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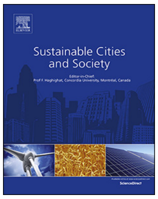

Effects of buildings' refurbishment on indoor air quality. Results of a wide survey on radon concentrations before and after energy retrofit interventions

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ABSTRACT

Energy regulation, policy and targets enhance energy retrofit in buildings with a wide distribution in Europe and Switzerland. These actions are mainly aimed at reducing heat dispersion through the envelope. The interventions affect the permeability of the envelope influencing indoor air quality. Focusing on radon concentration, this study reports the results of a survey on 154 buildings measuring the radon concentrations before and after energy remediation. The buildings were located in the southern part of Switzerland (Canton Ticino), a region with measurements of radon concentration in more than half of the buildings (over 55,000 building in 2018), within a population of approximately 355,000. These figures make this region an area with an exceptionally high number of radon measurements, performed in 2005–10 upon mandate of the local public health authorities. The survey reveals the increasing of radon concentrations, in particular where windows were replaced with more performant ones. Results underline the need of considering energy saving and indoor air quality at the same time, in the frameworks of orienting public and private investment towards improving long-term public health. Adequate techniques for improving ventilation could be very helpful to that end.

1. Introduction

Energy saving measures within the built environment (e.g. energy retrofit of existing buildings) represent an important institutional strategy of governments committed to the need to decrease fossil fuels utilization in the implementation of climate change national policies. Several programs and regulations at global and local level document this issue. However, since energy saving and indoor air quality (IAQ) are the two sides of the same coins, the impacts of the interventions have to be evaluated both in terms of energy performance improvement and in terms of indoor comfort preservation. Energy saving should be accomplished by proper measures in order to guarantee also healthy IAQ. When energy retrofit is improperly implemented, it can worsen IAQ, especially if energy saving measures are not accompanied by appropriate means of air exchanger between indoors and outdoors. Doors and windows that are not hermetically sealed can contribute to air change per hour (ACH) in a significant way. Because energy saving measures normally change the permeability of the building envelope and consequently decrease the ventilation rate, it is important to carefully evaluate this issue before energy retrofit is undertaken.

Regarding IAQ, many aspects and parameters can be considered; the research here presented focus on radon concentration. Radon has an enormous impact on the health of the occupants, being the second cause of lung cancer after smoke according to the World Health Organization. The dramatic effects of exposure to radon on human health are well known and documented (World Health Organization (WHO, 2009). According to a recent study (Milner et al., 2014), the effect of energy retrofit can increase the exposure to radon and risk of lung cancer. The implications of energy retrofit in terms of possible decrease of ACH "need to be carefully evaluated to ensure that the desirable health and environmental benefits of home energy efficiency are not compromised by avoidable negative impacts on indoor air quality".

For example, in Switzerland, where the problem is more serious than in other European countries (Vienneau et al., 2017), attention is payed to radon measurements and mitigation in homes and dwelling (Federal Office of Public Health (FOPH, 2011) and three official radon competence centers have been operating since 2008 in the different linguistic areas of the country, including the Italian part (see also: *Centro Competenze Radon – CCR* Radon Competence Centre). The Swiss

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federal programs and activities carried out by CCR makes Canton Ticino (that is a radon prone area with the most part of the territory with a medium radon risk, an important part with a high radon risk and a negligible part with a low radon risk[1]), the region with the highest density of residential measurements worldwide, to our knowledge, accounting for measurements in 55,440 buildings for a population of roughly 355,000 people. This data, referred to the state of the art in 2013, are available in Excel-format at www.ch-radon.ch.

Radon concentrations in buildings depend on different factors such as the amount of radon-producing uranium-238 in the underlying rocks and soils, the permeability of soils, the routes available for its infiltration into the buildings and the rate of exchange between indoor and outdoor air. Infiltration and diffusion of radon from the soil to the indoor air is promoted by differential pressure caused by the temperature differences between outdoor and indoor air, which itself is significantly influenced by the degree of tightness of the building envelope. A research (Collignan, Le Ponner, & Mandin, 2016) explained that the most important parameters affecting indoor radon concentration are: the nature of the ground and the soil air permeability and presence of cracks; some building characteristics, such as the type of foundation and the ventilation rate also affect the indoor radon concentration. In addition, they stressed that the improvement of building envelope airtightness primarily refers to the part of the dwelling shell that is above the floor. The floor in contact with the ground is generally not included. As a result, pressure differentials between indoors and outdoors could be accentuated and enhance the radon infiltration in the dwelling through the floor. Considering this phenomenon, along with a possible reduction of the ventilation rate, higher indoor radon concentrations can be expected in thermally retrofitted dwellings (Collignan et al., 2016).

An interesting study about multi-storey building construction underlines that in buildings constructed meeting new requirements on energy efficiency, radon concentration exceeds the average level in early-constructed buildings (Vasilyev, Yarmoshenko, & Zhukovsky, 2015). Authors conclude their experiment research stressing that the main factor that leads to higher radon concentrations indoors is low ventilation rates.

A recent research (Collignan & Powaga, in press) states that the parameters affecting the indoor radon activity concentration are indoor depressurization of a building and its ventilation rate and underline the importance of a correct management of ventilation as key factor in this filed. They provide a numerical tool adapted to the assessment of radon concentration as a function of the prevailing parameters. They compare different ventilation systems in relation to the French context and without taking into account the impact of occupant behavior (windows opening) and conclude stressing the need to install and to maintain an efficient ventilation system in new airtight buildings in order to prevent radon risks on health.

A research (Milner et al., 2014) found that increasing the air tightness of dwellings (without compensatory purpose-provided ventilation) heightened mean indoor radon concentrations by 56.6%, from 21.2 Bq/m^3 to 33.2 Bq/m^3. Fitting extraction fans and trickle ventilators to restore ventilation will help offset the additional burden, but only if the ventilation related energy efficiency gains are lost. Mechanical ventilation systems with heat recovery may lower radon levels while maintaining the advantage of energy efficiency for the most airtight dwellings, but there is potential for a major adverse impact on health if such systems fail. The authors stressed that the problem needs much research and debate before undertaking the planned large scale program of housing investments that may embed health problems for many years to come.

This paper focuses on the effects of buildings' refurbishment on indoor air quality and presents results of a wide survey on radon measurements performed in buildings before and after energy saving measures promoted by the government through its national energy policies. In particular, we referred to the Federal Program for energy retrofit launched from the Federal Office of Energy (available at www.dasgebäudeprogramm.ch).

The aim of the research is to give an answer to the following questions:

- Are radon concentrations inside buildings influenced by energy retrofit interventions?
- How much does radon concentration vary inside buildings due to these interventions?
- Which type(s) of interventions have the most influence on indoor air radon concentrations?

Therefore, suggestions about to plan and to monitor properly energy efficiency together with IAQ could be derived.

The innovation of this research is given by the large sample size: 154 buildings. Due to the difficulty of sampling buildings characterized both by radon measurement and energy retrofit interventions, most studies deal with a much smaller sample size, considering a limited number of buildings. In other words, although the question seems to be simple, the evidence-based answer is more difficult because radon measurements prior to remediation are quite rare. Thanks to a widespread measurement campaign performed in the last decade in the southern part of Switzerland, we were able to access a large amount of radon data collected from buildings before they underwent energy remediation. By crossing data from the National Radon Database (Federal Office of Public Health (FOPH, 2013) and data from energy-retrofit of buildings, it was possible to select a sample of 154 buildings with radon measurements data related to the situation before and after different types of energy retrofit interventions.

Information on which type of energy measures was performed in the different buildings was made available from the cited federal program launched from the Federal Office of Energy for improving buildings energy performance. This data availability permits to analyze the type of retrofit measures as well as their influence on IAQ.

Considering the systematic nature of the campaigns for the prevention of radon exposure in Switzerland and the representativeness of the sample of buildings analysed during the survey, the achieved results can represent a valid support to the decisions also in other territories exposed to the same problem.

2. Materials and methods

The Swiss Federal Office of Public Health (FOPH) provided documents, data and programs in order to monitor radon concentration in buildings and reduce the health risks derived by radon exposure in Switzerland.[2] The guideline value for dwellings defined in the Swiss Radiological Protection Ordinance (the so-called *Strahlenschutzverordnung* no. 814.501) is 300 Bq/m^3.

Radon concentrations can be easily measured using passive dosimeters. In our survey, radon measurements before and after energy retrofit were performed using Radtrak Radonova dosimeters[3]. The duration of exposure ranged from 1 to 3 months. The uncertainty of this measurement was estimated as +/− 12%. Concentrations were expressed in Bq/m^3.

Regarding the measurement, in each building, one dosimeter was positioned in the lower occupied room of the building during the winter season when space heating is in operation and windows are less open. At the end of the period of measurement, the dosimeters were sent to the CCR.

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[1] See also the map of radon risk in Switzerland (source: www.ch-radon.ch).

[2] This information are downloadable at www.ch-radon.ch.

[3] Former Landauer Nordic Gammadata; Uppsala, Sweden.

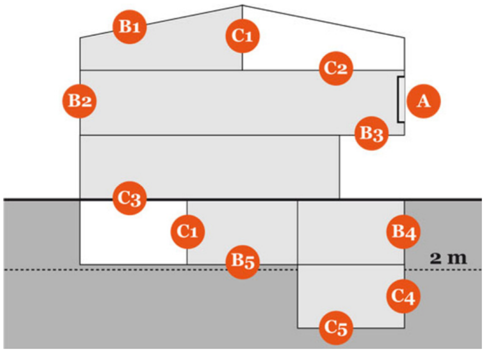

Fig. 1. Types of energy retrofit interventions all over Switzerland according to *Das Gebäudeprogramm.*

The measure was repeated in the same building exactly in the same way at the end of the energy retrofit: in the same room, during the same time of year (winter) and for a similar duration of time (about three months). Such conditions allow for comparison between the two measurements, providing strong evidence that any radon concentration variation is exclusively due to the energy retrofit interventions.

2.1. Definition of the sample of buildings

All the results presented are based on the cross-comparison of two main databases. The first one is completely dedicated to radon measurements in residential buildings while the second database contains information related to the federal incentive program for building energy retrofit. In the following sections, both databases are briefly described.

2.1.1. Radon measurements database

As mentioned in Section 1, during the last decades, a large number of radon measurements have been performed in Switzerland. The database is managed by the Swiss FOPH that accounts, in 2013, 55,440 buildings monitored in Canton Ticino, for the most part performed in single and two-family houses, on a total of 134,759 buildings monitored in Switzerland. The impressive extension of the survey makes the results obtained representative and translatable into robust and evidence-based recommendations.

The main information contained in the database is the measured radon concentrations as well as the places and duration of the measurements. Additional information regarding the building (precise location, address, age, building type, type of ground slab, crawl space) as well as the house owner (name, address, phone number, email) type of dosimeter used, information about the measurement (duration, uncertainness, eventual problems and radon values) are available.

2.1.2. Energy retrofit database

At the beginning of 2010, the Federal Office for Energy, in collaboration with the cantonal authorities, started a new incentive program (the mentioned *Das Gebäudeprogramm*), which aims to decrease the energy consumption in residential buildings as well as CO_2 emissions. This long–term program promotes energy retrofit in buildings and the use of renewable energies throughout Switzerland. The principal pieces of information of interest for this project are the type of building energy retrofit measures (Fig. 1) as well as the location of the building and the owner description. Thanks to this national program, about 500 houses in the southern part of Switzerland have been refurbished. The duration of the retrofit as well as the costs of the interventions are also information provided by the database.

During the last decade, 727 interventions were recorded in Switzerland. Precisely, according to the scheme reported in Fig. 1, they regard:

A Window replacements (290 interventions);
B Wall, floor, roof: thermal insulation of surfaces in contact to outside air (293 interventions);
C Wall, floor, roof: thermal insulation of surfaces in contact to ground or to not heated zones (144 interventions).

In a building, different interventions of type A, B or C can be combined.

2.2. Final data set

The integration of the two previously described databases allows the selection of buildings where pre-remediation radon measurements followed by energy remediation have both been performed (Fig. 2). The key criterion for assembling this database is correlating the location and the name of the building owner, an information present in both databases. New measurements made in the same buildings after remediation can provide information about the changes in radon concentration that refurbishment may have produced.

At the end of the selection, the sample analyzed regards 154 buildings in Canton Ticino.

The sample include 22 residential buildings with mechanical

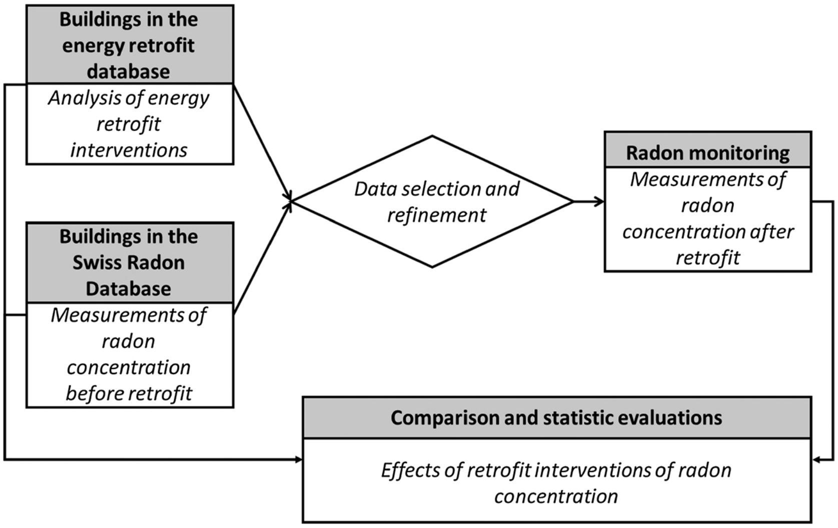

Fig. 2. Process of selection and evaluation of the sample of representative buildings.

Table 1
Types of measures of energy retrofit measures (accordingly to Fig. 1) and mean radon concentrations.

Type of building refurbishment	Number of cases	Mean radon concentration before energy retrofit [Bq/m^3]
Type A - Measures including windows replacement	82	148
Type B1 - measures without windows replacement (roof insulations to outside)	33	128
Type C2 - measures without windows replacement (roof insulations to not heated zones)	23	218
Combined measures without windows replacement	16	158
Total/average	**154**	**155**

ventilation, but we are not able to know if the ventilation systems has been active during the measurement.

For 14 buildings, measurements were carried out in underground or partially underground rooms.

The first step, as explained above, consisted of the selection of the study sample. Two main conditions underlie this selection: the radon concentration was measured in the buildings, and this measurement was performed before the building was refurbished. Next was information about the radon measurement after refurbishment. Radon was monitored by passive measures accomplished by CCR, which is accredited as ISO/IEC 17025:2005 (General requirements for the competence of testing and calibration laboratories) and recognized by the Swiss FOPH as radon measuring laboratory. ISO/IEC 17025:2005 specifies the general requirements for the competence to carry out tests and/or calibrations, including sampling. It covers testing and calibration performed using standard methods, non-standard methods, and laboratory-developed methods.

A detailed analysis of these results can determine if and to what extent building refurbishment can influence radon concentrations. In this analysis, we considered only houses with one or two units, since the recent energy remediation campaign has focused its efforts only on these buildings. Multi-family houses (dwellings with three or more units, where people are less exposed to radon from the ground) as well as non-inhabited buildings are not considered as risky as single-family dwellings and therefore were not measured (Arvela, Holmgren, Reisbacka, & Vinha, 2014). The information gathered allows us to evaluate the influence that a single intervention had on indoor air quality versus radon concentrations. Table 1 briefly describes the sample used for the analysis.

The originally selected sample was composed of 198 cases that can be described as follows: in 81 residential houses the refurbishments consisted only of window replacement, in 42 cases the roof was insulated, in 28 cases the ceiling was insulated in heated but not in non-heated rooms. In 47 other refurbished buildings, the interventions were different or more complex (possibly multiple interventions at the same time). Unfortunately, some homeowners did not want to participate in the follow-up survey (30), and others performed the follow-up measurement at the wrong place (4 cases).

In addition, in 6 cases the energy retrofit included also a ventilation system, in 2 cases dosimeters were located in different rooms after the retrofit and in 2 cases the description of the energy retrofit was not complete. Therefore, these last 10 cases were not included in the survey.[4]

Finally, the sample was reduced to 154 selected buildings as described in Table 1.

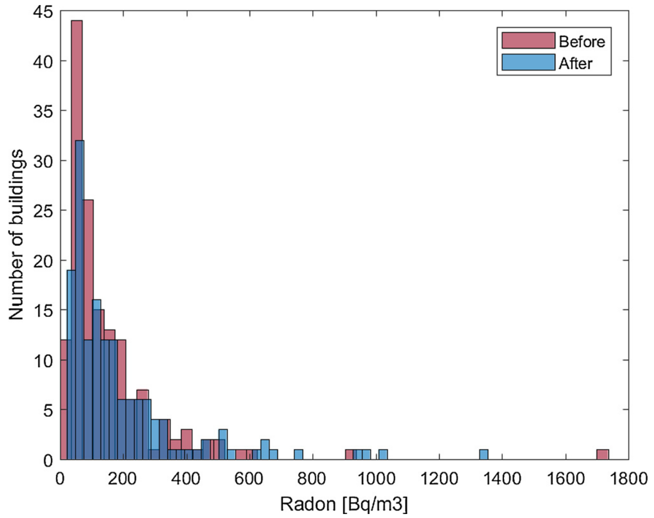

Fig. 3. Histogram of radon concentration before and after the implementation of energy saving measures.

In general radon concentrations before energy retrofit interventions are under the level suggested by the World Health Organization (300 Bq/m^3) for geological zone with high radon concentration. In order to have a benchmark, the average radon concentration in Swiss buildings is 78 Bq/m^3, but the range of variation is very large. For example, in particularly critical cases, concentrations of more than 10,000 Bq/m^3 have been measured in Ticino (Ufficio federale della sanità pubblica (UFSP, 2008).

3. Results and statistical analysis

Despite Table 1 reports mean value included in the range between 128 and 218 Bq/m^3, the radon concentrations are very variable.

The aim of this section is to study more precisely how radon concentrations are distributed before and after energy, retrofit and which are the most impacting type of interventions.

In particular, we refer to the statistic evaluation summarized in Fig. 3 (where the number of buildings belonging to each concentration range are represented), Fig. 4 and the following tables. In Table 2, it is possible to observe the increasing or decreasing of radon concentration due to energy retrofit by statistic indices. Radon concentration increases ever, except than for the minimum and maximum values.

The mean radon values before the implementation of energy measures was 156 Bq/m^3, with a minimum concentration of 20 Bq/m^3 and a maximum value of 1733 Bq/m^3. The median was much lower than the arithmetic mean, indicating the presence of some extreme values that increased the mean of the sample.

After the energy-saving measures, the radon measurements were significantly higher. Although the maximum value recorded appears to have decreased from 1733 Bq/m^3 to 1351 Bq/m^3, the mean has increased from 156 Bq/m^3 to 190 Bq/m^3. The most significant change, however, is the increase of the median from 94 Bq/m^3 to 121 Bq/m^3, with a difference of 29%. This means that following energy

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[4] In the study we have made a measurement before refurbishment (without additional insulation etc.) and one after. (with additional insulation etc.) in order to explore the effect of energy retrofit on radon concentrations within the building. If a controlled ventilation system is added to the building (with continuous air exchange in the rooms), the dynamics of the fluids within the building will completely change. Therefore, this type of interventions was excluded in our analysis. In addition, the number of cases with this type of interventions is very low, without statistical relevance.

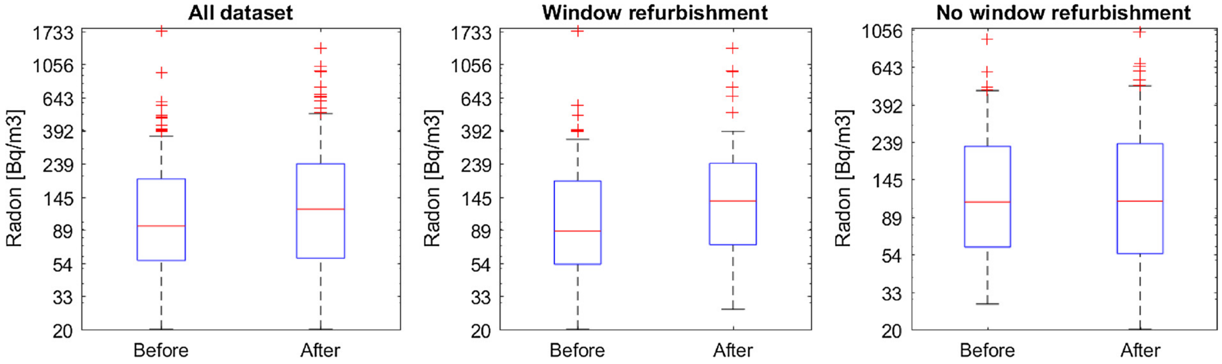

Fig. 4. Boxplots of the measurements before and after energy saving measures.

Table 2
Radon concentration distributions before and after energy saving measures.

Parameter	[Bq/m^3] Before energy retrofit	[Bq/m^3] After energy retrofit
Minimum	20	20
1° quartile (25%)	56	58
Median	94	121
Mean	156	190
3° quartile (75%)	190	238
Maximum	1733	1351

remediation, half of the monitored buildings presented radon concentrations above 121 Bq/m^3. These considerations can also be deduced from the box plots in Fig. 4 with the sets of measurements reflecting the situation before and after the implementation of energy saving measures.

As reported in Table 3, samples were assigned to two distinct categories depending on the different energy saving measures they received: with window replacement and without windows replacements. The 71 buildings assigned to the first category (accordingly to Table 1) were those receiving only window replacement; 11 buildings for which additional measures such as the insulation of walls, roof, floor and the basement ceiling were added to this category, for a total of 82 buildings.

For the other 72 analyzed buildings, the intervention was aimed at increasing the thermal insulation of the building without replacing windows, such as roof isolation (33 cases), ceiling insulation towards unheated spaces (23), cases the walls/floor to the exterior (8 cases) and intervention on multiple items (8 cases).

A more detailed statistic evaluation has been carried out as reported in Fig. 4. This evaluation allows investigating which types of interventions could negatively affect radon concentrations. The first graph shows boxplots for the whole dataset, the second one shows only buildings in which windows has been replaced, and the third one shows building in which windows were not replaced. The red lines represent the median; the blue boxes include all values between the 1° and the 3° quartile; the red crosses are the outliners. These were identified by the application of the boxplot function in Matlab®.[5] By default, an outlier is a value that is more than 1.5 times the interquartile range away from the top or bottom of the box. The more are the outliers the more the statistic distribution are skew. In our case, we have skew and asymmetric statistics. This representation is aimed at the statistic description of results.

For the whole sample, the arithmetic mean of radon concentration after remediation increased by 22%, from 155 Bq/m^3, recorded before the energy intervention, to 190 Bq/m^3 after the energy intervention. The increase is more important for buildings of category 1, where replacing the windows increased the measurements from 148 Bq/m^3 to 198 Bq/m^3 (+33%). For buildings in category 2, without windows replaced, the increase in radon concentration was much lower (+11%). In this case, concentrations increased from 163 Bq/m^3 to 181 Bq/m^3.

The same conclusion can be drawn from Table 4, wherein is highlighted the number of buildings undergoing a variation of concentrations depending on the type of energy measure implemented. Radon concentration increased in 59 out of 82 monitored buildings in category 1 (72%) and in 41 out of 72 in category 2 (57%).

In order to obtain statistical evidence on whether or not the energy retrofit affects the radon concentration, we perform a two-sample Kolmogorov-Smirnov and a Wilcoxon rank sum test on the data, before and after the refurbishment.

Both tests are nonparametric for continuous distributions. The first one compares the estimated cumulated density functions of two samples in order to assess if two samples come from the same probability distribution. The null hypothesis is that the two samples comes from the same distribution. The second one compares the order of the observations of the two samples to test if the samples come from continuous distributions with equal medians. The null hypothesis is that the two samples come from distributions with the same median. In both cases, if the null hypothesis is not rejected, the H value is 0, while is 1 otherwise.

The tests were repeated three times, the first using the whole dataset, the second one comparing only buildings in which windows has been replaced, and the third one comparing building in which windows were not replaced.

Table 5 summarises the outcome of the tests. As we can see, both Wilcoxon and Kolmogorov-Smirnov tests has the same results in terms of H values, for all the datasets. The dataset is grouped by buildings in which windows has been replaced, and buildings in which windows were not replaced.

In particular, we can see that, when considering the whole set of buildings, the null hypothesis of the tests cannot be rejected, meaning that the energy retrofit did not significantly affect the radon concentrations in buildings, by means of probability distributions and median values.

On the other hand, when we perform the tests on the subset of buildings undergoing a windows replacement, both tests reject the null hypothesis, meaning that the energy retrofit could have affected the radon concentrations.

These data show that the energy renovation of buildings can lead in some cases to a substantial increase in indoor radon concentrations. The increases in concentrations for category 1 are statistically significant, while interventions related to category 2 do not have the same statistical relevance on radon concentrations.

4. Discussion

The results of this study confirm what has already been suggested by studies, some of them carried out with a more limited number of cases

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[5] Description available at www.mathworks.com/help/stats/boxplot.html.

Table 3
Classification of the energy retrofit interventions by types (involving or not windows replacement).

Category	Types of energy-saving measure	Number of buildings [-]	Mean concentration before energy remediation [Bq/m^3]	Mean concentration after energy remediation [Bq/m^3]	Increase [Bq/m^3]	Increase [%]
1	Energy-saving measures involving the replacement of windows	82	148.4	198.0	49.6	33
2	Energy-saving measures not involving the replacement of windows	72	163.3	180.8	17.5	11
Total/Average		**154**	**155.4**	**189.9**	**34.6**	**22**

Table 4
Evaluation of the energy retrofit interventions for evaluating their influence on radon concentrations in terms of increasing or decreasing.

Category	Types of energy saving measure	Number of buildings [-]	Number of buildings with increased radon concentration [-]	Number of buildings with no variation of radon concentration [-]	Number of buildings with decreased radon concentration [-]
1	Energy saving measures involving the replacement of windows	82	59	2	21
2	Energy saving measures not involving the replacement of windows	72	41	0	31
	Total	**154**	**100**	**2**	**52**

Table 5
Results of the two-sample Kolmogorov-Smirnov and a Wilcoxon rank sum test for the whole dataset.

		H [-]	p-value [-]
Wilkoxon rank sum test	All the dataset	0	9.53E-02
	Energy saving measures involving the replacement of windows	1	2.72E-02
	Energy saving measures not involving the replacement of windows	0	8.97E-01
Two-sample Kolmogorov-Smirnov test	All the dataset	0	2.29E-01
	Energy saving measures involving the replacement of windows	1	3.24E-02
	Energy saving measures not involving the replacement of windows	0	9.56E-01

(Jirànek & Kačmaříková, 2014; Pressyanov, Dimitrov, & Dimitrova, 2015).

Energy efficiency interventions on buildings envelope increase the building's tightness and consequently may increase indoor radon concentrations. In particular, the replacement of the windows has a statistically significant influence on increasing radon concentrations.

The use of statistical analysis of a large sample of buildings here presented confirms the findings of previous studies for existing buildings. The effect of thermal retrofitting was evaluated through radon measurements performed before and after retrofit: the increase in indoor radon concentration may be due to the decrease in building air permeability after the thermal retrofit, which did not always include any or relevant ventilation management. Moreover, the induced modification of indoor pressure fields could promote radon entry into the dwelling (Collignan et al., 2016).

However, if radon comes from building materials, it is usually possible to decrease the energy needs of buildings to a reasonably low level without increasing the indoor radon concentration (Jirànek & Kačmaříková, 2014). Appropriate solutions can be founded, as confirmed in a study referring to Czech kindergartens (Fojtíkova & Navratilova Rovenska, 2014).

The scientific community agrees in pushing energy saving interventions in existing and new buildings and also the present work would like to support this approach. The need to reduce energy consumption and thus emissions of greenhouse gases should continue to be pursued in the future. Nevertheless, for the sake of long-term public health, it is necessary to consider air quality in general and radon in risky areas in particular while implementing these measures. In order to ensure good indoor air quality, adequate ventilation of the premises is essential.

Despite the strength of the research here summarized, some weaknesses are nevertheless inherent in the method used: firstly, the uncertainty of the measurement performed with passive dosimetry, which is estimated to range around 20%; secondly, the fact that it is impossible to exactly replicate the same measurement season to gather before and after readings.

5. Conclusions and developments

When converting existing buildings into energy-efficient buildings, the balance between energy savings and the quality of the indoor environment is a factor that must be taken into account, as reported also by Sharmin et al. (2015) and Hesaraki, Myhren, and Holmberg (2015). This is an important point for evaluating correctly the final energy saving, taking into account also the potential necessity of increasing ventilation for IAQ reasons after energy retrofit measures.

In the framework of energy saving and IAQ relations, this study represents an evidence-based demonstration with the example of radon, taking in account an unprecedented sample size: 154 buildings and according to many other studies (Jirànek & Kačmaříková, 2014; Ringer, 2014; Pressyanov et al., 2015; Collignan et al., 2016; Yarmoshenko et al., 2016).

The main innovation and strength of our research lies in the unprecedented large number of real data available, allowing the findings to reach statistical significance. In our survey, the sample of buildings analyzed includes different typical residential buildings, different set of measures of energy retrofit and different locations situated in a radon prone areas, improving the statistical significance of assessments. The accurate analysis confirms again that indoor radon concentration was on average higher after retrofit compared to the concentration before retrofit (65% of the monitoring buildings). This impact is significantly higher in interventions that include the replacement of windows (72% of the monitoring buildings).

The care and the attention paid in Switzerland about radon measures and the possibility to refer to wealthy and trusted databases will allow in the future enriching these surveys. Some critical issues can be overcome by studying in deep other correlations, i.e. considering also the age and other characteristics of the buildings.

The research takes into account well-documented case of studies, underlining the innovative value of the extensive experimentation accomplished. The method of our analysis could be extended in other radon prone areas with analogous characteristics and data availability. The results underline the need of spread radon monitoring. Energy retrofit measures, even more diffused to reach the local and global targets on energy efficiency of the built environment, could represent an occasion to promote widespread monitoring activities related both to energy consumption and indoor air quality.

Acknowledgments

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