of a multifunction air-to-water heat pump for heating, cooling and DHW; replacement of the radiators by high-efficient fan coils and low temperature radiators; LED lighting; installation of PV panels on the Southeast and the Northeast pitches of the roof. The following efficiency targets are expected to be reached: 86.5 % reduction of the use of primary energy, 86.3 % reduction of CO_2 emission, annual use of primary energy equal to 44.8 kWh/m^2, including summer cooling and dehumidifying, presently unavailable.

Description of the building and climatic data

The demonstration house is located in an area very close to the center of Bologna, main city of the region Emilia-Romagna, North-Center Italy. It is composed of three floors, with 2 apartments each, an unheated attic, and an unheated basement which contains the boiler room. The roof has 4 pitches, with orientations Southeast, Southwest, Northeast and Northwest. The first floor is larger than the second and the third, which are identical. The house has a small garden, with high trees. Street views of the Northeast and of the Southwest side of the house are reported in Fig. 4; 3-D models of the house, which illustrate the Northeast and Northwest sides and the Southwest and Southeast sides, are reported in Fig. 5. In the 3-D models, most trees have been hidden.

Apartments have been numbered as follows: Apartments 1a and 1b at the first floor; Apartments 2a and 2b at the second floor; Apartments 3a and 3b at the third floor. Apartments with letter a are facing Northwest; those with letter b are facing Southeast. The first floor is larger than the second and the third. One of the apartments at the first floor (Apartment 1b) has, as a part of the roof, an inaccessible plane terrace. The second and the third floor are identical. Plans of the apartments are reported in Fig. 6: the first floor is represented on the left, the second and the third floor (which are identical) are represented on the right. The rectangle which appears in the lower part of the figure at right represents the inaccessible terrace which forms a plane roof for a part of Apartment 1b. The heated floor areas of the apartments are as follows: Apartment 1a: 44.7 m^2; Apartment 1b: 80.2 m^2; Apartments 2a and 3a: 39.2 m^2; Apartments 2b and 3b: 39.3 m^2. The total heated floor area is 281.9 m^2.

The external wall, made of solid brick masonry, is 31 cm thick and uninsulated. Most windows are single glazed, with wood frame, except those of Apartments 2b and 3b, which are double glazed with aluminum frame. The internal height of each floor is 3.36 m, and the floor thickness is 0.27 m. The unheated basement is placed under Apartment 1a and under about one third of Apartment 1b. The rest of Apartment 1b is on the ground. No thermal insulation is placed between the first floor and the basement, or the ground, as well as between Apartment 1b and the terrace. The unheated

Table 2 Monthly mean values of temperature and relative humidity in Bologna, TRNSYS (first and third row) and UNI 10349 (second and fourth row)

Month	Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec
T_e [°C]	1.7	4.3	9.4	13.8	20.2	21.5	24.4	24.1	20.9	14.4	8.4	3.9
T_e [°C]	2.1	4.6	9.4	14.2	18.2	22.9	25.4	24.9	21.2	14.9	8.7	4
φ	0.82	0.78	0.71	0.73	0.71	0.70	0.66	0.68	0.71	0.75	0.83	0.82
φ	0.89	0.87	0.72	0.67	0.68	0.65	0.57	0.60	0.64	0.74	0.85	0.86

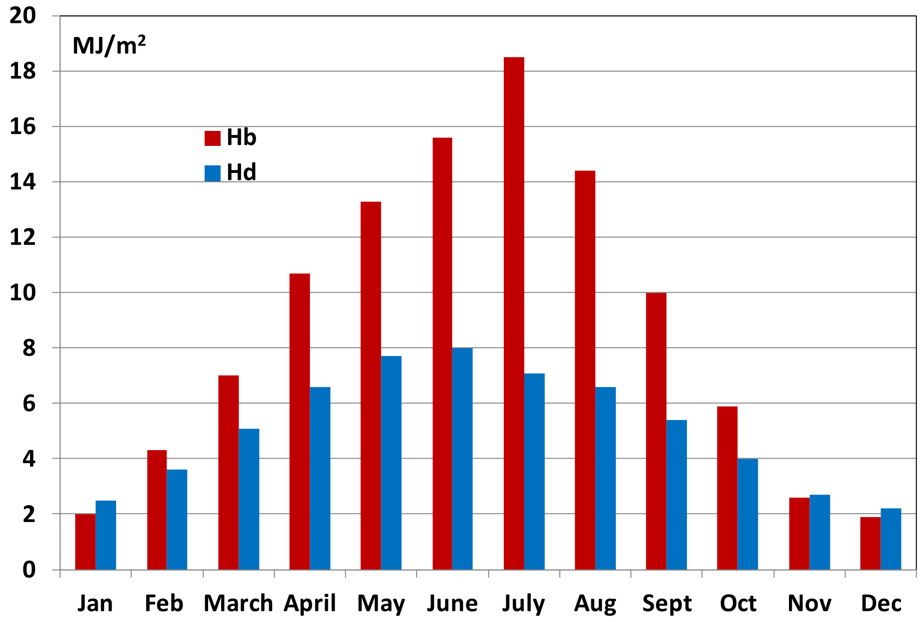

Fig. 7 Mean monthly values of direct and diffuse radiation on a horizontal surface, per day

loft is non ventilated and uninsulated; its lowest height is 0.20 m (at the sides), and its highest height is 1.60 m (at the center). It has a very small window, which is closed.

Space heating is supplied by means of a gas boiler, placed in the basement, and radiators in the rooms, under windows. The gas boiler is a modulating one, installed in 2007; it has a nominal power of 62 kW, a certified efficiency equal to 0.93 at nominal power and slightly higher at reduced power. A constant efficiency equal to 0.93 has been considered. The distribution, emission and control efficiencies of the heating system can be assumed as equal to 0.90, 0.95 and 0.97 respectively, according to the national standard UNI TS 11300–2. Thus, the overall efficiency of the heating system is 0.771.

DHW is supplied by single apartment boilers: electric boilers in Apartments 1a, 2a, 2b, 3a, 3b; a gas boiler in Apartment 1b. No summer air conditioning is present. All rooms, including bathrooms, have windows.

The main properties of the opaque enclosure elements in the present state (decription, thickness s, transmittance U), are summarized in Table 1; for each element, the description starts from the internal (heated) space. Heat transfer coefficients have been determined by considering standard thermal conductivities of the materials employed, without final roundations: there is no claim of accuracy in the last decimal places.

Bologna is located in the center of the region Emilia Romagna, at the border between the Padana flat and the foot of the mountains Appennino Tosco-Emiliano. The mean altitude is 54 m above sea level, the latitude is 44° 29’ North, the longitude is 11° 20’ East. Since the dynamic simulations of the building are performed through TRNSYS 17, the typical meteorological year (TMY) for Bologna available in that program is employed. The mean monthly values of the external air temperature T_e obtained from the TRNSYS TMY, listed in the first row of Table 2, are slightly lower than those reported in the National Standard UNI 10349, which are listed in the second row of Table 2. The values of the monthly mean relative humidity according to TRNSYS TMY are reported in the third row of Table 2, and those according to UNI 10349 are reported in the fourth row. The average wind speed, according to UNI 10349, is 1.6 m/s, with main direction Southwest. The mean monthly values of the beam radiation H_b and of the diffuse radiation H_d on a horiontal surface according to UNI 10349, in MJ/m^2 per day, are illustrated in Fig. 7.

Table 3 Main properties of the retrofitted enclosure elements

Element	Description	s [m]	U [W/(m^{2}K)]
Vertical wall	Internal plaster, solid brick masonry, external plaster, hydrate calcium silicates 16 cm	0.47	0.243
Floor on basement	Tiles, subfloor, floor brick and concrete, plaster, mineral wool 9.5 cm	0.355	0.274
Terrace floor	Plaster, floor brick and concrete, subfloor, tiles, mineral wool 14 cm	0.40	0.224
Loft floor	Internal plaster, floor brick and concrete, mineral wool 20 cm	0.29	0.187

Table 4 Heating power of the heat pump, kW, with hot water delivered at 40 °C

	Frequency [Hz]				
T_e [°C]	110	90	70	50	30
−7	7.63	6.01	4.53	3.15	1.89
2	9.99	7.91	6.01	4.19	2.51
7	11.70	9.14	6.95	4.90	2.93
12	13.50	10.60	8.09	5.66	3.41

Table 6 COP of heat pump for DHW production at 50 °C and evaporator in external air

	Frequency [Hz]				
T_e °C	110	90	70	50	30
−7	2.19	2.22	2.19	2.06	1.79
2	2.64	2.71	2.70	2.57	2.25
7	2.97	3.06	3.04	2.94	2.57
12	3.36	3.49	3.49	3.37	2.97
20	4.15	4.35	4.36	4.24	3.74
25	4.69	4.89	4.93	4.76	4.22
30	5.21	5.44	5.47	5.29	4.66
35	5.71	5.97	6.00	5.81	5.14

Simulation scenarios

The following simulation scenarios have been considered.

1. Present State
2. Retrofit 1 (thermal insulation of walls and floors)
3. Retrofit 2 (thermal insulation of walls and floors, replacement of windows)
4. Retrofit 3 (thermal insulation of walls and floors, replacement of windows, installation of an air-to-water heat pump for heating and DHW)
5. Retrofit 4 (thermal insulation of walls and floors, replacement of windows, installation of an air-to-water heat pump for heating and DHW, LED lighting)
6. Retrofit 5 (thermal insulation of walls and floors, replacement of windows, installation of an air-to-water heat pump for heating, cooling, dehumidifying and DHW, LED lighting, PV collectors).

In Scenario Retrofit 1, the following insulations of the opaque enclosure components are adopted. The vertical wall is insulated externally by a 16 cm layer of calcium silicate hydrates, with thermal conductivity 0.045 W/(mK). This material is recyclable and requires a very low use of primary energy for its production. The floor on basement is insulated by a 9.5 cm layer of mineral wool, with thermal conductivity 0.032 W/(mK). The terrace between first and second floor is insulated by a 14 cm layer of mineral wool, with thermal conductivity 0.037 W/(mK). The loft floor is insulated by a 20 cm layer of mineral wool, with thermal conductivity 0.04 W/(mK). The floor on ground and the roof are unchanged. The main properties of the retrofitted enclosure elements are reported in Table 3; for each element, the description starts from the internal (heated) space.

Besides the thermal insulation of the opaque enclosure elements, scenario Retrofit 2 includes the replacement of all windows by double glazed windows with wood frame, having a 16 mm Argon layer and low emissivity glass; the glass transmittance is $U_g = 1.00$ W/(m^{2}K) and frame transmittance is $U_f = 1.84$ W/(m^{2}K).

In addition to the retrofitting elements of Retrofit 2, Scenario Retrofit 3 includes the installation of a multifunction air-to-water heat pump with inverter, which provides heating and DHW. The capacity of the thermal storage for DHW is 1.0 m^3; that of the thermal storage for heating is 0.2 m^3. In order to ensure a high COP of the heat pump during the heating season and to allow also summer cooling and dehumidifying (additional service provided only in Scenario Retrofit 5), the present radiators are replaced by new high-efficiency fan coils for living rooms and bedrooms, and by low temperature radiators for bathrooms. The new fan coils and radiators operate, during the heating season, with a water inlet temperature between 40 °C and 38 °C. Values of the thermal power supplied by the heat pump in heating mode, with water delivered at 40 °C and return temperature 34 °C, for several values of the external air temperature T_e and of the compressor frequency, are reported in Table 4; the corresponding values of the COP are reported in Table 5.

Table 5 COP of the heat pump, with hot water delivered at 40 °C

	Frequency [Hz]				
T_e [°C]	110	90	70	50	30
−7	2.65	2.71	2.67	2.51	2.15
2	3.27	3.38	3.39	3.21	2.78
7	3.75	3.85	3.88	3.72	3.22
12	4.29	4.44	4.49	4.30	3.76

Table 7 EER of heat pump with cold water delivered at 7 °C and condenser in external air

	Frequency [Hz]				
T_e [°C]	110	90	70	50	30
20	4.78	5.22	5.43	5.34	4.62
25	4.08	4.45	4.63	4.56	3.98
30	3.48	3.8	3.96	3.92	3.45
35	2.97	3.24	3.39	3.36	3.00

Table 8 EER of heat pump with cold water delivered at 7 °C and heat supplied to DHW

	Frequency [Hz]				
T_{hw} [°C]	110	90	70	50	30
48	2.45	2.59	2.63	2.54	2.23
50	2.30	2.42	2.47	2.40	2.11

When the heat pump works for DHW production, water is delivered with highest temperature 50 °C and lowest temperature 48 °C. The corresponding return temperatures are 40 °C and 38 °C. Values of the COP of the heat pump working for DHW production with evaporator in external air and water delivered at 50 °C, for several values of the external air temperature and of the compressor frequency, are reported in Table 6.

In addition to the retrofitting elements of Retrofit 3, Scenario Retrofit 4 includes the replacement of incandescent light bulbs by LED lighting. Besides the retrofitting elements of Retrofit 4, Scenario Retrofit 5 includes the installation of PV collectors with a conversion efficiency 14.5 % in the Southeast pitch and in the Northeast pitch of the roof: an area of 21.45 m^2 is installed in the Southeast pitch; an area of 7.8 m^2 is installed in the Northeast pitch. The peak power of the PV system is 4.24 kW. The installation of PV panels in the Southwest pitch is not convenient because this pitch is shadowed by high trees. In Scenario Retrofit 5, the heat pump provides also summer cooling and dehumidifying. When the heat pump works in cooling/dehumidifying mode and heat for DHW is required, the condensation heat is supplied to the DHW thermal storage. In the cooling/dehumidifying mode, cold water is delivered at 7 °C and returns at 12 °C. Values of the EER of the heat pump with condenser in external air, for several values of the external air temperature T_e and of the compressor frequency, are reported in Table 7. Values of the EER of the heat pump with condensation heat supplied to DHW, either at $T_{hw} = 50$ °C or at $T_{hw} = 48$ °C, are reported in Table 8.

Building energy signature in the Present State

In order to validate the TRNSYS simulation model and the technical data collected for the building in the Present State, a pre-monitoring of the building started in May 2013 and is ongoing. The validation of the simulation code has been performed by considering the measured values of the internal air temperature, of the external air temperature and of the gas volume used for heating, with reference to the period from October 15th 2013 to April 15th 2014. Hourly values of the internal air temperature were measured by sensors placed in two rooms per apartment (kitchen and bedroom). Hourly values of the external air temperature were taken from measurements performed by the Urbana Weather Station, Bologna, close to the building. The volume of the gas used for heating was obtained through weekly readings of the gas meter connected with the central boiler. The values of the internal air temperature for Apartment 3a are reported in Fig. 8, as an example. The mean temperature for this apartment, in the period considered, was 20.3 °C for the berdroom and 20.9 °C for the kitchen. The mean internal-air temperature for the whole building, averaged among all apartments, was 20.2 °C, which can be considered as equal to the set temperature for the internal air, namely 20 °C. The values of the external air temperature, during the same period, are reported in Fig. 9 and compared with those

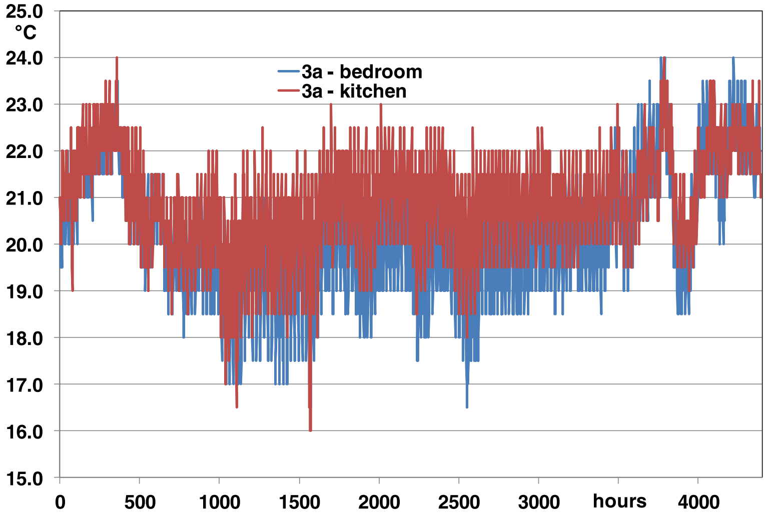

Fig. 8 Internal air temperature in Apartment 3a, from October 15th 2013 to April 15th 2014

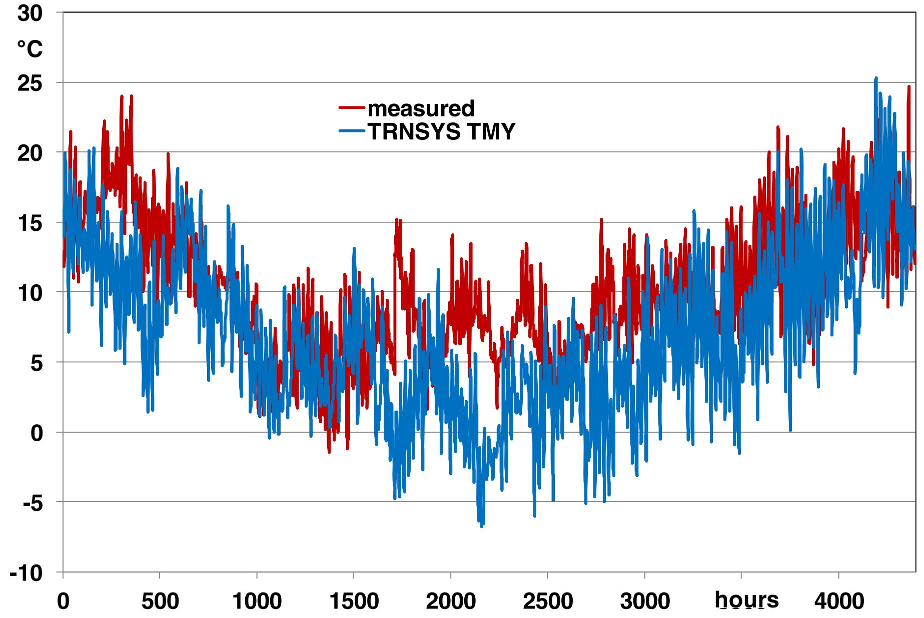

Fig. 9 Measured external air temperature compared with TRNSYS TMY, from October 15th 2013 to April 15th 2014

of TRNSYS TMY. The figure shows that winter 2013–2014 was much milder than usual: the mean temperature from October 15th 2013 to April 15th 2014 was 10.15 °C, while that of TRNSYS TMY is 6.99 °C. A similar anomaly is happening in winter 2014–2105.

The data employed to determine the experimental energy signature of the building are reported in Table 9. The duration of each period, in hours, is not always a multiple of 24 h, due to differences in the reading times, ranging from 1:30 pm to 5:00 pm. The lower heating value of the natural gas supplied to the building is 9.7 kWh/m^3. The equation of the energy signature obtained is

$$\dot{Q}_{\mathrm{exp}} = 26.209 - 1.3541\, T_e, \tag{1}$$

where $\dot{Q}_{\mathrm{exp}}$ is the mean value of the primary energy use per unit time, in kW, and T_e is the mean value of the external air temperature in °C.

Table 9 Data employed to determine the experimental energy signature

Period	Hours	Volume m^3	Energy kWh	Power kW	T_e °C
Oct. 15 – Oct. 30	360	110	1067	2.96	17.23
Oct. 30 – Nov. 30	744	866	8400.2	11.29	10.68
Nov. 30 – Dec. 12	288	584	5664.8	19.67	5.1
Dec. 12 – Jan. 20	936	1585	15374.5	16.43	7
Jan. 20 – Jan. 27	168	273	2648.1	15.76	7.91
Jan. 27 – Feb. 03	168	327	3171.9	18.88	5.18
Feb. 03 – Feb. 10	167.5	263	2551.1	15.23	8.64
Feb. 10 – Feb. 17	167.5	242	2347.4	14.01	9.13
Feb. 17 – Feb. 24	167	224	2172.8	13.01	9.24
Feb. 24 – March 03	169	236	2289.2	13.55	9.34
March 03 – March 10	170.5	214	2075.8	12.17	10.43
March 10 – March 17	167	165	1600.5	9.58	12.34
March 17 – March 24	168.5	135	1309.5	7.77	13.66
March 24 – March 31	166.5	171	1658.7	9.96	11.88
March 31 – April 07	170	108	1047.6	6.16	15.35
April 07 – April 15	190.5	74	717.8	3.77	16.1

Table 10 Data employed to determine the computational energy signature

Period	Hours	Energy kWh	Power kW	T_e °C
Oct. 1 – Oct. 15	360	404.7	1.12	16.62
Oct. 16 – Oct. 31	384	2668.2	6.95	12.39
Nov. 01 – Nov. 15	360	4169.6	11.58	10.30
Nov. 16 – Nov. 30	360	6109.5	16.97	6.48
Dec. 01 – Dec. 15	360	7732.7	21.48	4.57
Dec. 16 – Dec. 31	384	8513.4	22.17	3.24
Jan. 01 – Jan. 15	360	8997.3	24.99	1.15
Jan.16 – Jan. 31	384	9409.0	24.50	2.23
Feb. 01 – Feb. 15	360	8374.7	23.26	2.37
Feb. 16 – Feb. 28	312	5568.1	17.85	6.61
March 01 – March 15	360	5582.1	15.51	6.93
March 16 – March 31	384	3313.0	8.63	11.74
April 01 – April 15	360	1431.7	3.98	15.04
April 16 – April 30	360	1835.0	5.10	12.61

Table 11 Annual energy need for heating in each retrofit scenario, kWh

Scenario	Ap. 1a	Ap. 1b	Ap. 2a	Ap. 2b	Ap. 3a	Ap. 3b	Building
Present State	9487	17976	7479	6245	9475	8391	59,054
Retrofit 1	4579	9111	3435	2375	3867	2868	26,234
Retrofit 2 ÷ 5	2873	6114	1773	1608	2190	2112	16,670

The data employed to determine the energy signature of the building in the Present State by the dynamic simulation performed through TRNSYS 17 are reported in Table 10. The period considered is from October 1st to April 30th of the TRNSYS TMY, with intervals of half month. The primary energy use in each period has been determined by dividing the thermal energy need, calculated through the dynamic simulation, by the overall efficiency of the heating plant. The latter has been set equal to 0.795, namely the product of the boiler efficiency 0.93, the distribution efficiency 0.9, and the emission efficiency 0.95. In the comparison between the experimental energy signature and the computational one, the control efficiency has been set equal to 1, because the real average value of the internal air temperature was 20 °C. The equation of the computational energy signature for the Present State is

$$\dot{Q}_{\mathrm{comp}} = 27.575 - 1.6208\, T_e, \tag{2}$$

where $\dot{Q}_{\mathrm{comp}}$ is the mean value of the primary energy use per unit time, in kW, obtained throgh the dynamic simulation.

A comparison of the experimental energy signature and the computational one is illustrated in Fig. 10. The comparison shows that the gross heat loss coefficient of the building (namely the heat loss coefficient which takes into account also the plant efficiency) determined through the dynamic simulation, 1.62 kW/K, is 19 % higher that that found experimentally. Raesons for this discrepancy could be: a lower air exchange rate in the real operation with respect to that considered in the dynamic simulation (0.3 volumes per hour); a difference between the real heat loss coefficient and that calculated, for some enclosure elements; a higher plant efficiency

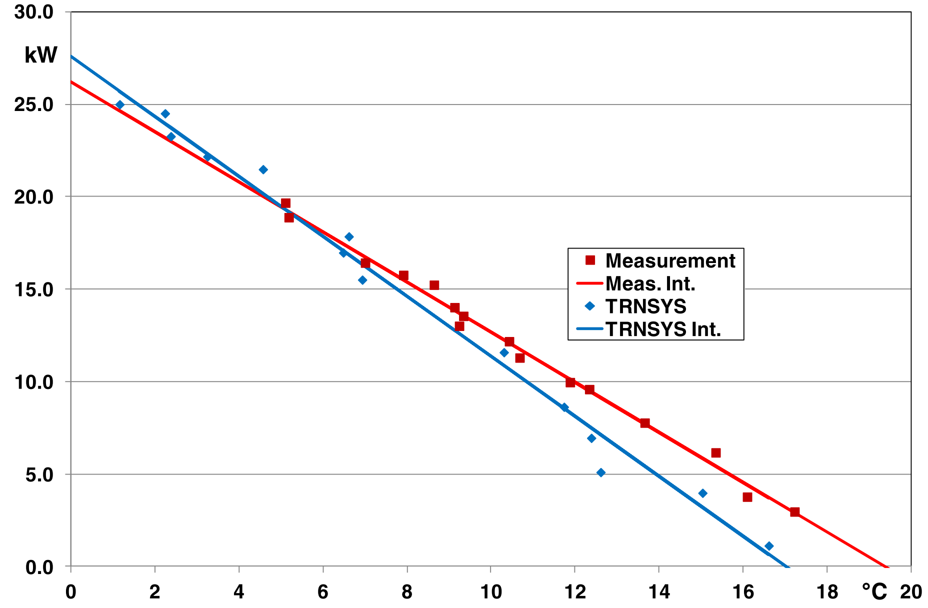

Fig. 10 Comparison between the experimental energy signature and the computational one

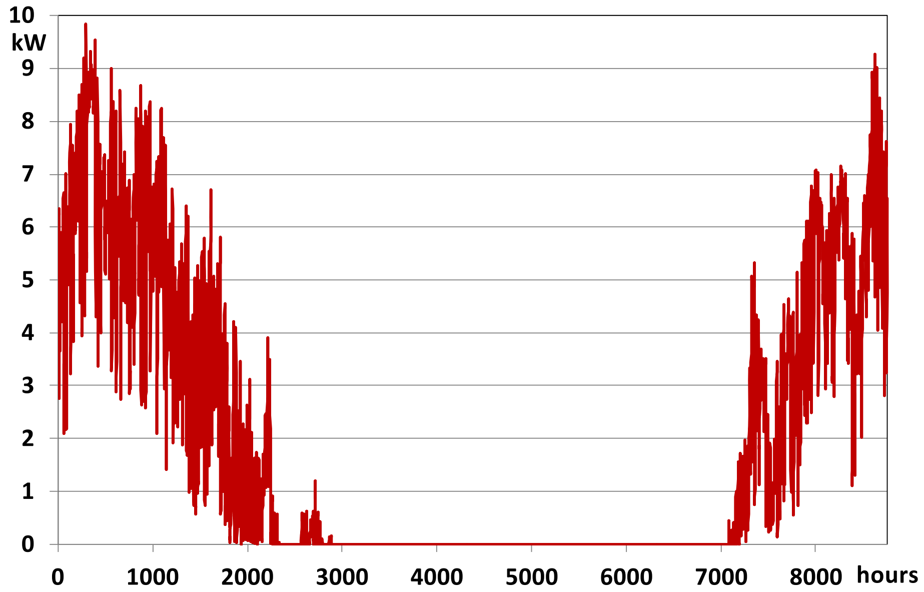

Fig. 11 Thermal power required by the building for heating, in Scenarios Retrofit 2 ÷ Retrofit 5

with respect to that considered; an inaccuracy of the gas volume meter. Another difference between the experimental energy signature and the computational one is the higher value of the zero-load temperature which occurs in the real case. This difference is probably due to the lower internal heat gains in the real case with respect to the standard ones.

In fact, during the period considered most of the tenants were often outside and had a small use of energy for cooking and lighting. A more detailed analisis of the comparison between the experimental energy signature and the computed one will be performed in a specific paper. Here we will assume that the comparison illustrated in Fig. 10 is an acceptable validation of the simulation code and of the technical data collected on the building in its present state.

In the following, the annual use of primary energy in each scenario will be considered as equal to that obtained through the dynamic simulation.

Annual use of primary energy in each retrofit scenario

The dynamic simulation of the building in each retrofit scenario was performed through TRNSYS 17. The dynamic simulation of the air-to-water heat pump, with gas-boiler auxiliary, was performed by two own MATLAB codes: one for operation in heating and DHW production mode (with heating from October 1st to April 30th); one for operation in cooling/dehumidifying and/or DHW production mode (with cooling and dehumidifying from May 1st to September 30th). The evaluation of the electric energy produced by the PV system was performed according to the National Standards UNI/TS 11300–4 (2012) and UNI/TR 11328–1 (2009)

Primary energy use for heating and DHW in the Present State and Scenarios Retrofit 1 and Retrofit 2

The dynamic simulations through TRNSYS 17 allowed to determine the annual energy need for heating of the building, in each retrofit scenario, for each thermal zone and, as a consequence, for each apartment and for the whole building. The values of the annual energy need for heating in kWh, in the Present State and in Scenarios Retrofit 1 and Retrofit 2 are reported in Table 11, for each apartment and for the whole building. The energy need for heating in Scenarios Retrofit 3, Retrofit 4 and Retrofit 5 coincides with that in Scenario Retrofit 2. A hourly plot of the thermal power required by the

Table 12 Annual use of primary energy for heating in Present State, Retrofit 1 and Retrofit 2, kWh

Scenario	Ap. 1a	Ap. 1b	Ap. 2a	Ap. 2b	Ap. 3a	Ap. 3b	Building
Present State	12,301	23,306	9697	8096	12,285	10,879	76,564
Retrofit 1	5937	11813	4453	3079	5014	3718	34,013
Retrofit 2	3725	7927	2299	2085	2839	2738	21,614

Table 13 Annual energy need for DHW, and use in Present State, Retrofit 1, Retrofit 2, kWh

	Ap. 1a	Ap. 1b	Ap. 2a	Ap. 2b	Ap. 3a	Ap. 3b	Building
Need	853.3	1367.4	748.3	750.2	748.3	750.2	5217.8
Use	2771	2188	2430	2436	2430	2436	14,689

Table 14 Annual use of primary energy for heating and DHW in Scenarios Present State, Retrofit 1 and Retrofit 2, kWh

Scenario	Ap. 1a	Ap. 1b	Ap. 2a	Ap. 2b	Ap. 3a	Ap. 3b	Building
Present State	15,071	25,494	12,127	10,532	14,715	13,315	91,254
Retrofit 1	8707	14,001	6883	5515	7444	6154	48,703
Retrofit 2	6495	10,115	4729	4521	5269	5174	36,303

building for heating, in Scenarios Retrofit 2 ÷ Retrofit 5, is reported in Fig. 11; it shows that the thermal power required by the building, in a TRNSYS 17 typical meteorological year, never exceeds 10 kW.

The primary energy use for heating in the Present State and in Scenarios Retrofit 1 and Retrofit 2 is determined by dividing the corresponding thermal energy need by the product of the following coefficients: boiler efficiency (0.93), distribution efficiency (0.90), emission efficiency of the radiators (0.95), control efficiency (0.97). The product of these coefficients is 0.771. The values of the primary energy use for heating in these scenarios are reported in Table 12.

The thermal energy need for DHW is determined by applying the National Standard UNI/TS 11300–2, where the hot water is assumed to be delivered at 40 °C. The annual need for the single apartments and for the building, in kWh, is reported in Table 13, first row of results.

In the Present State and in Scenarios Retrofit 1 and Retrofit 2, DHW is supplied by an electric boiler in each apartment, except Apartment 1b, where a gas boiler is employed. According to UNI TS 11300–2, the emission and distribution efficiencies can be assumed as equal to 0.95 and 0.94, respectively. For an electric boiler, the efficiency (including thermal losses) can be assumed equal to 0.75. Since the efficiency of the electricity production system in Italy is 0.46, the overall efficiency for the electric boilers of Apartments 1a, 2a, 2b, 3a, 3b (including emission and distribution) is 0.308. The efficiency of a DHW gas boiler (including thermal losses) can be assumed equal to 0.70; therefore, the overall efficiency (including emission and distribution) for the gas boiler of Apartment 1b is 0.625. The values of the primary energy use for DHW in Present State and in Scenarios Retrofit 1 and Retrofit 2 are reported in Table 13, second row of results.

Table 15 Electric energy used by heat pump and fan coils from October 1st to April 30th, in Scenarios Retrofit 3 and Retrofit 4, kWh

	Oct	Nov	Dec	Jan	Feb	March	April	Season
Heat pump	258	869	1485	1704	1253	692	275	6536
Fan coils	8	15	26	26	19	16	8	117
Total	266	884	1511	1730	1272	708	283	6653

Table 16 Electric energy used by heat pump for DHW from May 1st to September 30th, in Scenarios Retrofit 3 and Retrofit 4, kWh

	May	June	July	Aug	Sept	Season
Electric	133	123	118	120	125	619

The values of the primary energy use for heating and DHW, in the Present State and in Scenarios Retrofit 1 and Retrofit 2 are reported in Table 14.

Primary energy use for heating and DHW in Scenarios Retrofit 3 and Retrofit 4

In Scenarios Retrofit 3 and Retrofit 4, heating and DHW are provided by a multifunction air to water heat pump and the present radiators are replaced by high efficient fan coils (one for each room) and low-temperature radiators (in bathrooms). New distribution circuits for heating and DHW are installed. The distribution, emission and control efficiencies for heating can be assumed as equal to 0.98, 0.98, 0.98. The emission and distribution efficiencies for DHW can be assumed equal to 0.95 and 0.96, respectively. Relevant technical data of the heat pump are reported in Tables 4, 5 and 6. The amounts of electric energy used by the heat pump for heating and DHW from October 1st to April 30th have been determined by a MATLAB hourly simulation code. The monthly amounts of the electric energy used by the heat pump during that period, in kWh, are reported in the first row of Table 15; those used by the fan coils and the total amounts are reported in the second and in the third row. The amounts of electric energy used by the heat pump for DHW from May 1st to September 30th are reported in Table 16.

The total annual use of electric energy for heating and DHW is 7272 kWh. By considering the efficiency of the electricity production system in Italy, 0.46, one finds a corresponding use of primary energy of 15809 kWh. The primary energy used by the gas boiler, for integration during October÷May, is 414 kWh. Therefore, the total annual use of primary energy for heating and DHW in Scenarios Retrofit 3 and Retrofit 4 is 16223 kWh. By partitioning this use between the apartments, in proportion to their needs, one obtains the results reported in Table 17.

Primary energy use for lighting

An experimental study performed by Politecnico di Milano in 2004 (Di Andrea and Danese 2004) showed

Table 17 Annual use of primary energy for heating and DHW in Scenarios Retrofit 3 and Retrofit 4, kWh

Ap. 1a	Ap. 1b	Ap. 2a	Ap. 2b	Ap. 3a	Ap. 3b	Building
2762	5545	1869	1748	2178	2121	16,223

Table 18 Annual use of electric energy for lighting, kWh

Scenario	Ap. 1a	Ap. 1b	Ap. 2a	Ap. 2b	Ap. 3a	Ap. 3b	Building
Present State ÷ Retrofit 3	190	284	167	167	167	167	1141
Retrofit 4 and Retrofit 5	38	57	33	33	33	33	228

that the average annual use of electric energy for lighting in Italy, for apartments with an average area of 106 m^2, is 375 kWh, i.e., 3.54 kWh/m^2. The apartments considered in Ref. (Di Andrea and Danese 2004) had 80 % incandescent lamps, 15.8 % fluorescent lamps, and 4.2 % halogen lamps, a composition similar to that of the apartments under exam here, in scenarios Present State ÷ Retrofit 3. We assume that for apartments 1a, 2a, 2b, 3a, 3b, with an area of about 50 m^2, the energy use per unit area is 20 % higher, i.e., 4.25 kWh/m^2. With this assumption, the annual use of electric energy for lighting in kWh, for each apartment, is reported in Table 18. The first row refers to Scenarios Present State ÷ Retrofit 3, while the second row refers to Scenarios Retrofit 4 and Retrofit 5, where all lamps are replaced by LED lighting. The corresponding use of primary energy for lighting is reported in Table 19, where the efficiency 0.46 of the Italian electricity system has been considered.

Primary energy use for heating, DHW and lighting, in Scenarios Present State ÷ Retrofit 4

The total annual use of primary energy for heating, DHW and lighting, in Scenarios Present State ÷ Retrofit 4, in kWh, is resumed in Table 20. The primary energy use per unit area, in kWh/m^2, is reported in the last column. The table shows that Scenario Retrofit 4 yields a percent reduction of primary energy use equal to 82.2 % with respect to the Present State.

Primary energy use for heating, cooling, dehumidifying, DHW and lighting, in Scenario Retrofit 5

To further reduce the annual use of primary energy and to provide also summer cooling and dehumidifying, Scenario Retrofit 5 is considered, where PV panels are installed on the roof of the building: an area of 21.45 m^2 is installed in the Southeast pitch; an area of 7.8 m^2 is installed in the Northeast pitch. The amounts of electric energy used by heat pump and fan coils from October 1st to April 30th are the same as in Scenarios Retrofit 3 and Retrofit 4, and are reported in Table 15. The primary energy used by the gas boiler, in the same period, is 414 kWh.

Table 19 Annual use of primary energy for lighting, kWh

Scenario	Ap. 1a	Ap. 1b	Ap. 2a	Ap. 2b	Ap. 3a	Ap. 3b	Building
Present State ÷ Retrofit 3	413	617	362	363	362	363	2481
Retrofit 4 and Retrofit 5	83	123	72	73	72	73	496

Table 20 Annual use of primary energy for heating, DHW and lighting in Scenarios Present State ÷ Retrofit 4, kWh and kWh/m^2

Scenario	Ap. 1a	Ap. 1b	Ap. 2a	Ap. 2b	Ap. 3a	Ap. 3b	Building	per m^2
Present State	15,484	26,111	12,489	10,895	15,077	13,678	93,734	332.5
Retrofit 1	9120	14,618	7245	5878	7806	6517	51,184	181.6
Retrofit 2	6908	10,733	5091	4884	5631	5537	38,784	137.6
Retrofit 3	3175	6162	2231	2111	2540	2484	18,703	66.3
Retrofit 4	2844	5669	1941	1820	2250	2194	16,719	59.3

Cooling and dehumidifying is provided from May 1st to September 30th: the set point is 27 °C for the internal air temperature and 50 % for the relative humidity. The monthly amounts of thermal energy need for cooling and dehumidifying for the whole building, evaluated by dynamic simulation through TRNSYS 17, are reported in Table 21. Also the monthly amounts of the thermal energy use are reported in the last row, obtained by considering an overall distribution, emission and control efficiency equal to 0.98 × 0.98 × 0.98.

The monthly amounts of the electric energy used by the heat pump for cooling, dehumidifying and DHW production during the period from May 1st to September 30th were determined by applying a hourly MATLAB simulation code. The results, in kWh, are reported in Table 22. In the same table, also the estimated use of electric energy by the fan coils is reported. The primary energy used by the gas boiler for integration of DHW during this period is about 1 kWh.

The monthly values of the total electric energy used (for heating, cooling-dehumidifying, DHW and lighting) are reported in the first row of Table 23. Part of the electric energy used is provided by the PV system. Monthly

Table 21 Monthly amounts of the thermal energy need and use for cooling and dehumidifying, kWh

	May	June	July	Aug	Sept	Season
Sensible	566	1309	2350	2110	855	7190
Latent	102	175	286	273	125	962
Total	669	1485	2636	2383	980	8153
Total use	710	1577	2801	2532	1041	8662

Table 22 Monthly amounts of the electric energy used for cooling, dehumidifying and DHW from May 1st to September 30th, kWh

	May	June	July	Aug	Sept
Heat pump	353	526	824	779	423
Fan coils	8	15	26	26	8
Total	361	541	850	805	430

amounts of the electric energy produced by the PV system are reported in the second row of the table. In the other rows, the following monthly energy amounts are reported, in kWh: electric energy taken from the grid, corresponding primary energy, PV electric energy employed for self use, PV electric energy supplied to the grid. The table shows that the annual use of primary energy due to the use of electric energy from the grid is 12215 kWh. By adding the primary energy used by the gas boiler, 415 kWh, one obtains the total annual use of primary energy of the building, 12630 kWh, which corresponds to 44.8 kWh/m^2.

Synopsis of the total annual use of primary energy in Scenarios Present State ÷ Retrofit 5

A synopsis of the total annual use of primary energy per unit heated floor area in Scenarios Present State ÷ Retrofit 5 is given in Fig. 12. The proposed retrofit scenario is Retrofit 5, which yields 86.5 % saving of primary energy with respect to the Present State and provides also summer cooling and dehumidifying, a service not available in other scenarios.

Annual emission of CO_2 in each retrofit scenario

The emission of carbon dioxide caused by the use of fossil fuels and of electric energy can be calculated by employing the European Standard EN 15603:2008. The fuel employed in the building is natural gas. The CO_2 production coefficient is 277 kg/MWh for natural gas and 617 kg/MWh for electric energy.

The annual use of primary thermal energy for heating (THE heat), of electric energy for heating (EE heat), of primary thermal energy for DHW (THE DHW), of electric energy for DHW (EE DHW), of electric energy for lighting (EE light), of total primary thermal energy (THE), of total electric energy (EE), in kWh are reported in columns 2 ÷ 8 of Table 24. In columns 9 ÷ 11 of the same table are reported the kilograms of CO_2 due to the use of thermal energy (CO_2 THE), the kilograms of CO_2 due to the use of electric energy (CO_2 EE), the total kilograms of CO_2 emitted per year.

In Scenarios Retrofit 3 and Retrofit 4, the use of electric energy for heating (EE heat) includes that for the production of DHW during the heating period. In Scenario Retrofit 5, the total use of electric energy cannot be divided into use for heating (EE heat) and use for DHW (EE DHW), on account of the PV electricity input. The table shows that the reduction in CO_2 emission obtained in Scenario Retrofit 5 is 86.3 % with respect to the Present State.

Comfort improvement

A study on the thermal comfort has been carried out, to estimate the comfort improvement produced by the retrofitting. Dynamic simulations performed through TRNSYS 17 allowed to determine the time evolution of operative temperature, of the relative humidity, and of the Fanger indexes PMV (Predicted Mean Vote) and the PPD (Predicted Percentage Dissatisfied) (Fanger 1970) for each room, in scenarios Present State and Retrofot 5, with reference to TRNSYS TMY. The PMV index predicts the mean response of a large group of people according to a standard thermal sensation scale, ranging from +3 (hot) to −3 (cold), where 0 stands for neutral. The PPD index is related to the PMV index. Usual recommended limits for PMV and PPD indexes are $-0.5 < \text{PMV} < 0.5$ and $\text{PPD} < 20$ %, respectively. With reference to the standard UNI EN ISO 7730:2006, the following input conditions have been considered in winter and summer, respectively. For the heating period: clothing insulation of 1.0 clo (typical business suit), metabolic rate of 1.2 met (seated, light home work), air speed of 0.1 m/s; for the cooling period: clothing insulation of 0.5 clo (light summer clothing), metabolic rate of 1.2 met (seated, light home work), air speed of 0.3 m/s.

Table 23 Monthly electric energy balance and primary energy use in Scenario Retrofit 5, kWh

	Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
TOTAL	1749	1289	727	301	381	560	870	825	449	285	903	1530	9869
PV	148	224	356	467	564	603	681	577	431	306	167	139	4663
From grid	1601	1066	371	0	0	0	189	247	18	0	736	1391	5619
Primary	3481	2317	806	0	0	0	410	537	39	0	1600	3024	12,215
Self use	148	224	356	301	381	560	681	577	431	285	167	139	4251
To grid	0	0	0	166	183	43	0	0	0	21	0	0	413

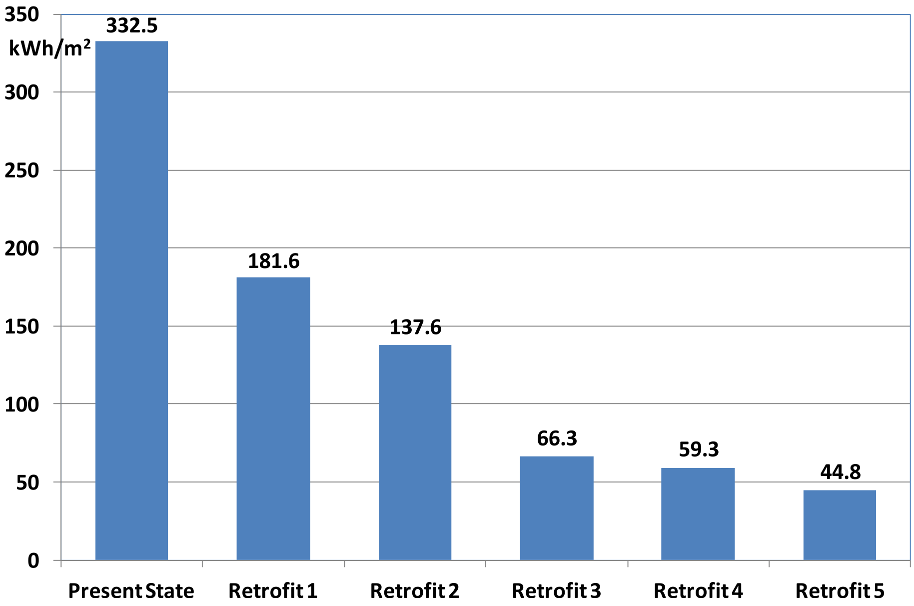

Fig. 12 Total annual use of primary energy per unit floor area in all Scenarios

The results show that a relevant improvement of the thermal comfort can be obtained by the retrofitting, especially during summer, and that in scenario Retrofit 5 the PPD is expected to remain below the recommended limit of 20 % for every room, during the whole year. Some results are illustrated in Figs. 13, 14, 15 and 16, with reference to Apartment 3b, kitchen.

Figures 13 and 14 illustrate, respectively, the time evolution of the operative temperature and of the PPD during winter, from November 1st to February 28th. Fig. 13 shows that, while in the Present State the operative temperaure is often lower than 18 °C, in Retrofit 5 it is very close to the set temperature of the internal air, 20 °C. Fig. 14 shows the corresponding reduction of PPD. Figs. 15 and 16 illustrate, respectively, the time evolution of the operative temperature and of the PPD during summer, from June 1st to August 31st. Fig. 15 evidences that the combined effects of the thermal resistance and of the thermal inertia of the thermal insulation keep the operative temperature of the room very stable, even if the external temperature suddenly decreases and remains low for some days. Fig. 16 shows that the PPD, dramatically high in the Present State, remains below 10 % in Retrofit 5.

Economic analysis

For each retrofit scenario, the additional cost with respect to the previuos scenario and the total cost have been determined. Then, for each scenario, the annual money saving due to the reduction of use of energy sources has been determined. Hence, for each retrofit scenario, the financial payback time at zero interest rate, zero annual increase of the cost of energy sources, zero inflation rate has been calculated.

The additional cost and the total cost of each retrofit scenario are summarized in Table 25. The additional cost of Retrofit 3 (replacement of the plant for heating and DHW) is very high because, for the building considered, the replacement of the plant requires a complete construction (or reconstruction) of the distribution circuit. In fact, no distribution circuit for DHW is present, and the distribution circuit for heating is uninsulated and obsolete. Indeed, the very high additional cost of

Table 24 Annual use of primary thermal energy and of electric energy, kWh, and annual emission of CO_2, kg

Scenario	THE heat	EE heat	THE DHW	EE DHW	EE light	THE	EE	CO_2 THE	CO_2 EE	CO_2
Present State	76,564	0	2187	5749	1141	78,751	6890	21,814	4251	26,065
Retrofit 1	34,013	0	2187	5749	1141	36,201	6890	10,028	4251	14,279
Retrofit 2	21,614	0	2187	5749	1141	23,801	6890	6593	4251	10,844
Retrofit 3	414	6653	0	619	1141	414	8413	115	5191	5305
Retrofit 4	414	6653	0	619	228	414	7500	115	4628	4742
Retrofit 5	414		1			415	5619	115	3467	3582

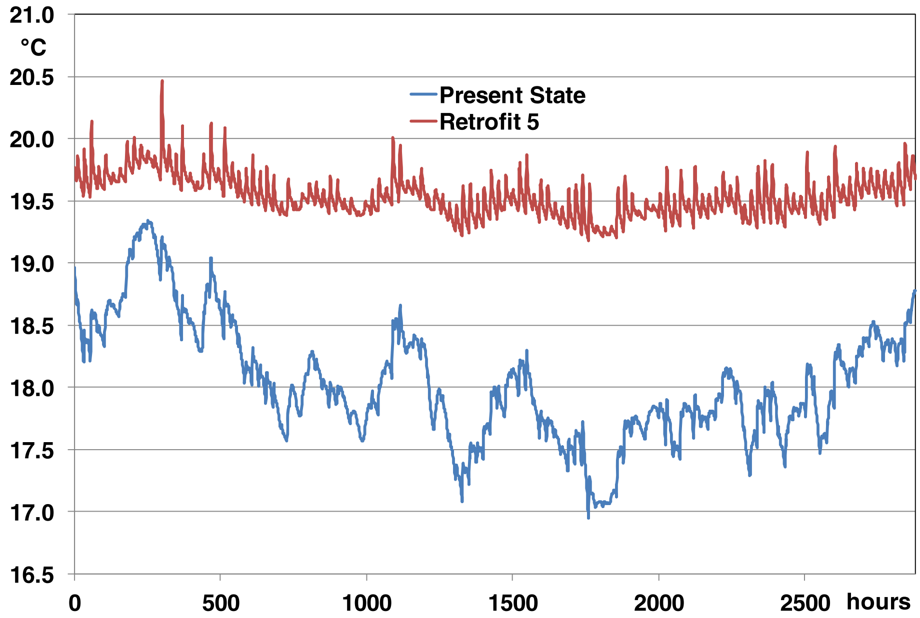

Fig. 13 Operative temperature for Apartment 3b, kitchen, from November 1st to February 28th

Retrofit 3 could be considered only in part as a cost for energy retrofitting, and in part as a necessary renovation cost of the building. The additional cost for the installation of heat pump, thermal storage tanks, fan coils and radiators is 24,555 Euro; the remaining additional cost (114,045 Euro) is for the installation of the new distribution circuits for heating and DHW and of heat meters.

In order to determine the annual economic savings, the following data on the employed fuel, natural gas, and on electricity have been employed:

- Natural gas: lower heating value 9.595 kWh/m^3; cost 0.9 Euro/m^3;
- Electricity: cost 0.2 Euro/kWh; value of electricity supplied to grid 0.0389 Euro/kWh

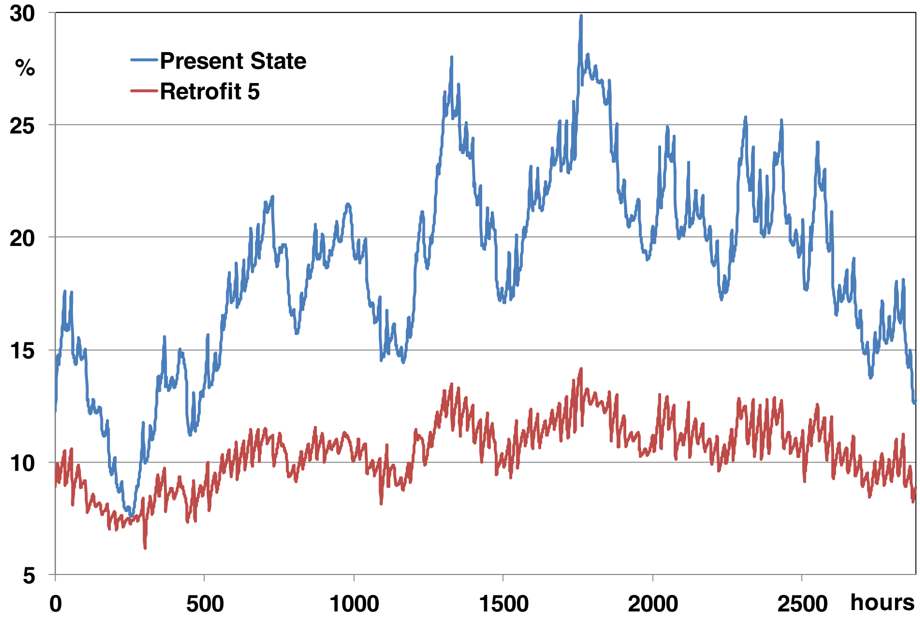

Fig. 14 PPD for Apartment 3b, kitchen, from November 1st to February 28th

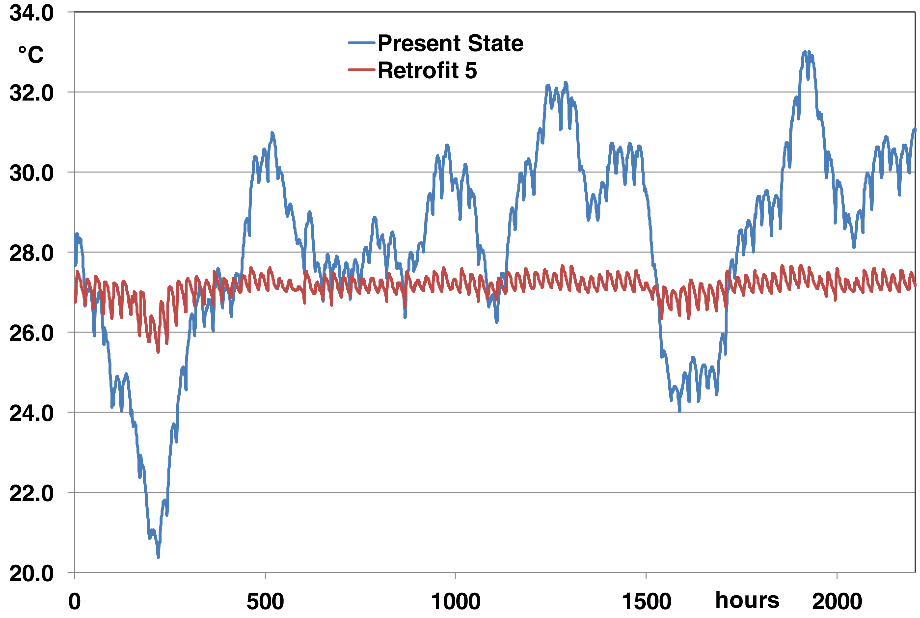

Fig. 15 Operative temperature for Apartment 3b, kitchen, from June 1st to August 31st

The value of the PV electricity supplied to grid is very low at present in Italy. This is a sudden change with respect to the policy of a few years ago, when very high incentives were given to PV energy production and also the electricity produced and self-used was paid.

The annual savings obtainable in each retrofit scenario are illustrated in Table 26. The columns of the table report, for each scenario: the annual use of thermal primary energy (kWh), the annual use of electric energy (kWh), the annual use of natural gas (m^3), the cost of the gas used (Euro), the cost of the electricity used (Euro), the total annual cost of gas plus electricity (Euro), the income due to PV electricity supplied to grid (Euro), the annual saving with respect to the Present State (Euro).

In the evaluation of the payback time, for each retrofit scenario, State incentives should be considered. Although

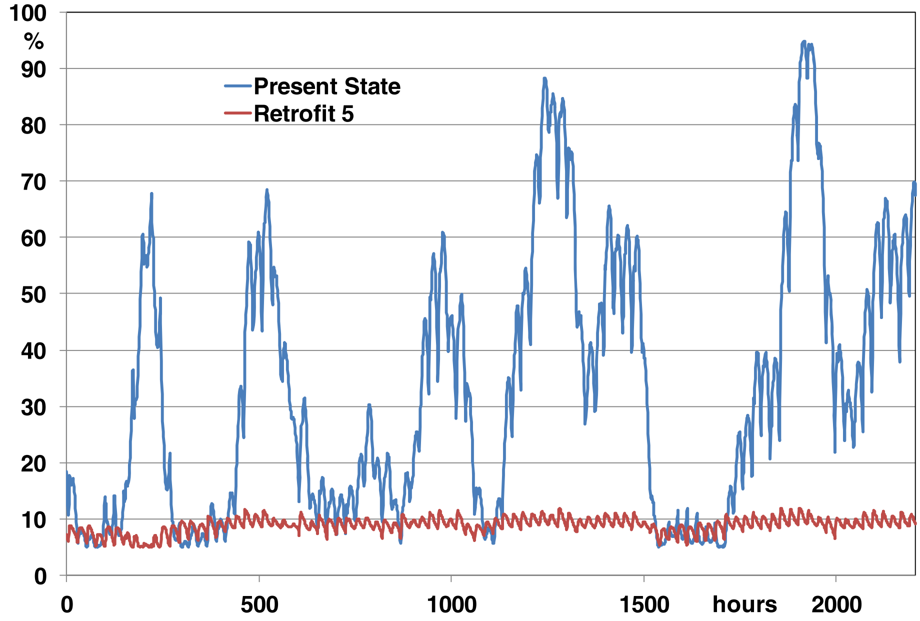

Fig. 16 PPD for Apartment 3b, kitchen, from June 1st to August 31st

Table 25 Additional cost and total cost of each retrofit scenario, Euro

Retrofit scenario	Add cost	Total cost
Retrofit 1	67,419	67,419
Retrofit 2	18,324	85,743
Retrofit 3	138,600	224,343
Retrofit 4	871	225,214
Retrofit 5	11,660	236,874

the building is owned by the Municipality of Bologna, reference is made to the Italian State incentives delivered to private citizens, as recommended by the HERB consortium. The retrofit interventions are considered in the following sequence: thermal insulation of vertical and horizontal walls (Retrofit 1); Retrofit 1 + replacement of windows (Retrofit 2); Retrofit 2 + replacement of the heating and DHW plant (Retrofit 3); Retrofit 3 + LED lighting (Retrofit 4); Retrofit 4 + PV system (Retrofit 5). In this sequence, each additive cost receives a State contribution equal to 65 % of the cost. The LED lighting and the PV system receive this contribution because they are parts of a general retrofit plan which yields an annual use of primary energy lower than the limit prescribed by the Government for the applicability of the 65 % contribution. The State contribution is given in the form of tax reduction in 10 equal amounts, during a period of 10 years. Since vanishing interest and inflation rates are assumed, the total State contribution is considered as a cost reduction available at the first year.

The total cost and the total payback time of each retrofit scenario, without incentives and with incentives, are reported in Table 27. As shown in the table, the replacement of the plant, with the installation of new distribution circuits, enhances the general payback time with incentives from about 6 to about 11 years. This intervention, however, yields several benefits to the building: the possibility of supplying heating, DHW, cooling and dehumidifying with a very low annual use of primary energy; the renovation of the distribution system.

Table 26 Use of energy sources and savings in each scenario, per year

Scenario	THE kWh	EE kWh	Gas m^3	Gas cost	EE cost	Cost	Income	Saving
Present State	78,751	6890	8119	7307	1378	8685	0	—
Retrofit 1	36,201	6890	3732	3359	1378	4737	0	3948
Retrofit 2	23,801	6890	2454	2208	1378	3586	0	5098
Retrofit 3	414	8413	43	38	1683	1721	0	6964
Retrofit 4	414	7500	43	38	1500	1538	0	7146
Retrofit 5	415	5619	43	39	1124	1162	16	7523

Table 27 Total cost (Euro) and total payback time (years) of each retrofit scenario

Scenario	Cost	Cost with incentives	Payback	Payback with incentives
Retrofit 1	67,419	23,597	17.1	6.0
Retrofit 2	85,743	30,010	16.8	5.9
Retrofit 3	224,343	78,520	32.2	11.3
Retrofit 4	225,214	78,825	31.5	11.0
Retrofit 5	236,874	82,906	31.5	11.0

Conclusions

Five scenarios for the energy retrofitting of a residential building with 6 apartments located in Bologna, North-Center Italy, have been analyzed through hourly dynamic simulations of the building and of the plant. Simulations of the building have been performed by TRNSYS 17; those of the multifunction heat pump system with thermal storage by own MATLAB codes. The simulation code has been validated, in the Present State scenario, by comparing the computational energy signature of the building with that determined experimentally by a pre-retrofit monitoring.

The proposed retrofit scenario is the most complete one, which includes: thermal insulation of the external vertical walls by calcium silicate hydrates; thermal insulation of horizontal enclosure elements by mineral wool; replacement of windows; installation of a multifuction heat pump with inverter and thermal storage for heating, cooling/dehumidifying, and DHW supply; installation of new distribution networks for heating/cooling and DHW; installation of high efficient fan coils and low temperature radiators; LED lighting; installation of a PV system on the roof. The proposed retrofit scenario yields a 86.5 % reduction of the use of primary energy, a 86.3 % reduction of CO_2 emission, and a relevant comfort improvement. The payback time for private owners, considering State incentives, is 11 years.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

EZ coordinated the research work, evaluated the energy use and the CO_2 production in each scenario, by employing simulation results provided by SL and CN, and wrote the paper. CN performed the dynamic simulations of the heat pump system. SL performed the dynamic simulations of the building. GLM evaluated the plant efficiency in the present state and gave suggestions for the choice of the retrofit scenarios. All authors read and approved the final manuscript.

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