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At the roots of the energy performance gap: Analysis of monitored indoor air before and after building retrofits

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ABSTRACT

The growing concern about climate change and energy security has fostered energy efficiency measures to reduce building consumption in many European countries. The policies and incentives behind these improvements typically rely on pre-calculated expected energy savings. However, evidence shows that the actual energy performance after such interventions often falls short of the expected targets. People's behavior is one of the causes of the energy performance gap between measured and predicted building energy performance. This study contributes to this discussion by analyzing data on air temperature, relative humidity, and Volatile Organic Compounds monitored in eleven apartments in Milan (Italy) before and after building renovation. These data were then used to simulate two representative flats, thus obtaining their energy demand for space heating. The analysis of the measured data shows that users adapt differently to building retrofits. Under the assumption of constant moisture generation during the periods monitored, some occupants appear to increase air change rates and reduce indoor air temperatures, while others show the opposite behaviour. These trends could be related to the fact that some users prioritize air quality over thermal comfort and vice versa. Energy simulations suggest that the former behaviour leads to a larger energy performance gap.

1. Introduction

Residential buildings are responsible for 27% of the final energy consumption in Europe [1]. Various directives and standards are provided at the national and international levels to control and reduce energy consumption; however, discrepancies can be found between metered energy consumption and the one expected by energy performance certificates or predicted by building energy simulations. This discrepancy is commonly called energy performance gap (EPG). The latter can be attributed to a number of factors, including inaccuracy in modeling (occupants' behavior, building parameters, climate data) and actual deviations due to malfunctioning equipment and non-optimal energy use from final users [2].

Already in the nineteenth century, Jevons [1] noticed that the potential benefit obtained by technological efficiency does not necessarily lead to a lower consumption of resources. This paradox, which is called rebound effect, also holds true for the energy retrofit of buildings. In the residential sector in particular, the rebound effect reflects the tendency of occupants to increase their energy demand for comfort when household energy efficiency is enhanced [3].On the other hand, the EPG can also be a result of an overestimated energy consumption before building renovations. This phenomenon, which is called 'prebound effect', generally indicates that occupants are not getting an adequate level of thermal comfort and could therefore be an indicator of energy poverty when associated with low-income areas [4].

People's views, habits, practices and resources determine whether and how buildings are retrofitted, and influence how energy is consumed before and after retrofitting. Furthermore, social factors interweave with technical factors in buildings' operation such that the two often co-determine each other [5]. Within the work of IEA EBC Annex 53, six factors have been defined as main contributors to the EPG, organized into two groups: physical and human influenced [6]. Physical-influenced variables are mostly related to building envelopes, climate, and building services that allow estimate the building's energy performance. Human-influenced factors include building occupants and the parameters that they can change to achieve a good indoor environmental quality. Despite the work of the scientific community, there is a lack of understanding about these factors influencing energy consumption. For instance, in a study about 481 dwellings belonging to six social housing buildings in the Basque countries, it was found that the energy consumption depends strongly on the occupant's behavior rather

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Nomenclature

GHI [W / m^2]	Global horizontal irradiance
G [kg/h]	Mass flow rate
Q_H [W]	Energy use for space heating
ρ [kg/m^3]	Density
RH [%]	Relative humidity
T [$°C$]	Dry-bulb air temperature
V [m^3]	Volume
x [kg_v/kg_a]	Specific humidity

Subscripts

a	Dry air
e	External (outdoor) air
i	Indoor air
v	Vapor

Acronyms

AA	Ante-Ante
ACR	Air change rate
EPC	Energy performance Certificate
EEPG	Energy performance gap
ESA	Energy saving achievement
ESD	Energy saving deficit
HVAC	Heating, Ventilation and Air Conditioning
IAQ	Indoor Air Quality
PA	*Post-Ante*
PP	*Post-Post*
PV	Photovoltaic
TVOC	Total Volatile Organic Compounds

than on the physical characteristics of the building [7].

Exadaktylos et al. [8] reviewed empirical studies on energy-related behaviors and found that limited rationality and willpower may increase rebound, while the effects of behaviors driven by bounded self-interest are less clear.

An extensive literature review presented by Ekim [9] identified the complexity and variability of users' behavior(s) as the main responsible for this trend. Contrarily to energy monitoring results, which are objective and can be easily obtained, predicting occupants' behavior requires a wide range of statistical data and algorithms. In fact, looking at the new perspective proposed by Schot et al. [10], users should be considered no longer as individual consumers but as active stakeholders involved in the transition process towards energy efficient systems. In fact, users are individuals whose choices may be influenced by market-based assumptions, or shape new routines based on energy saving policies.

Calì et al. [11] evaluated the monitored energy consumption before and after refurbishment of three apartment buildings in Germany upgraded in the period 2008–2010. From some assumptions concerning the indoor conditions, the simulated energy demand after the retrofit was calculated, evaluating an energy performance gap (EPG) between −12% and 287%, an energy saving deficit (ESD) between 5% and 28%, and a respective energy saving achievement (ESA) between 72% and 95%. ESD and ESA define the share of missing energy savings and the share actually achieved compared to the total energy savings expected as a result of an efficiency intervention.

Similarly, Galvin [12] studied three apartment buildings in Germany monitored both before and after retrofit. In this case, energy needs before and after retrofit were simulated, assuming the same indoor conditions. From this, whole-apartment building-level indices reported an annual EPG between 2% and 273% and an ESD between 1% and 44%.

Cozza et al. [13] examined the EPG on a sample of 1172 Swiss retrofitted buildings for which theoretical and actual metered consumption were known before and after retrofit. They found an ESD of 37%, mainly due to underestimation of the theoretical energy consumption pre-retrofit; on the contrary, the predicted savings with measured consumption before retrofit have a better agreement with the actual savings (ESD 3.6%).

A large-scale study of around 200,000 dwellings in the Netherlands [14] compared predicted energy consumption from energy performance certificates (EPC) and real monitored energy; the study proved that, although the estimation of energy use in non-efficient dwellings is higher than reality, the difference between the predicted energy consumption and the actual value will be decreased for non-efficient buildings (i.e., buildings with high values of specific primary energy consumption). On the contrary, for efficient buildings (high EPC level), the actual gas consumption often exceeds the predicted levels. Furthermore, they found out that the expected reduction of primary energy that should be achieved when improving building performance is lower than expected.

Hamburg and Kalamees [15] indicated an EPG between 2% and 30% from a sample of refurbished multi-family buildings in Estonia. They pointed out mistakes and simplified modeling of the buildings as the main reasons for such discrepancies. Beyond that, underestimating household's indoor air temperature was also considered a cause of the mismatch.

Papadopoulos et al. [16] investigated the effectiveness of retrofit measures on a sample of eight council-owned properties, where energy consumption and environmental parameters were measured ante- and post-retrofit. The study revealed that the total gas usage met expectations despite the average internal temperatures being higher in the post-retrofit period compared to the ante-retrofit period. At the same time, seven tenants out of eight reported an increase in warmth, i.e., improved thermal comfort. On the contrary, since the refurbishment mainly affected the gas consumption, the annual variation of electricity use was likely due to changes in user circumstances or behavior, since no cooling systems were installed.

Van der Brom [17] studied the energy performance gap of 90000 buildings that underwent retrofit actions. To reduce biases, the study has been carried out only for units with the same user before and after refurbishment. EPG has been shown in 7.6% of the cases where prebound and rebound effects occurred, depending on the renovation measure applied. The study confirmed that these effects tend to occur more often in deep-renovated buildings compared to buildings with single refurbishment actions. Moreover, monitoring the same users allowed to demonstrate that people responsible for high (low) energy consumption before retrofit maintain the same behavior after retrofit. This on one hand confirms the important role of the user in predicting energy savings, but also means that the rebound and prebound effect explain only part of the energy saving gap.

Calì et al. [18] monitored five apartments and suggested that window opening to improve users' thermal comfort is an important driver of the energy performance gap. They found that the most common driver to open a window was the time of the day, followed by the carbon dioxide concentration. The most common driver to close a window was the daily average outdoor temperature, followed by the time of the day.

Moeller et al. [19] considered forty apartments in Munich that had already been upgraded at the time of the analysis. They compared the energy demand simulated from assumed indoor conditions to the energy demand simulated from actual indoor conditions monitored by sensors installed inside the apartments. They found EPG values ranging from −59% to 318% for individual apartments.

Housez et al. [20] compared actual and projected heating demand for seven retrofitted buildings in Austria, along with monitored indoor air data before and after retrofit. They concluded that the change in air temperatures alone could not explain the energy performance gaps. Based on relative humidity data and user questionnaires, the research suggested that occupancy-driven window operation might have resulted in air change rates higher than those indicated in energy certificate calculations.

User adaptation and rebound effect have been evaluated in this paper, analyzing indoor environmental conditions monitored in several residential apartments in northern Italy before and after retrofit strategies. The main outline will be the determination of user habits, estimating their impact on energy savings by implementing dynamic energy simulations that combine different building properties and user behavior.

Van der Brom et al. [21] stated that the magnitude of influence related to user behavior lacks empirical demonstration. Research conducted by Mahdavi et al. [22] supported this theory, showing that literature is still not sufficient to support the evidence that human factors represent the main contributors to the actual energy consumption.

Therefore, bringing further data to support or contradict this claim is important to clarify the role of user behavior with regard to the energy performance gap.This paper addresses this research gap by analyzing the temperature, relative humidity and TVOC concentrations of indoor air monitored in eleven apartments in Milan (Italy) during three heating seasons, before and after the thermal insulation of the buildings' envelope. The change in the indoor environmental parameters was used to inform detailed energy simulations of two representative apartments, thus estimating the expected values of EPG and ESD. This research aimed to evaluate how users adapt to renovated building envelopes, thus having a better insight into the reasons why retrofit actions often result in lower energy savings than expected.

2. Case study

2.1. Building description

This study included apartments on three separate blocks in the suburbs of Milan, Italy, as shown in Fig. 1. This article will refer to them as apartment blocks B, F, and M.

Apartment block B consists of four buildings with 142 flats and was retrofitted between February and August 2019; for this block, monitoring data is available for two flats (B1 and B2). Building M is an apartment block of only ten flats, and the energy retrofit works took place between February and June 2019; monitoring data for six flats are available for this block (M1 to M6). Apartment block F consists of 47 flats within a single building, retrofitted between November 2020 and February 2021; data from twelve flats are available for it (F1 to F12). Heated areas range from 60 m^2 to 200 m^2 depending on the flat considered, and are commonly found between 80 and 100 m^2.

Fig. 1. Approximate location of the apartment blocks and the weather station.

Energy performance certificates provided information concerning the envelope properties and retrofit actions. External and internal walls are made of solid bricks, while floors and ceilings have a traditional brick-concrete structure. Interior partitions comprise 12 cm solid bricks with gypsum plaster on both sides (U = 1.43 W/(m^2 K)). Both floor slabs and external walls have been insulated with rock wool panels, while the windows have not been replaced. More details on the stratigraphy of the building envelope components are shown in Table 1.

The envelope structures facing the outdoor environment (external wall, roof ceiling, and the ceiling towards the basement) of buildings M and F have been insulated with rock wool panels on the outer side. In contrast, the envelope of building B was improved by blowing insulating material. Traditional gas boilers have been replaced with heat pumps coupled with a photovoltaic system (Blocks B and M) or with condensing boilers (Block F). All the buildings considered have a centralized heating system with vertical distribution and high temperature radiators, which was not changed.

2.2. Indoor air data

The monitoring program started before the renovation works to assess the change in environmental conditions after the intervention. The data collection has started from 8th to 14th November 2018, depending on the apartment. Each flat has one or two sensors, as shown in Table 2. The sensors were placed at the entrance, the living room, or the bedroom.

Two battery -powered environmental sensors like the one shown in Fig. 2 were installed in each apartment, providing dry-bulb air temperature, relative humidity, pressure, total volatile organic compounds (TVOC) concentration, and illuminance. However, the latter was not considered within this work. The accuracy of the sensors at 25 °C is ±0.5 °C for air temperature and ±3% for relative humidity measurements in the range 20%–80%. Measurements were logged with a time step of 1 h and transmitted to a gateway over Lorawan® network and then stored on a cloud server. Details about TVOC measurements are reported in Appendix B.

The vertical distribution of the heating system was not changed during the building retrofit. Therefore, both before and after retrofit the occupants could only interact with the system by adjusting the

Table 1
Thermal properties of the building envelopes ante- and post-retrofit.

Building component	Original structure		Retrofitted structure	
	Stratigraphy	U-value $W/(m^2 K)$	Stratigraphy	U-value $W/(m^2 K)$
External walls	Int. plaster (2 cm) Solid bricks (37 cm) Ext. plaster (2 cm)	1.40	Int. plaster (2 cm) Solid bricks (37 cm) Rock wool panels (14 cm) Ext. plaster (2 cm)	0.21
Floor slab	Ceramic tiles (1.5 cm) Concrete screed (7 cm) Brick-concrete slab (20 cm) Int. plaster (1.5 cm)	1.39	Ceramic tiles (1.5 cm) Concrete screed (7 cm) Brick-concrete slab (20 cm) Rock wool panels (14 cm) Internal plaster (1.5 cm)	0.21
Windows	Double-glazed windows	2.71	Double-glazed windows	2.71

Table 2
Characteristics of the monitored apartments.

Apartment block	Number of monitored (selected) flats	Number of sensors per flat	Average flat volume (min-max), m^3	Retrofit period
B	2 (1)	1	344 (328–360)	Feb–Aug 2019
F	12 (7)	2	413 (271–660)	Nov 2020–Feb 2021
M	6 (3)	2	255 (182–326)	Feb–Jun 2019

Fig. 2. Indoor environmental sensor.

thermostatic radiator valves.

2.3. Weather data

The weather data was provided by the Regional Agency for Environmental Protection (ARPA) of Lombardy [23]. The data were collected from the weather station of Lambrate due to the rather peripheral position (similar to the monitored buildings), thus reducing the risk of local urban effects on the climate. Lambrate was also chosen because it was one of the weather stations that included measurements of the global radiation on the horizontal plane (GHI), which is important because it affects the heat balance of the buildings and its effect is not directly reflected in a change of indoor air temperature, together with dry-bulb air temperature (T_e) and relative humidity (RH_e).

3. Methods

3.1. Analysis of monitored data

Selection of the periods. The study considered those flats where measured data were available for the period between November 14th and December 21st for three years: 2018 (ante-retrofit for all apartments), 2019 (ante-retrofit for apartments belonging to block F, post-retrofit for all the other ones) and 2021 (post-retrofit for all apartments). Such preselection led to the exclusion of 9 flats out of 20, thus reducing the size of our sample to 11 apartments (see Table 2), for which enough data were available *ante*- and *post*-retrofit, i.e., for years 2018, 2019, and 2021. The corresponding weather data are summarized in Table 3. This period was selected because the Christmas holidays were excluded, assuming that the occupancy in the different flats becomes too variable in such a period. January was excluded due to a lack of data, and February–April could not be considered as the refurbishment works had already started in some flats. In the analysis of the winter season, it was decided to exclude November and December 2020, as these months were strongly affected by the exceptional measures linked to the Covid-19 pandemic. Indeed, the rules imposed by the Italian government [24] strongly impacted users' habits, thus introducing a potential bias to the analysis.

Table 3
Mean values and standard deviation of weather data recorded between November 14th and December 21st for three years.

	2018	2019	2021
T_e [°C]	5.9 ± 3.5	7.6 ± 2.6	5.4 ± 3.2
RH_e [%]	80.7 ± 14.4	90.1 ± 10.8	85.9 ± 12.4
GHI [W /m^2]	54.6 ± 23.9	34.4 ± 26.8	52.8 ± 27.6

Table 3 shows that 2019 was warmer than 2018, with the outside air temperature being 1.7 °C higher on average. Despite the reduced solar radiation, this may have influenced the occupant driven natural ventilation of the interior spaces. Weather conditions in 2018 and 2021 were more similar concerning outdoor air temperature, relative humidity, and solar radiation. Therefore, all results shown in the manuscript refer to the comparison between 2018 (ante-retrofit) and 2021 (post-retrofit), and the comparison between 2018 and 2019 has been included in Appendix A.

Other assumptions. The average ventilation rate was estimated for each apartment from the hygrothermal balance, assuming a constant internal vapor generation of 0.375 kg_v/h, as shown in Equation (1).

$$G_a = \frac{G_v}{x_i - x_e} \quad (1)$$

The air mass flow rate (kg_a/h) was then converted into air change rate (volumes per hour) by normalizing the data with respect to the building net heated volume, as shown in Equation (2).

$$ACR = \frac{G_a}{\rho_a\, V} \quad (2)$$

The purpose of Equations (1) and (2) is to estimate the change in ventilation rates before and after the refurbishment rather than calculating actual values, which would require knowledge of the internal vapor generation and/or different monitoring methods, such as blower door tests. Concerning indoor air conditions, if two sensors were installed rather than one, hourly temperature and relative humidity values were calculated by averaging measurements from both sensors. While the average internal humidity and the estimated air change rate are calculated considering the full-day average (00:00–23:59), and the indoor air temperature was calculated excluding night hours when the central gas boiler is off (22:00–7:00), i.e., when the occupants have no possibility to control their indoor temperature through the thermostatic valves. Data were filtered by considering only those days with a minimum number of hourly measurements of 12 h if the full day was considered and 7 h if only day hours were considered.

After pre-processing the data, the comparison between ante and post-retrofit indicators was made based on daily average values. Outliers were filtered out to exclude negative air change rates or values higher than 2.0 h^{-1}. This value was obtained by considering an upper limit of 5 times the standard deviation from the mean obtained for all 11 flats considered in the study. The IAQ level based on the concentration of Total Volatile Organic Compounds (TVOC) was obtained from the sensor manufacturer's internal software. Different levels were identified based on the relative TVOC concentration pattern in each individual apartment, as explained in Appendix B. The IAQ levels are excellent, good, lightly polluted, moderately polluted, heavily polluted, severely polluted and extremely polluted air. If more than one sensor was present, the highest TVOC (worst IAQ level) was considered. This assumption is related to human activities being the most probable cause of low air quality. Therefore, the presence of occupants was considered more likely in rooms with the worst IAQ.

3.2. Energy simulations of reference apartments

In order to assess how energy demand for space heating would be influenced by the change in indoor environmental conditions after building retrofit, detailed dynamic simulations using EnergyPlus [25] were carried out, simulating two apartments with typical geometric configurations (called here "reference apartments" for sake of simplicity). The latter made it possible to compute the heating demand under different scenarios.

- Ante-Ante (AA): Both indoor environmental conditions and building envelope ante-intervention (i.e., before refurbishment).
- Ante-Post (AP): Retrofitted building envelope (i.e., after refurbishment) with the same indoor environmental conditions monitored ante-intervention.
- Post-Post (PP): Both indoor environmental conditions and building envelope post-intervention (i.e., after refurbishment).

The difference between AP and AA scenarios allowed to determine the impact of the envelope insulation on the energy demand for space heating. Simulation results of PP scenario makes it possible to indirectly evaluate the impact of the user behavior on the energy demand.

The apartments (M2 and M5) were deemed as representative in terms of heated areas and orientation of the main external walls. Simulations have been carried out considering two typical geometric configurations of the case studies and the average monitored conditions of the specific apartment before and after retrofit, modifying the envelope properties according to the building they belong to. The 3D views in Fig. 3 show the adiabatic surfaces in pink and the exterior surfaces in blue. Apartment M2 in Fig. 3(a) represents a medium-sized apartment (heated floor area of 98.5 m^2), while apartment M5 in Fig. 3(b) is representative of smaller residential units (heated floor area of 66.8 m^2). The latter is located above the basement (yellow), which is an unheated space.

Internal loads and related schedules were considered equal in all the simulation scenarios so that the calculated energy demands for space heating are not affected by occupancy changes. The input data of occupancy, lights, and appliances were taken from ISO 18523 [26] for typical residential buildings, considering an average occupancy of four (M2) and three (M5) people, with a laptop, a TV, and typical kitchen loads for a total peak load of 11.9 W/m^2 for apartment M5 and 9.7 W/m^2 for apartment M2.

3.3. Key performance indicators

The monitored data have been used to compare the indoor thermo-hygrometric conditions ante- and post-retrofit in order to discover patterns that could be linked to a change in user behavior. Based on both variables, the air change rates before and after building retrofits have been calculated as explained in Section 3.1. The main objective of the present work was to determine whether building retrofits drive users to change their indoor environmental conditions, such that the final energy use for space heating Q_H (kWh/m^2) is different from that expected before the refurbishment. To this end, dynamic building simulations have been carried out in three scenarios: ante-ante (AA), ante-post (AP), and post-post (PP), as explained in the previous Section. Three indicators have been calculated based on the simulation outputs: the Energy Performance Gap (EPG), the Energy Saving Achievement (ESA), and the Energy Saving Deficit (ESD). They are defined by Equations (3)–(5), respectively.

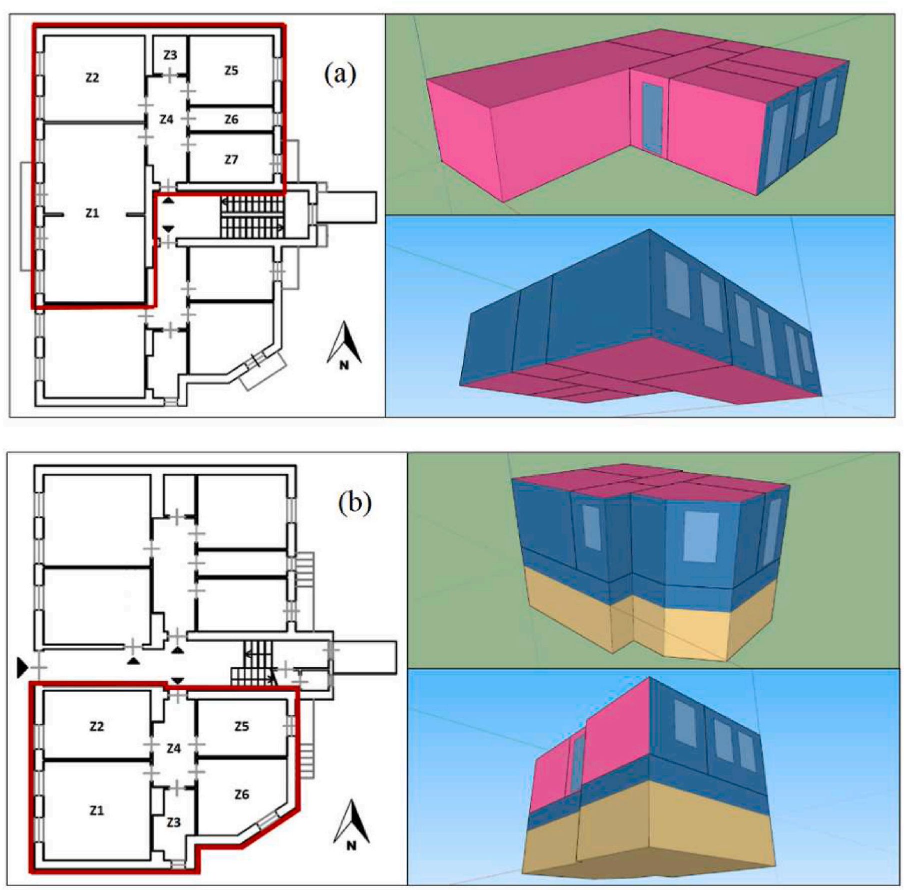

Fig. 3. Floor plans and 3D views of the reference apartments: (a) M2 and (b) M5.

$$EPG = \frac{Q_{H,PP} - Q_{H,PA}}{Q_{H,PA}} \tag{3}$$

$$ESD = \frac{(Q_{H,AA} - Q_{H,PA}) - (Q_{H,AA} - Q_{H,PP})}{(Q_{H,AA} - Q_{H,PA})} \tag{4}$$

$$ESA = 1 - ESD \tag{5}$$

4. Results

4.1. Analysis of monitored data

The average values of indoor air temperature for each flat in the two different years of analysis are shown in the graph in Table 4 and Fig. 4. As explained in Section 2.1, block B and block M were refurbished in the spring-summer of 2019, while in block F the retrofitting works were carried out during autumn-winter of 2020. As explained in Section 3.1, the indoor air temperatures shown here refer to November 14th – December 21st and exclude night hours. The weather conditions during the monitored periods are summarized in Table 2. Fig. 4 shows that higher indoor air temperatures were recorded after the building retrofit in eight flats out of eleven, i.e., in 73% of the households considered. Since indoor air temperatures are mainly affected by occupants' behavior through the adjustment of radiators' thermostatic valves and window opening, it seems that occupants prefer to increase the operative temperature after the building retrofit. In the remaining three apartments (F4, F8 and M5) the average indoor air temperatures are significantly lower after retrofit than the initial situation.

Table 4 shows that in half of these eight apartments (M2, M3, F11 and F12), also the relative humidity increases. An increase in relative humidity against a corresponding rise in temperature means that either internal water vapor generation increased due to different user behavior during the periods analyzed or the air change rate decreased. As no data was available on user activity, it was assumed that, on average, the water vapor generated by the occupants' activities over the two periods was constant. Consequently, all changes in indoor humidity are attributed to natural ventilation, i.e., to the frequency of indoor air renewal and the external air conditions (temperature and humidity). The latter changed in the two periods that have been compared, as already mentioned in Section 3.1.

On average, the estimated air change rate increases from 0.35 vol/hour to 0.37 vol/hour after retrofit. This variation might seem negligible, particularly compared to the variance of single apartments (the average standard deviation is 0.09 vol/hour). However, Fig. 5 shows that the air change rate varied significantly in many monitored apartments from 2018 to 2021. The change (increase or reduction) is greater than 10% in 8 flats out of 11.

The analysis of the monitored data revealed the existence of two groups of users. The first group, comprising six apartments (B2, F4, F5, F8, F9 and M5), increased the average air change rates from 0.40 to 0.50 vol/hour (+24%). The second group, made up of the remaining five apartments (F2, F11, F12, M2, M3), reduced their air change rates from 0.29 to 0.22 vol/hour (−24%). Indoor air temperatures for the first group of users decreased on average from 21.1 °C to 20.6 °C (−0.5 °C), while for the second group the air temperature increased from 21.5 °C to 22.6 °C (+1.1 °C).

Table 4
Indoor air temperature and relative humidity before (2018) and after retrofit (2021).

Apartment	Indoor air temperature (°C)		Indoor relative humidity (%)	
	Ante-retrofit (2018)	Post-retrofit (2021)	Ante-retrofit (2018)	Post-retrofit (2021)
B2	19.8 ± 0.8	20.6 ± 0.7	53.7 ± 4.4	50.2 ± 5.1
M2	21.3 ± 0.7	22.3 ± 1.0	57.0 ± 3.5	58.3 ± 3.1
M3	21.5 ± 0.6	23.1 ± 1.1	47.1 ± 5.7	51.3 ± 5.3
M5	22.7 ± 0.7	19.8 ± 0.9	51.8 ± 3.6	53.3 ± 5.2
F2	18.6 ± 0.6	20.6 ± 0.7	54.8 ± 8.0	57.2 ± 5.8
F4	19.1 ± 0.7	17.8 ± 1.2	50.0 ± 7.7	49.7 ± 5.5
F5	22.1 ± 0.8	23.2 ± 0.4	53.9 ± 5.8	49.5 ± 2.9
F8	22.3 ± 0.7	19.9 ± 0.8	43.3 ± 6.2	47.7 ± 7.5
F9	20.8 ± 0.9	22.5 ± 0.8	52.6 ± 6.4	46.7 ± 5.3
F11	22.9 ± 0.5	23.5 ± 0.4	44.6 ± 5.6	54.6 ± 5.4
F12	23.1 ± 0.9	23.7 ± 0.7	51.3 ± 6.9	53.4 ± 6.1

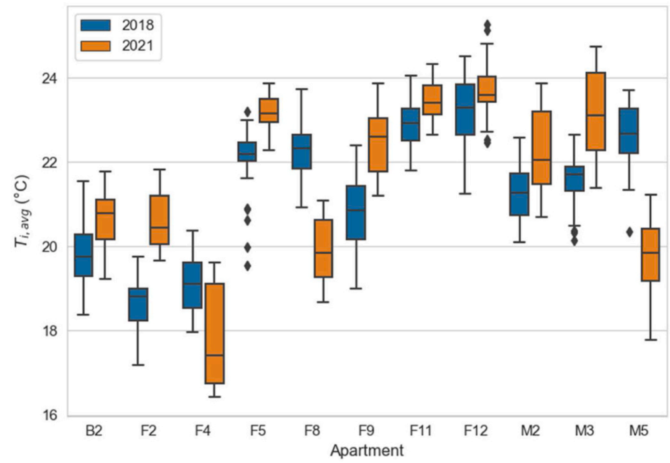

Fig. 4. Indoor air temperature measured before (2018) and after retrofit (2021).

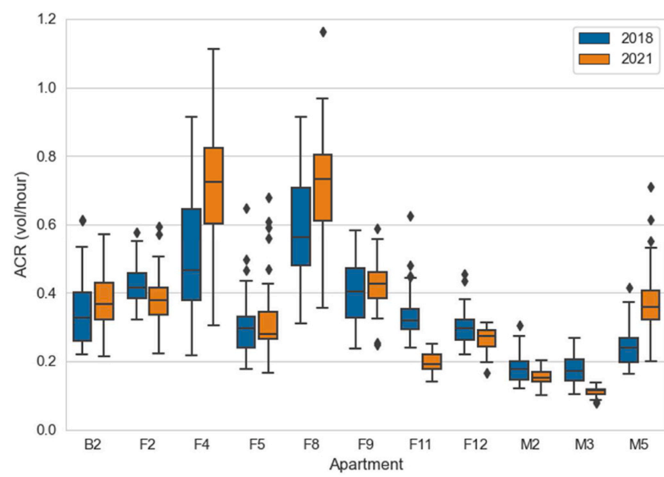

Fig. 5. Estimated air change rates before (2018) and after retrofit (2021).

Fig. 6 shows the number of days with a given IAQ range. The IAQ levels were obtained from a TVOC sensor, as specified in Section 3.1 and Appendix B. The question is whether the apartments with an estimated increase in air change rates also show better IAQ levels across the monitoring period and vice versa for apartments with an estimated decrease in ACR. Among eleven apartments considered, two cannot be considered due to significant days with missing IAQ data: 13 days are missing for F2 and 6 days for M2. In the remaining nine flats, those with a substantial change in the estimated ACR are M3 (−39%), M5 (+52%), F4 (+49%), F8 (+22%) and F11 (−44%). Fig. 6 confirms that IAQ levels increased in apartments M5 and F8 and that IAQ was reduced in apartment F11, as expected. However, F4 shows that despite an average increase in air quality (from 11 to 17 days with good air quality and a reduction from 15 to 9 days with lightly polluted air), there are two days with heavy pollution that did not appear before retrofit. Apartment M3, on the other hand, does not show a significant reduction in IAQ levels.

Apartment M5 seems to have the most evident increase in IAQ. This

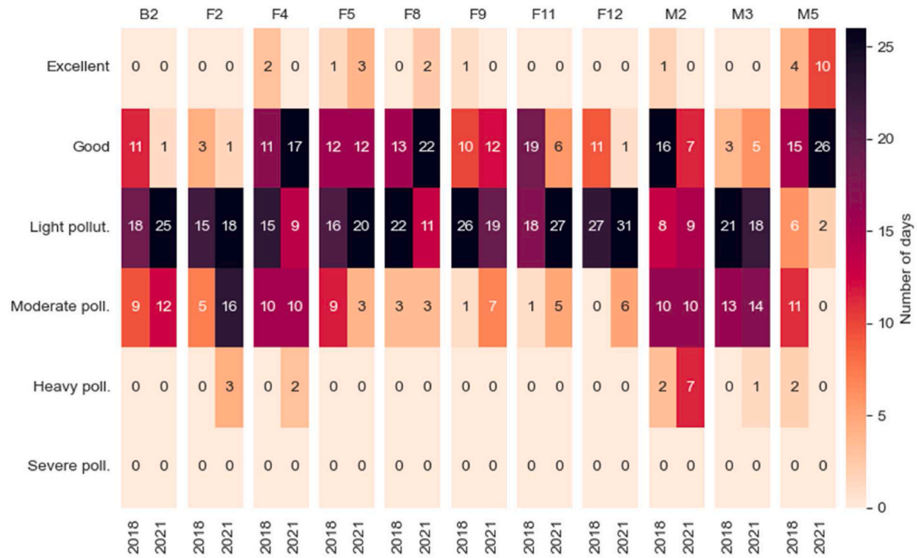

Fig. 6. Number of days with a given IAQ level before (2018) and after retrofit (2021).

might be caused by increased ACR, as suggested above, or by lower occupancy/human activity in the post-retrofit period.

4.2. Energy simulations of reference apartments

The energy demand of the buildings has been estimated for the conventional heating season, from October 15th to April 15th. Table 5 shows the energy needs for space heating obtained by simulating the reference apartments M2 and M5 with the boundary conditions (temperature setpoints and air change rates) estimated from the measured data before and after the retrofit actions. Simulation results of both M2 (second floor, net area of 98.5 m^2) and M5 (mezzanine floor, net area of 66.8 m^2) apartments showed that the energy retrofit actions reduced the energy demand for space heating in all the considered apartments.

Fig. 7 helps visualize the simulation results, in particular the difference between the PA scenario (orange) and the PP scenario (green). These scenarios evaluate the difference between the heating demand of the reference apartments after the building retrofit considering a change in the indoor air temperature and in the air change rates. The boxplots indicate that, on average, the difference is not considerable, although there is a slight tendency towards increasing the energy demand due to changed indoor environmental conditions.

Three indices were calculated to assess the impact of the users on the energy demand of the considered apartments: the energy performance gap (EPG), the energy saving deficit (ESD) and the energy saving achievement (ESA), as defined in Section 3.3. Fig. 8 shows the boxplots of the indicators grouped by apartment. Fig. 8(a) shows that the same user preferences in terms of setpoints and air change rates can lead to different heating demands depending on the building type. In particular, the EPG is higher in the smaller reference apartment (M5). The boxplot shows that both the range and the median value of M5 are higher than M2. Table 6 shows that the mean value is also significantly higher for M5 (9.7%) than M2 (4.4%). This means that the geometry and layout of the building have an impact on the energy saving that can be achieved, even when users behave similarly. This happens because different orientations and window-to-wall ratios lead to different solar heat gains, affecting the energy balance of the indoor environments considered. Even when the indoor air temperature is the same, a different amount of

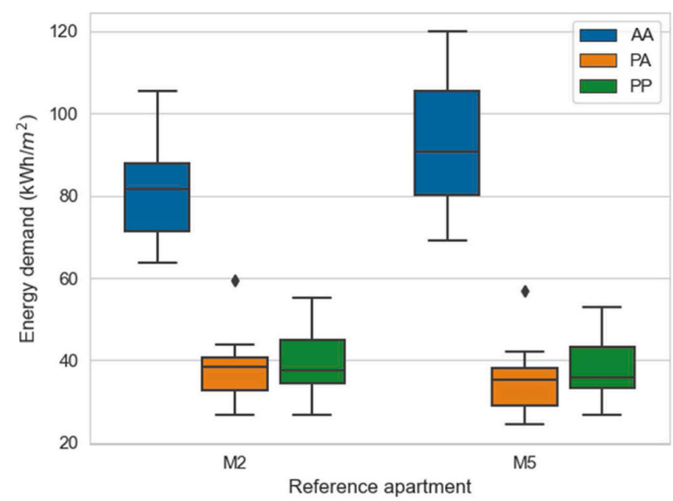

Fig. 7. Energy needs for space heating of the simulated reference apartments.

Table 5
Annual energy needs for space heating (kWh/m^2) simulated in two reference apartments in different scenarios.

User	Reference apartment M2 (medium-size)			Reference apartment M5 (small-size)		
	AA	PA	PP	AA	PA	PP
B2	71.4	32.7	37.0	77.0	29.3	35.2
M2	70.3	26.9	27.6	82.0	24.4	27.0
M3	71.5	27.4	26.9	84.0	25.0	26.8
M5	84.5	36.2	34.6	101.6	34.3	32.3
F2	63.7	32.8	37.7	69.0	28.8	35.8
F4	75.7	39.4	46.5	78.5	35.4	43.1
F5	84.7	38.6	43.7	99.1	36.2	43.4
F8	105.3	59.4	55.3	119.8	56.9	52.8
F9	81.5	39.7	49.2	90.6	36.6	48.3
F11	92.6	43.9	34.3	110.1	42.0	34.3
F12	91.0	41.6	40.7	109.6	39.9	40.8

Table 6
Key performance indicators of the simulated apartments.

Reference apartment	Heating demand (kWh/m^2)			EPG (%)	ESD (%)	ESA (%)
	AA	PA	PP			
M2	81.1	38.1	39.4	4.4%	4.2%	95.8%
M5	92.8	35.3	38.2	9.7%	6.3%	93.7%

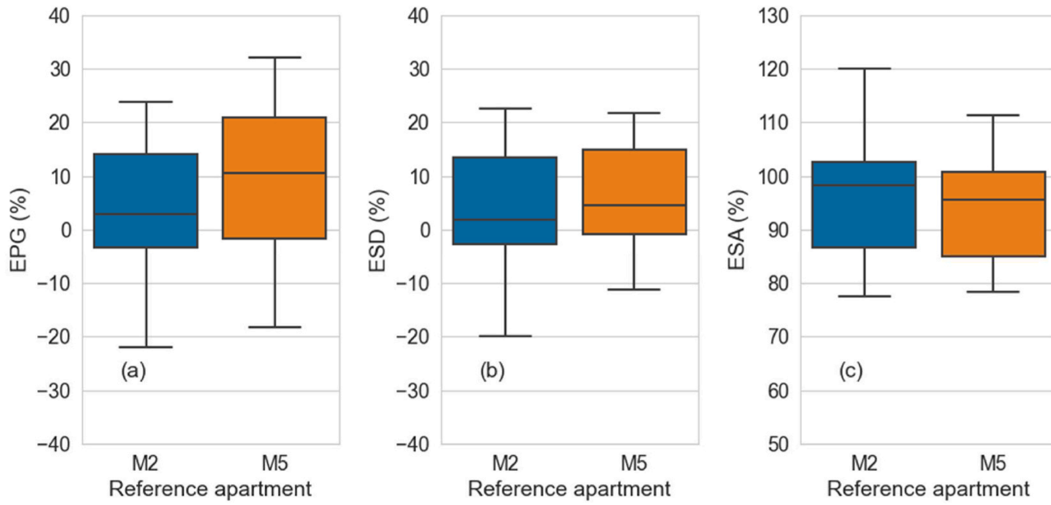

Fig. 8. (a) EPG, (b) ESD and (c) ESA of the simulated apartments.

heat entering the apartment due to solar and internal heat gains leads to a different thermal response of the dwelling depending on its heated volume, aspect ratio and equivalent thermal mass. Fig. 8(c) shows that the achieved energy savings range from 77% to 120% in apartment M2, whereas they range from 78% to 111% in apartment M5.

4.3. Discussion

As a preface, it is important to emphasize that this study deals with user behaviour, but that no direct detection of users' occupation or activities was carried out, nor were the interactions between the occupants and the heating systems. Therefore, the behavioural trends discussed in the results were deduced from the parameters measured by the environmental sensors.

In a previous paper [27], the authors compared indoor air temperature measurements and estimated air change rates in eight apartments (two in block B and six in block M, including those shown here) where the building envelope was retrofitted against twelve flats (block F) where the building had not yet been refurbished. The latter were considered as a benchmark. The study looked at the variation of these variables from 2018 to 2019. The study found that the air temperature was slightly higher, on average, in the refurbished buildings, and estimated a significant increase in the air change rates (+55%) using the same assumption made in this work. However, as the measured data in the benchmark group confirmed, these changes could not be entirely attributed to user behavior but, at least to some extent, to different weather conditions in the periods considered. Table 2 shows that the weather conditions in the five weeks analyzed in this paper (2021) are much more similar to those of the same weeks ante-retrofit (2018) regarding air temperature, relative humidity and solar radiation. Therefore, the disturbance introduced by different weather conditions is considerably lower in this study compared to the previous one. Appendix A shows that the trends discussed in the earlier Sections hold true when data from 2018 are compared to measurements from 2019.

Secondly, the data analysis suggests that users could be grouped into two categories according to the indoor environmental quality required after the building retrofit. In the first group, measurements indicate a trend towards increasing air change rates and decreasing indoor air temperature, while the second group shows an opposite trend. A possible reason behind these trends is that in the first group, the rebound effect is manifested in the demand for better air quality rather than an increase in operative temperature. In this case, the increased mean radiant temperature would compensate for the reduction in air temperature linked to increased natural ventilation. Measurements in the second group of apartments suggest that there the users behaves in the opposite way, i.e., reducing air renewal rates and rising air temperature significantly, despite the simultaneous increase in mean radiant temperature caused by the thermal insulation of the walls. This behaviour could be explained by an attitude towards underestimating the importance of proper room ventilation, which could be even more significant in those retrofits where windows are changed due to their higher air tightness. The analysis of TVOC concentrations on a subset of monitored users partially confirms that increases (reductions) in estimated ACR correlate with higher (lower) IAQ levels. However, it is worth noting that these trends rely on the assumption that indoor moisture generation remains unaltered, which in turn means that human activities are approximately the same in the two periods considered. Therefore, the existence of these groups of users should be treated as an hypothesis to be verified in future works.

Compared to the previous study, here the boundary conditions set in the building simulations (temperature setpoints and infiltration rates) do not come from average values across the whole sample of apartments, but rather from each individual flat monitored. This approach allowed us to obtain a range of expected energy performance gaps, which is more realistic compared to the deterministic value obtained in the previous study.

Moreover, this approach makes it possible to calculate the key performance indicators of different groups of users with similar habits. Fig. 9 and Table 7 show the indicators separating the group with increased ventilation rate (Group 1) from the group with lower or similar ACR before and after retrofit (Group 2). The different behaviour of the users before and after the retrofit can be analyzed by comparing the heating demand PA and PP scenarios. For the apartments where an increase of ACR was estimated, the energy demand was higher than expected, while for the second group of users, the energy demand after building retrofit period is closer to the expectations.

This trend is confirmed by the indices, calculated from the average energy demand of both M2 and M5 reference apartments.

The first group has an average EPG of 11.5%, compared to 1.8% of the second group of users. This difference is greater than the one between the reference apartments commented above. Results show that the energy saving deficits are significant, on average, only for the first group of users (almost 9%). In comparison, the average energy saving deficit is rather negligible (1%) for the second group. However, the boxplots in Fig. 9(b) show that significant differences might occur if individual users and apartments were considered.

5. Conclusions

Personal decisions and habits have a significant role in the evaluation

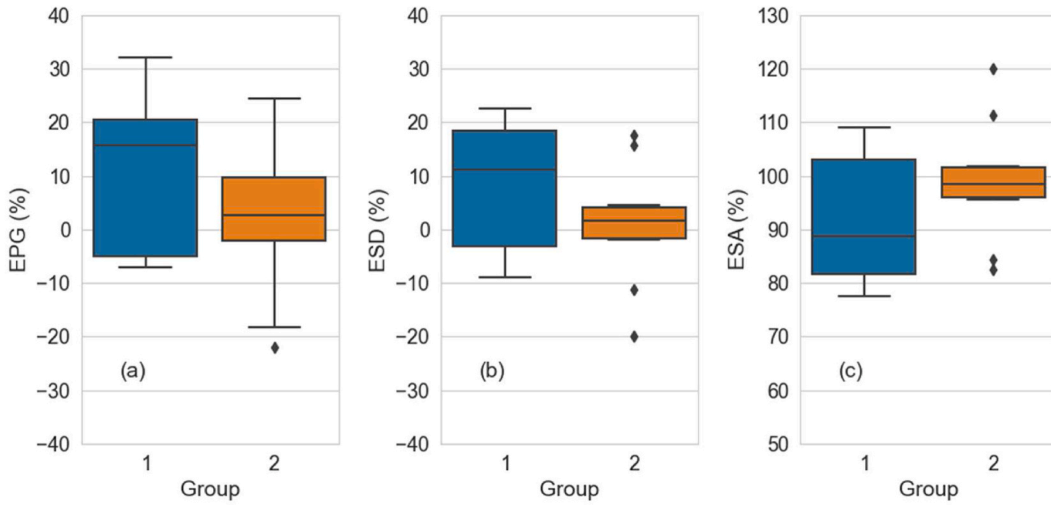

Fig. 9. (a) EPG, (b) ESD and (c) ESA of the simulated apartments by user group.

Table 7
Key performance indicators of the simulated apartments grouped by user type.

Group	Heating demand (kWh/m^2)			EPG (%)	ESD (%)	ESA (%)
	AA	PA	PP			
1	89.1	39.6	43.4	11.5%	8.8%	91.2%
2	84.4	33.3	33.2	1.8%	1.0%	99.0%

of the actual share of energy saved by means of building retrofit measures, which can be markedly different from the values estimated in the design phase.

This work analyzed the indoor air temperature, relative humidity, and IAQ level of eleven apartments in two periods of five weeks before and after building retrofit. Assuming a constant amount of daily moisture generation ante- and post-retrofit, the air change rate variations were estimated by means of a simple thermo-hygrometric balance of the indoor environment.

The analysis shows that on average, both indoor air temperature and estimated air change rates slightly increase. Yet a deeper look at the data revealed that such small variations arise from the combination of two groups of users with opposite trends: those who prefer to increase ACR and accept a slight drop in the air temperature, and those who reduce air change rates and increase the average indoor air temperature. In most cases, IAQ levels based on measured TVOC concentrations are consistent with estimated ACR variations, although uncertainty remains about the activities of occupants that drive these trends.

Energy simulations were carried out to calculate the effect of such changes in air temperature and air change rates on the heating demand of two representative apartments. Simulation results showed that the behavior of the former group of users might lead to energy performance gaps ranging between −7% and 32% (average 11.5%), while the EPG of the second group of users ranges between −18% and 24% (average 2%).

These results suggest that the rebound effect contributes significantly to the EPG and that the latter is not only driven by higher operating temperatures, but probably also by higher air change rates, depending on the user considered. Therefore, different window opening behaviors play a key role in determining the actual performance of naturally ventilated buildings after retrofit.

A bigger sample of monitored apartments and more insights into people's activities would be beneficial to support these findings. Furthermore, the energy performance gap should be considered by policy makers to set reasonable targets and mitigation actions to address this problem. Best practices should be shared to educate users concerning the influence of their behavior on energy savings, thus increasing their awareness and realizing the full potential of energy retrofit actions.

CRediT authorship contribution statement

Jacopo Vivian: Writing – original draft, Visualization, Supervision, Software, Methodology, Investigation, Data curation, Conceptualization. **Laura Carnieletto:** Writing – review & editing, Supervision, Methodology, Investigation. **Matteo Cover:** Software, Methodology, Investigation. **Michele De Carli:** Resources, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data are available either in a dedicated repository at https://github.com/BETALAB-team/ or upon request.

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Appendix A. Comparison 2018–2019

Table A1 shows the measured values (average ± standard deviation) of indoor air temperature and relative humidity, processed according to the methods specified in Section 3.1. Some values differ from those of the previous study [27] because of two reasons: (i) the period considered here is shorter and goes from 14 November to 21 December to exclude Christmas holidays, that could introduce further disturbances due to different occupancies; (ii) the number of flats considered here is smaller because those with unavailable measurements in one of the sensors were excluded.

Table A1
Indoor air temperature and relative humidity before (2018) and after retrofit (2019).

Apartment	Indoor air temperature (°C)		Indoor relative humidity (%)	
	Ante-retrofit (2018)	Post- retrofit (2019)	Ante-retrofit (2018)	Post- retrofit (2019)
B2	19.8 ± 0.8	19.6 ± 0.7	53.7 ± 4.4	59.8 ± 3.4
M2	21.3 ± 0.7	22.2 ± 0.5	57.0 ± 3.5	60.5 ± 3.0
M3	21.5 ± 0.6	23.5 ± 0.3	47.1 ± 5.7	54.9 ± 4.8
M5	22.7 ± 0.7	20.8 ± 0.6	51.8 ± 3.6	52.4 ± 6.1
F2	18.6 ± 0.6	20.4 ± 0.7	54.8 ± 8.0	62.2 ± 6.3
F4	19.1 ± 0.7	19.5 ± 0.7	50.0 ± 7.7	52.3 ± 5.4
F5	22.1 ± 0.8	19.9 ± 2.2	53.9 ± 5.8	59.1 ± 5.4
F8	22.3 ± 0.7	22.0 ± 0.4	43.3 ± 6.2	49.4 ± 4.2
F9	20.8 ± 0.9	20.3 ± 0.6	52.6 ± 6.4	57.4 ± 3.7
F11	22.9 ± 0.5	23.0 ± 0.4	44.6 ± 5.6	50.1 ± 5.5
F12	23.1 ± 0.9	23.2 ± 0.7	51.3 ± 6.9	58.0 ± 5.4

The same comparison carried out for the heating seasons 2018–2021, can be performed between 2018 and 2019. The analysis reveals that the average diurnal indoor air temperature remains constant to 21.3 °C, whereas air change rate increase on average from 0.35 vol/hr to 0.44 vol/hr (+26%). If only the apartments in the retrofitted buildings (B and M) are considered, a rather small difference emerges both in air temperature change (+0.2 °C) and in ACR variation (+29%). This means that such variations are likely related to general user preferences that do not necessarily depend on the building retrofit. This is confirmed by the last two rows of Table A2, where users are grouped as shown in Section 4.3: B2, M5, F4, F5, F8 and F9 belonging to Group 1 and the other flats belonging to Group 2. The first one gathers those users that exhibited an increase in the estimated air change rates and a reduction in air temperatures from 2018 to 2021. Interestingly, this tendency is evident also when seasons 2018 and 2019 are compared.

Table A2
Average indoor air temperature and air change rates (comparison 2018–2019).

	Indoor air temperature (°C)		Air Change Rates (vol/hr)	
	2018	2019	2018	2019
Retrofitted	21.3	21.5 (+0.2)	0.24	0.31 (+29%)
Non-retrofitted	21.3	21.2 (−0.1)	0.41	0.51 (+25%)
Group 1	21.1	20.4 (−0.7)	0.40	0.58 (+45%)
Group 2	21.5	22.5 (+1.0)	0.29	0.27 (−4%)

Appendix B. Indoor Air Quality measurements

The measurements of Total Volatile Organic Compounds (TVOC) have been carried out with a metal oxide-based sensor that detects VOCs by adsorption (and subsequent oxidation/reduction) on its sensitive layer [28]. Thus, the sensor reacts to most volatile organic compounds and many other gases polluting indoor air (one exception is, for instance, CO_2). In contrast to sensors, which are selective for one specific component, the used sensor can measure the sum of nearly all VOCs/contaminants in the surrounding air. This enables the sensor to detect, e.g., outgassing from paint, furniture, and/or garbage, high VOC levels due to cooking, food consumption, exhaled breath, and/or sweating [28].

As a raw signal, the sensor will output gas sensor resistance values and their changes due to varying gas concentrations (the higher the concentration of reducing VOCs, the lower the resistance and vice versa). Since this raw signal is influenced as well by parameters other than VOC concentration (e.g., humidity level), the raw values are transformed into an index for air quality (IAQ) by algorithms inside the proprietary software of the sensor manufacturer [28]. The IAQ scale ranges from 0 (clean air) to 500 (heavily polluted air), as specified in Table B1.

Table B1
Index for Air Quality (IAQ) classification.

IAQ Index	Air Quality	Impact (long-term exposure)	Suggested action
0–50	Excellent	Pure air; best for well-being	No measures needed
51–100	Good	No irritation or impact on well-being	No measures needed
101–150	Lightly polluted	Reduction of well-being possible	Ventilation suggested
151–200	Moderately polluted	More significant irritation is possible	Increase ventilation with clean air
201–250	Heavily polluted	Exposition might lead to effects like headacheheadaches depending on the type of VOCs	Optimize ventilation
251–350	Severely polluted	More severe health issueissues possible if harmful VOC is present	Contamination should be identified if level is reached even w/o presence of people; maximize ventilation & reduce attendance
>351	Extremely polluted	Headaches, additional neurotoxic effects possible	Contamination needs to be identified; avoid presence in the room and maximize ventilation

During operation, the algorithms automatically calibrate and adapt themselves to the typical environments where the sensor is operated (e.g., home, workplace, inside a car, etc.). The calibration process considers the recent measurement history (typically up to four days) to ensure that IAQ ~ 50 corresponds to "typical good" air and IAQ ~ 200 indicates "typical polluted" air. All the parameters are deduced from lab measurements under controlled environmental conditions, which comply with the ISO 16000-29 Standard "Test methods for VOC detectors". This operation mode ensures that single devices produce consistent measurements in their specific environment but makes difficult a direct comparison between different environments. TheThe manufacturer declares a sensor-to-sensor deviation in IAQ measurements of ±15%. However, since the scope of the work is to compare the change in IAQ in the same environments (residential units), the sensors were considered reliable for this scope. Besides ethanol (EtOH) as a target test gas, the sensors were also tested with breath-VOC (b-VOC). The b-VOC mixture is composed of ethane (5 ppm), isoprene/2-methyl-1,3 butadiene (10 ppm), ethanol (10 ppm), acetone (50 ppm)), and carbon monoxide (15 ppm) with nitrogen as carrier gas. The mixture represents the most important compounds in the exhaled breath of healthy humans.

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