


Article

Radon Investigation in 650 Energy Efficient Dwellings in Western Switzerland: Impact of Energy Renovation and Building Characteristics

Shen Yang ¹, Joëlle Goyette Pernot ^{2,*}, Corinne Hager Jörin ³, Hélène Niculita-Hirzel ⁴, Vincent Perret ⁵ and Dusan Licina ¹

¹ Human-Oriented Built Environment Lab, School of Architecture, Civil and Environmental Engineering, École Polytechnique Fédérale de Lausanne, CH-1015 Lausanne, Switzerland; shen.yang@epfl.ch (S.Y.); dusan.licina@epfl.ch (D.L.)

² Transform Institute, Western Swiss Centre for Indoor Air Quality and Radon (croqAIR), School of Engineering and Architecture of Fribourg, HES-SO University of Applied Sciences and Arts Western Switzerland, CH-1700 Fribourg, Switzerland

³ HumanTech Institute, School of Engineering and Architecture of Fribourg, HES-SO University of Applied Sciences and Arts Western Switzerland, CH-1700 Fribourg, Switzerland; corinne.hagerjoerin@hefr.ch

⁴ Department Health, Work and Environment, Center for Primary Care and Public Health (Unisanté), University of Lausanne, CH-1066 Epalinges, Switzerland; helene.hirzel@unisante.ch

⁵ TOXpro SA, CH-1227 Carouge, Switzerland; vincent.perret@toxpro.ch

* Correspondence: joelle.goyette@hefr.ch

Received: 8 November 2019; Accepted: 29 November 2019; Published: 4 December 2019



Abstract: As part of more stringent energy targets in Switzerland, we witness the appearance of new green-certified dwellings while many existing dwellings have undergone energy efficiency measures. These measures have led to reduced energy consumption, but rarely consider their impact on indoor air quality. Consequently, such energy renovation actions can lead to an accumulation of radon in dwellings located in radon-prone areas at doses that can affect human health. This study compared the radon levels over 650 energy-efficient dwellings in western Switzerland between green-certified (Minergie) and energy-renovated dwellings, and analyzed the building characteristics responsible of this accumulation. We found that the newly green-certified dwellings had significantly lower radon level than energy-renovated, which were green- and non-green-certified houses (geometric mean 52, 87, and 105 Bq/m³, respectively). The new dwellings with integrated mechanical ventilation exhibited lower radon concentrations. Thermal retrofitting of windows, roofs, exterior walls, and floors were associated with a higher radon level. Compared to radon measurements prior to energy renovation, we found a 20% increase in radon levels. The results highlight the need to consider indoor air quality when addressing energy savings to avoid compromising occupants' health, and are useful for enhancing the ventilation design and energy renovation procedures in dwellings.

Keywords: dwellings; indoor air quality; energy efficiency; building characteristics; thermal retrofitting

1. Introduction

Radon (²²²Rn) is a colorless and odorless radioactive gas that has been strongly linked to deleterious human health outcomes, specifically lung cancer [1–4]. It is the most important source of ionizing radiation among those that are of natural origin, as it constitutes the second cause of death by lung cancer after tobacco [5]. While the outdoor radon rarely reaches epidemiologically significant levels due to atmospheric dispersal and dilution, in enclosed environments such as residences, the level of radon can accumulate at levels as much as two orders of magnitude higher than outdoors in inadequately

ventilated spaces [6]. Radon mainly infiltrates indoors from the soil adjacent to the building foundation and construction materials [7,8]. The World Health Organization (WHO) [5] recommends maintaining the level of indoor radon at an annual average concentration limit lower than 100 Bq/m^3 in order to avoid the increase in prevalence of lung cancer [9–12]. In regions where the natural emission is too high to reach this target, a value of 300 Bq/m^3 should not be exceeded [5]. The US Environmental Protection Agency (EPA) also recommends remediation actions for radon concentrations higher than 4 pCi/L (equivalent to 148 Bq/m^3) [13]. The EU Council as well as the Swiss Federal Office of Public Health (FOPH) adopted the reference value of 300 Bq/m^3 [14,15]. Identifying the causes of residential radon accumulation at levels higher than these limits is therefore of high priority, as to develop effective interventions for radon level control.

Extensive international indoor radon investigations contributed to the worldwide indoor radon map [5,16–23], and revealed strong associations between indoor radon concentration and outdoor radon emissions as well as dwelling characteristics. Demoury et al. [24] evaluated the statistically significant association between indoor radon and geogenic radon potential, building materials and age, and foundation type in French residences. Collignan et al. [25] reported that dwellings in radon-prone parts of France, which are equipped with mechanical ventilation systems, had significantly lower radon concentrations than naturally ventilated ones. They also found that the construction materials were the most influencing factors, followed by the type of foundation. A similar relationship between indoor radon concentrations and aforementioned dwelling characteristics was observed in Denmark [26], England [27], Germany [28], Italy [29], and in Switzerland [30,31].

Radon in energy-efficient buildings is another area of increased public interest and concern [32,33]. The requirement for airtightness in energy-efficient buildings can lead to extremely low air infiltration, which can lead to build-up of radon concentrations if not sufficiently diluted by intentional ventilation. Thermal retrofitting, an effective approach to achieve energy-efficient dwellings via reducing air infiltration and increasing thermal insulation of building envelop, has been associated with elevated indoor radon concentrations. A recent study by Meyer [34] reported two times higher radon concentrations in retrofitted houses than in passive homes in Germany. A significant increase in indoor radon concentrations owing to energy retrofits was also observed in dwellings in the USA [35] and Lithuania [36]. In the case study by Jiránek and Kačmaříková [37], addition of an exterior thermal insulation in homes and retrofitting windows led to 3.4 times higher radon concentration. Based on the UK national radon database, Symonds et al. [38] found a significant increase of indoor radon levels in houses with double glazed windows, attic and wall insulation. In summary, radon alteration caused by thermal retrofitting could be a critical issue in energy-efficient dwellings.

Switzerland introduced the Energy Strategy 2050 policy to reduce energy-related environmental impact [39]. Key efforts include construction of energy-efficient buildings and nation-scale building energy renovation program (Programme Bâtiment) [40]. A building certification scheme, named Minergie, was also established to attest the high-energy efficiency of dwellings and occupants' comfort [41]. However, since Switzerland is predominantly situated in radon-prone area of Europe, energy-efficient measures of dwellings could lead to a build-up of indoor radon because of suspected lack of ventilation. Though a national indoor radon level database has been launched in Switzerland [42] which provides an informative Swiss radon map, limited emphasis is put on understanding the radon levels in energy-efficient dwellings. Pampuri et al. [43] found a significant increase in radon concentration after thermal retrofitting based on radon survey in 154 dwellings in southern Switzerland. Nevertheless, the study was restricted to only one Swiss canton and it did not take into account Minergie-certified dwellings.

To bridge this knowledge gap, we conducted indoor radon investigation in 650 energy-efficient dwellings in western Switzerland from 2013 to 2015. The objectives of this study were (1) to determine the indoor radon levels in Swiss energy-efficient homes and to compare them between green-certified (Minergie) and energy-renovated dwellings; (2) to probe the associations between radon and dwelling characteristics; and (3) to investigate the influence of thermal retrofitting on indoor radon level. Passive

samplers were applied for the radon measurements, and questionnaire surveys were used to collect information about dwelling characteristics and thermal retrofitting. The results of this study could be used to better understand the radon levels in energy-efficient dwellings and, potentially, to interpret the associated health risks. The study is also useful for improving the accuracy of exposure assessment of indoor radon, and for developing improved energy renovation strategies in terms of radon control.

2. Materials and Methods

2.1. Study Sample and Approach

Passive sampling of radon was performed within the framework of the ‘Mesqualair’ project on indoor air quality in energy-efficient dwellings from January 2013 to March 2016 in the western part of Switzerland. The owners of energy-efficient dwellings were selected from a list provided by the Romand Minergie Agency and the Cantonal Energy Service Offices. A total of 650 gave their consent to take part in the study (shown in Figure 1). A radon dosimeter was sent by post to each participating dwelling, together with a step-by-step instruction of sampling procedure (detailed in Section 2.3), and questionnaire regarding building characteristics. After sampling, the dosimeters were sent back to the project team for analysis. Two radon measurement campaigns took place during winter 2013–2014 (93 homes) and 2014–2015 (557 homes) to complete the 650 dwellings, while 616 homeowners returned the responded questionnaire in total.

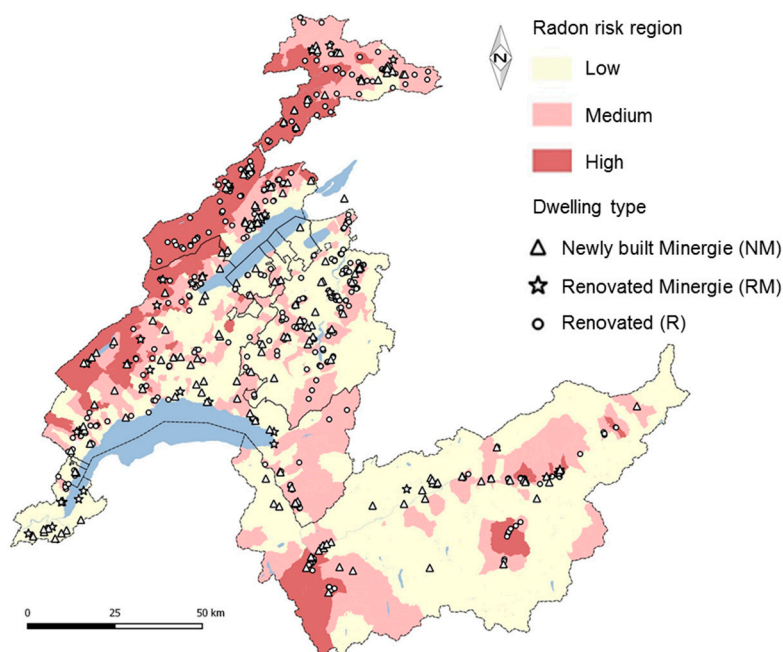


Figure 1. Distribution of the three types of sampled dwellings across different radon risk regions, according to the Swiss radon regulation based on radon measurements in over 150,000 homes [44].

2.2. Characteristics of Selected Dwellings

Most of the participating dwellings were individual or semidetached houses and most were occupied by owners. Among the 650 radon-tested energy-efficient dwellings, Minergie labelled buildings (M) accounted for 37% (217), and the remaining 433 homes were part of the national energy renovation program (Programme Bâtiment) for buildings (R). It is noteworthy that out of the 217 M buildings, most were newly built (NM, 182) and only 35 were renovated (RM), illustrated in Figure 1.

Table 1 summarizes the collected information for the 616 dwellings, including 170 NM, 32 RM, and 414 R homes. Most NM dwellings were built after 2000, while a large proportion of energy-renovated ones, both RM and R, were constructed between years 1950 and 1975. Masonry was the predominant

building structure in more than 50% of the sampled dwellings. A larger proportion of NM and RM dwellings had no natural ground floors (floors directly adjacent to the natural ground) compared to R dwellings. The majority of both M and R dwellings had completely excavated or back-grounded basements (schemed in Figure S1). The NM and R dwellings shared a similar distribution of garage type, while RM dwellings had higher proportion of outdoor parking. Only 36% of the selected dwellings were equipped with mechanical ventilation systems, distributed across 167 NM dwellings, 28 RM dwellings, and only 15 R dwellings. A relatively higher percentage of NM and RM dwellings were located in low radon risk regions.

Table 1. A summary of the characteristics of the 616 dwellings including newly built Minergie (NM), renovated Minergie (RM), and energy-renovated (R) dwellings. Responses with ‘I do not know’ or missing are excluded.

Dwelling Characteristics		NM No. (%)	RM No. (%)	R No. (%)	Total No. (%)
Built Year	2000–2015	169 (99)	2 (6)	1 (0)	172 (28)
	1975–1999	1 (1)	5 (16)	143 (35)	149 (25)
	1950–1974	0 (0)	9 (29)	146 (35)	155 (25)
	1925–1949	0 (0)	3 (10)	34 (8)	37 (6)
	1900–1924	0 (0)	4 (13)	27 (7)	31 (5)
	Before 1900	0 (0)	8 (26)	61 (15)	69 (11)
Building Structure	Masonry	78 (46)	11 (35)	261 (63)	350 (57)
	Wood	56 (33)	2 (6)	12 (3)	70 (11)
	Mixed	29 (17)	17 (53)	103 (25)	149 (24)
	Other or not clear	7 (4)	2 (6)	38 (9)	47 (8)
Radon Risk Region	Low	57 (34)	9 (28)	67 (16)	133 (21)
	Medium	87 (51)	19 (59)	225 (54)	331 (54)
	High	26 (15)	4 (13)	122 (30)	152 (25)
Mechanical Ventilation	Yes	168 (99)	29 (90)	14 (4)	211 (36)
	No	1 (1)	3 (10)	376 (96)	380 (64)
Basement Type	Completely excavated	50 (30)	8 (25)	126 (31)	184 (30)
	Semi-excavated	27 (16)	8 (25)	82 (20)	117 (19)
	Back-grounded	46 (28)	12 (38)	156 (38)	214 (35)
	No basement	44 (26)	4 (12)	47 (11)	95 (16)
Garage Type	Outdoor	43 (27)	19 (61)	123 (30)	185 (31)
	Independent	40 (25)	5 (16)	113 (28)	158 (27)
	Attached	42 (27)	5 (16)	97 (24)	144 (24)
	In basement	33 (21)	2 (7)	72 (18)	107 (18)
Natural Ground	Yes	46 (28)	14 (44)	204 (52)	264 (45)
	No	119 (72)	18 (56)	192 (49)	329 (55)
Thermal retrofitting					
Window	Yes	–	12 (60)	334 (81)	346 (80)
	No	–	8 (40)	78 (19)	86 (20)
Roof	Yes	–	13 (65)	238 (58)	251 (58)
	No	–	7 (35)	174 (42)	181 (42)
Floor and Exterior Wall	Yes	–	14 (70)	185 (45)	199 (46)
	No	–	6 (30)	227 (55)	233 (54)
Level of Retrofit	Partial	–	9 (45)	305 (74)	314 (73)
	Full	–	11 (55)	107 (26)	118 (27)

We received 432 effective responses regarding thermal retrofitting during energy renovation. The thermal retrofit included replacement of windows to reduce the air infiltration, renovation of roofs, and retrofitting of floors and exterior walls to increase the thermal insulation of the building envelop. A majority of the dwellings experienced replacement of windows and renovation of roofs, while <50% got floors and exterior walls retrofitted. Only 27% of renovated dwellings had all the three types of thermal retrofitting, as we called full retrofit. Since the focus of this study is to investigate the impact

of energy efficiency status, as well as energy renovation on indoor radon level, we did not acquire information regarding radon remediation actions in the involved dwellings via the questionnaire.

2.3. Radon Measurement

In January 2013 and 2014, a radon dosimeter was sent to each participating dwelling. The owners were asked to follow the step-by-step instruction to install the passive sampling dosimeter (Radtrak², Sweden, three-month detection range: 15–25,000 Bq/m³) at least 1.5 m above the ground, and away from windows and doors in a heated and regularly-occupied room at the closest floor of the dwelling from the ground. The sampling was performed over three months during the heating season, to allow a reliable representation of the average annual indoor radon concentration, as per ISO 11665-8 Standard [45]. During the sampling period, the occupants were asked to keep their living habits as usual, without touching or moving the dosimeter. After three-month collection, the dosimeters were sealed by the occupants and shipped back to the project team. We stored the dosimeters in a dry place protected from light, and organized the shipment to the laboratory of Landauer Nordic, Sweden within one month. The dosimeters were then analyzed following the ISO 11665-4 standard [46].

2.4. Statistical Analyses

The statistical analyses were performed using SPSS 21 software and customized coding in MATLAB R2014 software. The concentrations of indoor radon were log-normally distributed (seen in Figure S2). Therefore, the parametric *t*-test (number of categories $k = 2$) and analysis of variance (ANOVA) test ($k > 2$) were performed to test the relationship between the logarithmical transformed radon concentrations and the dwelling characteristics, and thermal retrofitting. Since the distribution of detected radon concentrations followed the lognormal pattern, the geometric mean (geo-mean) can better represent the mean value of radon concentrations in different categories for comparison. On the other hand, the median value is always important for statistics of a dataset, regardless of data distribution. Therefore, we considered both in the study.

3. Results and Discussion

3.1. Radon Concentration

The distribution of indoor radon concentrations in Swiss energy-efficient dwellings is shown in Figure 2. Across 650 dwellings, the median value of detected radon concentrations was 71 Bq/m³, while the geo-mean was 85 Bq/m³ with a geometric standard deviation of 2.8. The results were similar to those collected in the radon database of the FOPH for Swiss buildings (median value of 87 Bq/m³ [30]), where the difference was mainly attributed to the disparity in sampling amount, period, and geographic distribution between this study and the FOPH radon database. Compared to the maximum recommended value of 300 Bq/m³, by the WHO [5] and the FOPH [14], radon concentrations in only 11% of sampled dwellings exceeded the threshold. However, considering the reference value of 100 Bq/m³ by the WHO [5], around 40% of dwellings failed to meet the reference value. Notably, the maximum detected indoor radon level reached as high as 4280 Bq/m³, which is more than 40 times higher than the reference value.

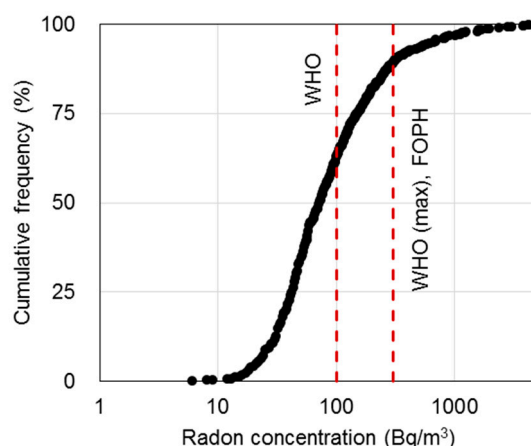


Figure 2. Cumulative frequency of radon concentration in 650 sampled energy-efficient dwellings. The two dashed lines represent the reference value of 100 Bq/m^3 by the WHO and maximum recommended value of 300 Bq/m^3 by the WHO and the Federal Office of Public Health (FOPH), respectively.

Figure 3 summarizes detected radon concentration as a function of three types of dwellings: newly built Minergie (NM), renovated Minergie (RM), and energy renovated (R). We observed significant differences in the radon concentrations in the three types of dwellings. The Minergie-labeled (M) dwellings had significantly lower radon concentrations compared to energy-renovated (R) dwellings (geo-mean 56 and 105 Bq/m^3 , respectively). Interestingly, we detected different radon levels even between new (NM) and renovated Minergie (RM) dwellings. Radon concentrations in NM dwellings were significantly lower than those in RM and R ones: the geo-mean radon of NM dwellings (52 Bq/m^3) were 40% less than that of RM ones (87 Bq/m^3), and were only half of that in R homes (105 Bq/m^3). The difference in radon levels of the RM and R dwellings was not significant ($p = 0.302$). Compared to the FOPH reference level (300 Bq/m^3), radon concentrations in around 3% of NM, 6% of RM, and 14% of R dwellings exceeded the limit value, while the proportions of levels beyond the reference threshold (100 Bq/m^3) across the three types of dwellings became 20%, 37%, and 44%, respectively. The results indicate that energy-renovated dwellings (either Minergie or non-Minergie) had generally higher indoor radon levels than newly built Minergie-certified dwellings. The results imply the importance of the thermal retrofitting on indoor radon concentrations, which is discussed in Section 3.3.

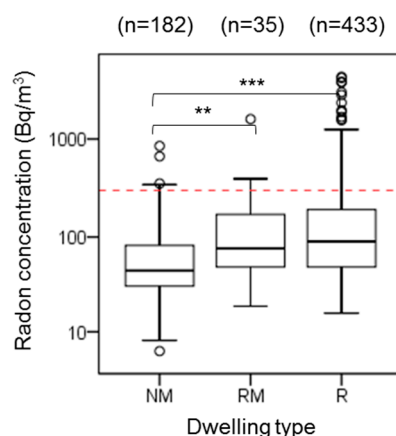


Figure 3. Comparison across different dwelling types of radon concentrations. NM = newly built Minergie; RM = renovated Minergie; R = energy renovated, ** $p < 0.01$ = significant; *** $p < 0.001$ = highly significant, n = the number of dwellings. The dashed line represents the maximum recommended value of 300 Bq/m^3 by the WHO and the FOPH. Box plots indicate minimum, 1st quartile, median, 3rd quartile, and maximum values. Dots represent outliers.

3.2. Associations with Dwelling Characteristics

As shown in Figure 4, the year of dwelling construction was strongly associated with indoor radon concentration ($p < 0.001$). Older houses had higher radon levels relative to more recently built dwellings, which was in agreement with the findings reported elsewhere [24,25]. We observe a negative linear relationship between log-transformed radon concentration and built year of dwellings ($\beta = -0.002$, $R^2 = 0.09$, $p < 0.001$, Figure S3). With the increase in building age, the geo-mean indoor radon concentration elevated gradually from 51 Bq/m³ in dwellings built in 2000–2015, to 150 Bq/m³ in dwellings built before 1900. Considering the reference level, only 3% of houses built in 2000–2015 exceeded 300 Bq/m³, while the exceed-limit proportion increased to 20% in dwellings built before 1900. We hypothesize that elevated levels of radon in old dwellings come as a combined result of inadequate sealing of the lowest floor against the ground and enhancement of airtightness of the dwellings without adjusting for ventilation needs.

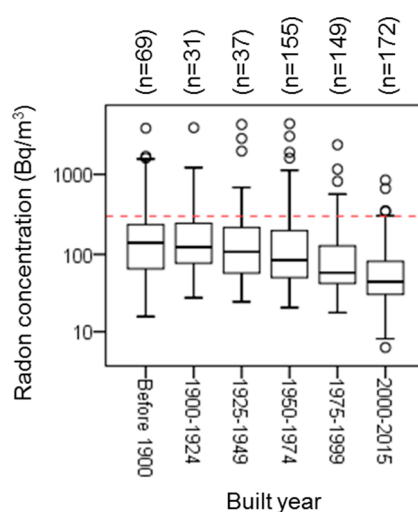


Figure 4. Influence of the dwelling construction year on indoor radon concentrations ($p < 0.001$). The dashed line represents the maximum recommended value of 300 Bq/m³ by the WHO and the FOPH, while n indicates the number of samples. Box plots indicate minimum, 1st quartile, median, 3rd quartile, and maximum values. Dots represent outliers.

Another important variable associated with indoor level of radon was geographical location of dwellings, as shown in Figure 5. The geo-mean radon concentration in dwellings located in a high radon risk region was more than three times higher than in dwellings built in a low risk region (200 vs. 56 Bq/m³, $p < 0.001$). Houses located in a low radon risk region also had significantly lower indoor radon levels than those in a medium risk region (geo-mean, 56 vs. 69 Bq/m³, $p < 0.05$). Only 0.01% of dwellings in low-risk areas and 5% of dwellings in medium-risk areas failed to meet the recommended radon exposure value. In contrary, 32% of the dwellings situated in high-risk zones exceeded the limit. The richness of radon in soil of high radon risk region can lead to the higher indoor radon levels caused by soil-building foundation transfer of radon [47], indicating the high importance of preventions for radon control in dwellings located in high radon risk regions.

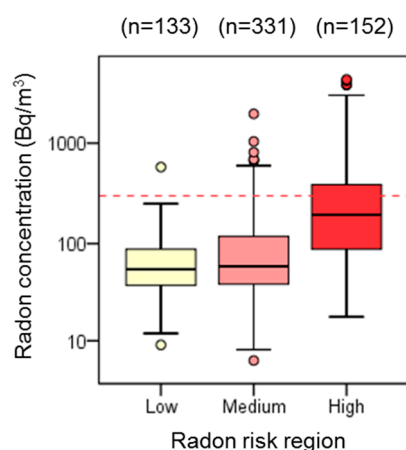


Figure 5. Association between radon risk region where dwellings are located and indoor radon concentrations ($p < 0.001$). The dashed line represents the maximum recommended value of 300 Bq/m^3 by the WHO and the FOPH; n represents number of samples. Box plots indicate minimum, 1st quartile, median, 3rd quartile, and maximum values. Dots represent outliers.

Indoor radon concentration is highly associated with building ventilation, which can dilute accumulated radon with outdoor air, and in some specific cases prevent the radon infiltration through pressurization [48]. Figure 6 demonstrates that the mechanical ventilation can have a profound effect on indoor radon. Relative to naturally ventilated residences, dwellings with mechanical ventilation systems had significantly lower radon concentrations (geo-mean, $58 \text{ vs. } 105 \text{ Bq/m}^3$, $p < 0.01$). Similar findings were reported by other studies as well [25]. The need for mechanical ventilation in controlling the indoor radon is a priority for dwellings located in high radon risk regions, as evidenced by the increased difference in radon concentrations between mechanically and naturally ventilated houses (geo-mean, $96 \text{ vs. } 251 \text{ Bq/m}^3$, $p < 0.001$).

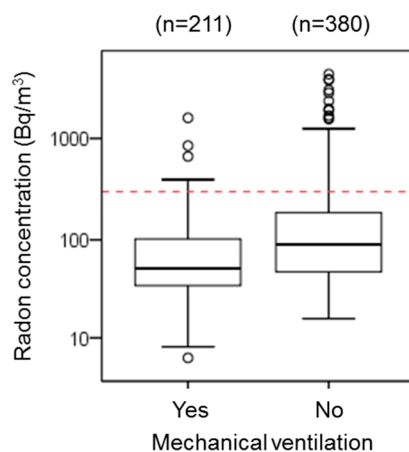


Figure 6. Association between installation of mechanical ventilation and indoor radon concentrations ($p < 0.01$). The dashed line represents the maximum recommended value of 300 Bq/m^3 by the WHO and the FOPH; n represents number of samples. Box plots indicate minimum, 1st quartile, median, 3rd quartile, and maximum values. Dots represent outliers.

We also observed significant associations between indoor radon concentrations and other dwelling characteristics, including type of the ground, building structure, type of basement, and type of garage. Specifically, dwellings with natural ground floor exhibited higher indoor radon levels compared to the ones without (geo-mean, $100 \text{ vs. } 77 \text{ Bq/m}^3$, $p < 0.01$), shown in Table S1. The natural ground floor allowed higher radon infiltration from the natural ground indoors, as similarly reported by

Diallo et al. [49] and Collignan et al. [25]. The geo-mean radon concentration in dwellings with wood structures was less than half of that in residences of masonry or mixed structures (Table S2). The significantly higher radon levels in houses with masonry and mixed structures can be attributed to lower air infiltration. With respect to the influence of basement type, dwellings with semi-excavated or back-grounded basements had significantly higher radon levels than houses with completely excavated basements, as shown in Table S3. A possible interpretation is that dwellings with back-grounded basements had a living space directly above the soil, where the radon test took place, unlike the dwellings with fully excavated basements. The construction of semi-excavated basements may also entail greater risk of radon infiltration, given the larger number of cutouts in the building envelope in contact with the ground. Moreover, the completely excavated basement can act as a buffer for radon transmission between the soil and the living space. We obtained the analogous results for the garage type: dwellings with garage in the basement had significantly lower radon concentrations (Table S4).

There is a clear link between dwelling characteristics and indoor radon concentrations, which may explain the lower radon levels in newly built dwellings compared to renovated ones. In addition to exogenous important factors such as geographical region of Switzerland, building construction features that led to reduced radon levels and that should be recommended include installation of mechanical ventilation or controlled natural ventilation, and building airtight ground floors, as we noticed that all the seven homes with extremely high radon levels (>2000 Bq/m³) were renovated ones located in high radon risk region but without mechanical ventilation.

3.3. Influence of Thermal Retrofitting

Based on 432 collected responses about type of thermal retrofit during energy renovation, we analyzed their influence on indoor radon concentrations. As presented in Figure 7a, dwellings with replaced windows with a goal to minimize heat exchange with the exterior led to slightly higher indoor radon concentrations compared to houses without retrofitted windows (geo-mean, 105 vs. 99 Bq/m³, respectively, $p = 0.69$). Similarly, renovated roof elevated radon levels by 9%, from geo-mean 99 to 107 Bq/m³, though without statistical significance either ($p = 0.47$). Retrofitting the floors and exterior walls increased the geo-mean radon concentration significantly by 38 Bq/m³ ($p < 0.001$). Altogether, the 118 dwellings that fully implemented all the thermal retrofitting strategies, had the geo-mean radon concentration of 131 Bq/m³, 50% higher than other residences that had undergone partial thermal retrofit.

The influence of thermal retrofitting can be further interpreted by comparing the radon concentrations before and after energy renovation. From the Swiss national radon database, we retrieved radon concentrations data from 60 dwellings prior to their retrofit, which were involved in the current campaign. By calculating the ratio of radon concentration prior and after the energy renovation, we found on average 20% increase in indoor radon levels caused by thermal retrofitting: the geo-mean value increased from 165 to 197 Bq/m³. However, as shown in Figure 8, this increase in radon levels was not statistically significant ($p = 0.15$). In some dwellings, the radon concentrations increased by as much as 4–8 times after thermal retrofitting. Owing to increase in airtightness of dwellings after thermal retrofit, the air exchange rate decreased, leading to elevated indoor radon concentrations. Similar findings were reported in other studies with radon [33,37] and other air pollutants, such as formaldehyde and volatile organic compounds [36,50]. The influence of thermal retrofit on radon concentration explains the relatively higher radon level in RM dwellings than NM ones.

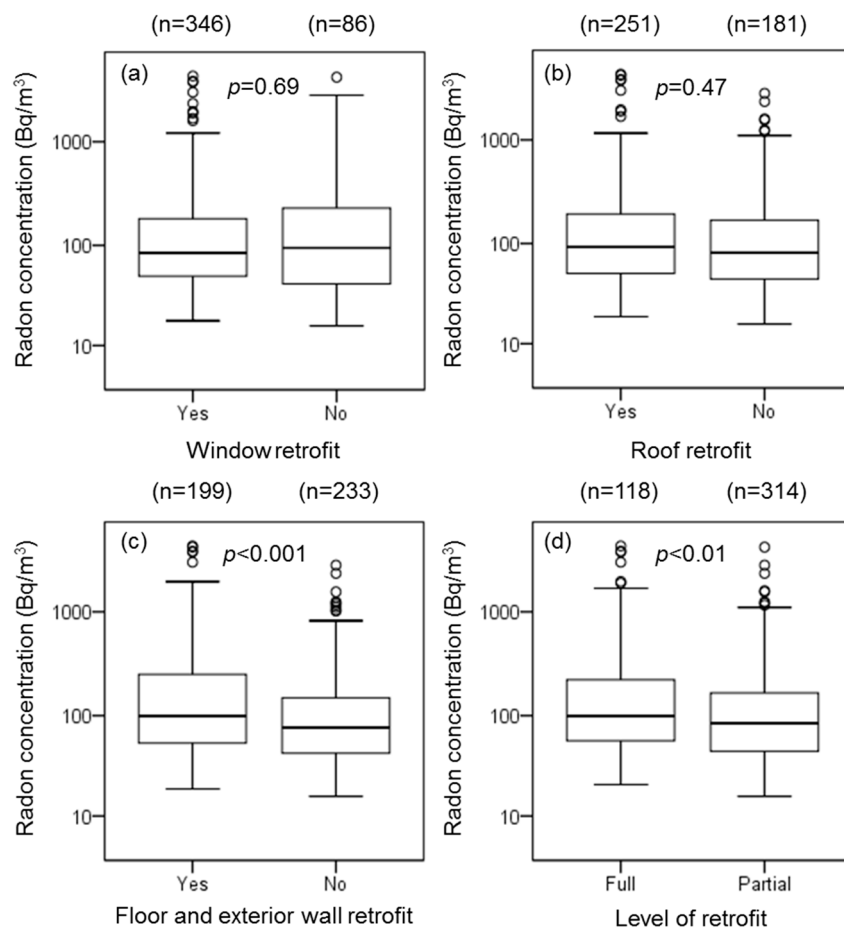


Figure 7. Influence of thermal retrofit on indoor radon: (a) window retrofit, (b) roof retrofit, (c) floor and exterior wall retrofit, and (d) level of retrofit. *n* represents number of samples. Box plots indicate minimum, 1st quartile, median, 3rd quartile, and maximum values. Dots represent outliers.

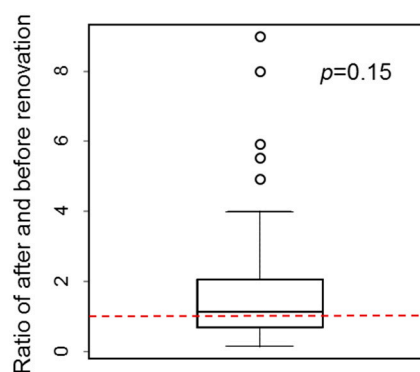


Figure 8. Distribution of ratio of radon concentrations after and before energy renovation in 60 dwellings. The dashed line represents the value of 1. Box plots indicate minimum, 1st quartile, median, 3rd quartile, and maximum values. Dots represent outliers.

3.4. Implications

The strong association between the presence of the mechanical ventilation in dwellings and reduced radon concentrations highlights the importance of adequate ventilation in limiting indoor radon exposure. Therefore, in both new constructed and energy-renovated dwellings, attention should

be given to effective ventilation design and operation for control of indoor radon. Nonetheless, as indicated by the relatively high radon level in RM dwellings, installation of mechanical ventilation was not enough to ensure low levels of radon. We identified that occupants living in RM dwellings were not aware of the necessity to operate the mechanical ventilation in homes: some of them have never switched on the system. Relatively high radon levels in naturally ventilated homes imply the importance of raising awareness of residents about window opening behaviors, which should accompany building retrofitting actions or new constructions.

It is also strongly recommended to implement radon measurements prior to energy renovation in order to adjust the renovation plan to effectively control indoor radon exposure. Radon prevention technologies need to be applied in cases of high radon concern. The main action is to install a specific sub-slab drainage against radon in order to make a depressurization and to extract radon from the ground before it enters a dwelling, as well as to enhance indoor ventilation [51]. In summary, to capitalize on the potential co-benefits of thermal retrofit in reducing energy consumption and maintaining high level of indoor air quality, we encourage stakeholders to pay special attention to adapting retrofit design based on specific building conditions (such as building age, construction type, and geographical location).

4. Conclusions

This study investigated the radon level in 650 energy efficient dwellings in western Switzerland. We examined the influences of building characteristics and thermal retrofit in new (NM) and renovated (RM) green-certified Minergie dwellings and in energy-renovated noncertified dwellings (R). We observed 40% lower radon levels in Minergie-certified dwellings, but there was no statistically significant difference between renovated Minergie (RM) and energy-renovated (R) dwellings. Indoor radon concentration was higher in older houses, especially in those built with masonry or mixed structures, and natural ground floors. Dwellings situated in high radon risk regions were prone to elevated radon risks. Installation of mechanical ventilation and completely excavated basement contributed to reduced radon concentrations in the living spaces. Thermal retrofitting of windows, roofs, floors, and external walls increased indoor radon concentrations, likely owing to reduced air exchange through air leakage.

Our results indicate that energy renovation measures without attention to indoor environment can adversely influence the level of indoor radon. Alongside the aggressive energy efficiency initiatives in Swiss buildings, these efforts should be accompanied with measures to minimize radon infiltration indoors and to secure adequate ventilation. Radon prevention constructions should take place in specific conditions, particularly for dwellings located in radon-prone areas like Switzerland. Alongside minimizing radon penetration from the ground, the ventilation design should take into account provision of a sufficient amount of outdoor air to dilute indoor radon either by mechanical means or by controlled natural ventilation. Occupants should be informed of the importance of indoor radon control, including renovating their ground floors and ventilating more often, especially in winter seasons. The recommendations should become part of the Swiss building renovation strategies and green-certification programs.

Supplementary Materials: The following are available online at <http://www.mdpi.com/2073-4433/10/12/777/s1>, Figure S1: Scheme of different basement types: (a) completely excavated; (b) semi-excavated; (c) back-grounded, and (d) no basement. Figure S2: P-P plot of measured log-transformed radon concentrations. Figure S3: Relationship between log-transformed radon concentration and built year of dwellings. Table S1: Influence of natural ground floor on indoor radon concentrations ($p < 0.01$). Table S2: Influence of building structure on indoor radon concentrations ($p < 0.001$). Table S3: Influence of basement type on indoor radon concentrations ($p < 0.001$). Table S4: Influence of garage type on indoor radon concentrations ($p < 0.001$).

Author Contributions: Conceptualization, J.G.P.; methodology, J.G.P.; formal analysis, J.G.P., C.H.J. and S.Y.; writing—original draft preparation, S.Y.; writing—review and editing, S.Y., D.L., J.G.P., C.H.J., H.N.-H. and V.P.; visualization, S.Y.; supervision, D.L. and J.G.P.; project administration, J.G.P.; funding acquisition, J.G.P.

Funding: This research was funded by PST-FR (Pôle scientifique et technologique du canton de Fribourg), grant number EB_41-13, Office fédéral de santé publique, grants number 13.006740/434.0000/-131 and 15.009001/444.0002/-75, Service de l’Energie du canton de Fribourg, Agence MINERGIE@romande, Losinger Marazzi SA, Suissetec, Fédération fribourgeoise des entrepreneurs, Hälgi et Cie SA, Maintenance Mugny et Marguet SA.

Acknowledgments: Western cantonal authorities for energy efficiency gave us the opportunity to contact owners of renovated buildings and a few freiburger architecture offices like Bovet-Jeker architectes Sàrl, Eco-logements, Kaspar architectes and Lutz architectes Sàrl did participate in the discussions during the project. Maps were prepared by GeoAzimut (www.geoazimut.com).

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

References

1. Clement, C. Assessment of the detriment from exposure to radon and its progeny. *Ann. ICRP* **2010**, *40*, 41e7.
2. Pacheco-Torgal, F. Indoor radon: An overview on a perennial problem. *Build. Environ.* **2012**, *58*, 270–277. [[CrossRef](#)]
3. Al-Zoughool, M.; Krewski, D. Health effects of radon: A review of the literature. *Int. J. Radiat. Biol.* **2009**, *85*, 57–69. [[CrossRef](#)] [[PubMed](#)]
4. Chauhan, V.; Howland, M.; Mendenhall, A.; O’Hara, S.; Stocki, T.J.; McNamee, J.P.; Wilkins, R.C. Effects of alpha particle radiation on gene expression in human pulmonary epithelial cells. *Int. J. Hyg. Environ. Health* **2012**, *215*, 522–535. [[CrossRef](#)] [[PubMed](#)]
5. World Health Organization. *WHO Handbook on Indoor Radon: A Public Health Perspective*; World Health Organization: Geneva, Switzerland, 2009.
6. Chen, J.; Harley, N.H. A review of indoor and outdoor radon equilibrium factors—Part I: 222Rn. *Health Phys.* **2018**, *115*, 490–499. [[CrossRef](#)] [[PubMed](#)]
7. Bruno, R.C. Sources of indoor radon in houses: A review. *J. Air Pollut. Control. Assoc.* **1983**, *33*, 105–109. [[CrossRef](#)]
8. Nazaroff, W.W. Radon transport from soil to air. *Rev. Geophys.* **1992**, *30*, 137–160. [[CrossRef](#)]
9. Darby, S.; Hill, D.; Auvinen, A.; Barros-Dios, J.M.; Baysson, H.; Bochicchio, F.; Deo, H.; Falk, R.; Forastiere, F.; Hakama, M.; et al. Radon in homes and risk of lung cancer: Collaborative analysis of individual data from 13 European case-control studies. *BMJ* **2005**, *330*, 223. [[CrossRef](#)]
10. Darby, S.; Hill, D.; Deo, H.; Auvinen, A.; Barros-Dios, J.M.; Baysson, H.; Bochicchio, F.; Falk, R.; Farchi, S.; Figueiras, A.; et al. Residential radon and lung cancer—detailed results of a collaborative analysis of individual data on 7148 persons with lung cancer and 14 208 persons without lung cancer from 13 epidemiologic studies in Europe. *Scand. J. Work Environ. Health* **2006**, *32* (Suppl. 1), 1–83.
11. Krewski, D.; Lubin, J.H.; Zielinski, J.M.; Alavanja, M.; Catalan, V.S.; Field, R.W.; Klotz, J.B.; Létourneau, E.G.; Lynch, C.F.; Lyon, J.I.; et al. Residential radon and risk of lung cancer: A combined analysis of 7 North American case-control studies. *Epidemiology* **2005**, *16*, 137–145. [[CrossRef](#)]
12. Krewski, D.; Lubin, J.H.; Zielinski, J.M.; Alavanja, M.; Catalan, V.S.; Field, R.W.; Klotz, J.B.; Létourneau, E.G.; Lynch, C.F.; Lyon, J.L.; et al. A combined analysis of North American case-control studies of residential radon and lung cancer. *J. Toxicol. Environ. Health A* **2006**, *69*, 533–597. [[CrossRef](#)] [[PubMed](#)]
13. US Environmental Protection Agency. A Citizen’s Guide to Radon: The Guide to Protecting Yourself and Your Family from Radon. Available online: https://www.epa.gov/sites/production/files/2016-12/documents/2016_a_citizens_guide_to_radon.pdf (accessed on 14 June 2019).
14. Swiss Federal Council. Radiological Protection Ordinance. Available online: <https://www.admin.ch/opc/en/classified-compilation/20163016/index.html> (accessed on 14 June 2019).
15. EU Council. COUNCIL DIRECTIVE 2013/59/EURATOM. Available online: <https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2014:013:0001:0073:EN:PDF> (accessed on 22 November 2019).
16. Nero, A.V.; Schwehr, M.B.; Nazaroff, W.W.; Revzan, K.L. Distribution of airborne radon-222 concentrations in US homes. *Science* **1986**, *234*, 992–997. [[CrossRef](#)] [[PubMed](#)]
17. Bochicchio, F.; Venuti, G.C.; Nuccetelli, C.; Piermattei, S.; Risica, S.; Tommasino, L.; Torri, G. Results of the representative Italian national survey on radon indoors. *Health Phys.* **1996**, *71*, 741–748. [[CrossRef](#)] [[PubMed](#)]
18. Quindós, L.S.; Fernández, P.L.; Soto, J. National survey on indoor radon in Spain. *Environ. Int.* **1991**, *17*, 449–453. [[CrossRef](#)]

19. Franco-Marina, F.; Segovia, N.; Ruiz, W.; Godinez, L.; Tavera, L.; Lopez, A.; Chavez, A.; Peña, P.; Ponciano, G. Short and long term indoor radon survey in Mexico City. *Radiat. Meas.* **2001**, *34*, 545–548. [[CrossRef](#)]
20. Al-Jarallah, M.I.; Abu-Jarad, F.; Al-Shukri, A. Indoor radon measurements in dwellings of four Saudi Arabian cities. *Radiat. Meas.* **2003**, *36*, 445–448. [[CrossRef](#)]
21. Kim, C.K.; Lee, S.C.; Lee, D.M.; Chang, B.U.; Rho, B.H.; Kang, H.D. Nationwide survey of radon levels in Korea. *Health Phys.* **2003**, *84*, 354–360. [[CrossRef](#)]
22. Dubois, G.; Bossew, P.; Tollefsen, T.; De Cort, M. First steps towards a European atlas of natural radiation: Status of the European indoor radon map. *J. Environ. Radioact.* **2010**, *101*, 786–798. [[CrossRef](#)]
23. Gruber, V.; Bossew, P.; De Cort, M.; Tollefsen, T. The European map of the geogenic radon potential. *J. Radiol. Prot.* **2013**, *33*, 51. [[CrossRef](#)]
24. Demoury, C.; Ielsch, G.; Hemon, D.; Laurent, O.; Laurier, D.; Clavel, J.; Guillevic, J. A statistical evaluation of the influence of housing characteristics and geogenic radon potential on indoor radon concentrations in France. *J. Environ. Radioact.* **2013**, *126*, 216–225. [[CrossRef](#)]
25. Collignan, B.; Le Ponner, E.; Mandin, C. Relationships between indoor radon concentrations, thermal retrofit and dwelling characteristics. *J. Environ. Radioact.* **2016**, *165*, 124–130. [[CrossRef](#)]
26. Andersen, C.E.; Raaschou-Nielsen, O.; Andersen, H.P.; Lind, M.; Gravesen, P.; Thomsen, B.L.; Ulbak, K. Prediction of ²²²Rn in Danish dwellings using geology and house construction information from central databases. *Radiat. Prot. Dosimetry* **2007**, *123*, 83–94. [[CrossRef](#)]
27. Hunter, N.; Muirhead, C.R.; Miles, J.C.; Appleton, J.D. Uncertainties in radon related to house-specific factors and proximity to geological boundaries in England. *Radiat. Prot. Dosimetry* **2009**, *136*, 17–22. [[CrossRef](#)] [[PubMed](#)]
28. Gerken, M.; Kreienbrock, L.; Wellmann, J.; Kreuzer, M.; Wichmann, H.E. Models for retrospective quantification of indoor radon exposure in case-control studies. *Health Phys.* **2000**, *78*, 268–278. [[CrossRef](#)] [[PubMed](#)]
29. Verdi, L.; Weber, A.; Stoppa, G. Indoor radon concentration forecasting in South Tyrol. *Radiat. Prot. Dosimetry* **2004**, *111*, 435–438. [[CrossRef](#)] [[PubMed](#)]
30. Kropat, G.; Bochud, F.; Jaboyedoff, M.; Laedermann, J.P.; Murith, C.; Palacios, M.; Baechler, S. Major influencing factors of indoor radon concentrations in Switzerland. *J. Environ. Radioact.* **2014**, *129*, 7–22. [[CrossRef](#)]
31. Hauri, D.D.; Huss, A.; Zimmermann, F.; Kuehni, C.E.; Rössli, M. A prediction model for assessing residential radon concentration in Switzerland. *J. Environ. Radioact.* **2012**, *112*, 83–89. [[CrossRef](#)]
32. Yarmoshenko, I.V.; Vasilyev, A.V.; Onishchenko, A.D.; Kiselev, S.M.; Zhukovsky, M.V. Indoor radon problem in energy efficient multi-storey buildings. *Radiat. Prot. Dosimetry* **2014**, *160*, 53–56. [[CrossRef](#)]
33. Vasilyev, A.V.; Yarmoshenko, I.V.; Zhukovsky, M.V. Low air exchange rate causes high indoor radon concentration in energy-efficient buildings. *Radiat. Prot. Dosimetry* **2015**, *164*, 601–605. [[CrossRef](#)]
34. Meyer, W. Impact of constructional energy-saving measures on radon levels indoors. *Indoor Air* **2019**, *29*, 680–685. [[CrossRef](#)]
35. Pigg, S.; Cautley, D.; Francisco, P.W. Impacts of weatherization on indoor air quality: A field study of 514 homes. *Indoor Air* **2018**, *28*, 307–317. [[CrossRef](#)] [[PubMed](#)]
36. Du, L.; Leivo, V.; Prasauskas, T.; Täubel, M.; Martuzevicius, D.; Haverinen-Shaughnessy, U. Effects of energy retrofits on Indoor Air Quality in multifamily buildings. *Indoor Air* **2019**, *29*, 686–697. [[CrossRef](#)] [[PubMed](#)]
37. Jiránek, M.; Kačmaříková, V. Dealing with the increased radon concentration in thermally retrofitted buildings. *Radiat. Prot. Dosimetry* **2014**, *160*, 43–47. [[CrossRef](#)] [[PubMed](#)]
38. Symonds, P.; Rees, D.; Daraktchieva, Z.; McColl, N.; Bradley, J.; Hamilton, I.; Davies, M. Home energy efficiency and radon: An observational study. *Indoor Air* **2019**, *29*, 854–864. [[CrossRef](#)] [[PubMed](#)]
39. Swiss Federal Council. Energy Strategy 2050. Available online: <https://www.bfe.admin.ch/bfe/en/home/policy/energy-strategy-2050.html> (accessed on 14 June 2019).
40. Swiss Federal Office of Energy. Programme Bâtiment. Available online: <https://www.dasgebaeudeprogramm.ch/de/> (accessed on 14 June 2019).
41. Minergie Schweiz. Available online: <https://www.minergie.ch> (accessed on 14 June 2019).
42. Swiss Federal Office of Public Health. Available online: <https://www.ch-radon.ch> (accessed on 14 June 2019).

43. Pampuri, L.; Caputo, P.; Valsangiacomo, C. Effects of buildings' refurbishment on indoor air quality. Results of a wide survey on radon concentrations before and after energy retrofit interventions. *Sustain. Cities Soc.* **2018**, *42*, 100–106. [[CrossRef](#)]
44. Ordonnance sur la Radioprotection (ORaP). Available online: <https://www.admin.ch/opc/fr/classified-compilation/19940157/201401010000/814.501.pdf> (accessed on 14 June 2019).
45. ISO 11665-8. *Measurement of Radioactivity in the Environment—Air: Radon-222. Part. 8: Methodologies for Initial and Additional Investigations in Buildings*; International Organization for Standardization: Geneva, Switzerland, 2012.
46. ISO 11665-4. *Measurement of Radioactivity in the Environment—Air: Radon-222. Part. 4: Integrated Measurement Method for Determining Average Activity Concentration Using Passive Sampling and Delayed Analysis*; International Organization for Standardization: Geneva, Switzerland, 2012.
47. Chen, J.; Ford, K.L. A study on the correlation between soil radon potential and average indoor radon potential in Canadian cities. *J. Environ. Radioact.* **2017**, *166*, 152–156. [[CrossRef](#)]
48. Collignan, B.; Powaga, E. Impact of ventilation systems and energy savings in a building on the mechanisms governing the indoor radon activity concentration. *J. Environ. Radioact.* **2019**, *196*, 268–273. [[CrossRef](#)]
49. Diallo, T.M.; Collignan, B.; Allard, F. Analytical quantification of airflows from soil through building substructures. *Build. Simul.* **2013**, *6*, 81–94. [[CrossRef](#)]
50. Földvály, V.; Bekö, G.; Langer, S.; Arrhenius, K.; Petráš, D. Effect of energy renovation on indoor air quality in multifamily residential buildings in Slovakia. *Build. Environ.* **2017**, *122*, 363–372. [[CrossRef](#)]
51. SIA 180/2014. *Thermal Insulation, Moisture Protection and Indoor Climate in Buildings*; Swiss Society of Engineers and Architects: Zurich, Switzerland, 2014.



© 2019 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>).