Building and Environment 171 (2020) 106618

Contents lists available at ScienceDirect

Building and Environment

journal homepage: http://www.elsevier.com/locate/buildenv

Energy, indoor air quality, occupant behavior, self-reported symptoms and satisfaction in energy-efficient dwellings in Switzerland

Shen Yang [a], Joëlle Goyette Pernot [b,*], Corinne Hager Jörin [c], Hélène Niculita-Hirzel [d], Vincent Perret [e], Dusan Licina [a]

[a] *Human-Oriented Built Environment Lab, School of Architecture, Civil and Environmental Engineering, École Polytechnique Fédérale de Lausanne, CH-1015, Lausanne, Switzerland*

[b] *Transform Institute, Western Swiss Center 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*

[c] *HumanTech Institute, School of Engineering and Architecture of Fribourg, HES-SO University of Applied Sciences and Arts Western Switzerland, CH-1700, Fribourg, Switzerland*

[d] *Department Health, Work and Environment, Center for Primary Care and Public Health (Unisanté), University of Lausanne, CH-1066, Epalinges, Switzerland*

[e] *TOXpro SA, CH-1227, Carouge, Switzerland*

ARTICLE INFO

Keywords:
Residences
Indoor air quality
Green certification
Energy renovation
Occupancy survey

ABSTRACT

We performed the first large-scale investigation of indoor air quality (IAQ), energy and occupant behavior and satisfaction, in 650 energy-efficient dwellings in western Switzerland. The investigation included comparative assessment of 217 green-certified Minergie (M) and 433 energy-renovated (R) dwellings. Data were collected through a combination of questionnaire survey of building characteristics and occupancy symptoms/satisfaction, as well as field measurements of radon, total volatile organic compounds (TVOC), formaldehyde and fungi. The results showed that 90% of M dwellings relied on renewable and low-carbon energy sources for space and water heating, as compared to only 40% of R dwellings. The annual electricity consumptions of M and R dwellings were similar (~33 kWh/m^2), however, R dwellings consumed more gas and heating oil, thus contributing more to greenhouse gas emissions. Concentration of sampled air pollutants in the two dwelling types was generally below the maximum guideline values. Interestingly, concentration of all air pollutants was significantly lower in M relative to R dwellings: Radon (48 vs. 91 Bq/m^3), TVOC (167 vs. 259 μg/m^3), formaldehyde (12 vs. 15 μg/m^3) and fungal colony forming units (33 vs. 48 CFUs). Statistical comparisons revealed that residents of naturally ventilated R dwellings tended to open window more frequently, while occupants of M dwellings relied on mechanical ventilation. We found no differences in occupant satisfaction and self-reported symptoms between the two dwelling types. The findings of this study are of potential utility for interpreting impacts of growing building energy renovation initiatives on indoor air quality, ventilation design and occupant satisfaction.

1. Introduction

Improving energy efficiency of buildings is an important approach to reduce greenhouse gas emissions, as energy consumed by buildings contributes approximately 40% of emissions [1] and total energy consumption around the world [2,3]. Apart from various energy-saving and emission-reduction technologies, one essential response to the high energy consumption and negative impacts on the environment caused by buildings is energy performance certification [4], as a strategic policy tool to assist governments in decreasing the building energy footprint. Worldwide, energy certifications initiatives in both residential and commercial buildings have witnessed a substantial growth in last decades [5]. In Switzerland, a building energy certification scheme, named Minergie, is established to attest the high energy efficiency and comfort of buildings [6]. In order to achieve the Minergie certification, buildings need to comply with requirements of annual energy consumed of the buildings for space heating, hot water and electrical ventilation, envelope airtightness and insulation, energy-efficient ventilation system and a large proportion of renewable energy supply. An additional certification goal is to secure high level of occupants' comfort, despite the lack of specific requirements to support such goal. Indoor air quality (IAQ) is also taken into consideration in the upgraded Minergie-ECO label. After

* Corresponding author.
E-mail address: joelle.goyette@hefr.ch (J.G. Pernot).

https://doi.org/10.1016/j.buildenv.2019.106618
Received 8 November 2019; Received in revised form 20 December 2019; Accepted 23 December 2019
Available online 25 December 2019

20 years of Minergie label promotion, over 40′000 Swiss buildings have been voluntarily certified, of which residential buildings comprise the majority. On the other hand, to accelerate the reduction of building energy footprint, renovating existing buildings without certification became a priority of climate policies in many countries (e.g. France [7,8], UK [9], North America [10,11] and China [12]) including Switzerland. Building energy renovation program is one of the first set of measures of Energy Strategy 2050 in Switzerland [13]. A Swiss nationwide building energy renovation program (*Programme Bâtiment*) was launched in 2010 to improve building energy efficiency, in which 1.5 billion CHF have been spent to support energy-saving renovation of buildings till 2017 [14]. Yet, knowledge about energy consumption, IAQ and occupants' feedbacks in Minergie certified and energy renovated residences remains limited [15,16].

Despite the primary intention aimed at improving building energy efficiency [17], studies revealed that some green-certified building consume more energy compared to conventional buildings. For instance, energy comparison between US-based certification, Leadership in Energy and Environmental Design (LEED) [18], and conventional buildings showed that, on average, energy performance of LEED-certified buildings is better, however, many individual LEED buildings consume more energy than their conventional counterparts [19,20]. This energy gap may, to a large extent, be attributed to occupants' behavior in LEED buildings [21,22], which is otherwise known to play an important role in building energy consumption [23,24]. Vice versa, characteristics of buildings also influence the behavior of occupants [25]. For instance, window opening behavior is strongly dependent on a dwelling type, ventilation strategy, and heating system [26]. However, the effect of building energy certification on occupant behavior remains ambiguous: some research reported that occupants in green buildings adopt more pro-environmental behavior than those in conventional buildings [27–29], while others showed that the building certification does not motivate such behavior [30,31]. Influence of energy certification on occupant comfort, satisfaction and self-reported health symptoms is relatively understudied. Some survey-based studies argue that green-certified buildings provide more satisfying environments and fewer health symptoms compared to conventional buildings [32,33]. In contrary, other researchers found negligible differences in occupants' satisfactions between green-certified and conventional buildings [34,35]. A recent survey in four Minergie office buildings in Switzerland showed that users' satisfaction with air temperature and indoor air quality was lower than 50% [36].

Indoor air quality (IAQ) is another topic of growing interest in green and energy renovated buildings [37]. The requirement for high airtightness in energy-efficient buildings can lead to extremely low air infiltration, and if not sufficiently compensated by intentional ventilation or other IAQ control strategies, it typically leads to deteriorated IAQ than that of conventional buildings [38]. Some studies emphasized the accumulation of air pollutants in the indoor environment after energy renovation. Increased level of indoor radon after energy retrofit has been observed in several studies [39,40,41]. A recent field test by Du et al. [42] found that radon and BTEX (benzene, toluene, ethylbenzene and xylene) concentrations significantly increased after energy renovation of multifamily dwellings in Finland. Similarly, higher concentration of formaldehyde was observed in renovated green homes than conventional ones [43]. In contrary, several studies demonstrated better IAQ in newly built energy-efficient housing than in conventional ones [44,45]. Another study reported a negative association between increase in household energy efficiency and fungi contamination [46]. A field investigation of IAQ in France showed that newly built energy-efficient houses had lower concentrations of fine particulate matter and radon, but higher levels of certain volatile organic compounds (VOCs) relative to national average [47]. Taken together, to propose control measures to improve IAQ in energy-efficient dwellings, there is a need for more research on understanding casual relationships between energy-efficient strategies in newly or renovated buildings and indoor air quality.

To bridge the knowledge gap, we conducted the first large-scale investigation of 650 energy-efficient dwellings in western Switzerland with and without Minergie certification. The objective of this study was to understand the influence of green certification and energy renovation measures of dwellings on energy consumption, IAQ, occupant behavior, self-reported symptoms and satisfaction. We used questionnaire survey to gain information about building characteristics, energy consumption, occupant behavior, self-reported symptoms and satisfaction, combined with a field quantification of representative pollutants of indoor air: radon, total VOCs (TVOC), formaldehyde and fungi. We performed statistical comparisons between the collected data in Minergie labelled and energy renovated dwellings. The results are of potential use for evaluation of energy renovation actions in residences, for development of improved guides for energy-efficient building design, and for better understanding of multidimensional intersections between occupants and energy-efficient buildings.

2. Materials and methods

2.1. Study sample

Data were collected within the framework of the extensive investigation conducted within 'Mesqualair' New Regional Policy collaborative project on IAQ in energy-efficient dwellings from January 2013 to March 2016 [41]. With the help from the Minergie Agency and Cantonal Energy Service Offices, we randomly selected 650 dwellings distributed in western (French-speaking) part of Switzerland (shown in Fig. S1) for questionnaire survey and IAQ field investigation. Among the investigated samples, Minergie labelled buildings (M) accounted for 33% (217/650), while there were 433 energy-renovated (R) dwellings which benefited from the national energy renovation project for buildings (*Programme Bâtiment*) [14]. Most of the dwellings were individual or semi-detached houses and renovated farms (91%) and occupied by direct owners (98%), who were well familiar with the dwelling characteristics.

2.2. Questionnaire

A self-administered questionnaire was designed to collect information about the sampled buildings and occupants, which could be categorized into four groups: 1) building characteristics (construction year, floor area, garage type, mechanical ventilation system, furniture type, etc.); 2) energy consumption (primary energy type for heating, backup heat, electrical energy consumption, consumption of fuel oil and gas); 3) occupant behavior and lifestyle (pet ownership, smoking habits, frequency of opening window); 4) occupants' satisfaction (perception of temperature, odor, air quality, sound and natural light) and self-report symptoms of dry eyes, stuffy nose, dry throat, and headache. Note that the participants answered the electrical energy consumption data based on their energy bills, which reported the annual energy consumption in kWh.

Prior to sending out the survey, building owners gave their consent to participate in the study. Owners of the surveyed dwellings were asked to fulfill the questionnaire and return to the project team via either online or postal mail. We received responses from as many as 616 surveyed dwellings, which included 202 responses from M dwellings (accounting for 33%, the same as the proportion of M buildings in the total samples).

2.3. IAQ measurements

Measurements of radon were conducted in 650 dwellings, while a representative number of dwellings was selected for quantification of TVOC and formaldehyde in indoor air and fungal colony forming units (CFUs) in settled dust. Radon measurements were conducted from January 2013 to July 2014 by means of passive dosimeters (Radtrak[2], Sweden). One dosimeter was set to each sampled dwelling, together with a detailed user-instruction of the sampling method. The participants were asked to place the dosimeter at least 1.5 m above the ground in a heated and regularly occupied room at the lowest floor of the dwelling. After at least three-month sampling, each dosimeter was sealed and shipped to the project team by postal mail. Then, all the dosimeters were sent to the laboratory for radon concentration analysis following the ISO 11665-4 standard [48].

TVOC and formaldehyde were investigated in 169 dwellings in September 2015, out of which 54 (32%) were Minergie certified dwellings. The TVOC and formaldehyde were sampled using passive devices (TOXpro SA, Switzerland) in compliance with ISO 16017–2 [49] and ISO 16000–4 [50] standards, respectively. One VOCs passive sampler (carbon molecular sieve) and one formaldehyde passive sampler (2,4-dinitrophenylhydrazine impregnated silica gel) were placed in the master bedroom of each sampled dwelling by the occupants following our step-by-step guidance. In each sampling room, the two samplers were located at the height between 1.0 m and 1.7 m, hanged or placed on the surface of furniture, and away from windows and any prominent VOC emission sources. The distance between the two samplers was larger than 0.3 m, to avoid cross contamination of the samplers, and less than 1.0 m to ensure the measurement in the same area of the bedroom. After a seven-day collection period, the samplers were returned and analyzed after solvent desorption in the laboratory under ISO 17025 [51] accreditation scheme (Advanced Chemical Sensors Co. Ltd, Florida, US). The VOCs were analyzed by gas chromatography (GC) with a mass selective (MS) detector for identification and quantification. Detected VOCs are summarized in Table S5. TVOC was identified as the total amount of compounds detected in the VOCs passive sampler, and the concentration was quantified as toluene equivalent. Formaldehyde was analyzed by high performance liquid chromatography (HPLC) with UV detection.

Fungi investigation was performed during the heating season, between September 2015 and March 2016. 169 dwellings received an Electrostatic Dust Collector (EDC) [52] with the instructions to install it in their main bedroom between 1.2 and 1.6 m above the floor. This passive dust collector was previously validated for its efficiency to trap the overall fungal diversity present in aerosols [53], for the duration being installed in the indoor environment. 164 homeowners returned the EDC after 12 weeks of sample exposure. Fungal particles and spores were collected from EDC by washing with a 0.1% Tween 80 solution. 100 μL of the harvested liquid were spread on plates with dichloran-glycerol culture medium and then placed in an incubator at 25 °C. After five days, the total number of CFUs was counted.

2.4. Data processing and statistical analysis

Effective response rates of most items in the returned questionnaires were higher than 70%. We excluded blank and ‘I do not know’ responses for the purpose of data analysis. To normalize the energy consumption data of each dwelling, we divided the individual electricity, gas and fuel oil consumption data by the reported total floor area of each dwelling.

The statistical analyses were performed using SPSS 21 software and customized coding in MATLAB R2014 software. For comparison between the M and R dwellings from categorical variables, e.g. building characteristics, occupant behavior, self-reported symptoms and satisfaction, the chi-square test was applied. On the other hand, we performed the non-parametric Wilcoxon Mann-Whitney U test for comparison between the two types of dwellings from continuous variables – energy consumption and concentrations of indoor air pollutants.

3. Results and discussion

3.1. Building characteristics

The analysis of the survey responses revealed that most of the M dwellings were newly constructed, after 2000. In contrast, almost all the surveyed R dwellings were built in the last century, indicating that dwellings involved in the national building energy renovation project were predominantly old ones. Table 1 summarizes the key building characteristic features of the two types of dwellings.

As seen in Table 1, larger proportion of M dwellings had no basement nor floor with the natural ground beneath compared to R dwellings, which has implications for radon exposure (see section 3.4). Regardless of dwelling types, about 80% of the surveyed buildings were not equipped with crawl space. The proportion of attached garages was similar in the two types of dwellings, less than 50%. Another characteristic of M dwellings was the larger proportion of modern furniture, which is likely attributed to younger occupants in this building type, as shown in Fig. S2.

A unique feature of M dwellings was the installation of mechanical ventilation system in 98% cases, owing to the requirement of Minergie certification scheme for mechanical ventilation system [6]. In contrary, only 4% of R dwellings were mechanically ventilated. Unlike R dwellings, many M dwellings had Canadian well, which takes the advantage of ground heating and cooling [54].

3.2. Energy type and consumption

Fig. 1a presents the comparison between the two building types in terms of primary energy use for space heating. Space heating of M dwellings was mainly supplied from renewable and low-carbon sources: heat pump (accounting for 30% of total energy used for heating), followed by geothermal (20%), wood pellet (18%) and solar thermal (10%). Conversely, over 40% of R dwellings mainly utilized heating oil for space heating. Application of renewable energy sources for space heating in R dwellings was less than 50%, while its proportion in M dwellings exceeded 90%. Additionally, among 58% of both M and R dwellings which owned the backup heating system, M dwellings were equipped with wood stoves mainly, while the predominant backup heating type in R buildings was wooden fireplace, as shown in Table S1.

The difference in the secondary source of energy type (if available) between M and R dwellings was also significant, as shown in Fig. 1b. Energy supplied by solar thermal technology in M dwellings is the main secondary source (>50%), which is certainly for domestic hot water, followed by wood and electricity. The R dwellings consumed wood predominantly, followed by solar thermal energy and electricity. In summary, demands for space and water heating in Minergie-certified

Table 1
Comparison of surveyed building characteristics in Minergie (M) and energy-renovated (R) dwellings.

Characteristic	Description	M No. (%)	R No. (%)
Newly built (After 2000) ***	Yes	171 (84)	1 (0)
	No	31 (16)	413 (100)
Basement type[a],***	Completely excavated	58 (29)	126 (30)
	Semi-excavated	35 (17)	82 (20)
	Back-grounded	58 (29)	156 (38)
	No basement	48 (24)	47 (11)
Natural ground[a],***	Yes	60 (30)	204 (52)
	No	137 (70)	192 (48)
Crawl space[a]	Yes	30 (19)	77 (23)
	No	126 (81)	256 (77)
Attached garage[a]	Yes	82 (43)	169 (42)
	No	107 (57)	236 (58)
Mechanical ventilation[a],***	Yes	195 (98)	14 (4)
	No	4 (2)	376 (91)
Canadian well[a],***	Yes	62 (34)	6 (2)
	No	123 (66)	341 (98)
Furniture type[a],***	Ancient	4 (2)	33 (8)
	Modern	111 (56)	88 (22)
	Mixed	83 (42)	288 (70)

***$p < 0.001$.
[a] Responses with ‘I do not know’ or not given were excluded.

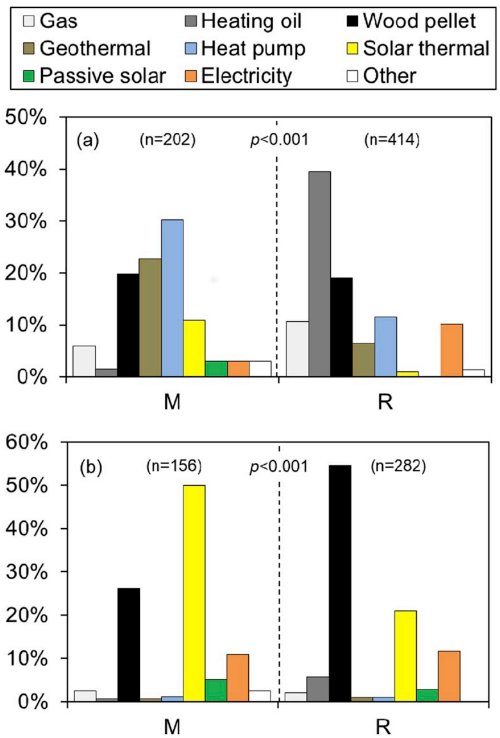

Fig. 1. Comparison of (a) primary and (b) secondary energy type in Minergie (M) and energy-renovated (R) dwellings (total sample 616 dwellings).

dwellings were typically offset by renewable or low-carbon energy sources, thus minimizing their environmental impact, whereas R dwellings relied on combination of clean energy sources and fossil fuels.

In spite of the difference in sources of energy utilized in the two types of dwellings, the disparity in distribution of annual electricity consumption per floor area was not significant ($p > 0.05$), as shown in Fig. 2. The median values of annual electricity consumption in the two types of dwellings were approximately the same, about 33 kWh/m^2, though the mean value of M buildings was lower than that of R ones (37 vs. 45 kWh/m^2). The similarity in electrical energy consumption does not mean that R dwellings are as environmentally friendly as M dwellings, because R dwellings rely heavily on fossil fuels (Fig. 1). The results suggest that electricity consumption should not be the only parameter for evaluation of energetic performance of dwellings, but also the energy source structure. The electricity consumption data in this study are in line with those recorded in Germany and Austria, but substantially

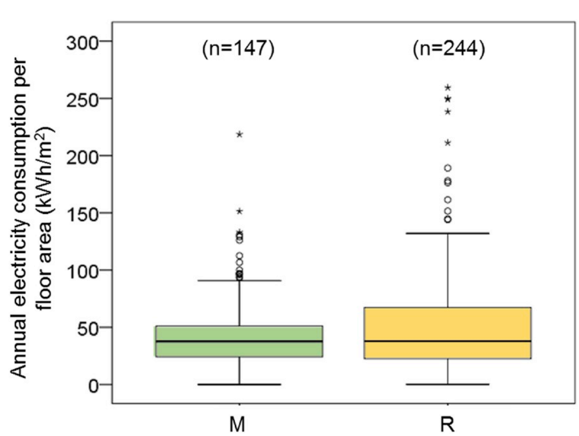

Fig. 2. Comparison of annual electricity consumption per floor area between Minergie-certified (M) and energy-renovated (R) dwellings ($p > 0.05$). Box plots indicate minimum, 1st quartile, median, 3rd quartile and maximum values.

below another Swiss neighbor, France, and many other European countries [55]. However, a long road remains for Swiss energy-efficient dwellings to achieve the established targets for "Passivhaus" Standard for high energy performance housing, with end-use electric consumption less than 18 kWh/m^2 [56].

3.3. Occupants' lifestyle and behavior

Other than the significant difference in age distribution (Fig. S2), occupants living in M and R dwellings had multiple aspects of their lifestyle in common, as summarized in Table 2. Almost half of them owned pets, and about 60% used insecticides indoors. Smoking habits only existed in less than 10% dwellings, while about 90% of them had indoor plants. The habit of collecting rocks, relevant to radon exposure, was also rare in occupants as it was reported in about 12% samples. The proportion of occupants using indoor fragrances was relatively low in both dwelling types, and significantly larger in R dwellings than in M ones.

Significant disparities in frequency of opening windows in different seasons were observed between M and R dwellings, as shown in Fig. 3. Occupants in R dwellings tended to open window for ventilation on a much more frequent basis than those in M dwellings across all seasons. Expectedly, the frequency of window opening in both two types of buildings varied seasonally: highest in summer, followed by similar behavior in spring and autumn, and lowest in winter. In summer, over 90% of occupants in R dwellings opened windows for ventilation every day, while less than 60% of respondents of M dwellings opened windows on a daily basis, and 30% of them reported 'sometimes'. In spring and autumn, only about 20% of occupants in M dwellings opened window every day, while the proportion of everyday window-opening habits remained at over 80% in R buildings. Even in winter, 75% of occupants in R dwellings tended to open windows every day, whereas half of occupants in M dwellings never opened windows and only 10% of them reported everyday opening. The significant difference in window-opening behavior between the two types of buildings can be attributed to the difference in the ventilation strategy used. Occupants of M dwellings tended not to open windows for ventilation since they relied on the mechanical ventilation. Despite the lack of mechanical systems, occupants of R dwellings were mostly aware of the importance of natural ventilation for comfortable indoor environment.

Fig. 4 shows the frequency comparisons of using backup heating in different seasons between occupants in M and R dwellings. Occupants of both types of dwellings used backup heating more frequently in winter (on average ~30% reported daily) than in spring and autumn (below 10% reported daily). Frequency of backup heating was significantly higher in R compared to M dwellings. The reduced need for backup heating in M dwellings may indicate that the main energy system is able to provide and maintain comfortable indoor thermal environment. We must note that the difference may be also attributed to higher number of

Table 2
Comparison of occupants' lifestyle in the two types of surveyed dwellings.

Lifestyle	Description	M No. (%)	R No. (%)
Pets ownership	Yes	88 (44)	178 (43)
	No	114 (56)	236 (57)
Indoor smoking[a]	Yes	7 (3)	35 (9)
	No	193 (97)	373 (91)
Indoor plants[a]	Yes	184 (92)	364 (88)
	No	17 (8)	48 (12)
Indoor fragrances[a,*]	Yes	69 (35)	189 (46)
	No	127 (65)	218 (54)
Indoor Insecticides[a]	Yes	118 (61)	234 (57)
	No	76 (39)	176 (43)
Rock collection[a]	Yes	23 (11)	54 (13)
	No	179 (89)	355 (87)

*$p < 0.05$.
[a] Responses with 'I do not know' or not given were excluded.

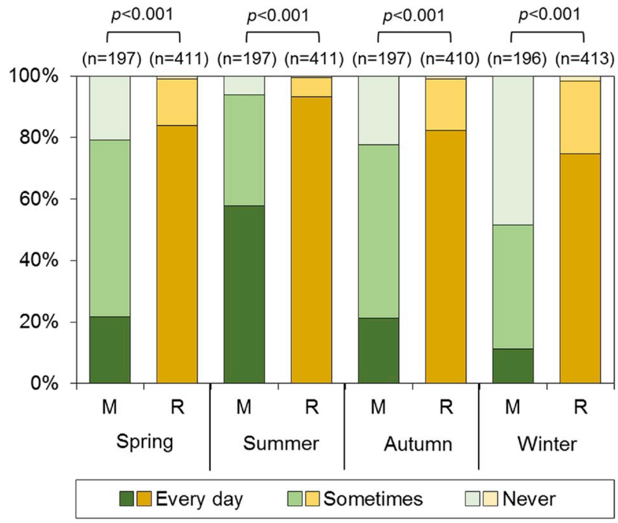

Fig. 3. Comparison of window-opening frequency across four seasons in Minergie-certified (M) and energy-renovated (R) dwellings.

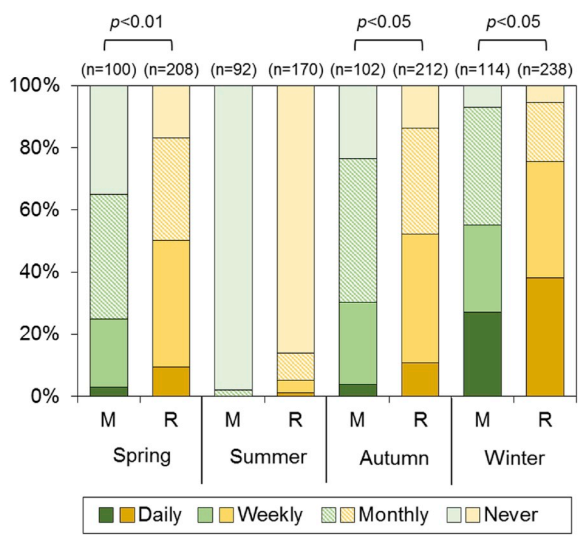

Fig. 4. Seasonal comparison of backup heating frequency between the Minergie-certified (M) and energy-renovated (R) dwellings.

elderlies in R dwellings, who generally prefer warmer environments [57].

3.4. Indoor air quality

Fig. 5a shows that the radon concentrations in M dwellings were significantly lower than in R ones, of which the median values were 48 and 91 Bq/m^3, respectively. Compared with the maximum guideline exposure value of 300 Bq/m^3 recommended by World Health Organization (WHO) [58] and Swiss Federal Office of Public Health (FOPH) [59], the median values were both below the reference value. However, the concentration of radon in 14% of R dwellings by far exceeded the reference value, while only 3% of M buildings exceeded the reference value. Fig. 5b indicates significantly less fungal CFUs in the settled dust of M dwellings than in that of R ones (33 vs. 48 CFUs). As the relationship between dampness, microbial exposure and health effects cannot be quantified precisely, no quantitative, health-based guideline values or thresholds was recommended by WHO for acceptable levels of contamination by microorganisms. As for TVOC and formaldehyde, lower concentrations were recorded in M dwellings as well, as illustrated in Fig. 5c and d. The median TVOC concentrations in M and R dwellings (167 and 259 μg/m^3, respectively) were below the 1000 μg/m^3 recommendation value proposed by the FOPH [60]. The TVOC limit value was exceeded in ~6% of M dwellings and 10% of R dwellings, peaking at 2300 μg/m^3 and 2200 μg/m^3, respectively. The median formaldehyde concentrations were far lower in every dwelling than the FOPH recommended value of 125 μg/m^3 [60], averaging at 12 and 15 μg/m^3 for M and R dwellings, respectively.

Majority of M and R dwellings had low concentration of sampled air pollutants. However, all the pollutants tested accumulated more in R than in M buildings. This difference may be explained by the installation of a mechanical ventilation system that enables continuous air exchange to eliminate indoor air pollutants in M but not in R buildings. The radon penetration in R buildings was favored by the geographic distribution through radon risk areas and the large proportion of natural ground basement in those buildings by comparison of M ones (the relative presence of R vs M dwellings in high radon-risk areas is shown in Fig. S3) [61].

3.5. Occupants' satisfaction and self-reported symptoms

As shown in Fig. 6, the proportion of occupants' complaints with various aspects of indoor environment in both M and R dwellings were relatively low, averaging below 20% in most dwellings. The main sources of complains were general air quality, especially during the winter season (42% of respondents) and less during the summer season (15%). Seasonal differences also affected air temperature perceptions. Specifically, occupants in both types of dwellings felt less uncomfortable about indoor temperature in winter than in summer, though the ratios of uncomfortable votes were both relatively low in the two seasons. While the difference between M and R dwellings was on a low end, more complaints about draft sensations were collected in R dwellings ($p <$ 0.01 and 0.001 for summer and winter respectively). Occupants' ratings on unpleasant odor, sound and natural light were independent from seasons and dwelling types, with relatively small proportion of complaints. The p-values of the chi-square test for comparisons in occupants' satisfactions between M and R dwellings can be seen in Table S3.

When being asked to express their overall feelings about indoor environment, occupants never voted 'uncomfortable' (see Table S2). Interestingly, a larger proportion of occupants in M dwellings tended to vote 'very comfortable' than that in R ones (85% vs. 67%, $p < 0.001$), suggesting more positive responses from occupants in green-certified dwellings [62]. In addition, 11% of occupants in M dwellings and 19% of those in R ones reported mold smell (see Table S2 for details). The difference in locations of mold smell between the M and R dwellings was significant ($p < 0.001$) all mold smell reports were in secondary rooms (technical room, cellar, etc.) in M dwellings, while 1/3 of the reports were in the living space of R houses.

Rates of occupants' self-reported symptoms were similar in M and R dwellings, as illustrated in Fig. 7 (p-values can be seen in Table S4). Stuffy nose, runny nose and sneezing were the three symptoms with the highest reporting rate, as high as 70%. They were followed by headache, dry skin, fatigue and dry throat symptoms with 40–50% reporting. On the other hand, only around 20% of occupants reported the symptoms of dry eyes or eye irritation. Proportions of self-reported respiratory difficulties, dizziness and feeling weak were even lower, about 10–15%. Further research efforts are required on the symptoms with high reporting rate to discover the possible root causes.

3.6. Implications and limitations of this study

Similarity in normalized annual electricity consumption and occupants' satisfaction between M and R dwellings implies, to some extent, the effectiveness of the national building energy renovation project: energy-renovated old dwellings are comparably energy-efficient as Minergie-labelled ones. However, strong reliance on fossil fuels in R

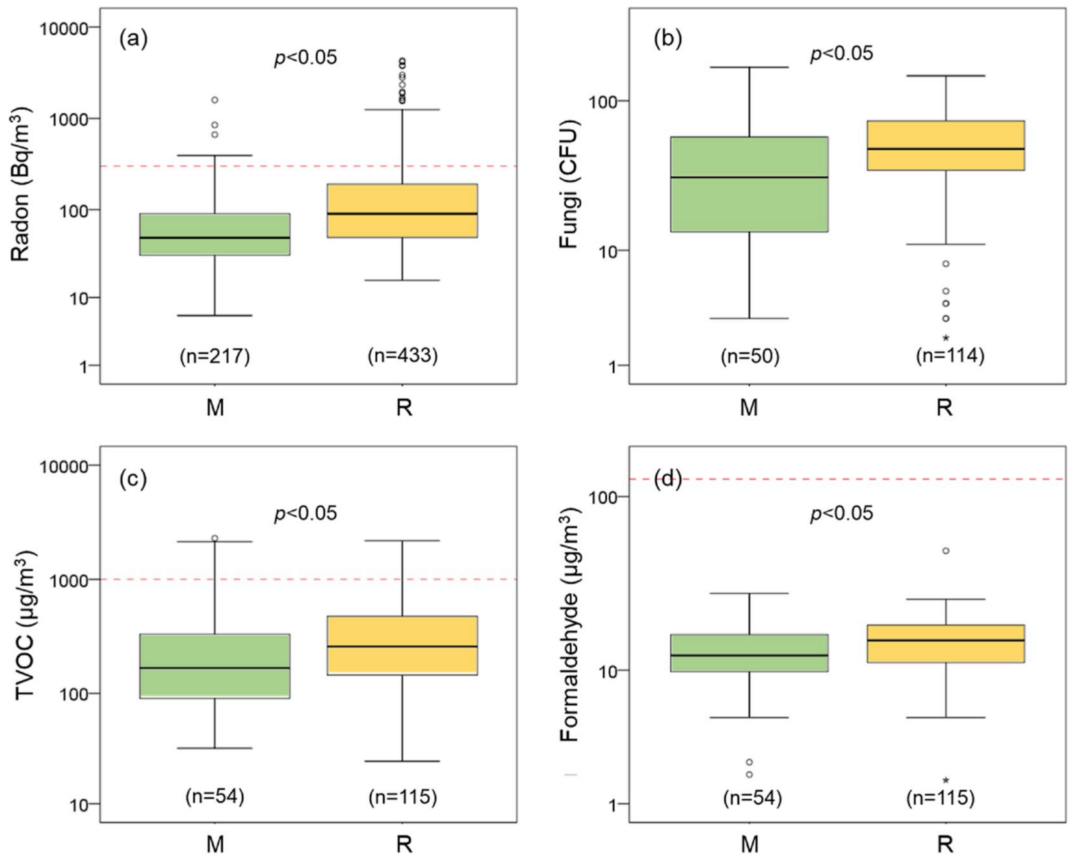

Fig. 5. Comparison of indoor airborne concentrations of (a) radon, (b) fungal CFUs in settled dust, (c) TVOC and (d) formaldehyde between the Minergie-certified (M) and energy-renovated (R) dwellings. The dashed lines represent reference value fixed by WHO and FOPH for radon and upper limit values recommended by FOPH for TVOC and formaldehyde. The concentration of TVOC was quantified in toluene equivalent.

dwellings for space heating is an issue to be faced, which indicates that energy renovation of buildings should focus on not only thermal retrofit, but also upgrade of energy sources to more sustainable solutions.

The high frequency of window opening in naturally ventilated R implies a high consciousness of residents in Switzerland about required space aeration. Though the concentration of sampled air pollutants in R dwellings was higher than that in M ones, the air pollutant levels in majority of dwellings were below the guideline limits. Nonetheless, a concern remains over a subset of more than 10% of R dwellings exceeding the existing upper limits for radon and TVOC. In addition, about 5% of M dwellings failed to meet the upper limits for indoor radon or TVOC, even though they were equipped with mechanical ventilation. This suggests that designers and building practitioners should pay a special attention to source-control and mechanical ventilation in residences located in the high radon-risk zones. Moreover, we found that occupants living in renovated M dwellings were not well aware of the necessity to operate the mechanical ventilation in the houses. Indoor monitoring and further raising awareness of residents about improved ventilation habits may be helpful to decrease the occupants' exposure to such air pollutants.

In interpreting the study results, several limitations should be acknowledged. The energy consumption data were collected via questionnaire survey rather than by direct reading or monitoring by the researchers. Building owners reported their annual energy consumption data in *kWh* based on energy bills which could increase uncertainty in reported energy consumption. In addition, the homeowners reported the total floor area of dwellings rather than heated space, which may cause bias in the interpretation of the area-normalized energy consumption. However, the consistency in median electricity consumption data in this study and in the studies performed in other European countries suggests a sufficient robustness of our dataset. More accurate analysis of energy consumption in Swiss energy-efficient dwellings, and therefore more accurate estimation of carbon footprint, needs to be based on direct energy monitoring [63]. Relative to house ownership, most dwellings involved in the campaign were occupied by the owners, of which the living style and satisfaction may differ from those of tenants. Lastly, the short period of IAQ measurements did not capture seasonal variation of air pollutant levels. Despite the expected lower rate of off-gassing of organic chemicals, higher TVOC concentrations are expected in winter time, owing to lower ventilation rates, particularly in naturally ventilated homes [64]. In this context, the TVOC measurements performed in September in this study could potentially underestimate yearlong occupants' exposures.

4. Conclusions

Within the framework of the first large-scale investigation on indoor air quality (IAQ) in energy-efficient dwellings in western part of Switzerland, we compared Minergie-labelled (M) and energy-renovated (R) dwellings based on building characteristics, energy consumption, occupants' behavior, self-reported symptoms and satisfaction, and measured IAQ. We deployed a combination of questionnaire surveys and field tests of indoor levels of radon, TVOC, formaldehyde and fungi.

The results demonstrate that electrical energy consumption in the two dwelling types was similar, but the sources of energy varied greatly across the two building stocks. The percentage of renewable and clean energy sources in M building by far exceeded the one of R ones. The results indicate the importance of upgrading energy sourcing structure in dwellings in addition to routine thermal retrofitting.

Concentration of sampled air pollutants in the two dwelling types

Fig. 6. Comparison of occupants' satisfactions with (a) air temperature, (b) noise, (c) natural daylight, (d) unpleasant odor, (e) general air quality and (f) draft sensation in different seasons between the Minergie-certified (M) and energy-renovated (R) dwellings. $*p < 0.05$, $**p < 0.01$, $***p < 0.001$.

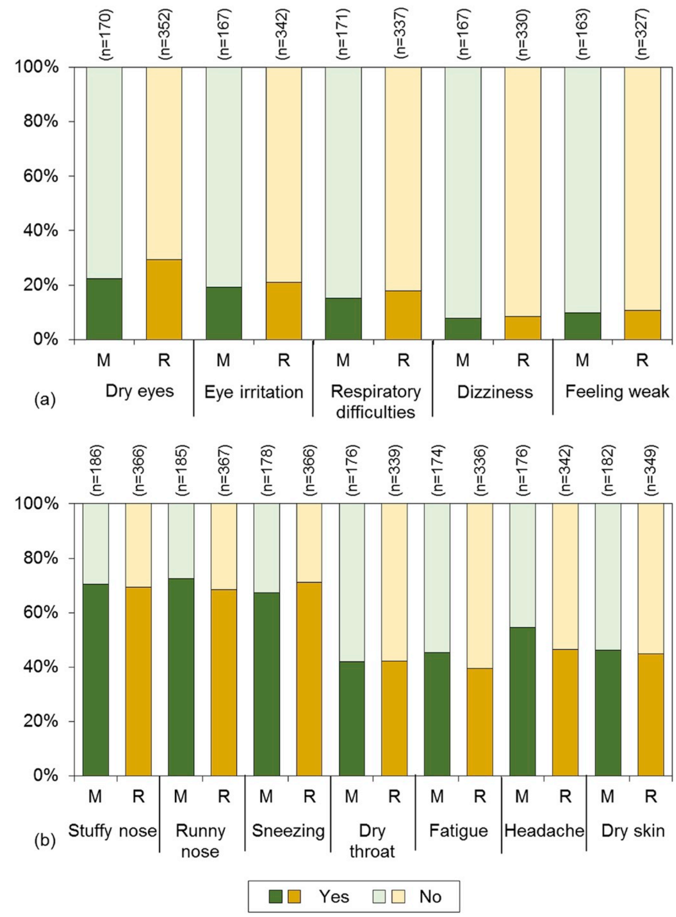

Fig. 7. Occupants' self-reported symptoms in Minergie-certified (M) and energy-renovated (R) dwellings with (a) low reporting rate (<1/3 of total respondents) and (b) high reporting rate (>1/3 of total respondents).

was generally below the recommended upper limit or reference values. Interestingly, mean concentration of all air pollutants was lower in M relative to R dwellings, respectively: radon (48 vs. 91 Bq/m^3), TVOC (167 vs. 259 μg/m^3), formaldehyde (12 vs. 15 μg/m^3) and fungi (33 vs. 48 CFUs). However, between 5 and 10% of dwellings substantially exceeded the permissible radon and TVOC limits.

Ventilation habits of residents in the two dwelling types substantially differed. Occupants in R dwellings opened their windows often, while the occupants in M dwellings rarely opened their windows owing to the fact that more M dwellings than R ones were equipped with mechanical ventilation system. The levels of occupant satisfaction and self-reported symptoms in the two buildings were similar. We also identified a relatively high reporting rate of multiple health symptoms in the two dwelling types, such as stuffy nose, sneezing and runny nose.

In conclusion, the results presented could find utility in designing more efficient dwellings with due attention to indoor air quality and occupant satisfaction. In order to meet the new energy targets, we are expected to undergo more aggressive building energy-efficiency measures. They should be accompanied with stronger reliance on renewable energy sources and improved or at least non-compromised indoor air quality. There recommendations should become the essence of the Swiss building renovation and green-certification strategies.

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.

Acknowledgements

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 15.009001/444.00702/-5, Service de l'Energie du canton de Fribourg, Agence Minergie romande, Losinger Marazzi SA, Suissetec, Fédération fribourgeoise des entrepreneurs, Hälg et Cie SA, Maintenance Mugny et Marguet SA. 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 to the discussions during the project. Maps were prepared by GeoAzimut (www.geoazimut.com).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.buildenv.2019.106618.

References

[1] P. Wilkinson, K.R. Smith, M. Davies, H. Adair, B.G. Armstrong, M. Barrett, et al., Public health benefits of strategies to reduce greenhouse-gas emissions: household energy, The Lancet 374 (9705) (2009) 1917–1929.
[2] L. Pérez-Lombard, J. Ortiz, C. Pout, A review on buildings energy consumption information, Energy Build. 40 (3) (2008) 394–398.
[3] A. GhaffarianHoseini, N.D. Dahlan, U. Berardi, A. GhaffarianHoseini, N. Makaremi, M. GhaffarianHoseini, Sustainable energy performances of green buildings: a review of current theories, implementations and challenges, Renew. Sustain. Energy Rev. 25 (2013) 1–17.
[4] J. Zuo, Z.-Y. Zhao, Green building research–current status and future agenda: a review, Renew. Sustain. Energy Rev. 30 (2014) 271–281.
[5] L. Pérez-Lombard, J. Ortiz, R. González, I.R. Maestre, A review of benchmarking, rating and labelling concepts within the framework of building energy certification schemes, Energy Build. 41 (3) (2009) 272–278.
[6] Minergie Schweiz, 2019. www.minergie.ch. (Accessed 14 June 2019).
[7] International Energy Agency (IEA), Promoting Energy Efficiency Investments: Case Studies in the Residential Sector, International Energy Agency, Paris, France, 2008.
[8] International Energy Agency (IEA), Energy Efficiency Market Report: Market Trends & Medium-Term Prospects, International Energy Agency, Paris, France, 2013.
[9] M. Dowson, A. Poole, D. Harrison, G. Susman, Domestic UK retrofit challenge: barriers, incentives and current performance leading into the Green Deal, Energy Policy 50 (2012) 294–305.
[10] R.K. Dixon, E. McGowan, G. Onysko, R.M. Scheer, US energy conservation and efficiency policies: challenges and opportunities, Energy Policy 38 (11) (2010) 6398–6408.
[11] C.E. Hoicka, P. Parker, J. Andrey, Residential energy efficiency retrofits: how program design affects participation and outcomes, Energy Policy 65 (2014) 594–607.
[12] N. Zhou, M.D. Levine, L. Price, Overview of current energy-efficiency policies in China, Energy Policy 38 (11) (2010) 6439–6452.
[13] Swiss Federal Office of Energy (SFOE), 2019. https://www.bfe.admin.ch/bfe/en/home/policy/energy-strategy-2050/the-first-set-of-measures/measures-for-increasing-energy-efficiency.html. (Accessed 14 June 2019).
[14] Swiss Federal Office of Energy, 2019. https://www.dasgebaeudeprogramm.ch/de/. (Accessed 14 June 2019).
[15] M. Hall, A. Geissler, B. Burger, Two years of experience with a net zero energy balance–analysis of the Swiss MINERGIE-A® standard, Energy Procedia 48 (2014) 1282–1291.
[16] J. Zgraggen, M. Barthassat, P. Haefeli, B. Lachal, B. Schmid, W. Weber (Eds.), Case Study of a Low-Energy (Minergie®) Multifamily Complex in Switzerland. First Appraisal after Two Years of Exploitation. PLEA2006. 23rd Conference on Passive and Low Energy Architecture, Geneva, Switzerland, 2006.
[17] G.R. Newsham, S. Mancini, B.J. Birt, Do LEED-certified buildings save energy? Yes, but…, Energy Build. 41 (2009) 897–905.
[18] U.S. Green Building Council, Leadership in Energy and Environmental Design Green Building Rating System for New Construction and Major Renovations (LEED-NC) Version 4.1, USGBC, Washington, DC, 2013.
[19] G. Newsham, B. Birt, C. Arsenault, L. Thompson, J. Veitch, S. Mancini, et al., Do Green Buildings Outperform Conventional Buildings. Indoor Environment and Energy Performance in North American Offices, 2012.
[20] J.H. Scofield, Do LEED-certified buildings save energy? Not really…, Energy Build. 41 (2009) 1386–1390.
[21] Z.M. Gill, M.J. Tierney, I.M. Pegg, N. Allan, Low-energy dwellings: the contribution of behaviours to actual performance, Build. Res. Inf. 38 (5) (2010) 491–508.
[22] S. Browne, I. Frame, Green buildings need green occupants, Eco-Mgmt. Aud. 6 (2) (1999) 80–85.
[23] R.V. Andersen, J. Toftum, K.K. Andersen, B.W. Olesen, Survey of occupant behaviour and control of indoor environment in Danish dwellings, Energy Build. 41 (1) (2009) 11–16.
[24] D. Zhao, A.P. McCoy, J. Du, P. Agee, Y. Lu, Interaction effects of building technology and resident behavior on energy consumption in residential buildings, Energy Build. 134 (2017) 223–233.
[25] V. Fabi, R.V. Andersen, S. Corgnati, B.W. Olesen, Occupants' window opening behaviour: a literature review of factors influencing occupant behaviour and models, Build. Environ. 58 (2012) 188–198.
[26] A. Roetzel, A. Tsangrassoulis, U. Dietrich, S. Busching, A review of occupant control on natural ventilation, Renew. Sustain. Energy Rev. 14 (3) (2010) 1001–1013.
[27] N.S.M. Azizi, S. Wilkinson, E. Fassman, Strategies for improving energy saving behaviour in commercial buildings in Malaysia, Eng. Construct. Architect. Manag. 22 (1) (2015) 73–90.
[28] D. Steinberg, M. Patchan, C. Schunn, A. Landis, Determining adequate information for green building occupant training materials, J. Green Build. 4 (3) (2009) 143–150.
[29] N.S.M. Azizi, S. Wilkinson, E. Fassman, An analysis of occupants response to thermal discomfort in green and conventional buildings in New Zealand, Energy Build. 104 (2015) 191–198.
[30] N. Mazar, C.-B. Zhong, Do green products make us better people? Psychol. Sci. 21 (4) (2010) 494–498.
[31] J. Ouyang, E. Long, K. Hokao, Rebound effect in Chinese household energy efficiency and solution for mitigating it, Energy 35 (12) (2010) 5269–5276.
[32] H.-H. Liang, C.-P. Chen, R.-L. Hwang, W.-M. Shih, S.-C. Lo, H.-Y. Liao, Satisfaction of occupants toward indoor environment quality of certified green office buildings in Taiwan, Build. Environ. 72 (2014) 232–242.
[33] P. MacNaughton, J. Spengler, J. Vallarino, S. Santanam, U. Satish, J. Allen, Environmental perceptions and health before and after relocation to a green building, Build. Environ. 104 (2016) 138–144.
[34] W.L. Paul, P.A. Taylor, A comparison of occupant comfort and satisfaction between a green building and a conventional building, Build. Environ. 43 (11) (2008) 1858–1870.
[35] S. Altomonte, S. Schiavon, Occupant satisfaction in LEED and non-LEED certified buildings, Build. Environ. 68 (2013) 66–76.
[36] L. Pastore, M. Andersen, Building energy certification versus user satisfaction with the indoor environment: findings from a multi-site post-occupancy evaluation (POE) in Switzerland, Build. Environ. 150 (2019) 60–74.
[37] A. Steinemann, P. Wargocki, B. Rismanchi, Ten questions concerning green buildings and indoor air quality, Build. Environ. 112 (2017) 351–358.
[38] V. Foldvary, G. Beko, S. Langer, K. Arrhenius, D. Petras, Effect of energy renovation on indoor air quality in multifamily residential buildings in Slovakia, Build. Environ. 122 (2017) 363–372.
[39] L. Pampuri, P. Caputo, C. Valsangiacomo, 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. 42 (2018) 100–106.
[40] B. Collignan, E. Le Ponner, C. Mandin, Relationships between indoor radon concentrations, thermal retrofit and dwelling characteristics, J. Environ. Radioact. 165 (2016) 124–130.
[41] S. Yang, P.J. Goyette, J.C. Hager, H.H. Niculita, V. Perret, D. Licina, Radon investigation in 650 energy efficient dwellings in western Switzerland: impact of energy renovation and building characteristics, Atmosphere 10 (12) (2019) 777.
[42] L. Du, V. Leivo, T. Prasauskas, M. Taubel, D. Martuzevicius, U. Haverinen-Shaughnessy, Effects of energy retrofits on Indoor Air Quality in multifamily buildings, Indoor Air 29 (4) (2019) 686–697.
[43] K.C. Coombs, G.L. Chew, C. Schaffer, P.H. Ryan, C. Brokamp, S.A. Grinshpun, et al., Indoor air quality in green-renovated vs. non-green low-income homes of children living in a temperate region of US (Ohio), Sci. Total Environ. 554 (2016) 178–185.
[44] M.D. Colton, P. MacNaughton, J. Vallarino, J. Kane, M. Bennett-Fripp, J. D. Spengler, et al., Indoor air quality in green vs conventional multifamily low-income housing, Environ. Sci. Technol. 48 (14) (2014) 7833–7841.
[45] S. Langer, G. Beko, E. Bloom, A. Widheden, L. Ekberg, Indoor air quality in passive and conventional new houses in Sweden, Build. Environ. 93 (2015) 92–100.
[46] R.A. Sharpe, K. Le Cocq, V. Nikolaou, C. Thornton, Identifying risk factors for exposure to culturable allergenic moulds in energy efficient homes by using highly specific monoclonal antibodies, Environ. Res. 144 (2016) 32–42.
[47] M. Derbez, B. Berthineau, V. Cochet, M. Lethrosne, C. Pignon, J. Riberon, et al., Indoor air quality and comfort in seven newly built, energy-efficient houses in France, Build. Environ. 72 (2014) 173–187.
[48] 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, 2013.
[49] ISO 16017-2, Indoor, Ambient and Workplace Air – Sampling and Analysis of Volatile Organic Compounds by Sorbent Tube/thermal Desorption/capillary Gas Chromatography. Part 2: Diffusive Sampling, International Organization for Standardization, Geneva, Switzerland, 2003.
[50] ISO 16000-4. Indoor Air. Part 4: Determination of Formaldehyde – Diffusive Sampling Method, International Organization for Standardization, Geneva, Switzerland, 2011.
[51] ISO 17025, General Requirements for the Competence of Testing and Calibration Laboratories, International Organization for Standardization, Geneva, Switzerland, 2005.
[52] I. Noss, I.M. Wouters, M. Visser, D. Heederik, P. Thorne, B. Brunekreef, et al., Evaluation of a low-cost electrostatic dust fall collector for indoor air endotoxin exposure assessment, Appl. Environ. Microbiol. 74 (18) (2008) 5621–5627.
[53] M. Frankel, M. Timm, E.W. Hansen, A.M. Madsen, Comparison of sampling methods for the assessment of indoor microbial exposure, Indoor Air 22 (5) (2012) 405–414.
[54] S. Amara, B. Nordell, B. Benyoucef, Using fouggara for heating and cooling buildings in sahara, Energy Procedia 6 (2011) 55–64.
[55] U. Berardi, A cross-country comparison of the building energy consumptions and their trends, Resour. Conserv. Recycl. 123 (2017) 230–241.
[56] S.R. Hastings, Breaking the "heating barrier": leaning from the first houses without conventional heating, Energy Build. 36 (4) (2004) 373–380.
[57] J. Van Hoof, J.L. Hensen, Thermal comfort and older adults, Gerontechnology 4 (4) (2006) 223–228.
[58] WHO Handbook on Indoor Radon: A Public Health Perspective, WHO, Geneva, 2009.
[59] Swiss Federal Office of Public Health, Ordonnance sur la radioprotection, 2017. https://www.admin.ch/opc/fr/official-compilation/2017/4261.pdf. (Accessed 28 August 2019).
[60] Swiss Federal Office of Public Health, 2019. https://www.bag.admin.ch/bag/fr/home/gesund-leben/umwelt-und-gesundheit/wohngifte.html. (Accessed 14 June 2019).
[61] Swiss Federal Office of Public Health, 2019. www.ch-radon.ch. (Accessed 14 June 2019).

[62] A. Leaman, B. Bordass, Are users more tolerant of 'green' buildings? Build. Res. Inf. 35 (6) (2007) 662–673.
[63] S. Cozza, J. Chambers, M.K. Patel, Measuring the Thermal Energy Performance Gap of Labelled Residential Buildings in Switzerland, Energy Policy, 2019, p. 111085. In press.
[64] S. Langer, O. Ramalho, M. Derbez, J. Ribéron, S. Kirchner, C. Mandin, Indoor environmental quality in French dwellings and building characteristics, Atmos. Environ. 128 (2016) 82–91.