RadoNorm
Managing risks from radon and NORM

Deliverable 2.1:

Critical report of spatial and temporal variabilities in relation to protocols for measuring indoor radon concentration

Work Package 2

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The original title of subtask 2.1.1 did not align with the intermediate outputs (i.e., milestones MS 3, 4, 5, and 6), which are not related to methods. Therefore, the title was revised to better reflect the planned activities for this subtask, also considering the milestones.

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Executive Summary

Within the European RadoNorm project, work package 2, which is dedicated to the better characterization of human exposure to ionizing radiation, includes Subtask 2.1.1, entitled “Uncertainty of measurements with passive/active detectors – temporal and spatial variability.”. This subtask is aimed at doing some step forward to characterize uncertainty in radon assessment evaluation, due to spatial and temporal variability affecting indoor radon concentration.

Identifying potential sources of spatial and temporal variability, and, if possible, quantifying such variability, is essential for improving measurement protocols used for radioprotection purposes. This is particularly important for tasks such as exposure assessment or classification of areas with high radon levels. The evaluation of annual radon concentration is, in fact, the foundation for any activity related to protection from radon exposure (for both the public and workers), including the comparison of the annual radon concentration with a reference value of up to 300 Bq/m³ (Directive 2013/59/Euratom).

Measurement protocols applied to predict annual or long-term radon concentration vary widely with respect to the period and duration of exposure and features of the object subject to evaluation, as well as from country to country. Often measurements are made over a few months or only in the basements and they are used to predict annual radon concentrations. In epidemiological studies, 1-year measurement is commonly used as representative of the long-term radon concentration (i.e., average radon concentration over a period of several past years).

Spatial and temporal variabilities should be consciously considered when drafting measurement protocols, which can serve different purposes, in order to reduce uncertainties in radon concentration assessment and achieve a more accurate estimate of annual radon concentration.

There is a large body of scientific literature dedicated to radon variability (both temporal and spatial), and the aspects to be studied regarding spatial and temporal variability are numerous. For this reason, it was agreed to address specific issues within this subtask, aiming to contribute to filling potential gaps in knowledge on particular aspects of spatial and temporal variability. The topics of study were chosen based on general considerations discussed with the collaborators of Subtask 2.1.1. For example, regarding temporal variability, measurements shorter than one year were considered of interest to assess whether they could be representative of the annual radon measurement. Regarding spatial variability, increasing knowledge of variability within and between residential buildings with several apartments was considered useful for the general purpose of identifying buildings with higher radon concentrations, which is essential for identifying situations that need remediation.

The list of issues addressed in this report is outlined in the introduction, with each section is dedicated to a specific issue. In general, the focus is on identifying and quantifying spatial and temporal variability, rather than investigating the sources and causes of such variability.

For each issue, an independent literature review was conducted. However, for all reviews, the approach followed was based on explicit criteria, shared and agreed upon with the subtask collaborators, to ensure a consistent methodology across all experts involved in the review process. The methodology followed to perform the review on the different issues on temporal and spatial variabilities is outlined in milestone MS3.

The literature review revealed that a variety of methods have been used to compare radon concentration measurements in studies of spatial and temporal variability. In some cases, the ratio between measurements was analysed; in others, the absolute difference was considered. Commonly used metrics to assess variability include the coefficient of variation (the ratio between the standard deviation and the arithmetic mean) and the geometric standard deviation (GSD) of radon concentration values.

Moreover, within Subtask 2.1.1, it was expected that partners would collect new data to investigate different aspects of temporal and spatial variability. The informational needs of Subtask 2.1.1 partners varied significantly, depending on the datasets already available in each country and the requirements and measurement protocols outlined in national recommendations and regulations. As a result, it was not possible to plan a new survey with a common protocol in the strict sense. Instead, each partner planned new measurements tailored to their specific national context. However, these new measurements were carried out within a coordinated framework, ensuring that, despite their diversity, the different surveys could still provide valuable insights into spatial and temporal variability. The various contexts in which the measurements were performed represent a strength of the coordinated plan, as this has enriched the diversity of data in relation to the factors potentially affecting radon variability.

The new measurements collected within the RadoNorm project were used for part of the analyses presented in this deliverable. The measurements planned by Subtask 2.1.1 partners were described in milestone MS4. These new measurements were generally performed on a convenience sample of dwellings or workplaces and were intended to supplement existing datasets where they were insufficient to address the relevant variabilities. Both passive detectors and electronic radon monitors (ERM) were used to assess spatial and/or temporal variabilities; ERMs were preferred for evaluating temporal variability, as they are capable of continuously monitoring radon concentrations on an hourly basis (or at similar time intervals).

Additionally, for the purposes of Subtask 2.1.1, new analyses based on data already available to the partners were also conducted.

All datasets used are described in the various sections of this deliverable, generally presented separately for each country. For clarity, the names of the partners contributing to each section are provided.

Regarding the conclusions, for a complete overview, readers are referred to the conclusions presented in the specific sections of the text. Below is a brief summary of the main conclusions drawn from each section, based on the analyses reported therein.

Temporal variability

Year-to-Year Variability: The Finnish analysis observed a mean CV between years of 16%, in good agreement with some previous studies (including Antignani et al. (2021), and Mäkeläinen in Darby et al., 2006). The greater variability obtained in other studies could be linked to shorter measurement durations.

Short-term (few months) variability: The Swiss analysis suggested a limited seasonal effect—likely due to mild winters that reduce heating demand and stack effects, whereas in the analysis performed on the Norwegian dataset, seasonal variability appears to be quite large, leading to high variability in the calculated seasonal correction factors (CV = 56%).

Very short-term (few days) variability: The Finnish analysis concluded that short-term radon measurements are not yet a suitable alternative to current protocols. Moreover, the marked radon fluctuations observed in September (potentially related to climate change) support postponing the start of the measurement season in Finland.

Daily Variability: The Italian analyses (based on measurements in apartments) estimate a radon concentration during day (9:00-19:00) 30% lower than during the night (20:00-8:00). The analyses show no difference in the ratio between working days and holidays, possibly due to widespread remote working in the post-COVID years (2022–2024). Seasonal effects are more prominent, especially in winter, when the IRC day/night ratio is closer to 1 and less variable—likely due to more stable indoor conditions.

Spatial variability

Within-dwelling variability: The Norwegian analyses highlight that the radon concentration, on average, is higher in the homes (detached houses) where the measured rooms are at different floors than when they are at the same floor. Further, the ratio (bedroom/living room) is very close to 1 when the rooms are situated at different floors. When the bedroom and living room are at the same floor, the radon activity concentration in the bedroom is, at average, 85% of the concentration in the living room. Finally, the ratios of measurements taken in the same dwelling at the same floor and at different floors are very much the same.

Within-building variability: Spatial variability within buildings was somewhat elevated, with a median CV of 28–36% observed across Italy and Norway. Differences between apartments on the same floor versus different floors were minimal and not statistically significant. While radon levels were generally higher on lower floors, this pattern did not always hold: 15%–25% of buildings in the Italian datasets showed higher concentrations on upper floors.

The GSD values in the Finnish data were slightly higher (median = 1.5), which may be due to the inclusion of adjacent buildings being part of the same housing cooperative, compared to the Italian data (median = 1.3 for apartments in the same building).

Results underscore that low radon concentrations in one apartment or building do not guarantee similarly low levels in adjacent ones.

Variability in workplaces: Overall, the studies on spatial variability in non-residential buildings show that the spatial variation of radon concentration, especially in large workplace buildings, is very high. The Finnish analysis estimated that even if radon concentrations are generally low across the workplace (GM radon concentration 50 Bq/m³), the probability of finding a radon concentration exceeding the reference level in at least one workspace becomes significant (>20%), if 10 or more measurements are needed at the workplace. Therefore, it is very important to ensure sufficient measurement density within the building's indoor spaces.

Results of the Polish analysis confirm that even in small areas, significant spatial variability of radon concentrations in buildings is observed. In the analysed area, the main factor determining the possibility of radon transport and migration is the geological structure of the bedrock. Even damages to some buildings constructed over post-mining voids could facilitate radon infiltration.

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Introduction

It has been shown that significant spatial and temporal indoor radon variations can occur and represent an important source of uncertainty when estimating annual or long-term radon exposure (e.g., Steck et al., 1992; Fisher et al., 1998; Bossew et al., 2007; WHO, 2009; Barazza et al., 2015; Curguz et al., 2020). Spatial variability can be observed even on a small scale (between rooms in the same dwelling); moreover, exposure time and period of the measurement significantly affect radon exposure estimates due to (diurnal, seasonal, annual, …) fluctuation of radon concentration (temporal variability). Even the assumption that measured annual average radon concentration is constant during several years could not be reliable due to year-to-year variability.

This report aims to provide further insights into specific aspects of spatial and temporal variability affecting indoor radon concentration. The focus was mainly on radon in residential environments, although in some cases information on radon levels in workplaces was also reported.

The specific issues considered are outlined below:

Temporal variability in dwellings and/or workplaces

Year-to-year variability

Few months vs. annual variability & seasonal variability

Very short term (few days) vs. annual variability

Daily variability

Spatial variability in dwellings

- *Within dwelling*

  Room-to-room (same floor)

  Room-to-room (different floors
- *Within buildings*

  Dwelling-to-dwelling (same floor)

  Dwelling-to-dwelling (different floor)

Spatial variability in workplaces

Spatial radon variability in relation to geology

Each topic is addressed in a dedicated section of the report. For clarity, the names of the partners contributing to each section are provided.

For the sake of brevity, the term *radon concentration* sometimes is used throughout the report instead of *radon activity concentration*.

1 Temporal variability

1.1 Year-to-year variability

(Contributors: ISS, STUK)

1.1.1 Background and literature review

(Authored by ISS)

In epidemiological studies, long-term radon exposure—typically defined as the radon exposure of individuals over the past 20–30 years—is generally evaluated using the average radon concentration from a single current one-year measurement. This measurement is assumed to represent the "true" radon exposure of dwelling inhabitants during the last 20–35 years. However, this approach introduces uncertainty, as annual radon measurements are not constant. Aside from observable trends, which may occur due to factors such as changes in building regulations that alter construction methods or the implementation of radon action plans, annual radon levels are subject to random fluctuations. It is crucial to estimate radon variability across years and account for it in analyses conducted in epidemiological studies. Failing to do so may introduce bias in the estimation of radon-related risk.

This section presents the results of a systematic literature review on the year-to-year variability of radon concentration in dwellings.

A comprehensive systematic literature review of published studies on indoor radon yearly variability was conducted and reported in the paper *"A 10-year follow-up study of yearly indoor radon measurements in homes, review of other studies and implications on lung cancer risk estimates"* (Antignani et al., 2021). The details of the review, including keywords, are provided in the mentioned article.

A new search was conducted using the same keywords, limited to articles published in English, and applying the same eligibility criteria: only studies measuring radon concentrations with passive detectors exposed for 2 to 12 months were included, while short-term measurements, studies with fewer than 10 dwellings, and measurements in uninhabited rooms (e.g., cellars) were excluded.

In the new search, an additional database (Scopus) was also used, and the review was updated to cover the most recent period not included in the previous review.

The search was updated as of January 2025.

A total of 234 records were screened. At this stage, the selection was based primarily on the title and, when necessary, on the abstract. In the end, 14 papers were retrieved and carefully evaluated for eligibility. Of these, 12 were deemed suitable for inclusion in the review.

Compared to the review presented in Antignani et al. (2021), no recent papers (published after 2021) were selected for inclusion. However, the total number of selected papers is 12 —three more than in the 2021 review— due to the following reasons:

- The Antignani et al. (2021) review article itself was counted, as it includes results from a study on annual variations.
- A previous Italian study (Bochicchio et al., 2009) on annual variations was included, despite covering a shorter time span. This was considered useful for assessing the potential impact of different time spans on year-over-year variability.
- A study reported in Heid et al. (2004) was included, which had been excluded from the previous review due to its relatively small sample size (11 houses). This study involved basements of laboratories and houses with very high radon levels in Schneeberg, a former uranium mining area. In this review, it has been included for completeness.

The most commonly used parameter to estimate year-to-year variability is the coefficient of variation (CV) of radon measurements (on the original scale) between years, defined as the standard deviation (SD) on the original scale divided by the mean on the original scale. Due to the log-normality assumption, the CV is often derived as:

$$\mathrm{CV}=\sqrt{\exp\left(\sigma^2_{\log(Rn)}\right)-1} \qquad [1]$$

where $\sigma_{\log(Rn)}$is the SD of Rn concentration on the log-scale.

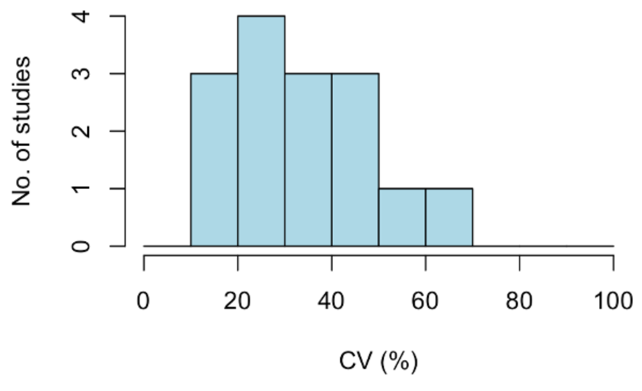
Sometimes, year-to-year variability is estimated using statistical models (e.g., random-effects ANOVA models, as used, for example, in Slezakova et al. (2013), or in Antignani et al. (2021)). These models decompose the total variability of radon concentration measurements, aiming to separate — and estimate — the portion of variability attributable to repeated measurements within the same house across different years.

Most of the CV values reported in the selected studies for this review are collected in a summary table (Table 2) in Antignani et al. (2021). This table also includes a measure of uncertainty (i.e., confidence intervals) for each CV estimate. Moreover, it provides various details about the studies in which yearly radon variability was estimated, such as sample size, dwelling type, number of years with repeated measurements, time span, number of detectors used, duration of measurements per year, and average radon concentration. For these details, please refer to the review paper.

In Table 1, only the CV values extracted from the aforementioned Table 2 in Antignani et al. (2021) are reported, along with the values for the two additional studies that were not included in the table.

The CV was derived using different approaches: in some studies, it represents the median or average value of the CVs calculated for individual houses (e.g., Martz et al., 1991; Zhang et al., 2007; Bochicchio, 2009 et al.; Steck, 2009;). In other cases, it was obtained from a statistical model, such as a linear mixed model (e.g., Heid et al., 2004; Hunter et al., 2005; Lubin et al., 2005; Slezakova et al., 2013; Antignani et al., 2021).

Overall, the Table 1 shows that the year-to-year variability of radon concentration is quite different among studies, with a CV ranging from 14% to 63%, with a median value of 36%, and an arithmetic mean of about 33%. In Figure 1, summary statistics and distribution of the CVs values are shown.



Year-to-Year Coefficient of Variation	
N	15
Min	14%
AM	35%
Q1	23%
Median	36%
Q3	45%
Max	63%

Figure 1: Summary statistics and distribution of the CVs considered in the present review

An additional analysis was performed to explore whether year-to-year variability is related to average radon concentration levels, but no clear correlation was found between the mean Rn concentration and the annual coefficient of variation.

Table 1: Summary of the studies included in the present review

Country	**Reference**	**Geometric mean Rn conc (Bq/m^3) – first measurements**	**Coeff. Of Variation**
Czech Republic	Slezakova et al., 2013	473	**0.36**
Czech Republic	Slezakova et al., 2013	790	**0.46**
Finland	Mäkeläinen, personal communication, in Darby et al., 2006	319	**0.62**
Finland	Mäkeläinen, personal communication, in Darby et al., 2006	196	**0.36**
Italy	Bochicchio et al., 2009	78	**0.14**
Italy	Antignani et al., 2021	84	**0.17**
Sweden	Falk, personal communication, in Darby et al., 2006	178	**0.39**
UK	Lomas and Green, 1994 & Darby et al., 2006	107 [a]	**0.51**[e]
UK	Hunter et al., 2005	94	**0.44**[e]
USA (Grand Junction)	Martz et al. 1991	69 [b]	**0.25**
USA (Upper Midwest)	Steck, 1992	NA	**0.22**
USA (Iowa)	Zhang et al., 2007	176 [c]	**0.15**
USA (Iowa)	Zhang et al., 2007	184 [c]	**0.24**
USA (Minnesota)	Steck, 2009	120	**0.28**
China (Gansu Province)	Lubin et al., 2005	348	**0.43**[e]
Germany	Heid et al., 2004	NA [d]	**0.63**[e]

[a] last measurements; [b] median; [c] arithmetic mean; [d] measurements performed in houses with very high radon levels and also in basements of laboratories;
[e] derived applying formula [1]

1.1.2 Analysis of Finnish data acquired in RadoNorm

(Authored by STUK)

1.1.2.1 Sample selection and measurements

A random selection of 1000 homes were made from the national radon database in April 2021. The selection criteria were:

- All 7 regions of Finland are covered proportional to the size of their population.
- The building year is proportional to the national data (separately for detached, semi-detached and terraced houses, and bocks of flats).
- The building type (detached, semi-detached and terraced houses, and bocks of flats) is proportional to the national data.
- Last radon measurement was carried after January 1st, 2013.
- The radon concentration was between 50–300 Bq/m^3.

The last two criteria were chosen to ensure that the residents might be interested in participating and that there would not be need for radon mitigation during the survey.

The aim was to find about 300 test homes. Initially, 600 invitations were sent (randomly selected from the listing of 1000 homes) to the homeowners. This allowed for a reserve in case the desired number of homes could not be recruited from the first round of invitations. The first invitation was successful, with 277 homes willing to participate.

1.1.2.2 Characterization of the sample set

The 277 homes participating in the study accurately represent the demographic distribution in Finland (Table 2).

Table 2 Proportion of Finnish population in the 7 regions (May 2021) and the proportion of test homes in these regions (AVI= Regional State Administrative Agency).

Region	Population	Random Sample	Participants
N	5.54 milj.	1000	277
Southern Finland AVI	43%	38%	43%
Southwestern Finland AVI	13%	11%	13%
Eastern Finland AVI	9.8%	12%	11%
Western and Inland Finland AVI	22%	25%	23%
Northern Finland AVI	8.8%	7.0%	7.2%
Lapland AVI	3.2%	3.8%	2.9%
State Department of Åland	0.55%	3.1%	0.72%

Radon in the indoor air of flats located on the first floor or higher in a block of flats primarily originates from building materials and outdoor air. These were excluded from the scope of this study. The number of ground-floor apartments in apartment buildings in Finland is not statistically recorded. Therefore, it was assumed that 15% of the apartments are on the ground floor. The construction year of the building is available for different types of dwellings (Table 3).

Table 3: Proportion of Finnish dwellings excluding flats on the first floor or higher by dwelling type and year of construction. Data obtained from Statistics Finland and assuming that 15% of flats are on the ground floor.

Construction year	Detached and semi-detached houses	Terraced house	Ground floor flats
–1920	3.1%	0.2%	0.2%
1921–1939	3.2%	0.1%	0.5%
1940–1959	12%	0.3%	1.0%
1960–1969	6.1%	0.9%	1.9%
1970–1979	8.8%	4.7%	2.7%
1980–1989	11%	7.8%	1.4%
1990–1999	7.3%	4.1%	1.3%
2000–2009	8.1%	2.8%	1.1%
2010–	5.4%	2.0%	1.6%
Total	65%	23%	12%

The random selection of 1000 dwellings was successful in terms of dwelling type and year of construction (Table 4). However, detached houses and semi-detached houses were somewhat overrepresented among the survey participants, accounting for 77% of the total (N=277). Gro1und-floor apartments in apartment buildings were underrepresented compared to their proportion in Finnish housing.

Table 4: Proportion of dwellings by type and year of construction in the survey. The first figure represents the randomly selected 1000 dwellings, and the figure in brackets the number of survey participants (N=277).

Construction year	Detached and semi-detached houses	Terraced house	Ground floor apartments in blocks of flats
–1920	3.2% (3.6%)	0.0% (0.0%)	0.0% (0.0%)
1921–1939	3.1% (3.6%)	0.0% (0.0%)	0.4% (0.0%)
1940–1959	13% (12%)	0.4% (1.4%)	0.5% (0.0%)
1960–1969	5.6% (5.8%)	0.7% (0.0%)	1.2% (0.07%)
1970–1979	9.3% (9.7%)	4.7% (5.1%)	3.0% (1.1%)
1980–1989	12% (17%)	8.0% (6.9%)	1.2% (0.7%)
1990–1999	7.3% (9.4%)	4.2% (2.9%)	1.3% (0.0%)
2000–2009	8.4% (10%)	2.7% (2.2%)	0.8% (0.07%)
2010–	5.6% (6.5%)	2.0% (0.7%)	1.6% (0.4%)
Total	67% (77%)	23% (19%)	10% (3.6%)

Residents sometimes have surprisingly poor knowledge about the type of ventilation or foundations of their residential buildings. In these cases, residents hopefully choose “I don’t know” or leave that section of the form blank, although there has been clear evidence that some residents select an incorrect option (Table 5).

Unfortunately, Finland does not have statistics on the types of ventilation systems or foundations in dwellings. However, data from the national radon database indicate that until the 1970s, over 90% of homes had passive ventilation. Mechanical exhaust ventilation began to become more common, and by the 1990s, about 45% of homes were ventilated using mechanical exhaust ventilation. Along with mechanical exhaust ventilation, mechanical supply and exhaust ventilation (also known as balanced ventilation) also became more common. Almost all homes built after 2005 have mechanical supply and exhaust ventilation. There are few on-demand ventilation systems (which intensify ventilation based on occupancy and water usage) in homes built after 2020, and they were likely not included in this study.

Until 1960, the majority of detached and semidetached houses had either basement foundations or were hillside houses. At that time, slab-on-ground foundations began to become more common. Due to their affordability and simplicity, nowadays more than half of buildings use this type of foundation. About one in ten (semi)detached houses have crawl space foundations, about one in five are hillside houses, and the rest have either edge-reinforced slab foundations or basements.

It is a well-known fact that slab-on-ground foundations pose the greatest radon risk to buildings, especially if the foundation wall is made of lightweight aggregate concrete blocks and the house is built on a slope. Perhaps for this reason, there were a significant number of slab-on-ground foundations among the participants. The three main methods of handling residential ventilation were approximately equally represented.

Table 5: Ventilation and foundation type in the dwellings among the survey participants.

Ventilation method		**Foundation type**	
Passive	39%	Slab-on-grade	83%
Mechanical exhaust	25%	Unknown or no answer	11%
Mechanical supply and exhaust (balanced)	31%	Crawl space	3%
Unknown or no answer	5%	Edge-reinforced	1%
		Combination	1%
		Other	1%

The arithmetic mean radon concentration from previous measurements was 128 Bq/m³, with a significant proportion (76%) falling within the range of 100–200 Bq/m³. The mean radon concentration in (semi)detached and terraced houses in Finland is 121 Bq/m³ (Mäkeläinen et al., 2009). Considering the low participation rate of people living in flats, the dwellings in this survey are representative of the typical housing stock.

1.1.2.3 Measurements and related uncertainties

One track-etch detector was dispatched to each dwelling in June 2021, and the measurement lasted for 1 year. The detector is an in-house model based on Makrofol film and electro-chemical etching. The method is accredited by the national accreditation body, FINAS. It is suitable for long radon measurements, with no correction needed for fading of latent tracks (Turtiainen et al., 2024).

In the following years (2021–2024), new track-etch detectors were sent in June, along with a return envelope for the old detector. At the time of writing (April 2025), three subsequent years have been measured, and the final year has commenced.

Before the third year of measurement, participants were asked if they would be interested in performing continuous measurements in their homes over a year to study short-term (day, week, month, season) variations in radon levels. The response was enthusiastic, and all 60 continuous radon monitors allocated to the study were sent to homes. The instruments used were RadonEye Plus2 radon monitors, which were individually calibrated at STUK's radon standard laboratory. RadonEye has a good detection efficiency and a very short response time. It is therefore ideally suited for the study of the temporal variation of radon concentration (Turtiainen et al., 2021, Dimitrova et al., 2024). These results have been published in a separate article (Turtiainen et al., 2025).

There are several components of uncertainty relating to the measurement results of the track-etch detector. These include uncertainties in the number of gross tracks, background tracks on the fresh film, background tracks due to mailing, and due to non-uniformity of the film material. Additionally, there are uncertainties due to variations in detector housing dimensions, etching solutions and conditions, the fitting of the calibration function, and the accuracy of the radon reference instrument used for calibration.

When comparing results obtained with the same measurement method, it is possible to remove from the uncertainty budget those components that remain the same for all measurements. Thus, in the case of a track-etch detector, the uncertainty of the reference instrument used for calibration don't need to be considered. The measurement uncertainties associated with the method for 365 days of measurement are shown in Table 6.

When comparing variations in radon concentrations between years, these measurement uncertainties must be taken into account so that they are not mistaken for year-to-year variations in concentration.

Table 6: Measurement uncertainties of the STUK track-etch detector for 365 days sampling at different radon levels.

Mean radon concentration, C, (Bq/m^3)	**relative uncertainty $u_{rel}(C)$ for k=1, incl. uncertainty of the reference instrument**	**relative uncertainty $u_{rel}(C)$ for k=1, without uncertainty of the reference instrument**
10	10.1 %	9.5 %
20	7.5 %	6.8 %
50	6.4 %	5.5 %
100	6.1 %	5.2 %
400	5.9 %	5.0 %
1000	5.9 %	5.0 %

It is unlikely that all participants will be able to stop and start measuring for exactly one year. Therefore, all results were adjusted to represent exactly one year of measurement. In other words, the impact of missing or excessive measurement days during the summer months on the annual average was minimized.

1.1.2.4 Data analysis

Only the first three years of data were available as of April 2025. The data was filtered according to criteria:

- The duration of each consecutive 1-year measurement was 1 year±30 days
- All subsequent measurements had been reported to be carried out in the same room
- No radon mitigation/remediation was reported but normal renovations, such as new flooring or installing new doors was allowed

If the measurement period deviated from the 365-day (366 days during the leap year) period by ±30 days, the measurement result was corrected to account for the lower radon concentration likely to occur in the summer months. The annual mean radon concentration C_{AM} was estimated according to the Equation 1:

$$C_{AM} = \frac{t\cdot C}{365-0.60\cdot(365-t)} \tag{1}$$

in which t is the actual measurement time and C being the average radon concentration during the measurement time. With this method, a measurement that is ±30 days too short or too long will result in a ±3% correction to the result.

1.1.2.5 Results

202 dwellings fulfilled the criteria and were included in the analysis. Three consecutive years of measurement was not sufficient to investigate the distribution of annual average radon concentrations. As reported by Antignani et al. (2021), it is generally considered to follow log-normal distribution.

Geometric coefficients of variation were calculated for each dwelling according to equation 1. The arithmetic mean (AM), geometric mean (GM) and median of geometric CVs were 15.7%, 10.4% and 10.7%, respectively. The AM, GM and median of dwelling-specific geometric standard deviations (GSDs) were 1.18, 1.16 and 1.11, respectively.

The probability distribution of geometric CVs was strongly right-skewed—the 5th percentile value was 2.9% and the 95th 39.2% (Figure 2). There was a non-significant small correlation between the three-year mean radon concentration and geometric CV (r_S =–0.1043, p=0.1395).

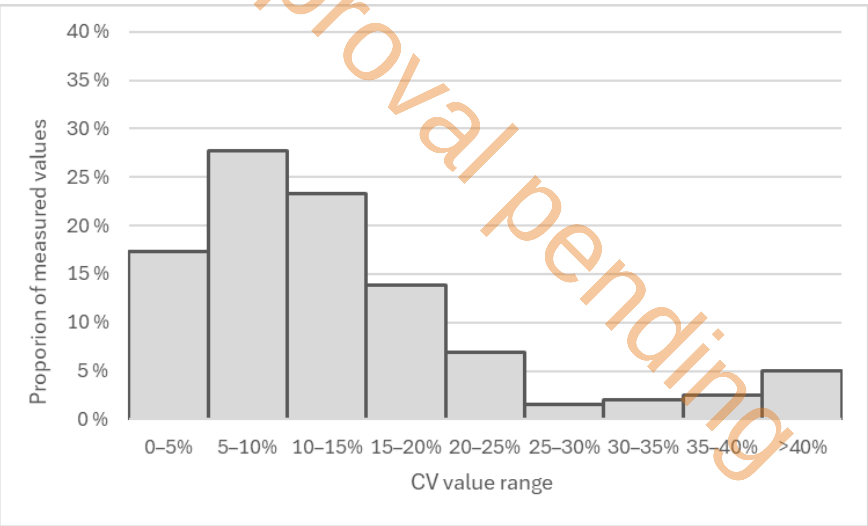


Figure 2: Histogram of the geometric CV of annual average radon concentration in 202 homes measured in three consecutive years.

However, if we assume normal distribution of annual average radon concentrations in a dwelling, we can calculate AM, SD and the CV for each of the 202 homes, accordingly. The probability distribution of dwelling-specific CVs is also strongly right-skewed, with AM, GM and median values being 15.1%, 10.3% and 10.9%. It is noteworthy that similar values are obtained for both geometric CV and CV.

Using 95% confidence interval, no differences in the geometric mean radon concentrations between the years could be observed (Figure 3).

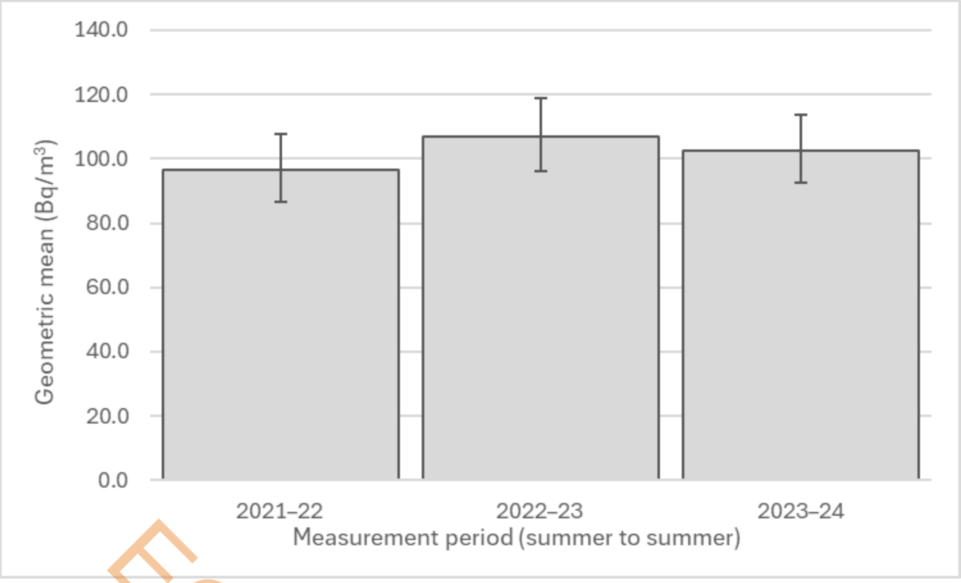


Figure 3: Geometric mean radon concentrations in the homes (N=202) and the 95% confidence interval.

1.1.3 Discussion on year-to-year variability

(Authored by STUK)

The observed CV in annual average radon concentrations have an excellent agreement with the studies by Bochicchio *et al.*, 2009 and Antignani *et al.*, 2021. The mean CV between years observed in this study (15.7%) were also similar to the *variances on logarithmic scale* (probably the same as geometric CVs in this study) in Finnish homes reported by Mäkeläinen (Darby *et al.*, 2006), which were 33% and 12%, the first being obtained from mostly 2-month measurement data (N=301) during winter and the latter being mostly 1-year measurements with some 2-month measurements included (N=80). The larger variance in the first figure is mostly due to the short measurement duration.

1.1.4 References

Antignani, S., Venoso, G., Ampollini, M., Caprio, M., Carpentieri, C., Di Carlo, C., ... & Bochicchio, F. (2021). A 10-year follow-up study of yearly indoor radon measurements in homes, review of other studies and implications on lung cancer risk estimates. *Science of the Total Environment*, *762*, 144150.

Bochicchio, F., Ampollini, M., Antignani, S., Bruni, B., Quarto, M., & Venoso, G. (2009). Results of the first 5 years of a study on year-to-year variations of radon concentration in Italian dwellings. *Radiation measurements*, *44*(9-10), 1064-1068

Darby, S., Hill, D., Deo, H., Auvinen, A., Barros-Dios, J. M., Baysson, H., ... & Doll, R. (2006). 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. *Scandinavian journal of work, environment & health*, 1-84.

Dimitrova, A., Georgiev, S., Todoro, V., Daraktchieva, Z., Howarth, C.B., Wasikiewicz, J.M., Sabot, B., Mitev, K. (2024). Calibration and Metrological Test of the RadonEye Plus2 Electronic Monitor- Radiation Measurements, 175: 107169. https://doi.org/10.1016/j.radmeas.2024.107169

Heid, I. M., Küchenhoff, H., Miles, J., Kreienbrock, L., & Wichmann, H. E. (2004). Two dimensions of measurement error: classical and Berkson error in residential radon exposure assessment. *Journal of Exposure Science & Environmental Epidemiology*, *14*(5), 365-377.

Hunter, N., Howarth, C. B., Miles, J. C. H., & Muirhead, C. R. (2005). Year-to-year variations in radon levels in a sample of UK houses with the same occupants. In *Radioactivity in the Environment* (Vol. 7, pp. 438-447). Elsevier.

Lomas, P. R., & Green, B. M. R. (1994). Temporal variations of radon levels in dwellings. *Radiation Protection Dosimetry*, *56*(1-4), 323-325.

Lubin, J. H., Wang, Z. Y., Wang, L. D., Boice Jr, J. D., Cui, H. X., Zhang, S. R., ... & Kleinerman, R. A. (2005). Adjusting lung cancer risks for temporal and spatial variations in radon concentration in dwellings in Gansu Province, China. *Radiation research*, *163*(5), 571-579.

Martz, D. E., Rood, A. S., George, J. L., Pearson, M. D., & Lang, G. H. (1991). Year-to-year variations in annual average indoor 222Rn concentrations. *Health Physics*, *61*(3), 409-413.

Mäkeläinen, I.; Kinnunen, T.; Reisbacka, H.; Valmari, T.; Arvela, H. (2009) Radon Suomalaisissa Asunnoissa—Otantatutkimus 2006 (Radon in Finnish Dwellings—Sample Survey 2006; STUK-A242; STUK: Helsinki, Finland; pp. 1–68.

Slezáková, M., Navrátilová Rovenská, K., Tomášek, L., & Holeček, J. (2013). Short-and long-term variability of radon progeny concentration in dwellings in the Czech Republic. *Radiation protection dosimetry*, *153*(3), 334-341.

Steck, D. J. (1992). Spatial and temporal indoor radon variations. *Health Physics*, *62*(4), 351-355.

Steck, D. J. (2009). Annual average indoor radon variations over two decades. *Health Physics*, *96*(1), 37-47.

Turtiainen, T., Kojo, K., Laine, J-P., Holmgren, O. Kurttio, P., (2021). Improving the assessment of occupational exposure to radon in above-ground workplaces. Radiation Protection Dosimetry; 196 (1–2): 44–52.

Turtiainen, T.; Laine, J.-P.; Rantanen, S.; Oinas, T. (2024) Nonlinear Calibration and Temperature Sensitivity of Makrofol Solid-State Nuclear Track Detectors for Radon Measurement. Atmosphere, 15, 1179.

Turtiainen, T.; Kojo, K.; Kurttio, P. (2025). Short-Term Temporal Variability of Radon in Finnish Dwellings and the Use of Temporal Correction Factors. Atmosphere 16(5), 489.

Zhang, Z., Smith, B., Steck, D. J., Guo, Q., & Field, R. W. (2007). Variation in yearly residential radon concentrations in the upper midwest. *Health physics*, *93*(4), 288-297.

1.2 Variability of short-term (few months) vs. annual measurements (including seasonal variability)

(Contributors: HES-SO, GIG, DSA)

1.2.1 Background and literature review

(Authored by HES-SO)

Indoor radon levels exhibit temporal variability influenced by seasonal, diurnal, and weather-related factors. Radon concentrations typically peak in winter due to increased indoor air tightness and reduced ventilation, while levels are lower in summer. Daily fluctuations are driven by temperature gradients, pressure differences, and HVAC usage. Weather events, precipitations and high winds, also impact radon entry from soil. It is therefore essential to investigate the temporal variations in radon levels. This section delves into the differences between short-term (a few months) and annual variability, as well as seasonal variability.

First, Bochicchio et al. (2005) explored seasonal variability using ratios of radon concentrations across different seasons. The study emphasized the heightened radon levels in winter, driven by reduced ventilation and increased indoor activity. Different authors, from different countries and years, highlighted higher indoor radon levels during winter months (Kamgang et al., 2023; Rey et al., 2022; Stanley et al., 2019; Groves-Kirkby et al., 2015; Barazza et al., 2015; Miles et al., 2012; Suzuki et al., 2010; Omori et al., 2009; Bossew & Lettner, 2007). These papers depict a yearly indoor radon cycle.

Based on this observation, seasonal correction factors for indoor radon measurements were developed. Radon levels tend to be higher in colder months due to reduced ventilation from tighter sealing of homes, while warmer months allow for better ventilation, leading to lower concentrations. These fluctuations could result in inaccurate measurements if not adjusted for seasonal differences, potentially affecting health risk assessments and mitigation strategies. Seasonal correction factors ensure more reliable and consistent radon measurements, helping to assess health risks more accurately. Different authors investigated seasonal correction factors and their respective applications (Daraktchieva, 2017; Groves-Kirkby et al., 2015; Kozak et al., 2011; Denman et al., 2007).

These studies collectively underscore the seasonality of indoor radon levels. This raises the issue of benchmarking various official protocols for indoor radon measurement. To obtain the most representative assessment of indoor radon levels, a measurement spanning during a full year is ideal. However, in certain countries, this measurement period is shortened in accordance with specific national regulations. In some countries, the measurement duration has been reduced to three months, as in Switzerland [FOPH website at: https://www.bag.admin.ch/bag/en/home/gesund-leben/umwelt-und-gesundheit/strahlung-radioaktivitaet-schall/radon.html], or two months, as in France [IRSN website at: https://www.irsn.fr/EN/Research/publications-documentation/radon] and Finland [STUK website at: https://www.stuk.fi/web/en/topics/radon], with testing conducted specifically during the heating period (October to March). Conversely, the United Kingdom [UKHSA website at: https://www.ukradon.org/] and Ireland [EPA website at: https://www.epa.ie/environment-and-you/radon/] uses seasonal correction factors to adjust 3-months measurements carried out whenever during the year, ensuring they account for seasonal variations in radon levels.

However, seasonal correction factors derived from specific studies are valid on average but may not reliably apply to individual cases and may result in incorrect estimates of the annual mean. This is demonstrated, for example, in a case study examining the application of seasonal correction factors to indoor radon concentrations in the UK by Gillmore et al. (2005) and in a study performed in North American residential environment (Stanley et al., 2019). Such studies question the usefulness of seasonal correction values. In addition, several studies highlight situations in which atypical, or reverse (even extreme), seasonal variations of indoor radon concentration are observed (e.g., among the most recent, Di Carlo, et al. 2023; Moreno et al., 2016; Sundal et al., 2007; Li et al., 2006; Friedmann, 2005).

This review highlights several key considerations regarding the comparison between short-term measurements (a few months) and annual radon variability, as well as the impact of seasonal fluctuations. First, a clear seasonal dynamic is evident, with higher indoor radon levels typically recorded during winter and lower levels during summer. This seasonal variability is influenced by multiple factors, including climate, building characteristics, and occupant behavior (Rey et al., 2022). Additionally, these influencing factors can vary from year to year. For example, the average temperature in a given location during March can range from 2 to 12°C (fictive numbers), which may result in differing average radon concentrations for the same month across different years. This underscores the complexity of accurately assessing radon levels based on short-term measurements and the need to account for these dynamic factors. Seasonal correction factors were developed to reduce the uncertainty associated with short-term radon measurements by accounting for seasonal variations. However, their application can also introduce certain biases, potentially affecting the accuracy of the corrected results.

1.2.2 Overview of the analyses

To investigate the issue of variability of short-term measurements (a few months) and annual radon measurements, two datasets were used:

- One Polish dataset, with measurements performed in one single-family detached house;
- One Norwegian dataset, with measurements performed in 14 terraced houses and 4 blocks of flats;
- One Swiss dataset, with measurement performed in 20 single-family homes in the framework of a study aimed at evaluating performance of different radon devices.

1.2.3 Analysis of Polish data: an example of monitoring in one family house

(Authored by GIG)

In Poland, measurements were performed in one single family detached 3-levels house. Detectors were placed at each level in following rooms: basement, living room, bedroom.

The duration of observations: one year measurement campaign consisting of one-year continuous measurement, four quarterly and 12 monthly measurements. The detectors were installed in March 2022, and the campaign was finished in March 2023. The measurements were performed using passive detectors RADOSYS type with CR-39 foil. Results are presented in Table 7 below.

Table 7: The results of radon measurements in chosen room of investigated building.

Location	**Min (Bq/m³)**	**Max (Bq/m³)**	**SD (Bq/m³)**	**AM (Bq/m³)**	**MED (Bq/m³)**
One month exposition					
Basement	78	570	143	251	188
Ground floor (living room)	36	163	34	78	66
First floor (bedroom)	24	203	44	78	72
Quarterly exposition					
Basement	225	264	18	239	233
Ground floor (living room)	40	86	21	64	66
First floor (bedroom)	33	64	14	52	55

Results of one-year measurements:

- Basement: 227 ± 51 Bq/m^3
- ground floor: 50 ± 12 Bq/m^3
- first floor: 39 ± 9 Bq/m^3

Figures below show temporal variability for monthly measurements (Figure 4) and comparison of results from annual measurement, quarterly average and monthly average (Figure 5).

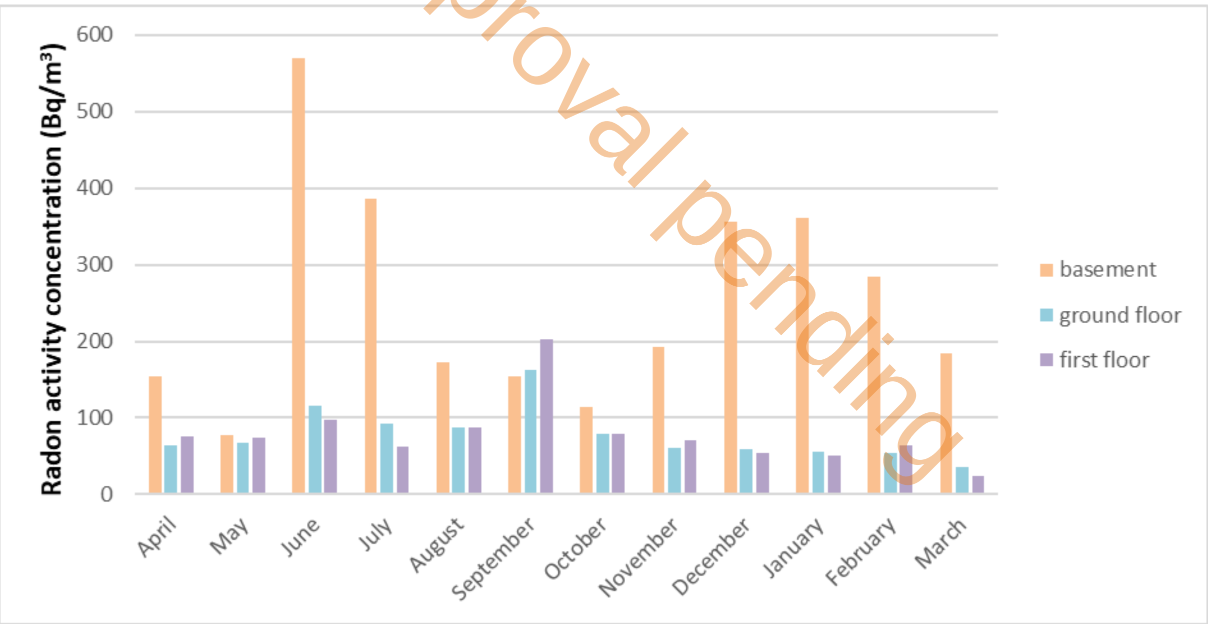


Figure 4: Temporal variability for monthly measurements

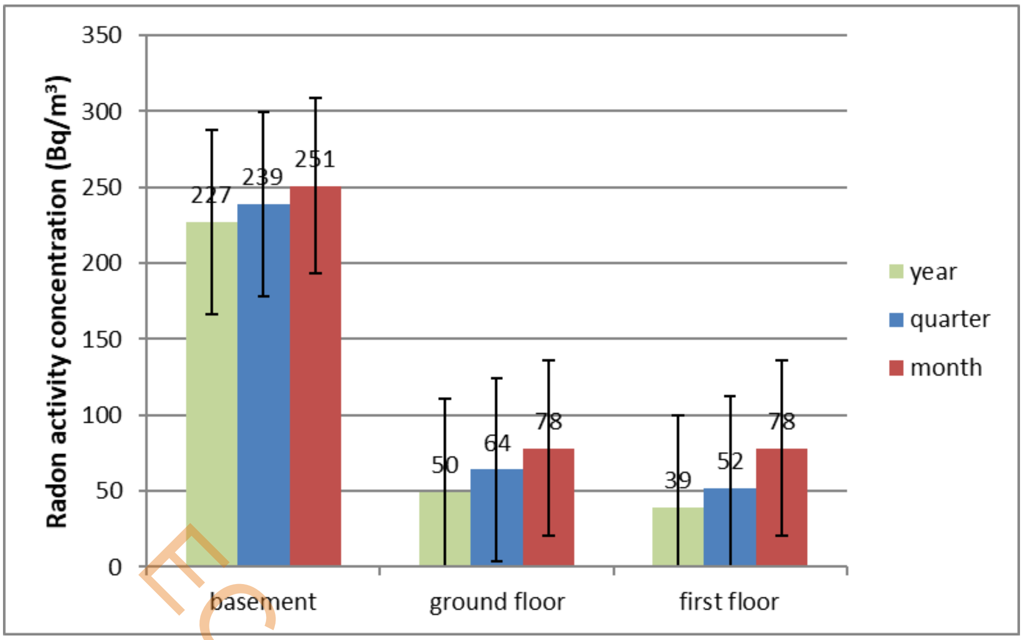


Figure 5: Comparison of results from annual measurement, quarterly average and monthly average

Analysing the results of the measurements, it was noted that the results of the annual measurements, in each of the rooms, are lower than those from the quarterly and monthly measurements.

The analysis of the monthly results, on the other hand, showed that the habits of the residents and their deviations (e.g., closed windows during a long absence in June or intensive ventilation during hot weather, e.g., August and unusually warm October) cause significant deviations from the average value.

We therefore suggest that the measurements to estimate the doses to residents should take much longer than 1 month. On the other hand, in the case of high radon concentrations, an annual measurement may result in an unreliable result (underestimation) due to an overloaded CR39 film. It seems reasonable to carry out measurements on a quarterly basis, especially when it will be the heating season.

1.2.4 Analyses of Norwegian data: Variability of calculated correction factors

(Authored by DSA)

1.2.4.1 Investigating measurements in one 2-month period compared to a 1-year measurement period in block of flats and terraced homes.

In the capital of Oslo 14 terraced houses and 4 blocks of flats were chosen for this study, originally for the investigation of spatial variation (see sections 2.2). However, it was decided to simultaneously conduct a limited pilot study of the seasonal correction factor but limited to only one 2-month measurement compared to a 1-year measurement.

The background for the study, from the perspective of the Norwegian authorities (DSA), was to check whether the correction method is accurate, and possibly equally accurate, for apartments in apartment buildings and in terraced houses.

Since measurements in this study are made over only one 2-month period, the study does not fully answer the research question of how much the choice of months for measurement matters for the assessment of radon activity concentration. However, the study provides an opportunity to study whether there is a large variation between nearby homes with respect to a real correction factor (1-year measurement divided by 2-month measurement), and further whether building type, floor and room type is important. Further, some homeowners started the measurements as soon as they received the detectors, while others for unknown reasons started two weeks later (the deadline given by DSA), giving the opportunity to study whether a two-weeks shift in the start and stop of the measurement influence the correction factor.

To determine the annual average of radon activity concentration in Norwegian homes, the authorities recommend that measurements be taken for at least two months during the heating season (mid-October to mid-April, https://www.dsa.no/en/radon/radon-measurements-in-residential-dwellings). To convert two-month measurements to an annual average, seasonal correction factors are used. The seasonal correction factors used for dwellings in Norway are based on a nation-wide survey of approximately 7500 randomly selected dwellings distributed over a period of two years (1987-1989) (Strand T, 1995). Example of seasonal correction factor calculation is given in the measurement protocols, appendix 2 and 3 (DSA, 2013).

Two different conversion factors are used to calculate the annual average value in Norway (Table 8).

Period	**Factor**
15th October – 31st Oktober	1
1st November – 31st March	0.75
1st April – 15th April	1

Table 8: Conversion factors used to calculate the annual average value in Norway

Example:

> A measurement is carried out in the measurement period from February 10 to April 15. This means that it has been measured for 64 days. 49 of the days are in a period with a conversion factor of 0.75. 15 of the days are in a period with a conversion factor of 1. This gives the following conversion factor for the current measurement period:

$$\frac{49 * 0.75}{64} + \frac{15 * 1}{64} = 0.81$$

Homeowners of all the 136 apartments in the 4 blocks of flats and 14 terraced houses were offered 2-months and 1-year measurements with integrating track etched detectors. In the apartments in blocks of flats the homeowner was asked to measure the living room and a bedroom. In the apartments in the terraced homes the homeowner was asked to measure the living room, a bedroom and an optional occupied room. Both 2-month and 1-year measurements were carried out in 33 apartments in the block of flats and 41 apartments in terraced houses. Due to incomplete filled forms, it was not always possible to find out which 2-month and 1-year measurements belonged together. These therefore had to be discarded. In addition, one more apartment in a terraced house was excluded because the home was mitigated during the 1-year measurement period. Hence, in the first place it was possible to find 61 pairs of measurements in the apartment buildings and 117 pairs in the terraced apartments. However, some pairs had to be excluded because of too long or too short measurement periods or having been sent back to the laboratory too late. In the letter of information, the homeowner was asked to place the detectors preferable at once, alternatively no later than 15th February, and further to send the first set of detectors back after two months. All the participants started the measurements within the period 28th

January and 15th February 2022, but 25% of the so called “2-month” measurements lasted for more than 10% than two months. Normally the measurement season in Norway ends 15th April, but in 2022, this coincided with the Easter holidays and detector submissions were accepted until 20th April. By further omitting measurements that deviated more than10% from the measurement period for the 1-year measurements, the data set then consisted of altogether 154 measurement pairs, 56 and 98 in block of flats and terraced houses respectively. The range of measured days for the “2-month” and the 1-year measurements were 57-81 and 347-398 respectively, and the arithmetic means were 63 and 360 days.

The descriptive statistics and boxplots of the measured radon activity concentrations and the calculated seasonal correction factors are provided in Table 9, and to visualize the results, boxplots are shown in Figure 6 and Figure 7. The coefficient of variance (CV) for the calculated seasonal correction factors was 56%.

Table 9: Descriptive statistics for 2-month and 1-year long measurements for all 154 measurement pairs.

	2-month measurements (Bq/m³) **N=154**	**1-year measurements (Bq/m³)** **N=154**	**Seasonal factor (1-year/2-month)** **N=154**
Aritmethic mean	68	70	1.12
Standard deviation (SD)	76	85	0.65
Median	46	42	0.95
Minimum	10	7,51	0.16
Maximum	574	561	4.76

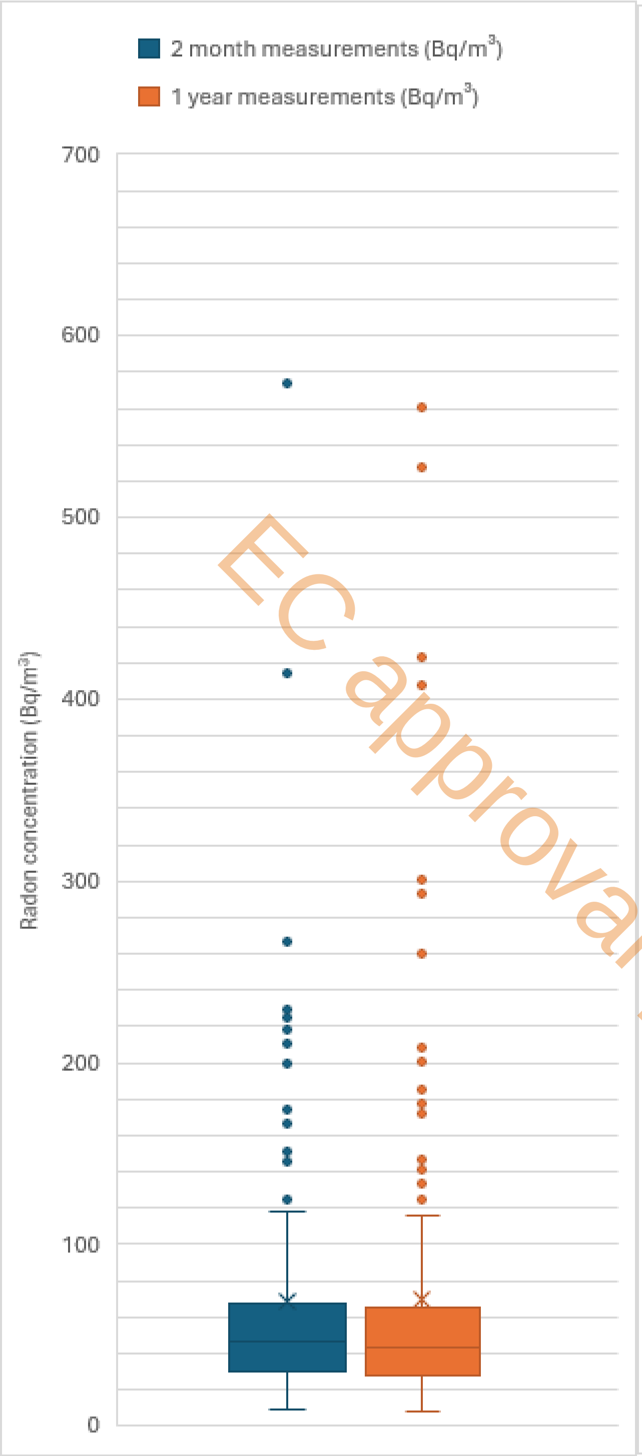


Figure 6: 2-month compared to 1-year measurements for altogether 154 pairs of measurements in apartments in block of flats and terraced houses.

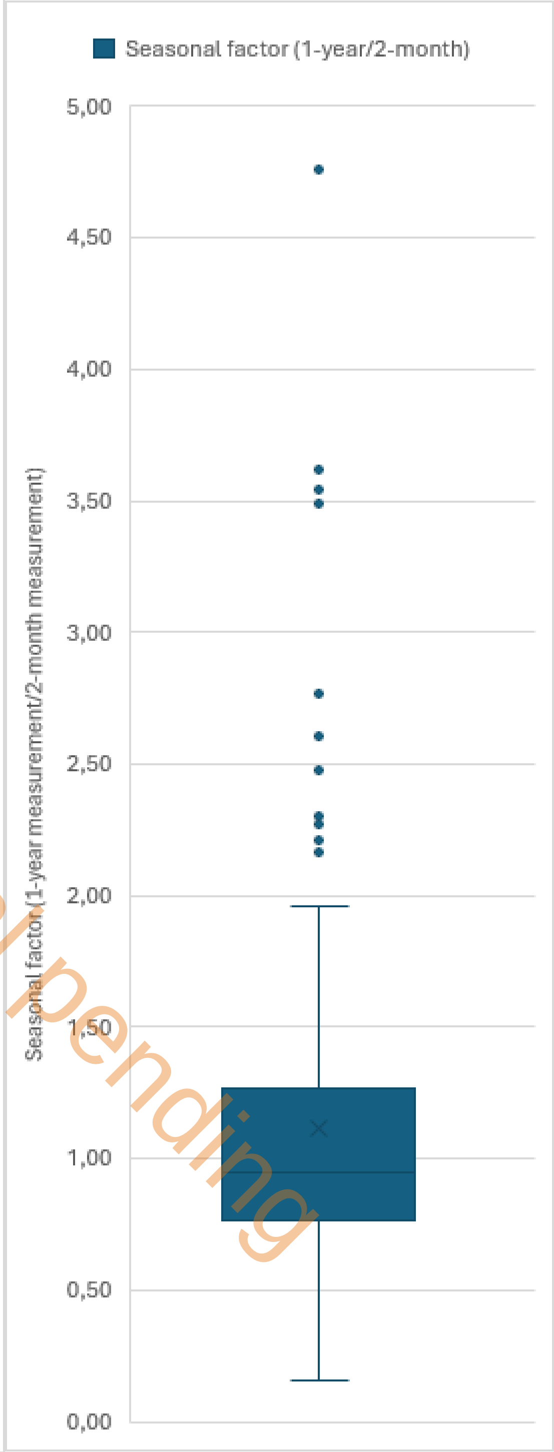


Figure 7: Calculated seasonal correction factor (1-year divided with 2-month measurement for altogether 154 pairs of measurements in apartments in block of flats and terraced houses.

To take a closer look at the calculated seasonal correction factors for the different housing types and floors, the descriptive statistics is provided in Table 10, and boxplots are provided in *Figure 8* and *Figure 9*.

Table 10: Descriptive statistics for 2-month and 1-year long measurements, for apartments in block of flats and terraced houses.

	Apartments in block of flats			**Apartments in terraced houses**		
	2-month measurements (Bq/m³) N=56	**1-year measurements (Bq/m³) N=56**	**Seasonal factor (1-year/ 2-month) N=56**	**2-month measurements (Bq/m³) N=98**	**1-year measurements (Bq/m³) N=98**	**Seasonal factor (1-year/ 2-month) N=98**
AM	35	35	1.18	87	90	1.08
SD	28	26	0.69	89	101	0.62
Median	34	28	1.04	59	55	0.93
Minimum	10	8	0.31	12	15	0.16
Maximum	210	151	3.5	574	561	4.76

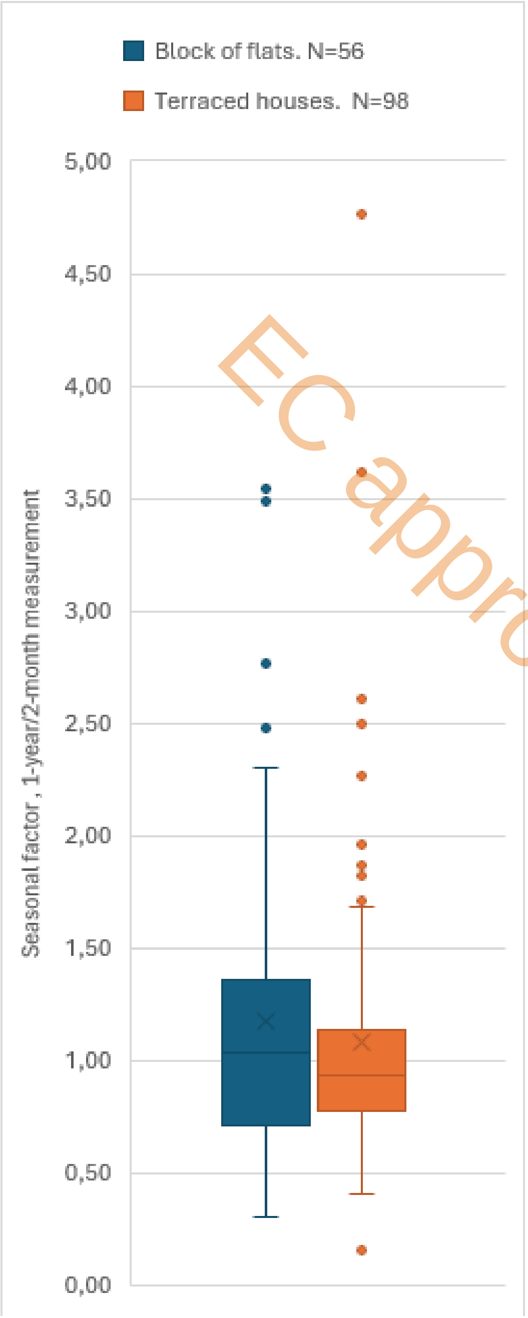


Figure 8: Comparison of calculated seasonal correction factor for apartments in block of flats and terraced houses.

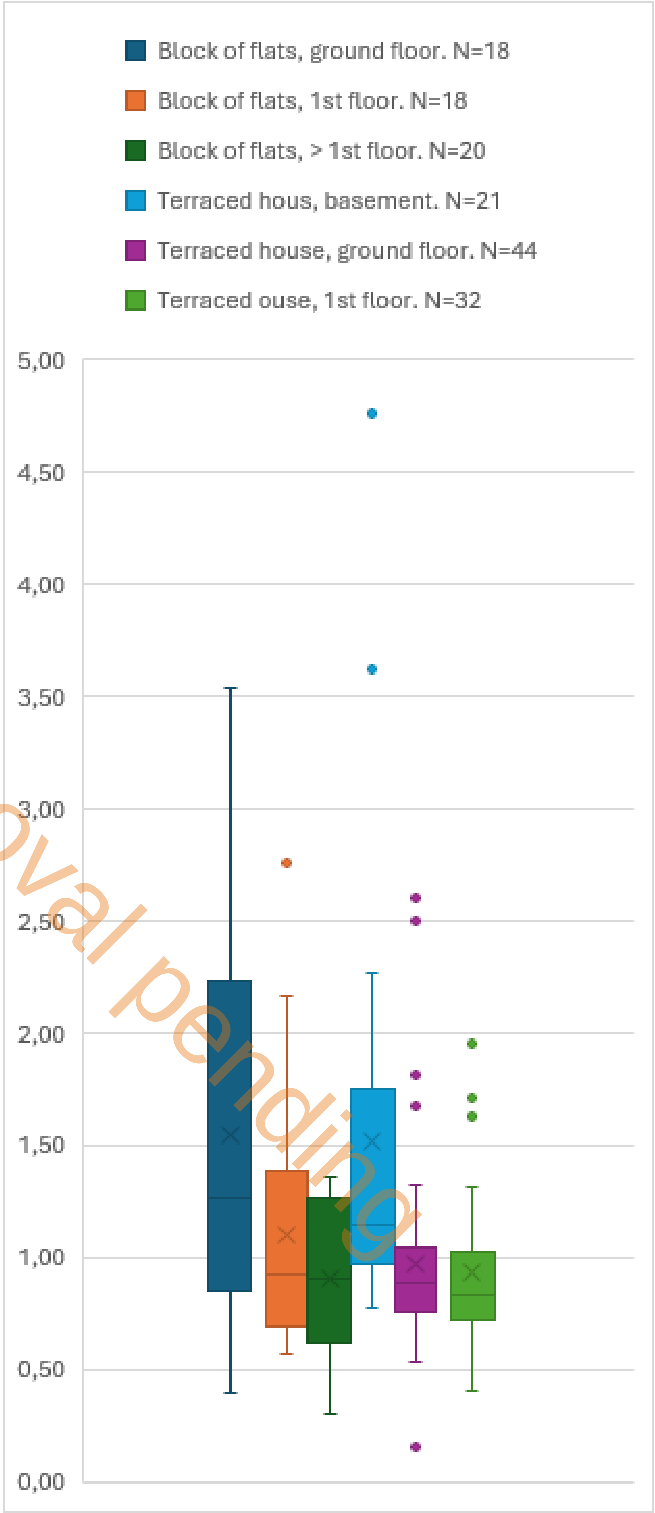


Figure 9: Comparison of calculated seasonal correction factor for different floors in apartments in block of flats and terraced houses.

In this study, homeowners were asked to measure in the living room and in a bedroom. In the terraced houses, homeowners were also asked to measure in an optional third occupied room. This room was often reported as "other" on the form. These "other" rooms can be an extra living room, (which in Norway is often located in the basement), office, kitchen, etc. To take a closer look at the difference between 1-year and 2-month measurements for the different type of rooms, the descriptive statistics is provided in Table 11, and boxplots are provided in Figure 10.

Table 11: Descriptive statistics for seasonal factor (1-year/2-month) for different room types in apartments in block of flats and terraced houses.

	Block of flats		**Terraced houses**		
	Living room 1-year/ 2-month N=28	**Bedroom 1-year/ 2-month N=28**	**Living room 1-year/ 2-month N=39**	**Bedroom 1-year/ 2-month N=34**	**Other 1-year/ 2-month N=24**
AM	1.14	1.21	1.03	0.93	1.37
SD	0.53	0.83	0.47	0.37	0.97
Median	1.14	0.95	0.89	0.84	1.00
Minimum	0.31	0.34	0.54	0.16	0.57
Maximum	2.77	3.54	2.61	2.0	4.76

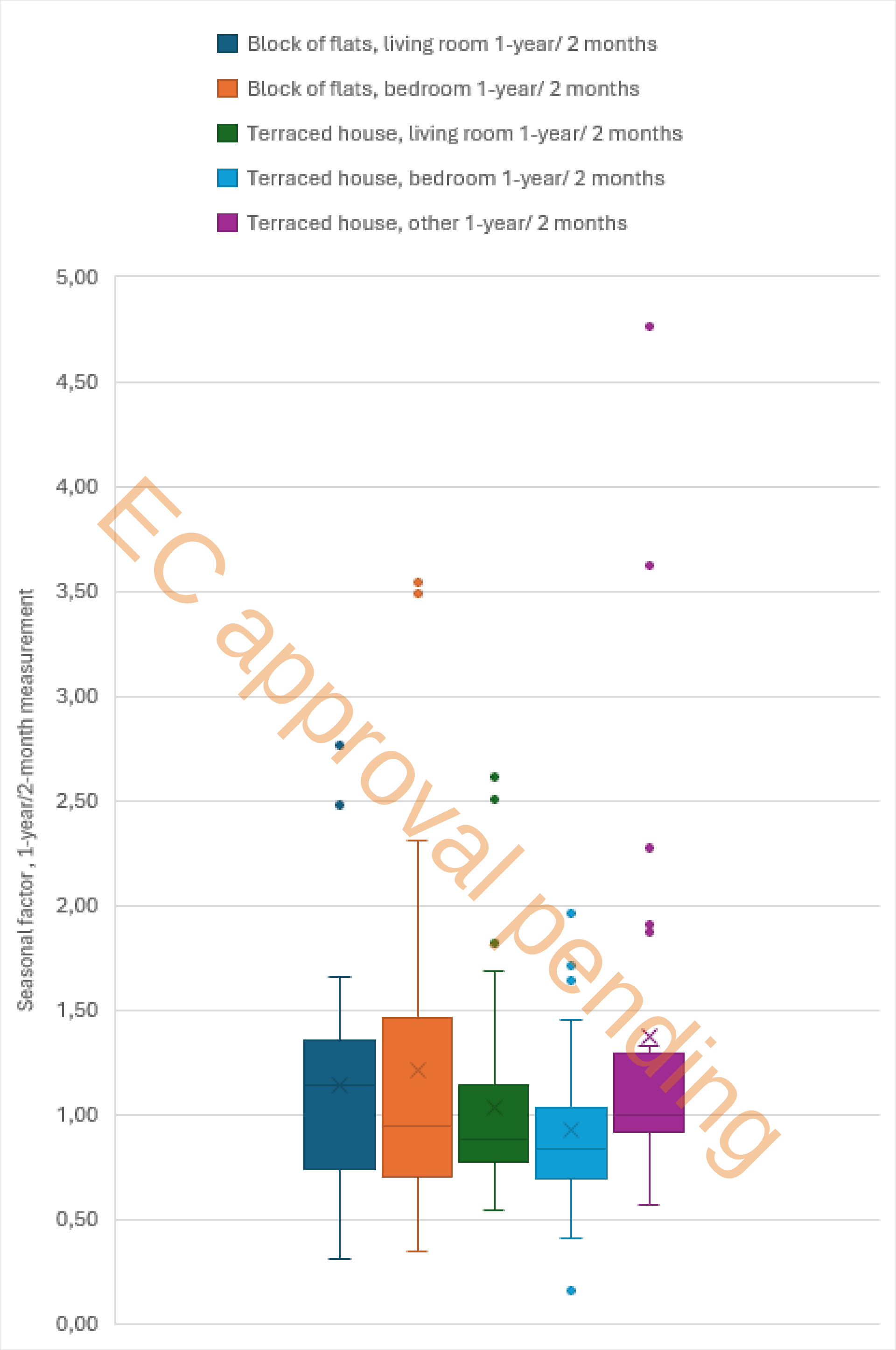


Figure 10: Calculated seasonal correction factors (1-year/2-month), for apartments in block of flats and terraced houses and for different type of rooms.

As additional information to Table 10 and Figure 10, it can be mentioned that for the apartments in terraced houses most of the living rooms (80%) are placed on the ground floor, most of the bedrooms (85%) are placed on the 1st floor and most of the "other" rooms are evenly distributed on the basement floor (50%) and ground floor (46%).

1.2.4.2 The influence of start and stop time and length of measurements

All the homeowners received the invitation letter 1st February, +/- a few days. In the information they received, the homeowner was asked to place the detectors preferable at once, alternatively no later than 15th.

Of the 154 measurements carried out in the winter of 2022 (the so-called 2-month measurements), 29 measurements (8 in blocks and 21 in terraced houses) were not initiated before the deadline of February 15. These measurements had a duration of 59-63 days. To investigate whether the time of initiation played any role, these measurements were compared with the measurements that were started in the period from January 29 to February 3, and which also had a measurement period of 59-63 days. This was a total of 46 measurements, 28 and 18 in blocks of flats and terraced houses, respectively. The descriptive statistics and boxplots are provided in Table 12 and Figure 11, respectively.

Table 12: Descriptive statistics for seasonal factor (1-year/2-month) for measurements starting around 1st February (early start) and 15th February (late start).

	Block of flats, early start N=28	**Block of flats, late start N=8**	**Terraced houses, early start N=18**	**Terraced houses, late start N=21**
AM	1.35	1.10	1.07	1.04
SD	0.86	0.36	0.31	0.89
Median	1.12	0.99	1.02	0.92
Minimum	0.31	0.73	0.78	0.16
Maximum	3.54	1.66	1.91	4.76

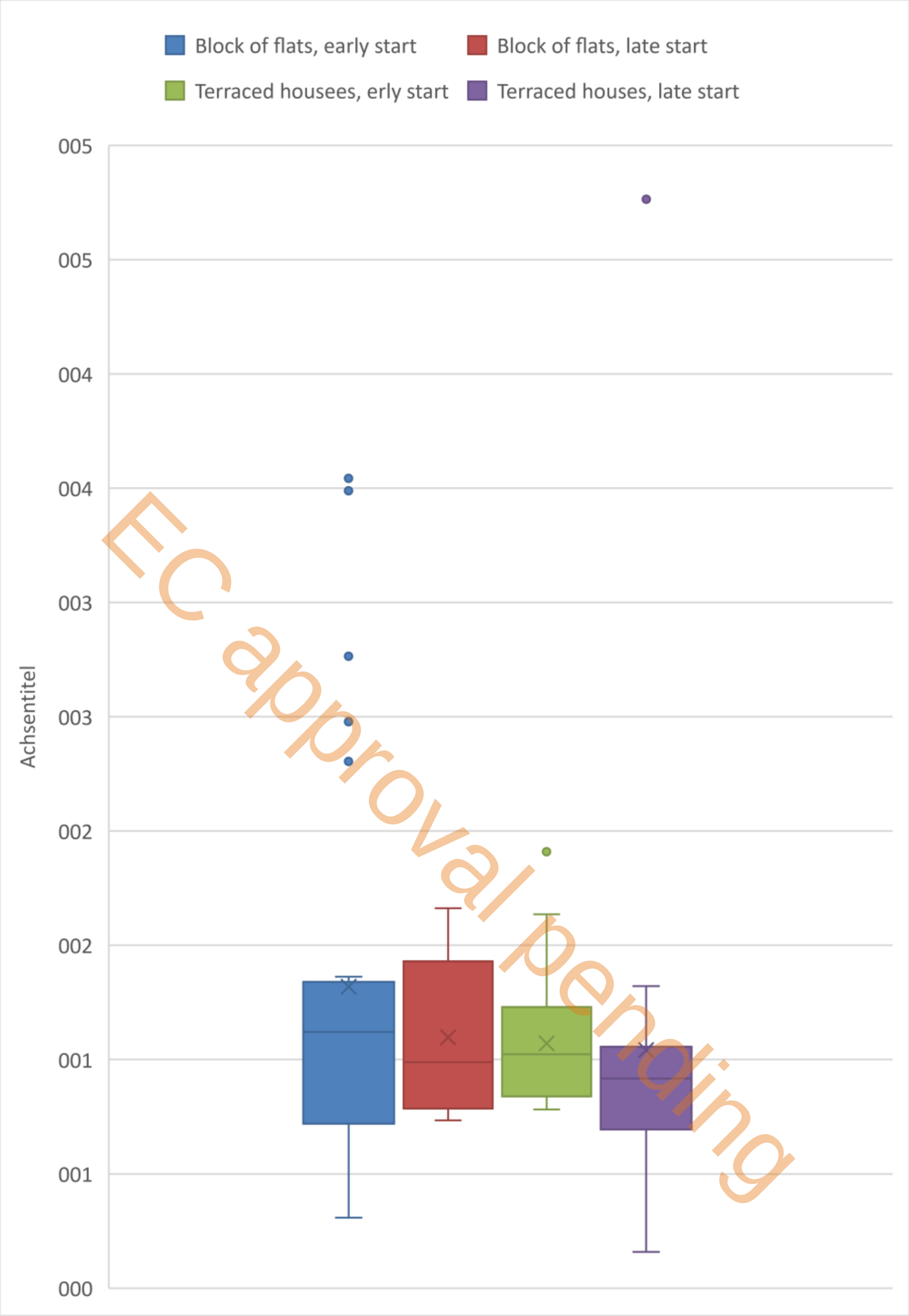


Figure 11: Calculated seasonal correction factors (1-year/2-month), for apartments in block of flats and terraced houses for measurements starting around 1st February (early start) and 15th February (late start).

1.2.4.3 Discussion and conclusion

The coefficient of variance (CV) for all the calculated seasonal correction factors in this study was 56%, which shows that the seasonal variation for the measurements in this study is quite large. Further, for this study, it may appear that the calculated seasonal correction factors vary more in apartments in blocks of flats than in terraced houses (ref. Table 9, Figure 6 and Figure 7). However, with an average radon activity concentration in apartment blocks and in terraced houses of 35 and 90, respectively, variation in a factor will have less significance in apartment blocks.

It may appear that the calculated seasonal correction factors vary systematically with floor (ref. Figure *8* and Figure 9). The calculated seasonal correction factors decrease with increasing floor in both block of flats and terraced houses, which further means that the 1-year measurement is more often higher than the 2-month measurements on lower floors, and that the relative difference between the two measurements is also greater. However, when comparing with the Table 10 and Figure 11, showing the descriptive statistics and the boxplots of different type of rooms, and knowing that for the apartments in terraced houses most of the living rooms (80%) are placed on the ground floor, most of the bedrooms (85%) are placed on the 1st floor and most of the "other" rooms are evenly distributed on the basement floor (50%) and ground floor (46%), then it is not possible to know whether it was the type of room or the floor that was important for the differences.

Some homeowners install the detectors immediately after they are delivered, while others wait until the deadline. In this case, this made a difference of about 15 days. When looking at the descriptive statistics (Table 11) and the boxplot (Figure 11) for the calculated correction factors for early starters and late starters it may appear that there are shift of the median value from above to below 1 for both apartments in block of flats and terraced homes. However, this represented a small change that is well within the uncertainty of the measurements and no clear conclusion can be drawn.

There are quite some outliers in the dataset of the calculated seasonal variation factors (Figure 7). These have not been studied in detail, but there are no immediate clear reasons for these. There is no information on radon mitigation or other renovation during the year, and further no information on apartments being abandoned longer periods than normal vacations. However, this cannot be ruled out.

In this study, use of the seasonal variation factor as provided by the authorities in the national measurement procedure for radon measurements in private homes (DSA, 2013) would in many cases have given a different value than the actual measured one-year measurement. Since this is a quite small study, and the geographical area is small, this points to the need for a larger study of seasonal variation factors.

1.2.5 Analyses of Swiss data

(Authored by HES-SO)

The results are presented in detail in Rey *et al.* (2025), entitled Performance evaluation of radon measurement techniques in single-family homes, aimed at comparing different measurement devices available in Switzerland. Various measurement protocols of different durations were tested during a one-year field campaign. Three spaces (two occupied, one unoccupied) in 20 buildings were investigated. Below, only a summary of the main results is reported.

Different investigation periods have been tested across the 20 buildings. Short-term measurements (3- and 6-months) showed strong correlation with annual results. Winter 3-month readings closely matched annual data (slope = 1.03, R = 0.84), while summer readings slightly overestimated (slope = 1.16, R = 0.87) due to geological influences like karstic radon flows. Winter 6-month measurements also tended to overestimate (slope = 1.13, R = 0.98) but showed better internal consistency. All correlations were statistically significant ($p < 2.2 \times 10^{-16}$), indicating high reliability of passive dosimeters even for shorter measurement periods, with some seasonal variation (Figure 12).

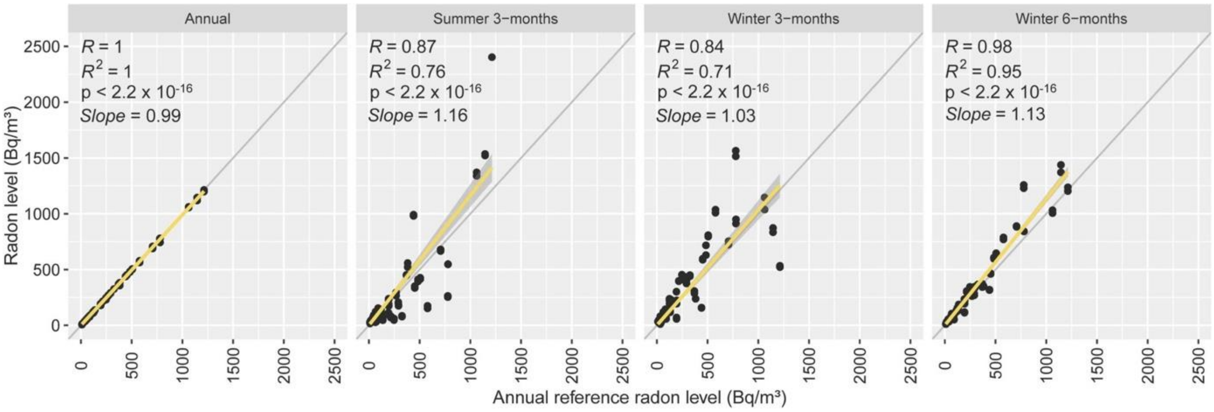


Figure 12: Direct comparison of passive radon measurements of different durations with the annual measurement (taken from Rey et al., 2025)

1.2.6 References

Barazza, F., Gfeller, W., Palacios, M., & Murith, C. 2015. An investigation of the potential causes for the seasonal and annual variations in indoor radon concentrations. Radiation protection dosimetry 167,1-3: 75-81.

Bochicchio, F., et al. 2005. Annual average and seasonal variations of residential radon concentration for all the Italian Regions. Radiation Measurements 40, 2-6 686-694.

Bossew, P., and Lettner, H. 2007. Investigations on indoor radon in Austria, Part 1: Seasonality of indoor radon concentration. Journal of Environmental Radioactivity 98, 39-345.

Daraktchieva, Z. 2017. New correction factors based on seasonal variability of outdoor temperature for estimating annual radon concentrations in UK. Radiation Protection Dosimetry 175, 1: 65-74.

Denman, A. R., Crockett, R. G., Groves-Kirkby, C. J., Phillips, P. S., Gillmore, G. K., & Woolridge, A. C. 2007. The value of seasonal correction factors in assessing the health risk from domestic radon — a case study in Northamptonshire, UK. Environment International 33, 1: 34-44.

Di Carlo, C., Ampollini, M., Antignani, S., Caprio, M., Carpentieri, C., Caccia, B., & Bochicchio, F. 2023. Extreme reverse seasonal variations of indoor radon concentration and possible implications on some measurement protocols and remedial strategies. Environmental Pollution 327: 121480.

DSA, 2013. Protocol for radon measurements (in Norwegian), Norwegian Radiation and Nuclear Safety Authority (DSA): 2013, https://www.dsa.no/publikasjoner/maleprosedyre-for-radon-i-boliger/M%C3%A5leprosedyre_radon_boliger_2013.pdf

Friedmann, H. 2005. Final results of the Austrian radon Project. Health Physics 89: 339–348.

Gillmore, G. K., Phillips, P. S., & Denman, A. R. 2005. The effects of geology and the impact of seasonal correction factors on indoor radon levels: a case study approach. Journal of Environmental Radioactivity 84, 3: 469-479.

Groves-Kirkby, C. J., Crockett, R. G., Denman, A. R., & Phillips, P. S. 2015. A critical analysis of climatic influences on indoor radon concentrations: Implications for seasonal correction. Journal of Environmental Radioactivity 148: 16-26.

Kamgang, S. L. M. F., Monti, M. M., & Salame-Alfie, A. 2023. Temporal Variation in Indoor Radon Concentrations Using Environmental Public Health Tracking Data. Health physics 124, 4: 342-347.

Kozak, K., Mazur, J., Kozłowska, B., Karpińska, M., Przylibski, T. A., Mamont-Cieśla, K., ... & Kołodziej, R. 2011. Correction factors for determination of annual average radon concentration in dwellings of Poland resulting from seasonal variability of indoor radon. Applied Radiation and Isotopes 69, 10: 1459-1465.

Li, X., Zheng, B., Wang, Y., Wang, X. 2006. A study of daily and seasonal variations of radon concentrations in underground buildings. Journal of Environmental Radioactivity. 87,1: 101–106.

Miles, J. C. H., Howarth, C. B. and Hunter, N. 2012. Seasonal variation of radon concentrations in UK homes. Journal of Radiological Protection 32, 3: 275.

Moreno, V., Bach, J., Font, L., Baixeras, C., Zarroca, M., Linares, R., Roque, C. 2016. Soil radon dynamics in the Amer fault zone: an example of very high seasonal variations. Journal of Environmental Radioactivity 151**:** 293–303.

Omori, Y., Tohbo, I., Nagahama, H., Ishikawa, Y., Takahashi, M., Sato, H., & Sekine, T. 2009. Variation of atmospheric radon concentration with bimodal seasonality. Radiation measurements 44,9-10: 1045-1050.

Rey, J. F., Goyette, S., Gandolla, M., Palacios, M., Barazza, F., & Goyette Pernot, J. 2022. Long-term impacts of weather conditions on indoor radon concentration measurements in Switzerland. Atmosphere 13, 1: 92.

Rey, J. F., Licina, D., & Pernot, J. G. 2025. Performance evaluation of radon measurement techniques in single-family homes. Indoor Environments, 2(2):100087.

Stanley, F. K., Irvine, J. L., Jacques, W. R., Salgia, S. R., Innes, D. G., Winquist, B. D., ... & Goodarzi, A. A. 2019. Radon exposure is rising steadily within the modern North American residential environment, and is increasingly uniform across seasons. Scientific reports 9,1 : 18472.

Strand T. 1995. Time variation of indoor radon concentration in Norwegian homes. I: The natural radiation environment VI: Sixth International Symposium on the Natural Radiation Environment (NRE-VI), Montreal, Quebec, Canada, 5-9 June 1995

Sundal, A.V., Jensen, C.L., Anestad, K., Strand, T. 2007. Anomalously high radon concentrations in dwellings located on permeable glacial sediments. Journal of Radiological Protection 27,3: 287–298.

Suzuki, G., Yamaguchi, I., Ogata, H., Sugiyama, H., Yonehara, H., Kasagi, F., ... & Kimura, S. 2010. A nation-wide survey on indoor radon from 2007 to 2010 in Japan. Journal of radiation research 51,6: 683-689.

1.3 Variability of very short-term (a few days) vs. annual measurements

(Contributors: STUK)

1.3.1 Background and literature review

(Authored by STUK)

The resolution of short-term radon concentration variability is here defined as being at least one day but less than a calendar month. Longer observation periods are used primarily to study seasonal variations in concentration, whereas shorter ones examine the effect of time of day on radon levels (e.g., diurnal concentration changes in homes, the impact of ventilation automation in workplaces).

Competent authorities' recommendations or regulations in Europe for radon measurement are typically based on the ISO 11665-8 standard (ISO, 2019), according to which the initial radon survey is performed using an integrated measurement lasting at least two months. However, there are situations where a rapid assessment of indoor radon concentration is desired—such as measurements in connection with real-estate transactions, verification of the success of radon remediation, or the tuning of an active mitigation system. Because short-term measurements are in demand, several companies in Europe offer them to consumers. In Finland, for example, some public libraries and homeowner associations have acquired inexpensive electronic radon monitors that can be borrowed for a week. Thus, short-term measurements are being carried out continuously throughout Europe.

In the United States, by contrast, short-term measurements are typical. According to Tsapalov and Kovler (2021), the prevalence of short-term tests explains why radon measurements in the U.S. are conducted at roughly twenty times the rate per capita compared to Europe; the number of remediated buildings is nearly fifty times greater than in Europe, partly due to the ease of short-term testing. Price and Nero (1996) reported results from both short- and long-term radon measurements in the U.S., finding that short-term tests are poorly suited for predicting a home's long-term average radon concentration. On the other hand, with appropriate correction factors, short-term data can be effectively used for regional and national radon mapping.

Most of the literature on short-term radon variability has focused on validating short-term tests performed alongside long-term integrated measurements. Parameters that directly describe variability—such as the coefficient of variation (CV) geometric standard deviation (GSD) or the geometric coefficient of variation (GCV) of measured concentrations—are rarely reported. Consequently, the most common approach has been linear regression and its coefficient of determination (CD, or R^2), which indicates the proportion of short-term measurement results explained by the long-term measurement. A more practically oriented method has been to specify action levels or action-level intervals that bound a chosen proportion of false negatives and false positives.

Al-Jarrallah *et al*. (2008) measured the one-day average radon concentration in 34 homes in Saudi Arabia and compared it to the six-month average. The linear regression yielded $R^2 = 0.38$, and the ratio of the six-month to one-day measurements ranged from 0.6 to 2.7.

Phillips *et al.* (2004) reported differences between seven-day measurements and annual averages in 34 homes, finding R^2 values of 0.62 (alpha-track detector, type 1), 0.89 (alpha-track detector, type 2) and 0.79 (electret). Of the electret measurements, 20% agreed with a three-month integrated measurement within ± 20%.

Using the same data, Groves-Kirkby *et al.* (2006) essentially confirmed these findings. Denman *et al.* (2007) then calculated action-level intervals for 7–10 d measurements, recommending that tests falling outside these intervals be repeated. For electrets the interval was 59–667 Bq/m^3, for charcoal detectors 68–519 Bq/m^3, and for alpha-track detectors 75–478 Bq/m^3; in each case, the proportions of false negatives below the lower bound and false positives above the upper bound were under 5%. These results were compared to the UK reference level of 200 Bq/m³. Denman *et al.* (2016) later revised these action-level intervals for all week-long tests to 56–720 Bq/m³. Complementing the U.K. studies, Miles et al. (2001) conducted 4- and 7-day activated charcoal tests in three homes: compared to the annual average, deviations were from –60 % to +260 % in one home and from –60 % to +100 % in the other two.

Martinez *et al.* (2001) examined 12 homes in Mexico with electret detectors (2–4 d tests in spring) alongside integrated measurements to determine the yearly average. They reported R^2 of 0.87 and concluded that a short-term spring measurement gives a reasonably good estimate of the annual average.

Steck (2005) studied 75 U.S. homes using 2- and 4-day charcoal tests and year-long integrated alpha-track measurements, finding $R^2 = 0.38$. Both test durations showed a CV around the annual average of 70 %.

Barros *et al.* (2014) measured radon in the basements of 158 U.S. homes with 7–10 d electret tests and year-long alpha-track measurements. The CD of the log-transformed short-term versus annual concentrations was 0.75. They reported 95 instances where the annual average exceeded a reference level of 148 Bq/m³ but 11 short-term tests yielded a false negative; false positives occurred in 16 cases out of 63 cases where annual average was below the reference level. Their 2016 reanalysis of the same data complimented with measurement results from other floors found that the predictive value of a short-term basement measurement for exceeding the reference level in all living areas was 44 %, while the predictive value for staying below the reference level was 98 % (Barros et al., 2016).

Complementing these U.S. studies, Kotrappa *et al.* (2010) conducted continuous measurements in a single home, reporting standard deviations (i.e., CV) of 40 % for two-day and 30 % for week-long measurement periods.

Ruano-Ravina *et al.* (2008) reported on 391 Spanish homes where short-term charcoal tests (3–4 d) and alpha-track detectors (5 months) were deployed. Despite advising residents not to ventilate, the geometric mean (GM) for the charcoal tests was 39 Bq/m³ versus 69 Bq/m³ for the five-month tests. Surprisingly, the variability was similar: GSD = 2.9 for short-term and 2.8 for long-term measurements.

Sferle *et al.* (2020) used continuous, in-house ICA monitors in six homes to record one-day integrals, finding arithmetic means of 248–825 Bq/m³ and coefficients of variation of 27–44 %.

Tsapalov and Kovler (2018) analysed continuous radon measurements in 10 Russian rooms to define action levels analogous to Denman et al. (2007). They introduced the coefficient of temporal variation (K_V) for assessing the action levels. It was recommended to be derived empirically so its 95 % coverage interval spans 95 % of observed values, and factored in measurement uncertainty U_D (typically 10–30 %) and a seasonal correction factor k. They reported K_V values for 1, 2, 3, 5 and 7 d measurements of 2.30, 1.60, 1.40, 1.20 and 1.20, respectively. For assessing the action level for false negatives, the following equation was given:

$$AL = \frac{C_{RL}}{\left(k \times \left[1 + \sqrt{K_V^2 + U_D^2}\right]\right)}$$

Tsapalov and Kovler (2021) further performed continuous tests in 12 Israeli rooms and observed that U_D is typically small enough to be neglected. In their 2022 paper, they selected data from six Russian and 12 Israeli rooms and modeled short-term (< 1 month) results as log-normally distributed. Thus, GM × GSD² corresponds to the 97.5th percentile and GM ÷ GSD² to the 2.5th percentile (95 % coverage). The K_V for a given duration can then be calculated accordingly. For a reference level of 300 Bq/m³, the resulting action levels for 2, 3, 5 and 7 d tests were given as 113, 122, 132 and 134 Bq/m³, respectively.

1.3.2 Analyses of Finnish data acquired in RadoNorm

(Authored by STUK)

The new data collected in RadoNorm project and its comprehensive analyses are reported by Turtiainen *et al.* (2025) (**https://doi.org/10.3390/atmos16050489**) and need not be repeated here (**https://doi.org/10.3390/atmos16050489**).

1.3.3 Discussion

(Authored by STUK)

As the literature review has shown, short-term temporal variability of radon concentration has been studied, but the reported data are difficult to compare with one another. Based on linear regression, the reported coefficient of determination (CD) values have sometimes had only a small explanatory power; in both Saudi Arabia and the USA, the measured CD values were 0.38. On the other hand, it has also been observed that both short- and long-term measurements fit a linear model well, and the CD values have demonstrated reasonably good consistency between results. For example, CD values reported from the UK ranged from 0.62 to 0.89 depending on the method, and in Mexico they were 0.87. A linear regression performed on logarithmically transformed data showed good agreement in the USA.

Whether the results are distributed normally or log-normally appears to admit two different interpretations. In some cases, the standard deviation or the coefficient of variation has been reported, while in others the geometric standard deviation or the coefficient of temporal variation (K_V) has been used. To clarify this, the data from Turtiainen *et al.* (2025) were reanalysed to determine what distributions could be expected.

For each measured dwelling, the daily measurement results were normalized with respect to the annual average. The normalized results were then pooled for the entire year (N = 19,169) and for the actual measurement period (N = 12,238). According to the Kolmogorov–Smirnov test, neither dataset was normally distributed. When a logarithmic transformation was applied, a statistically significant deviation from normality was still observed. However, the deviation was very small in both cases (effect size D = 0.095 for the full-year dataset and D = 0.076 for the measurement-period dataset). Hence, we can practically assume that the distribution of the log-transformed data is normal, and the distribution of normalized data is log-normal. QQ-plots for the log-transformed data are shown in Figure 13.

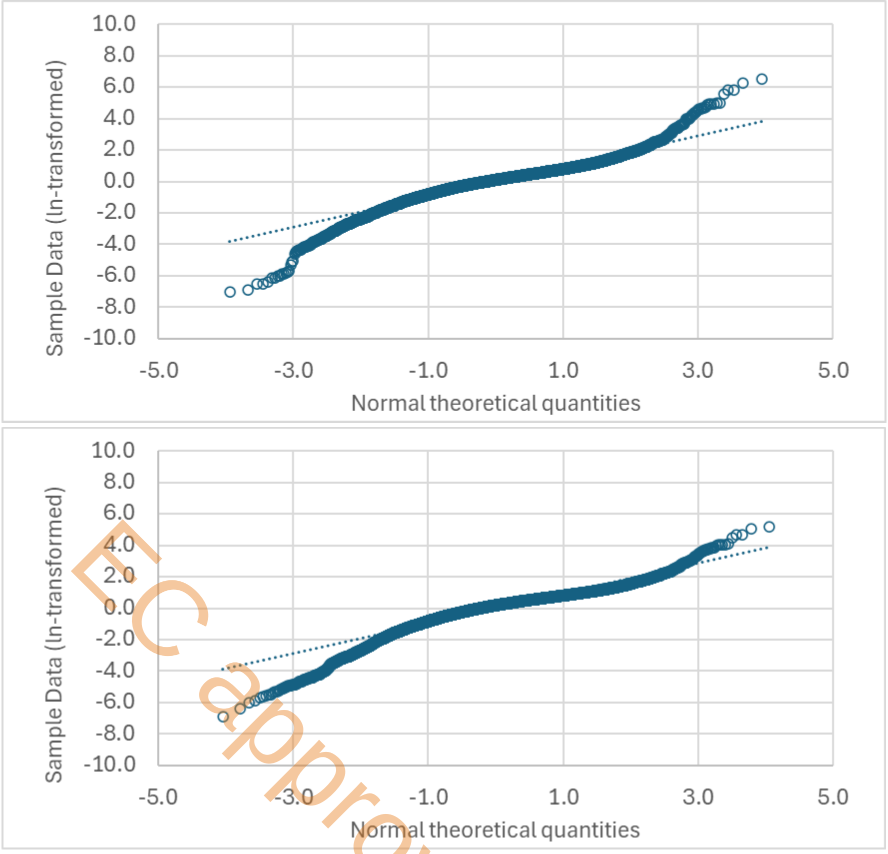


Figure 13: QQ-plots for the normalized and log-transformed 1-day measurements during the whole year (upper panel) and the measurement season (lower panel) show only small deviation from normality.

When using the method presented by Kovler and Tsapalov (2022) to assess action levels, it is important to ensure that the GSD value used in the calculation is correct. For example, in the dataset by Turtiainen et al. (2025), the GSD values for the daily variation of radon concentrations in individual homes (N=55) ranged from 1.11 to 3.30 when analysing the data from the measurement period (1 Oct–15 May). The median, AM, and GM of the GSD values were 1.32, 1.43, and 1.48, respectively. However, when the temporal variability of the entire dataset (N=12,238 normalized concentrations) was evaluated, the GSD value was 1.58 (GM=1.05). Therefore, the Coefficient of Temporal Variation (K_V) cannot be calculated from the mean or median of the individual home GSD values, but the variation must be determined for the entire normalized dataset.

Using a GSD value of 1.58, the action level for a 24-hour measurement calculated using the method by Tsapalov and Kovler (2022) is 108 Bq/m³, with a reference value of 300 Bq/m³. Since the reliability level is 95%, the action level corresponds to the 2.5th percentile. Turtiainen et al. (2025) calculated the action levels using a probabilistic method based on the empirical result distribution. The 2nd percentile and 3rd percentile for the 24-hour action level were 100 and 120 Bq/m³, respectively. Both methods lead to the same conclusion.

However, if the generic GSD value is incorrectly estimated as the arithmetic mean of the individual GSD values, an overly high action level is obtained. In the dataset by Turtiainen et al. (2025), the arithmetic mean of the GSD was 1.48, which would result in a calculated action level of 128 Bq/m³.

1.3.4 References

Al-Jarallah, M.I., Fazal-ur-Rehman, Abdalla, K. (2008). Comparative study of short- and long-term indoor radon measurements. *Radiation Measurements* 43: S471–S474.

Barros, N.G., Steck, D.J., Field, R.W. (2014). A comparison of winter short-term and annual average radon measurements in basements of a radon-prone region and evaluation of further radon testing indicators. *Health Physics* 106(5): 535–544.

Barros, N.G., Steck, D.J., Field, R.W. (2016). Utility of short-term basement screening radon measurements to predict year-long residential radon concentrations on upper floors. *Radiation Protection Dosimetry* 171(3): 405–413.

Denman, A.R., Crockett, R.G.M., Groves-Kirkby, C.J., Phillips, P.S., Gillmore, G.K., Woolridge, A.C. (2007). The value of Seasonal Correction Factors in assessing the health risk from domestic radon—A case study in Northamptonshire, UK. *Environment International* 33: 34–44.

Denman, A.R., Crockett, R.G.M., Groves-Kirkby, C.J., Phillips, P.S. (2016). Interpreting short and medium exposure etched-track radon measurements to determine whether an action level could be Exceeded. *Journal of Environmental Radioactivity* 162–163: 279–284.

Groves-Kirkby, C.J., Denman, A.R., Crockett, R.G.M., Phillips, P.S., Woolridge, A.C., Gillmore, G.K. (2006). Time-integrating radon gas measurements in domestic premises: comparison of short-, medium- and long-term exposures. *Journal of Environmental Radioactivity* 86: 92–109.

ISO, 2019. ISO 11665-8; *Measurement of Radioactivity in the Environment—Air: Radon-222—Part 8: Methodologies for Initial and Additional Investigations in Buildings, 2nd ed.* ISO: Geneva, Switzerland, 2019; pp. 1–19.

Kotrappa, P, Stieff, F. (2010). Comparison of two-day consecutive radon measurement results to a 90-day average measurement results using the data from continuous radon monitors in a typical single-family home in Frederick, MD, USA. In: *Proceedings of 20th International Radon Symposium, Columbus, OH, USA*. [https://aarst.org/symposium-proceedings/]

Martinez,T., Navarrete, M., Cabrera, L., González, P., Ramirez, A. (2001). Relationship between short- and long-term radon measurements. *Radiation Physics and Chemistry* 61: 687–688.

Miles, J.C.H. (2001). Temporal variation of radon levels in houses and implications for radon measurement strategies. *Radiation Protection Dosimetry* 93(4): 369–375.

Phillips, P.S., Denman, A.R., Crockett, R.G.M., Gilmore, G., Groves-Kirkby, C.J., Woolridge, A. (2004). *Comparative analysis of weekly vs. three monthly radon measurements in dwellings. DEFRA Report No: DEFRA/RAS/03.006.* Northampton: Department for Environment, Food and Rural Affairs, 2004.

Price, P.N., Nero, A.V. (1996). Joint analysis of long- and short-term radon monitoring data from the northern U.S. *Environment International* 22, Suppl 1: S699–S714.

Ruano-Ravina, A., Castro-Bernárdez, M., Sande-Meijide, M. Vargas, A., Barros-Dios, J.M. (2008). Short- versus long-term radon detectors: a comparative study in Galicia, NW Spain. *Journal of Environmental Radioactivity* 99: 1121–1126.

Sferle, T, Dobrei, G., Dicu, T., Burghele, B-D., Brişan, N., Cucoş (Dinu), A., Catalina, T., Istrate, A., Lupulescu, A., Moldovan, M., et al. (2020). Variation of indoor radon concentration within a residential complex. *Radiation Protection Dosimetry* 189(3): 279–285.

Steck, D.J. (2005). Residential radon risk assessment: How well is it working in a high radon region? In: *Proceedings of 15th International Radon Symposium, San Diego, CA, USA*. [https://aarst.org/symposium-proceedings/]

Tsapalov, A., Kovler, K. (2018). Indoor radon regulation using tabulated values of temporal radon variation. *Journal of Environmental Radioactivity* 183: 59–72.

Tsapalov, A., Kovler, K. (2021). Studying temporal variations of indoor radon as a vital step towards rational and harmonized international regulation. *Environmental Challenges* 4: 100204.

Tsapalov, A., Kovler, K. (2022). Temporal uncertainty versus coefficient of variation for rational regulation of indoor radon. *Indoor Air* 32: e13098.

Turtiainen, T., Kojo, K., Kurttio, P. (2025). Short-Term Temporal Variability of Radon in Finnish Dwellings and the Use of Temporal Correction Factors. *Atmosphere* 16 (5): 489.

1.4 Daily variability

(Contributor: ISS)

1.4.1 Background and literature review

(Authored by ISS)

1.4.1.1 Methodology

A search of papers studying indoor radon activity concentration daily variability was conducted using as resources the Web of Science, Scopus, Elicit and Semantic Scholar search engines. The keywords used in the search were: “radon”, “daily variations”, “day”, “night”, “variability”, sometimes used all together, sometimes in subgroups.

The search was limited to articles published in English. Papers not extensively analysing daily variability, with an insufficient sample size (only one dwelling taken into account) or not focusing on dwellings or workplaces but, for instance, caves or atmospheric radon, were excluded (see flowchart in Figure 14).

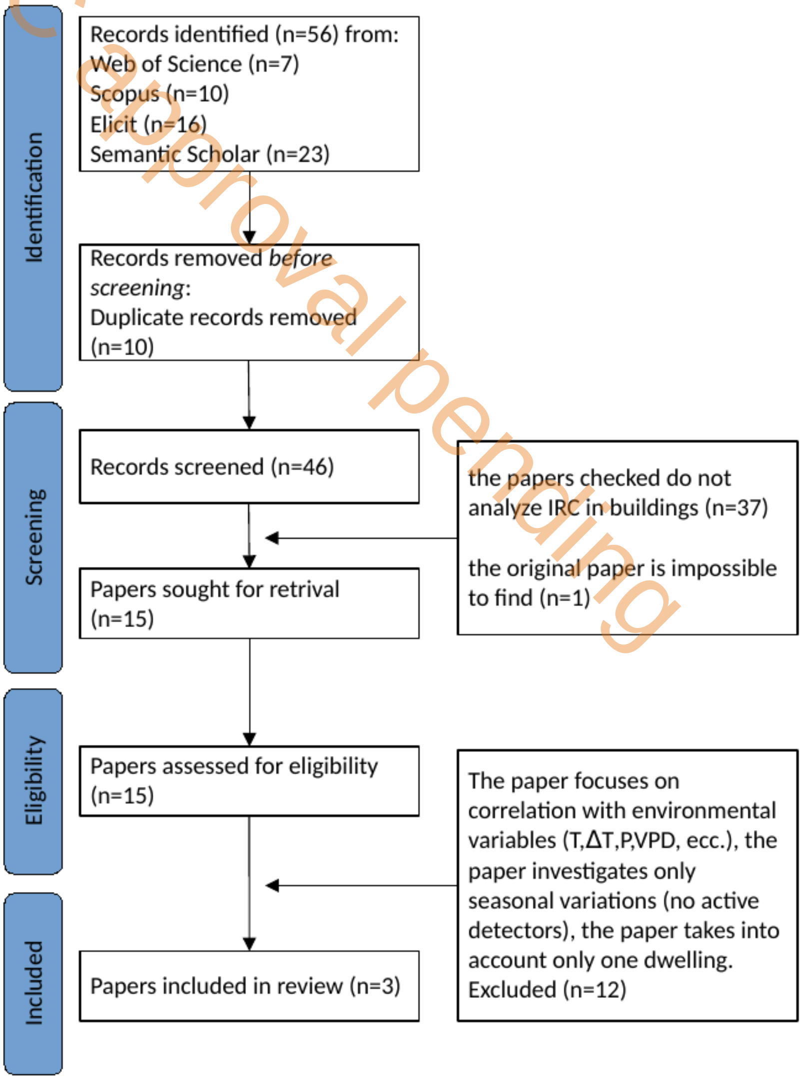


Figure 14: Flowchart for the review on year-to-year radon variability in dwellings

The search was updated until April 2025.

In the end, tthrough the literature review, only three relevant articles were identified. This limited number is due to the fact that analyses on daily variability are typically secondary or complementary within studies primarily focused on other aspects of radon concentration assessment. As a result, such analyses are often not explicitly mentioned in the titles, abstracts, or keywords, making them difficult to retrieve through standard keyword-based literature searches

1.4.1.2 Discussion of the selected papers

The articles summarized here represent only a small selection, as most studies in the literature primarily focus on exploring the correlations between indoor radon concentration (IRC) and various external or internal environmental variables. These include factors such as external temperature, temperature and pressure difference between outdoor and indoor air, vapor pressure deficit and others None of the reviewed studies (among those selected) explicitly and quantitatively examine the distribution of day/night IRC or the ratio between radon concentration in working days vs. holidays. Such information can only be indirectly inferred from research conducted with different primary objectives. This is actually the case for all the three selected papers summarized here: Marley (2001), Venoso et al. (2021) and Yarmoshenko et al. (2021).

Yarmoshenko et al. (2021) focus on dwellings and office premises in high raise buildings, Marley (2001) analyses both dwelling and workplaces (hospitals and clinics), while Venoso et al. (2021) focus on different type of workplaces. In both Yarmoshenko et al. (2021) and Marley (2001) the main factors influencing IRC are forced ventilation and heating systems. In contrast, Venoso et al. (2021) find that IRC variations are mainly driven by human activity, specifically work-related behaviors.

Yarmoshenko et al. (2021)

The study analyses long-term radon time series in 14 rooms and offices, using three AlphaGUARD PQ2000 PRO radon monitors. The aim of the study is the search for factors influencing indoor radon concentration in high-rise buildings, in relation with human activity. In order to highlight this factor, the average hourly indoor radon concentrations were calculated. The authors classify dwellings, basing on (high-low) human activity.

The dynamics of radon concentration was observed to have a significant impact on residential rooms in apartments with two or more residents. On the other hand, the daily radon dynamics were less noticeable in apartments with only one tenant and dwellings with low human activity.

For what concerns winter/summer variability different behaviors are observed depending on the kind of use:

- In rooms with high human activity, radon concentration in the warm season is lower than in the cold season.

- In rooms with low human activity, the seasonal variations of radon concentration are the opposite with respect with the previous ones.

- In office environments, radon concentrations tend to vary between summer and winter, as summer is often characterized by vacation periods and reduced occupant activity compared to winter.

The authors don’t explicitly quantify day/night radon concentration variation or the one between working days and holidays, however, such information is generically available through many graphics shown all along the paper. From those figures one can observe that, while in rooms characterized by low human activity CV is stable (but different) during the day both in summer and winter, in high human activity rooms sharp changes (usually a rapid increase in the morning) take place.

Seasonal and diurnal variations in rooms with normal human activity are produced by the increase in ventilation produced by inhabitants in the warm season. Both the concentration of radon and its coefficient of variation in rooms with normal human activity are subject to the dwellers' activity during various periods of the day.

Marley et al. (2001)

Marley F. doctoral thesis investigates on the relation between IRC in dwellings and workplaces and atmospheric conditions (temperature, atmospheric pressure and vapor pressure), modified by the structural characteristics of the building and heating system.

The four buildings selected, located on the Northampton sand formation bedrock, had the geological source potential for elevated radon levels. The measures took place:

a. in January through to early May from four contiguous rooms, part of a day clinic;
b. in the latter part of October into November for a small office in the administration block of a second medical establishment (admin) and on the same site;
c. in the same period of time in a room in a building some four hundred meters distant (day-care center).

The heating system in the three locations was switched on from Monday to Friday and off in the weekend.

The real-time data for radon gas were collected with electronic radon monitors. Also, in this case the primary target of the analysis was finding a clear relation between the collection of time-series data relating to radon, progeny, with internal temperature and relative humidity along with external ambient conditions.

In order to identify the basic mechanism that drives the cyclical nature of the series, time-series analysis was employed by the author to identify any cyclical behavior of radon, progeny, and other variables. In order to determine the frequency domain form in long-run data sets, spectrum analysis was utilized.

The average values of IRC ratios in workdays/weekends and daytime/nighttime (during winter, spring and fall) in the clinic are summarized in Table 13.

Table 13 Average results of radon measurement in the 5 rooms of the clinic monitored in Marley (2001)

Day/Night-time	Workday	Weekday	Weekend	Ratio
9:00-21:00	127 (Bq/m^3)	153 (Bq/m^3)	262 (Bq/m^3)	2.06
22:00-8:59	259 (Bq/m^3)	259 (Bq/m^3)	289 (Bq/m^3)	1.12
Ratio	2.04	1.69	1.11	1.84

Moreover, compared to similar summer readings taken in August, a seasonal influence was also evident, since the concentrations observed in this case were less than half the ones recorded in winter/spring months of the year.

Venoso et al. (2021)

The investigation was conducted in 33 workplaces of different types, where different levels of radon are expected to occur during working hours, due to the likely increase in natural or mechanical ventilation. These workplaces were mainly located in Municipalities classified as radon prone areas in Italy, among those resulted to have an average annual radon concentration higher than 150 Bq/m^3.

The analysis by Venoso et al. (2021) studies in detail the distribution of the ratios between IRC measured during working hours (RnWH) with respect to the average value measured along the week (RnH24). The average radon level over the working hours generally resulted lower than the RnH24 one: this difference is always below 50% and in most cases is not above 20% for each type of workplaces.

In particular, along the whole exposure period, the average value of RnWH/RnH24 is 0.9 (range: 0.8–1.0). For each 7-day period of the year, the interquartile ranges of RnWH/RnH24 are from about 0.6 to 1.1, with a minimum of about 0.3, and maximum value of 1.6.

Estimating RnWH/RnH24 using a randomly selected 7-day period over the year introduces uncertainty in terms of the coefficient of variation, which averages 17% and can range from 7%-26%. The uncertainty decreases as the number of days chosen for the estimation of RnWH/RnH24 increases. In particular, the CV is on average, for a period of 30 and 90 days, 14% and 10% respectively.

The results of the study suggest that a period of several months should be an optimal choice, in order to properly estimate, using electronic radon monitors, the impact of ventilation during working hours with respect to the average annual radon concentration.

This review highlights that in the literature (at least as far as we were able to observe) a thorough quantitative study on daily variability of radon values is nowadays missing, either in the form of an analysis of the day/night coefficient of variation, or a systematic study of the day/night IRC ratios distribution.

In particular, in Marley (2001) and Yarmoshenko et al. (2021), the authors knew the times of activation of heating systems and forced ventilation, information often not available in analysis of IRC in dwellings. A more statistical approach would be therefore more than useful.

On the other hand, Venoso et al. (2021) answer the question of what is the actual exposure of workers to radon during working hours, once measured the average value, extensively studying the RnWH/RnH24 ratio; but a similar analysis is not nowadays available for dwellings and their inhabitants.

1.4.2 Analysis of Italian data acquired in RadoNorm

(Authored by ISS)

The Italian dataset, used to investigate the issue of daily variability, contains measurements obtained from electronic radon monitors TSR4M and TSR3DM, placed (in occupied rooms) in 23 dwellings of 8 buildings in the city of Rome (Italy). The electronic radon monitors were calibrated immediately before and after data collection and radon concentration values were interpolated accordingly. Based on considerations related to the sensitivity of the radon monitors and the fact that the Italian national background value was estimated at 7 Bq/m^3 (and that in the city of Rome this background value is also higher) (Bochicchio et al., 1996, Bochicchio et al., 2005), any lower value has been raised to 7 Bq/m^3.

The details about dwelling floor, days of exposition and average radon concentration is available in the following Table 14.

Table 14: Overview of the measures performed in each of the 23 dwellings

Building ID	Dwelling Floor	Average IRC (Bq/m^3)	Days of exposure
Building 1	0 (a)	93	365
	0 (b)	141	364
	2	173	289
	5	63	365
Building 2	0	105	365
	7	102	365
Building 3	0	40	364
	2	34	93
Building 4	1	52	365
	2	49	365
	3	129	365
Building 5	0	358	365
	1 (a)	187	365
	1 (b)	203	365
	2	155	180
Building 6	0	38	365
	1	92	365
	4	39	366
Building 7	1	151	267
	2	36	201
Building 8	0	221	366
	3	118	358
	4	94	366

In order to derive diurnal and nocturnal radon concentrations, two different approaches for defining 'daytime' and 'nighttime' hours were used:

- based on the Meeus ephemerides algorithm (Meeus, J., 1991 - Astronomical Algorithms. Willmann-Bell, Inc.) for the sunrise/sunset hours calculation at Rome coordinates. It was then possible to calculate the ratio IRC_day/IRC_night for each day for each dwelling of each building, and study the statistical distributions obtained gathering such ratios by dwelling and by building.
- based on more 'artificial' definitions of diurnal and nocturnal hours, where fixed hours are assigned every day to correspond to human activity. Those arbitrary hours were chosen, according to the average population’s habits, as 9:00 in the morning and 19:00 in the evening (daylight saving time was of course taken into account).

The choice of time delimiters used to define day and night hours turns out to have an impact on the analysis results. The hypothesis is that when using the first type of delimiter (sunrise and sunset), the analysis focuses more on the influence of environmental factors on indoor radon concentration. In contrast, using the second type (fixed clock-based hours) tends to highlight the impact of human activity and behaviour on IRC variations, likely associated with the level of ventilation in the dwelling. In the first case the average day/night IRC ratio is 0.877, while in the second one 0.715.

A further characterization of IRC data was performed analysing separately working days and holidays. Such a distinction was established according to the official calendar of national holidays in Italy. Saturdays and Sundays were considered as non-working days as well. The ratio day/night (using the definition 9-19) was analysed separately for holidays and working days (Table 17 and Table 18). The impact of the different definitions of “daytime” and “night-time” (as described above) is analysed in a separate section (compare Table 15 and Table 19).

Collecting together all the measurements performed in the eight buildings, the overall IRC distribution has an arithmetic mean (AM) of 139 ± 120 Bq/m^3 with CV=86%, min=7* Bq/m^3, median=105 Bq/m^3, max=1159 Bq/m^3. The *symbol related to the minimum value reminds that for low values (i.e., ≤7 Bq/m^3), the uncertainty is high, making them not statistically distinguishable; therefore, as already explained, all values below 7 Bq/m^3 were set to 7 Bq/m^3.

A first look on the variations between daytime and night-time IRC measurements is available in Table 15. The subdivision between day hours and night hours explored in this subsection is the “artificial” one (daytime hours: 9:00–19:00). As expected, night-time measurements are generally higher, and elevated IRC values occur more frequently.

Table 15: Descriptive statistics of radon concentration distributions by time periods, reflecting human activity (daytime hours: 9:00-19:00)

	AM (Bq/m^3)	**SD (Bq/m^3)**	**CV (%)**	**Min (Bq/m^3)**	**Median (Bq/m^3)**	**Mode (Bq/m^3)**	**Max (Bq/m^3)**
Rn Day*	117	110	94	7**	84	13	1126
Rn Night	155	124	80	7**	120	42	1159
Ratio (day/night)	0.71	0.28	39	0.07	0.71	0.78	3.06
* daytime hours: 9:00-19:00 ** all the Rn measurements under 7 Bq/m^3 were set to 7 Bq/m^3							

Daytime and night-time measurements can be characterized as two separate log-normal distributions (see Figure 15), since both human behaviour and environmental climatic background conditions are very different during the two distinct phases of the day.

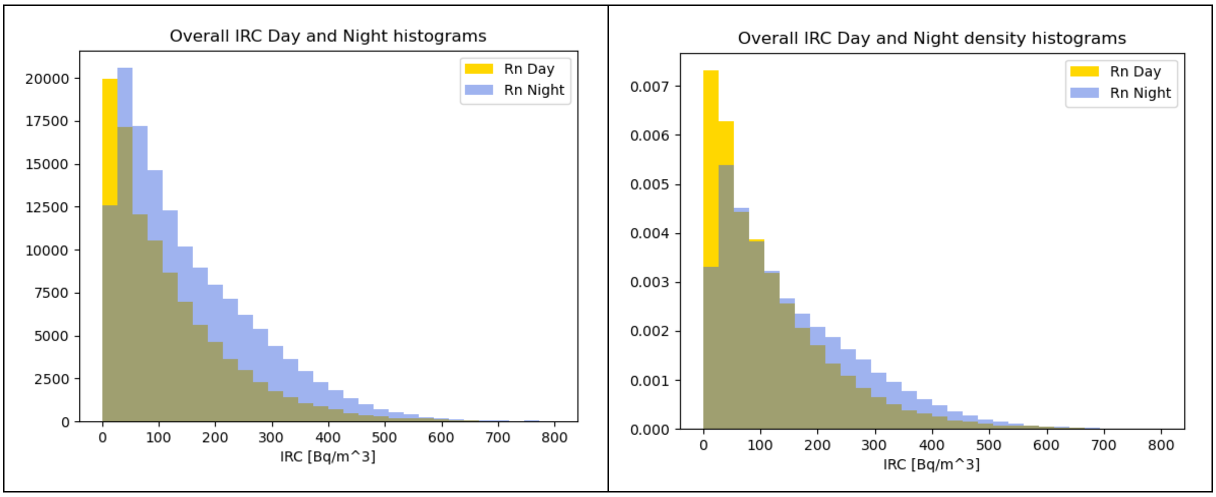


Figure 15: Histograms of the daytime and night-time indoor radon concentration measures (in Bq/m^3) in the 23 monitored dwellings. On the left the plain measure histograms, on the right the normalized density histograms. (daytime hours: 9:00-19:00)

Once formalized the delimitation hours between the “artificial” daytime and night-time, for every single day all the hourly measures labelled as diurnal and nocturnal were gathered and an average value calculated both for day and night. The day-by-day IRC day/night ratios were then collected all together. The distribution of day-night IRC ratios is almost symmetric with AM, median value and mode quite close to each other.

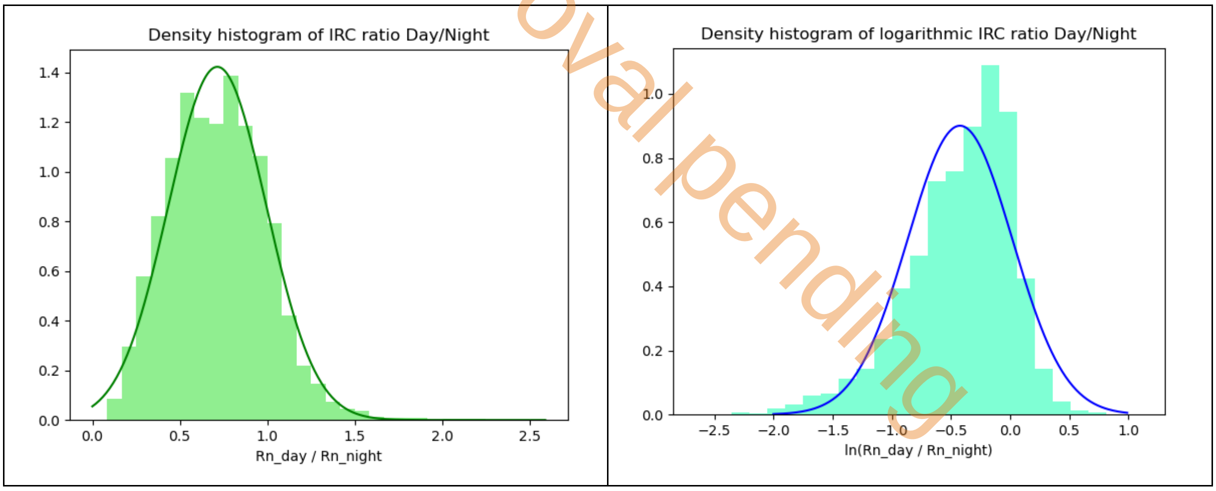


Figure 16: Normalized histograms of IRC_day/IRC_night ratios distribution (on the left) and their logarithms (on the right). The histograms are superposed with the gaussian curves with the distributions AM and STD. (daytime hours: 9:00-19:00)

In order to quantify the normality of such an “almost symmetrical” distribution, a Shapiro-Wilk normality test was performed both on the Day/Night Rn ratio distribution and its log version (see Figure 16 for a direct visualization). In both cases the p-value turned out to be extremely low, rejecting the normality hypothesis.

1.4.2.1 Workdays and Holidays

An analysis was conducted to compare indoor radon concentrations on weekdays (i.e., working days) versus weekends and holidays, based on the assumption that occupancy patterns differ between these days — particularly with respect to household ventilation.

Holidays are the 31% and working-days the 69% of the total days in the time interval (1/1/2022 - 31/12/2024). The two subsets are quite similar in terms of IRC measurements distribution (see Table 16), which probably means that the inhabitants of the selected dwellings don't change much behaviour between working and non-working days.

Table 16: Descriptive statistics of radon concentration distributions by working days and holidays.

	AM (Bq/m^3)	SD (Bq/m^3)	CV (%)	Min (Bq/m^3)	Median (Bq/m^3)	Mode (Bq/m^3)	Max (Bq/m^3)
Rn Workdays	138	119	86%	7*	104	13	1059
Rn Holidays	142	122	86%	7*	106	28	1151
* all the Rn measurements under 7 Bq/m^3 were set to 7 Bq/m^3							

Given the similitude between the two datasets, the two distributions are almost the same, the two histograms might seem different, however this is just due to the different number of measures they show. Once normalized, they are almost entirely superposed except for a small surplus of low IRC values during working days (see *Figure 17*).

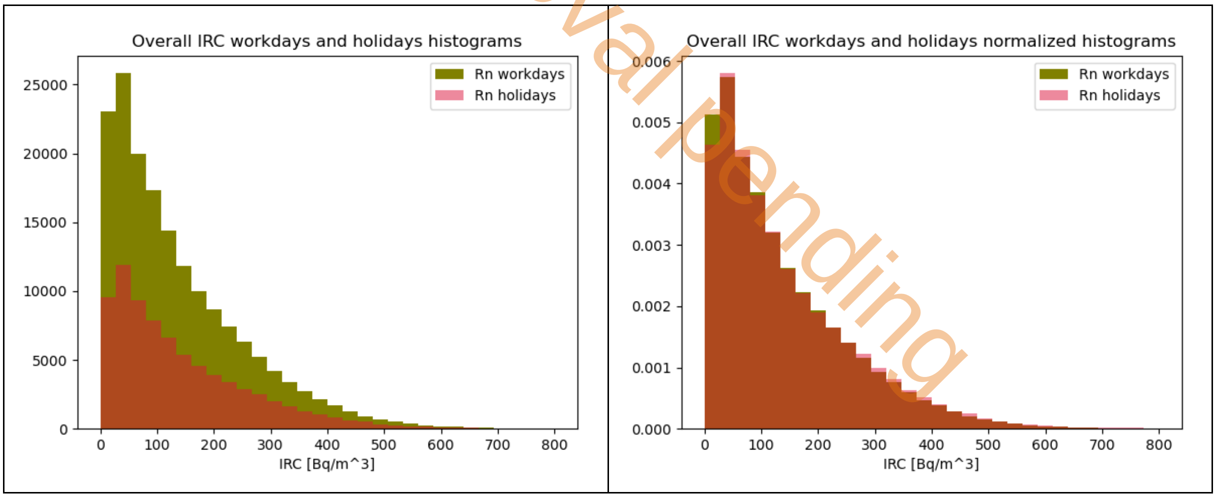


Figure 17: Histograms of the IRC measurements (in Bq/m^3) in all the 23 monitored dwellings, performed during workdays (green) and holidays (red). On the left the plain measurements histograms, on the right the two superposed normalized density histograms.

An additional analysis was carried out to investigate whether the day/night variability in radon concentration differs between working days and holidays, based on the assumption that the dwelling is occupied (and thus ventilated) differently during working days with respect to holidays The analysis was performed using the "artificial" subdivision of daytime hours, specifically from 09:00 to 19:00.

Table 17: Descriptive statistics of radon concentration distributions during working days, by time periods reflecting human activity (daytime hours: 9:00-19:00)

Workdays	**AM (Bq/m^3)**	**SD (Bq/m^3)**	**CV (%)**	**Min (Bq/m^3)**	**Median (Bq/m^3)**	**Mode (Bq/m^3)**	**Max (Bq/m^3)**
Rn Day*	116	109	94%	7**	84	13	1126
Rn Night	153	123	80%	7**	118	21	1159
Ratio (day/night)	0.72	0.29	40%	0.07	0.71	0.78	3.06
* daytime hours: 9:00-19:00 ** all the Rn measurements under 7 Bq/m^3 were set to 7 Bq/m^3							

We can observe that both nights and days in holidays have slightly higher values (higher AM and median values) and higher IRCs are a little more frequent (higher mode), however the coefficients of variation are very similar between them and to the overall distribution, as well as day/night ratios (AM, CV, median), since the overall, holidays and workdays, IRC distributions have the same shape.

Table 18: Descriptive statistics of radon concentration distributions during holidays, by time periods, reflecting human activity (daytime hours: 9:00-19:00)

Holidays	**AM (Bq/m^3)**	**SD (Bq/m^3)**	**CV (%)**	**Min (Bq/m^3)**	**Median (Bq/m^3)**	**Mode (Bq/m^3)**	**Max (Bq/m^3)**
Rn Day*	119	114	96%	7**	84	27	1051
Rn Night	158	125	79%	7**	123	48	1043
Ratio (day/night)	0.71	0.26	37%	0.11	0.71	0.42	1.93
* daytime hours: 9:00-19:00 ** all the Rn measurements under 7 Bq/m^3 were set to 7 Bq/m^3							

The analyses reveal that the ratio between IRC during the day and during the night does not differ between working days and holidays (0.72 vs 0.71). However, it is worth noting that these analyses were conducted between 2022 and 2024, in the years following the COVID-19 pandemic, which significantly altered work habits—most notably through the widespread adoption of remote working—which may have contributed to the absence of a detectable difference.

1.4.2.2 Natural vs. artificial day-night definition

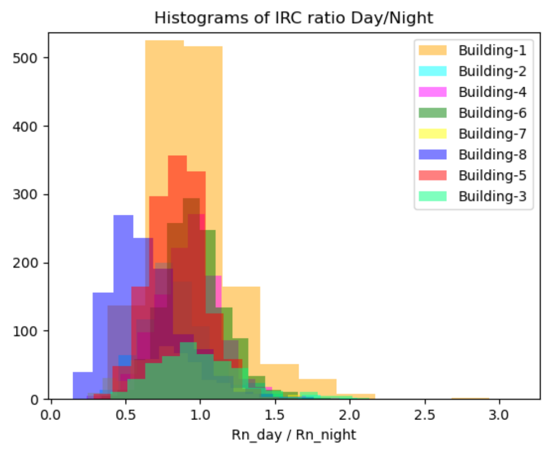
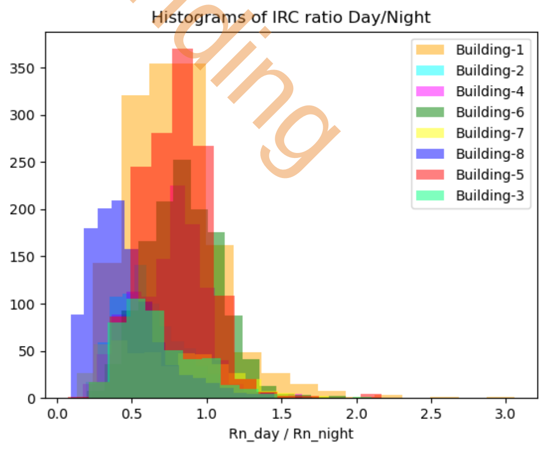
In this paragraph we are mostly interested in studying the radon measures distributions and their temporal variations in dwellings, without focusing on the environmental causes of such variations. However, interesting indirect information can be inferred confronting different datasets obtained subdividing data basing on different temporal criteria. As already mentioned, the day/night splitting can be defined basing on natural basis (sunrise/sunset hour) or artificial basis (higher/lower human activity). While subdividing the dataset by sunrise and sunset we expect to observe mostly the effect of external environmental parameters such as atmospheric pressure and temperature, humidity *etc*. on IRC (with some noise due to human activity), on the other hand, subdividing daytime and night-time according to an artificial human definition (daytime being set to 9:00-19:00 h) we can observe the effect of human activities such as opening/closing windows and doors, activating forced ventilation systems and so on.

Table 19: Descriptive statistics of radon concentration distributions by time periods, based on natural divisions of daytime and night-time (sunrise and sunset).

	AM (Bq/m^3)	SD (Bq/m^3)	CV (%)	Min (Bq/m^3)	Median (Bq/m^3)	Mode (Bq/m^3)	Max (Bq/m^3)
Rn Day*	124	114	92%	7**	90	13	1126
Rn Night	154	124	81%	7**	120	25	1159
Ratio (day/night)	0.88	0.27	30%	0.15	0.87	0.87	4.21
* daytime hours: between sunrise and sunset ** all the Rn measurements under 7 Bq/m^3 were set to 7 Bq/m^3							

Comparing the values in Table 19 with the ones in Table 15, we can clearly observe how in general human activity seems to lower IRC more efficiently than environmental factors. Even if the two IRC_day/IRC_night ratios of 0.71 ± 0.28 and 0.88 ± 0.27 are less than one sigma apart, the higher ratio values also in terms of median and mode in the "artificial" subdivision case, suggests the difference to be systematic.

The wider IRC difference between daytime and night-time radon concentrations, with the artificial day/night definition, is of course a generic phenomenon, and we expect the effect to depend on the characteristic inhabitants' habits, as well as building characteristics. Therefore, changing day/night definition does not have the same effect in all cases as shown in Figure 18.

Natural Sunrise/Sunset subdivision	**Artificial 9:00/19:00 subdivision**
	

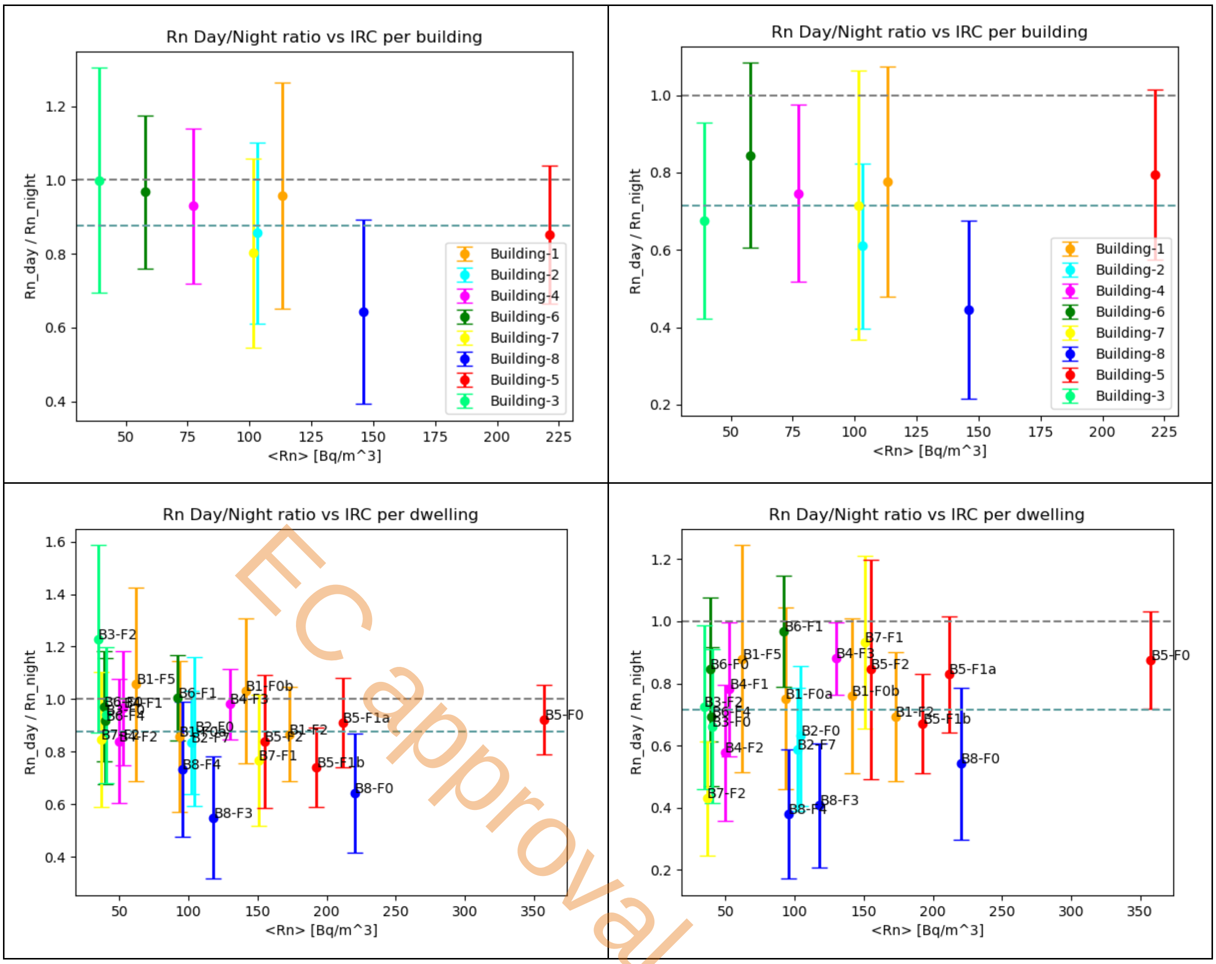


Figure 18: On the left column the pictures related to the natural day/night subdivision, on the right one the artificial definition (9:00-19:00). The top graphics represent the IRC histograms building-by-building in the two cases, while the other four show the shift of the ratios' arithmetical means in the two cases by building (central pictures) and by dwellings (bottom pictures). The labels on each dwelling in the graph indicate the building number (B) and the floor (F).

The "artificial" time definition has a clear effect, for instance, on Building 3 in which with the natural sunrise/sunset definition a dwelling has even a day/night ratio >1.2, while on the other case all the dwellings' ratios fall below 1. We can see a smaller effect for Buildings 4 and 6 and basically no effect for Building 7. However, in no case the buildings' ratio AM is lower with natural daytime definition with respect to the artificial one. We can argue that in the buildings where we see a smaller effect the situation is more chaotic and the inhabitants' timetables do not align with those of the general population, or maybe poor thermal insulation makes environmental conditions similar between day and night.

Another interesting feature of the different ways to define daytime hours and the different IRC ratios distributions that come with them, is that further subdividing the data by season (according to solstices and equinoxes) two very different pictures arise (see Figure 19). In the sunrise/sunset subdivision summer and autumn (autumn in Rome is characterized by mild temperatures) have frequently day/night ratios very close to one, since weather conditions between day and night in those two seasons are very similar. On the other hand, analysing the artificial subdivision we can observe even lower ratios values in summer and autumn than in spring and winter (exactly the opposite behaviour than the distribution with sunrise/sunset definition). We can argue that maybe in this case dwellings inhabitants tend to keep windows open longer, due to mild temperatures during the day.

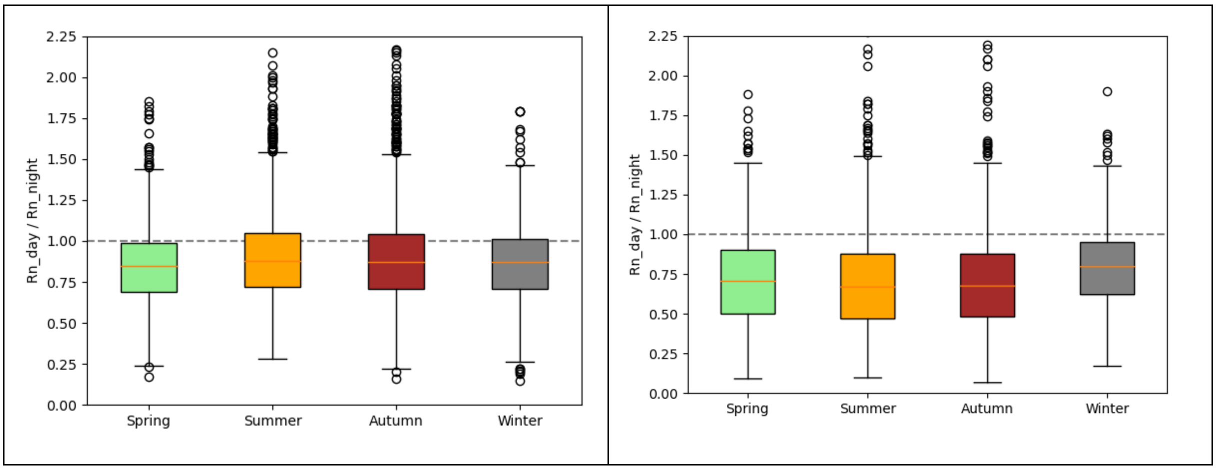


Figure 19: Boxplots of Indoor radon concentration ratios between day and night across different seasons, according to a natural daytime definition (sunrise/sunset, on the left), and according to an artificial daytime definition (9:00-19:00, on the right).

Separating the dataset by seasons appears to have a more significant effect than the subdivision by weekdays/holidays, probably because in this way clear changes can be observed both on human behaviour and climate, which are the main features respectively characterizing the two datasets, whereas in the other case such a distinction is way less sharp.

1.4.3 Conclusions

(Authored by ISS)

Analyses performed through Italian data acquired in the framework of RadoNorm is, of course, only a preliminary exploration of how IRC time series in dwellings—and their interactions with internal and external factors—can be analysed through the statistical distribution of the measurements. Further investigations using more advanced techniques, such as machine learning and other numerical approaches, and incorporating additional factors (e.g., geology, building type, and inhabitants' age), could yield more insightful conclusions with relatively little additional effort.

At this stage, based on the available dataset, it was possible to confirm a few general patterns: the IRC day/night ratio is nearly symmetrical (though not perfectly normally distributed); IRC tends to vary more between day and night than between holidays and working days. Moreover, the distribution of IRC ratios does not significantly differ between working days and holidays.

Seasonal differences, however, appear more relevant: in winter, when using the 9:00–19:00 definition for the daytime period, the day/night ratio is closer to 1 and shows less variability. This may reflect more stable indoor occupancy and reduced ventilation during colder months.

Comparing the analyses performed using different definitions of day- and night-time, we can conclude that, overall, the habits of the inhabitants appear to have a stronger influence on daily IRC variations than external climatic conditions.

1.4.4 References

Bochicchio, F., Venuti, G., Nuccetelli, C., Piermattei, S., Risica, S., Tommasino, L., Torri, G. (1996). Results of the Representative Italian National Survey on Radon Indoors. Health physics. 71: 741-748.

Bochicchio F, Forastiere F, Farchi S, Quarto M, Axelson O. (2005) *Residential radon exposure, diet and lung cancer: a case-control study in a Mediterranean region*. Int J Cancer. May 10;114(6):983-91. doi: 10.1002/ijc.20799. PMID: 15645434.

Marley, F. (2001). *Radon, progeny and health: investigation in different environments in Northamptonshire.* Doctoral thesis (2001). University of Leicester, URI: http://nectar.northampton.ac.uk/id/eprint/2814

Venoso, G., Iacoponi, A., Pratesi, G. *et al.* (2021). Impact of temporal variability of radon concentration in workplaces on the actual radon exposure during working hours. Scientific Reports 11: 16984.

Yarmoshenko, I., Zhukovsky, M., Onishchenko, A., Vasilyev A., Malinovsky, G. (2021). Factors influencing temporal variations of radon concentration in high-rise buildings. Journal of Environmental Radioactivity 232: 106575.

2 Spatial variability

2.1 Spatial variability within dwellings

(Contributor: DSA, HES-SO)

2.1.1 Background and literature review

(Authored by DSA)

This review addresses spatial variability within dwellings, with a particular focus on room-to-room differences in radon concentration—both between rooms located on different floors (e.g., ground floor and first floor) and between rooms situated on the same floor.

In this review, the following search terms were used, combined with the following Boolean operators:

the word "radon" (and its variants) in the title
AND
the words "spatial" OR "room" OR "floor" (and their variants) in the title or abstract
AND
the words "variation" OR "CV" OR "scatter" (and their variants) in the title or abstract
AND NOT
the locution "radon transform" in the title.

This query got 539 records. The title and abstracts of these records were carefully reviewed, and we ended up with 14 relevant papers dealing with dwellings, and 6 papers addressing variability in workplaces, that are discussed in the corresponding section 2.3.1.

A brief summary of the 14 selected articles dealing with dwellings is provided below.

2.1.1.1 Variability in dwellings: room to room – same floor

- In UK, Public Health of England and its predecessor organizations measured and reported radon concentration in 367 370 homes during the years 1982-2017. These data were analysed by Daraktchieva (2021). Measurements were performed in two occupied rooms situated either on different floors or on the same floor. The radon distribution on all floors had a range of 1-42740 Bq/m³. The geometric mean (GM) of radon concentration on the ground floor were on average 30% lower than those in the basement and 35% higher than those at the first floor. The GM ratio was 1.6 for properties where the living rooms were situated on a lower floor than bedrooms. For rooms at the same floor, the ratio was 1.1. In this study, the author emphasizes that house characteristics and energy efficiency had strong association with indoor radon concentrations.
- In Serbia, Žunić et al. (2014) conducted a study at the Balkan region to investigate the relationship between the indoor radon concentration and the geological background, with a focus on the geology. The indoor measurements, where detectors were placed in living areas at the same floor, were conducted for one year in 222 houses in three very different geological regions. The radon concentration in the rooms of the same floor differed by more than one order of magnitude. No detailed analyses were performed. According to the authors, every room with significant occupation time should be investigated if one wants representative radon concentrations.
- In four localities in Romania, Cucos et al. (2012) performed radon measurements with 2300 detectors in 303 dwellings, all detectors were placed in the lowest levels of inhabited area of each building, independent of room type. The total average radon (AM) concentration was 241 Bq/m³ with a total CV of 74%. The coefficient of variation within ground floor rooms of the same house ranged from 0.9% to 120% with an AM of 46%, show the large variability among rooms in the

surveyed dwellings. For kitchens and bedrooms, the CV was 98% and 91% respectively. The difference of concentrations in bedrooms above cellars and bedrooms in houses without cellars was also investigated, with the highest concentrations in bedrooms without cellars in the house. Indeed, the CV was similar for both groups, around 70%. The authors explain the high variability in concentrations to type of building, behavior of the occupants, various air exchange systems and age of construction. Also, in this study the authors highlight the importance of multiple detectors in different rooms to achieve representative exposure.

- In Egypt, Ghany (2006) evaluated radon concentration and exhalation rates in a neighborhood in Cairo. We consider concentration only to be relevant for this summary. The study comprised indoor radon measurements for one month in living rooms, bedrooms, bathrooms and kitchens in fourth floor of six identical apartments. The radon concentrations ranged from 48 to 84 Bq/m³. The radon concentration in kitchen and bathrooms were significantly higher than in living rooms and bedrooms. The author suggests ventilation and building materials as possible cause of these differences.
- In connection with the Iowa Radon Lung Cancer Study, Fisher et al. (1998) between the years 1993-1997 measured the variation of yearlong spatial radon concentrations in 918 homes where both spatial variation between floors and between rooms on the same floor were described. Detectors were placed on each level and in bedrooms and homework places. Then, the ratio between floors and CV calculated as a measure of relative variation between multiple measurements were determined. The ratio between floors varied between 0.51 and 1.02. The overall mean CV in different locations on the same floor was 9.5% with a range of 0% to 119%. The spatial radon concentration variation between rooms on the same floor was low, as 60% of them had CV less than 10%. The authors emphasize that wide individual radon variation between floors and between different areas on the same floor serve as a reminder of the importance of performing multiple radon measurements in various parts of the home.

2.1.1.2 Variability in dwellings: room to room - different floors

- In 23 states in the US, Li et. al (2022) investigated the spatiotemporal gradients in ratios between the radon concentrations in the upstairs and basements, defined as upstairs/basement ratio. Passive detectors were placed upstairs and basements in 10774 dwellings during the years 2005 to 2018, where short term upstairs/basement ratios were calculated. In addition, 3508 simultaneous long-term measurements were performed to verify the short-time measurements. Upstairs/basement concentration ratios were <1, for both short term- and long-term measurements, which means that upstairs radon concentrations were generally lower than basement concentrations. The ratios for the short-term measurements were higher in winter than other seasons, which emphasize the risk of exposure misclassifications compared to long term measurements.
- In a combined review-paper where also measurements in Italy were compared with other studies, Antignani et al (2021) present a table with average radon concentrations in different floors of the measured dwellings. The purpose of this study was to estimate the year-to-year variations during a period of ten years. Thus, no detailed room-to-room information was available. Anyway, the average radon concentration distribution in the different floors was as expected; ground floors 155 Bq/m³, 1st floors 96 Bq/m³ and >1st floors 88 Bq/m³.
- In northern Croatia, 15 randomly selected locations short-term indoors radon concentration was measured between July 2018 to July 2019 by Ptiček Siročić et al. (2020). Measurements were performed in different types of rooms and floors in residential and office buildings, family house and weekend cottages. Family houses tended to show smaller radon concentrations compared to residential buildings due to different types of constructions. Not surprisingly, the radon levels were higher in basements than in upper floors. An interesting finding was the high concentrations in office

buildings because doors and windows were closed after working hours and during weekends, which allowed the radon to accumulate to the higher floors.

- In Alexandria, Egypt, Abd-Elzaher (2012) measured the concentration of radon gas in living rooms, bedrooms, and kitchen in 56 dwelling in 14 districts. Houses in Egypt are mainly built of materials which contribute as a significant source of indoor radon. The average radon concentration for all dwellings was 58 Bq/m³, 41 Bq/m³ and 35 Bq/m³ for basements, ground floors and first floors, respectively. The mean values of the radon levels in living rooms, bedrooms and kitchen were 33 Bq/m³, 44 Bq/m³ and 56 Bq/m³, respectively. The rooms in this survey were situated in all floors of the houses, thus the detailed information regarding rooms is dependent on floor level.

- In the ICRU report 88 - Measurements and reporting of radon exposures (ICRU, 2012) -, the variation between room at the ground floor and between rooms in the upper floors and ground floors and between rooms in the upper floors are described. This report has the same conclusions as most of the single papers; the variations are caused by variations in convective air flows from beneath the floor slab, in air exchange, and, on a smaller scale, building materials.

- In Pakistan, Faheem et al. (2007) conducted a study to find out the average indoor radon concentrations during four seasons, summer, autumn, winter and spring. 40 representative houses in six different districts were surveyed, in total 240 houses. Both single storey and double storeys houses were included, and measurements were carried out in living/bedrooms of the ground floor. Average radon concentrations are presented for bedrooms and living rooms, and no further analyses were performed. The highest concentrations were found during the winter. With a few exceptions, higher indoor radon levels were observed in bedrooms compared to living rooms. The authors anticipate that this difference where due to the ventilation and building characteristics of the houses.

- In India, Sannappa et al. (2006) performed a study concerning the variation of radon and thoron in different rooms in old and new buildings. Here only radon is presented. The concentration of radon was higher in the rooms of old type of buildings and lower in the new type and in air-conditioned rooms. The authors emphasize this difference because of ventilation and tighter flooring in new type of buildings.

- In a work to estimate lung cancer risk, Matiullah et al. (2003) measured indoor radon concentration levels in 100 properties distributed in seven cities in Pakistan, all in all 700 homes. The survey was carried out for four seasons: summer, autumn, winter, and spring. The measurements were performed in living rooms and bedrooms. There was no information on which floor the rooms were situated. The results are presented as arithmetic and geometric mean in the living rooms and bedrooms with no further analyses. The GM was quite similar for both bedrooms and living rooms. The lack of information makes it difficult to interpret results.

- In Illinois, USA, Harley et al. (1991) measured the indoor concentration of radon in 52 homes. Each home had six detectors on average, with four at fixed locations and two personal monitors. We will not pay any attention to the personal monitors in this summary. The detectors were placed on each floor of the home and in the basement or family-room if one existed. For all 52 homes the ratio of first floor to basement was 0.20 with a range of 0.05 to 1.4. There was one basement value which showed a very high value compared to the other measurements. When this value was excluded, the ratio of first floor to basement increased to 0.48. The second floor to first floor ratio was close to unity regardless of the basement concentration.

2.1.1.3 Conclusions

In this review, the main question posed was whether the room-to-room variability in radon concentration is greater between rooms located on different floors of multi-level dwellings, compared to the variability observed between rooms on the same floor of a single-level dwelling. Based on the available studies, it is difficult to draw a clear conclusion about whether these types of variability differ significantly.

Regarding room-to-room variations on the same floor, radon concentrations can differ significantly, and it is difficult to identify any consistent pattern. These differences may be due to variations in building materials, ventilation conditions, and occupant behaviour. As an example, an open or closed window will have significant influence on the radon concentration.

Regarding room-to-room variations between floors, this review confirms that the concentration is highest where the rooms have direct ground contact. The concentration on the first and second floor is almost always lower than the basement, and the concentration depends on how the air flow is between the floors.

This review emphasizes the fact that the use of units is very different among the papers. Unsystematic use of coefficient of variation (CV), arithmetic mean (AM), geometric mean GM) and raw measurements data makes it difficult to compare the results among the reviewed papers. In addition, personal behaviour and use of building materials will also contribute to further make interpretation of practical use of collected data difficult. This is applicable both for measurements between floors and same floors.

In conclusion, several authors emphasize that high variation in radon concentration between floors and between different rooms at the same floor serve as a reminder of the importance of performing multiple radon measurements in all occupied rooms in homes, schools, or offices. A common protocol for measurements and presentation of data could be useful.

2.1.2 Overview of the analyses

To investigate the issue of spatial variability within dwellings, the following datasets were used:

- One Swiss dataset, with measurement performed in 20 single-family homes in the framework of a study aimed at evaluating performance of different radon devices;
- Three Norwegian datasets, with measurements obtained from three national surveys.

2.1.3 Swiss analyses

(Authored by HES-SO)

The results are presented in detail in Rey et al. (2025), entitled Performance evaluation of radon measurement techniques in single-family homes, aimed at comparing different measurement devices available in Switzerland. Various measurement protocols of different durations were tested during a one-year field campaign. Three spaces (two occupied, one unoccupied) in 20 buildings were investigated. Below, only a summary of the main results is reported.

Passive dosimeters from all investigation periods were compared to the annual reference radon level, taking into account the occupancy status of the investigated spaces. Occupancy did not have a significant impact on the accuracy or reliability of the measurements, as indicated by the slope values (Figure 20) highlighting the robustness of passive dosimeters across different exposure durations.

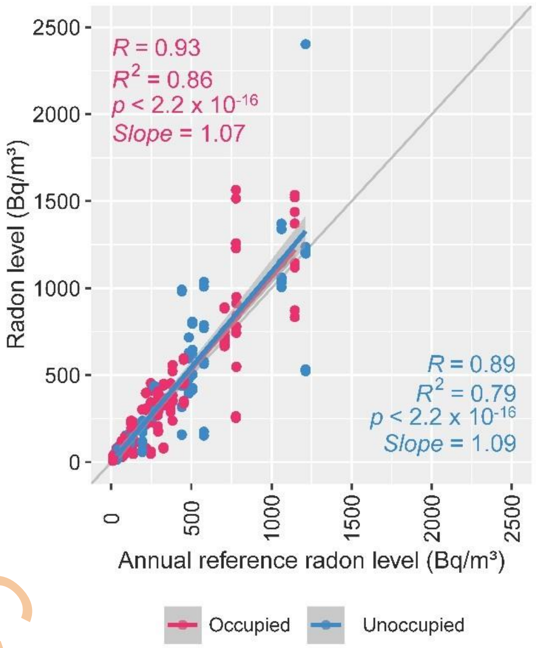


Figure 20: Radon concentration over different exposure durations, relative to the annual measurement, by occupancy status.

2.1.4 Analyses of Norwegian data: national random sample datasets

(Authored by DSA)

2.1.4.1 Presentation of the datasets

In Norway, three surveys (1998, 2013 and 2019) have been carried out in which homes have been randomly selected across the country. In all three surveys, radon activity concentrations were collected with track-etch detector for one year in the living room and one bedroom. In the 1998 survey, there is no information about which of the two detectors was placed in the living room and which one was placed in a bedroom. In the other two surveys (2013 and 2019), information on the room type is provided for each detector for the majority of homes.

Descriptive statistics for the mean radon activity concentration (RnC) in the homes are presented in Table 20. The 2019 survey is approximately half the size of the surveys conducted in 1998 and 2013. The 2013 survey recorded the highest arithmetic mean RnC (68 Bq/m^3), although only slightly higher than those in the 1998 and 2019 surveys. The 2019 survey showed the highest median and geometric mean RnC values, but the lowest percentages of RnC measurements exceeding 100, 200, and 300 Bq/m^3.

Table 20: Descriptive statistics of the mean RnC from the two measurements per home, presented separately for each of the three surveys and for all surveys combined.

	All (N=2869)	***1 998 (N=1291)***	***2 013 (N=1024)***	***2 019 (N=553)***
AM* (Bq/m^3)	64	61	68	63
SD (Bq/m^3)**	121	101	122	157
Median (Bq/m^3)	34	32	34	36
GM* (Bq/m^3)**	33	29	34	39
GSD******	3	4	3	2
Maximum (Bq/m^3)	3 350	1 239	1 947	3 350
N (%) > 100 Bq/m^3	447 (16)	199 (15)	178 (17)	70 (13)
N (%) > 200 Bq/m^3	145 (5)	66 (5)	61 (6)	18 (3)
N (%) > 300 Bq/m^3	72 (3)	32 (2)	31 (3)	9 (2)

*AM=Arithmetic mean, **SD=Standard deviation, ***GM=Geometric mean, ****GSD=Geometric standard deviation

The RnC thresholds of 100, 200, and 300 Bq/m^3 presented in Table 20 represent the recommended reference levels by the WHO (WHO, 2009) and commonly used national reference levels in European and other countries, respectively (see Table 21, adapted from D5.1 - RadoNorm, 2022)).

Table 21: Comparison of RnC reference levels across selected countries (D5.1 - RadoNorm, 2022)

Country	**Reference levels for RnC in dwellings (Bq/m^3)**	
	New	**Existing**
Argentina	300	300
Australia	200	200
Austria	300	300
Belgium	300	300
Canada	200	200
Croatia	300	300
Czech Republic	300	300
Estonia	300	300
Finland	200	300
France	300	300
Germany	300	300
Ireland	200	200
Italy	200	300
Norway	100/200	100/200
Poland	300	300
Portugal	300	300
Romania	300	300
Russian Federation	200	400
Slovenia	300	300
Sweden	200	200
Switzerland	300	300
United Kingdom	200	200

Norway differs from the other countries in having a two-part system of reference values – an action level of 100 Bq/m^3 and a maximum level of 200 Bq/m^3. The action level is the highest annual average radon activity concentration which may be accepted before radon mitigation should be carried out. Sometimes mitigation will not be able to bring the RnC below 100 Bq/m^3, and a higher RnC has to be accepted. Maximum level refers to the highest annual average radon level which is considered to be accepted in a frequently occupied room.

For the majority of the houses in the 1998-survey information on the housing type was not provided. For the 2013 and 2018 surveys, the householder was asked to give information on the housing type. To fill in the form, the householder had to choose between the housing types; detached house, terraced house, semi-detached house (horizontally divided), apartment in block of flats, terraced apartments and other (Figure 21). Some householders did not fill in the housing type, and these are designated as "not stated" in Table 22.

Figure 21: Housing types. From the left: detached house, terraced house, semi-detached houses (horizontally divided), block of flats, terraced apartments. Illustration: DSA

Table 22: Distribution of housing types in the 2013 and 2019 surveys.

	2013 survey	2019 survey
	Number (%) of homes	**Number (%) of homes**
Detached houses	742 (72)	363 (66)
Terraced houses	117 (11)	85 (16)
Semi-detached houses (horizontally divided)	27 (3)	15 (3)
Block of flats	81 (8)	60 (11)
Terraced apartments	17 (2)	5 (1)
Other	23 (2)	13 (2)
Not stated	18 (2)	12 (2)
Total	1025 (100)	553 (100)

In Table 23 the dataset from the 2013 and 2019 surveys are combined, and the descriptive statistics are given for all housing types.

Table 23: Descriptive statistics of the mean RnC from the two measurements per home for different housing types in the 2013 and 2019 surveys.

	Detached houses	Terraced houses	Semi-detached houses (vertically divided	Apartment in a block of flats	Terraced apartments	Other	Not stated
	N=1107 (71%*)	**N=202 (13%)**	**N=42 (3%)**	**N=141 (9%)**	**N=22 (1%)**	**N=36 (2%)**	**N=202 (13%)**
AM**	78	50	42	28	37	37	79
SD**	158	74	40	23	45	30	121
Median**	40	31	26	22	22	27	33
GM**	40	32	28	22	23	26	34
GSD	3.01	2.55	2.55	2.02	2.5	2.43	3.91
Maximum**	3350	875	183	168	187	150	468
N (%*) > 100 Bq/m^3**	215 (19)	20 (10)	4 (10)	2 (1)	2 (10)	1 (3)	3 (17)
N (%*) > 200 Bq/m^3**	71 (6)	5 (3)	0 (0)	0 (0)	0 (0)	0 (0)	3 (17)
N (%*) > 300 Bq/m^3**	38 (3)	1 (0.5)	0 (0)	0 (0)	0 (0)	0 (0)	1 (6)

*% of 1568, which is all the houses in 2013 and 2019

**Unit: Bq/m^3

***% of the housing type

The Table 23 are showing that the highest mean, median, GM, and percentage of RnC measurements exceeding 100, 200 and 300 Bq/m^3 are all found in detached dwellings and the "not stated" houses. Since detached houses make up 71% of the housing stock in the surveys, it is natural to assume that the "not stated" group mainly consists of single-family homes as well – which in turn may explain why we find a high AM, GM and percentage above 100 Bq/m^3 in this group.

Horizontally divided semi-detached houses are a designated housing type in the Norwegian housing register. In these homes, one family lives on the bottom floor, and another family on the upper floor. Different radon activity concentrations are expected depending on whether the lowest or highest apartment is measured.

In apartments in block of flats, the radon activity concentration is, according to "common knowledge" expected to be lower at higher floors, although this is a truth that is challenged in some cases (see literature review about spatial variation within buildings in chapter 2.2.1). Terraced apartments are often built into the terrain. Hence, high radon activity concentrations might be expected in higher floors in this housing type. However, of the four apartments in block of flats and terraced apartments where the mean RnC was exceeding 100 Bq/m^3, two were on the ground floor, one on the first floor, and one was unknown.

2.1.4.2 Investigation of room-to room variability

To highlight and investigate the room-to-room variability between rooms on different floors and between rooms at the same floor, several analyses have been conducted:

A. Descriptive statistics for rooms at the same floor and rooms at different floors
B. Descriptive statistics for bedrooms and living rooms, at the same floor and rooms at different floors
C. The radon activity concentration ratios for rooms at the same floor and different floors were investigated and compared
D. It was investigated how often performing only one measurement would have failed to find homes above the reference level (RL).

A. Descriptive statistics for rooms with the highest and lowest RnC, at the same floor and at different floors

For all the dwellings a pair of measurements were conducted – sometimes on the same floor (N=1418) and sometimes on different floors (N=1321). Normally, one measurement showed a higher concentration than the other. The measurement with the highest concentration was called "highest" and the one with the lowest concentration was called "lowest". In cases where the concentration was identical, one was still called "highest" and the other "lowest". Descriptive statistics were then performed on all the lowest and all the highest measurements on the same floor, and likewise for the measurements made on different floors (Table 24).

Table 24: Descriptive statistics of the lowest and highest measured RnCs at the same floor and different floors in all 3 surveys combined

	Measurements at different floors (N=1321)		**Measurements at same floor (N=1418)**	
	Highest RnC	**Lowest RnC**	**Highest RnC**	**Lowest RnC**
AM (Bq/m^3)	92	58	66	42
SD (Bq/m^3)	182	125	112	68
Median (Bq/m^3)	48	30	34	22
GM (Bq/m^3)	48	28	34	20
GSD	3	3	3	4
Maximum (Bq/m^3)	4000	2700	1637	1188
% > 100 Bq/m^3	24	13	16	9
% > 200 Bq/m^3	9	4	6	3
%> 300 Bq/m^3	5	2	3	1

The descriptive statistics in Table 24 shows that the radon activity concentrations, at average, the geometric mean and median are higher in the homes where the measured rooms are at different floors than when they are at the same floor. As seen from Table 23, the RnC in apartments in block of flats tend to be lower than in other housing types, and each apartment normally have only one floor. There is therefore reason to believe that the lower radon concentrations in homes where measurements were taken on the same floor in Table 24 are due to the fact that many of the homes are apartments.

To be able to study the difference between the floors without the influence of e.g. apartments in block of flats, detached houses were selected for further study, and the descriptive statistics are shown in Table 25.

Table 25: Descriptive statistics of the lowest and highest measured RnC values at the same floor and different floors in detached homes, all 3 surveys combined.

	Different floors (N=558)		**Same floor (N=488)**	
	Highest RnC	**Lowest RnC**	**Highest RnC**	**Lowest RnC**
AM (Bq/m^3)	110	70	75	51
SD (Bq/m^3)	243	169	98	68
Median (Bq/m^3)	51	33	43	29
GM (Bq/m^3)	55	34	41	26
GSD	3	3	3	3
Maximum (Bq/m^3)	4000	2700	814	490
% > 100 Bq/m^3	28	15	21	13
% > 200 Bq/m^3	12	6	8	4
%> 300 Bq/m^3	6	3	3	2

The descriptive statistics still shows that the RnCs (both the lowest one and the highest one), at average as well as the median and geometric mean, are higher in the homes where the rooms measured are at different floors than when they are at the same floor. The reason for this is unclear. The total number of floors are known for most of the homes. The homes with the two measurements at the same floor have an average of 2.1 floors. The homes with the two measurements at different floors have an average of. 2.6 floors. A hypothetical explanation for the higher RnC in the homes with the most floors could be that multiple floors, and open staircases between floors, will be able to produce a chimney effect. Further, the more floors, the higher the chimney effect and RnC. However, this has not been investigated further in this study.

All housing types taken together, the difference between the two measurements is on average 24 and 32 Bq/m^3 for measurements on the same floor and different floors, respectively. Correspondingly, the median differences between the two measurements are 8 and 11. However, as can be seen from the boxplots (Figure 22) showing the differences between the two measurements (highest minus lowest RnC) in all house types, the differences in some of the dwellings are quite large and even above 1000 Bq/m^3.

To further investigate the variation between the two measurements in this dataset, see section C. Ratios.

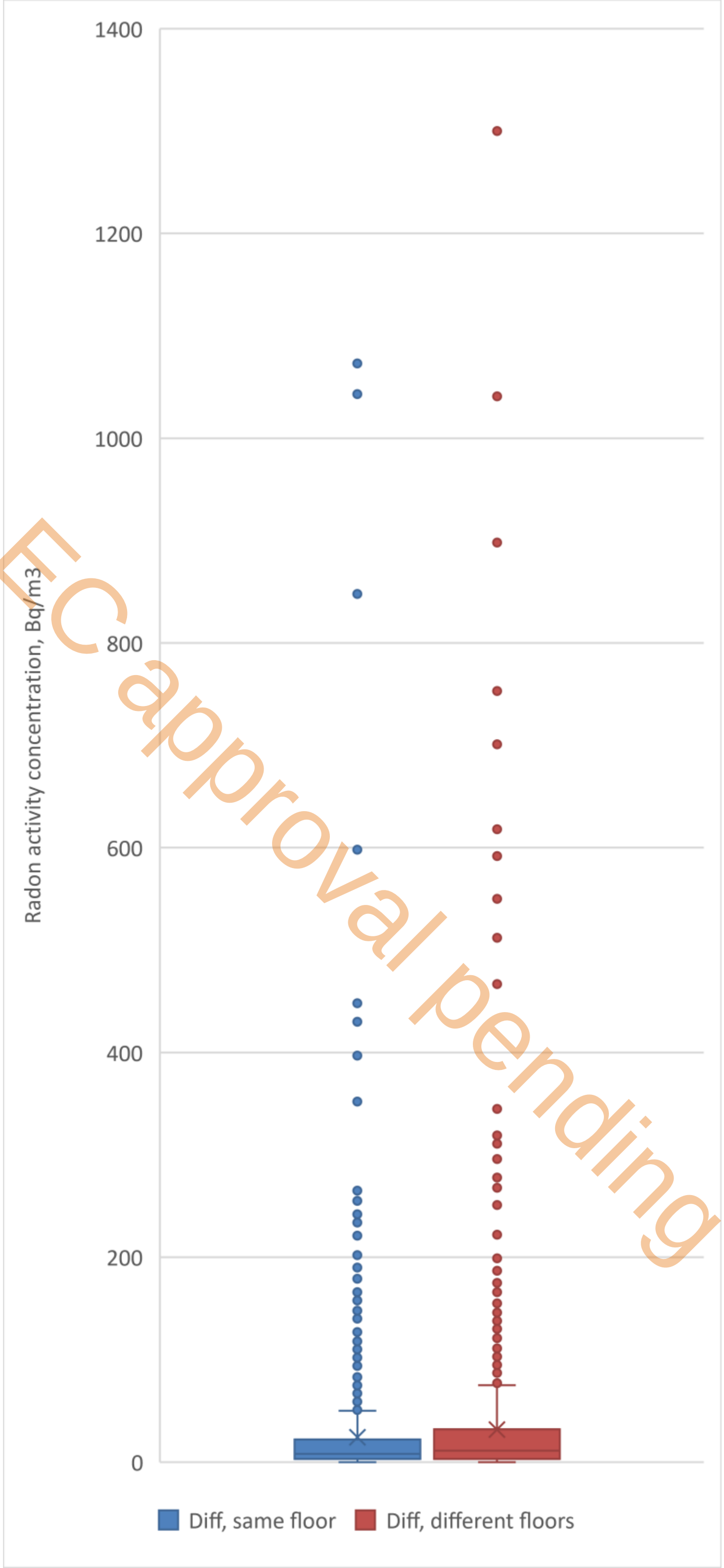


Figure 22*: RnC differences (highest RnC minus lowest RnC), measured at the same floor and at different floors for all housing types.*

B. Descriptive statistics for bedrooms and living rooms, at the same floor and at different floors

In this section the different room types, living rooms and bedrooms, are investigated. Room type is known only in the 2013 and 2019 surveys. To be able to study the difference between the floors without the influence of e.g. apartments in block of flats, detached houses and apartments in block of flats were studied separately, and the descriptive statistics are shown in Table 26.

Table 26: Descriptive statistics of the RnC values in bedrooms and living rooms in detached houses and apartments in block of flats in the 2013 and 2019 surveys combined, when the bedroom and the living room are at the same floor and at different floors.

	Detached houses Different floors (N=558, ratio*= 1)		**Detached houses Same floor (N=486, ratio*=0,82)**		**Apartments in block of flats, Same floor (N=132, ratio*= 1,00)**	
	Living room	**Bedroom**	**Living room**	**Bedroom**	**Living room**	**Bedroom**
AM (Bq/m^3)	96	84	72	54	29	27
SD (Bq/m^3)	229	189	96	72	26	24
Median (Bq/m^3)	46	39	41	30	22	22
GM (Bq/m^3)	48	39	39	28	23	21
GSD	3	3	3	3	2	2
Max (Bq/m^3)	4000	2700	814	522	216	200
% > 100 Bq/m^3	24	18	20	14	2	2
% > 200 Bq/m^3	9	8	8	5	1	0
%> 300 Bq/m^3	5	4	3	2	0	0

* The AM of Ratios (RnC in the bedroom divided by the RnC in the living room).

The descriptive statistics shows that the RnCs, at average, are higher in the living rooms and bedrooms when those are located on different floors than when they are located on the same floor, which is the same finding as found in the section A. In apartments with only one floor, the radon activity concentration in living rooms and bedrooms are equal with respect to AM, GM and Median.

The difference between the measured radon activity concentration in the living room and the bedroom (living room minus bedroom) for all housing types and when the rooms are at different floors varies between -1041 Bq/m^3 and + 1300 Bq/m^3. When the rooms are at the same floor the difference varies between -194 and +598 Bq/m^3. The distribution of the difference between the living room and the bedroom, measured at the same floor and at different floors, is shown in the boxplot in Figure 23. The figure clearly shows that there are many outliers.

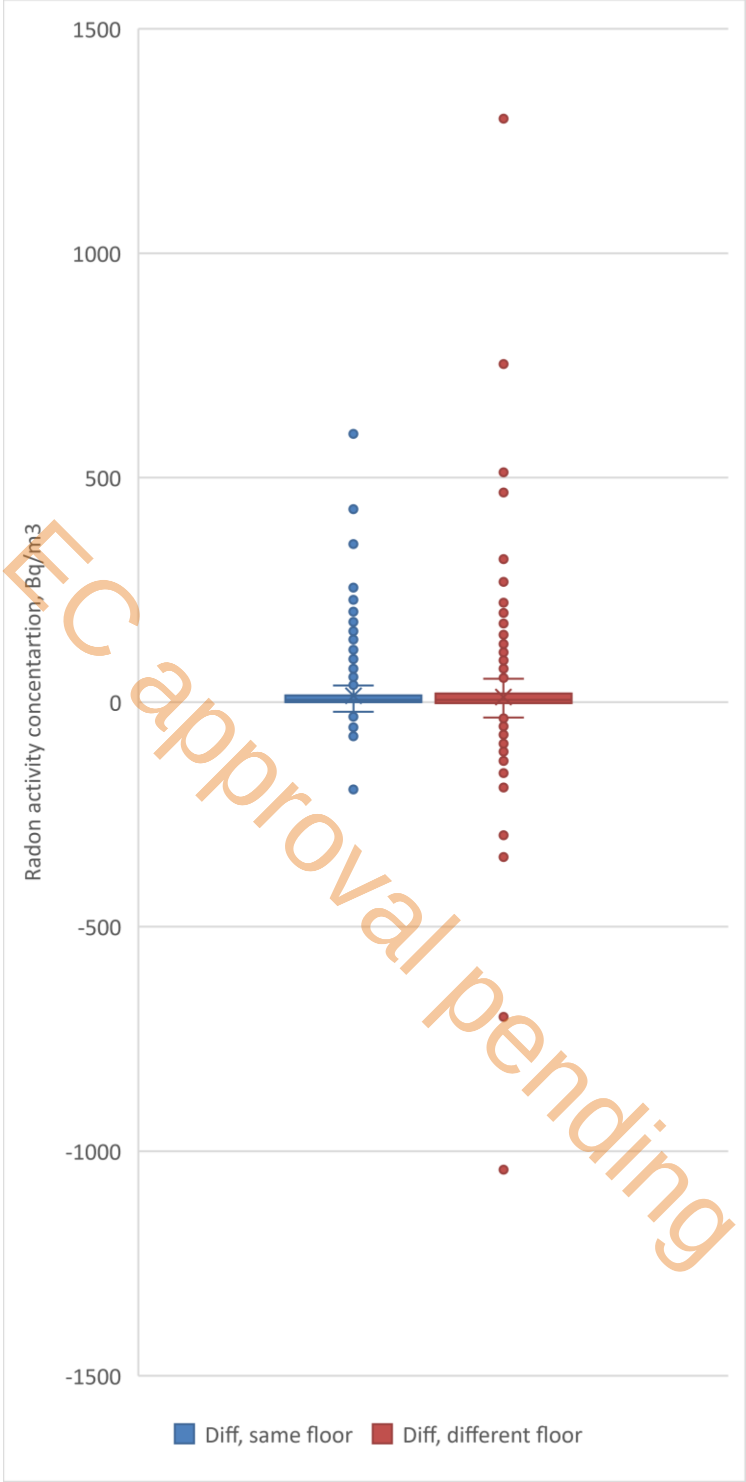


Figure 23: Radon activity concentration differences (living room minus bedroom), measured at the same floor and at different floors – all housing types.

C. Ratios

To be able to make descriptive statistics on the ratios, zeros in the denominator had to be non-zero. All RnC= 0 Bq/m^3 was changed to 1 Bq/m^3. The descriptive statistics are given in Table 27. Boxplots of ratios for two measurements measured at the same floor and different floors are shown in Figure 24.

Table 27: Descriptive statistics of the ratios (lowest RnC/highest RnC in the home) for the 1998, 2013, 2019 survey, and all surveys combined.

	All same floor	**All different floors**	**1998 same floor**	**1998 different floors**	**2013 same floor**	**2013 different floors**	**2019 same floor**	**2019 different floors**
N	1418	1321	683	586	473	465	262	270
AM (Bq/m^3)	0.66	0.66	0.60	0.63	0.69	0.66	0.78	0.72
SD (Bq/m^3)	0.25	0.25	0.27	0.26	0.23	0.24	0.18	0.21
Median (Bq/m^3)	0.71	0.70	0.61	0.65	0.74	0.70	0.83	0.75
Min (Bq/m^3)	0.04	0.02	0.04	0.03	0.04	0.02	0.22	0.12
Max (Bq/m^3)	1	1	1	1	1	1	1	1

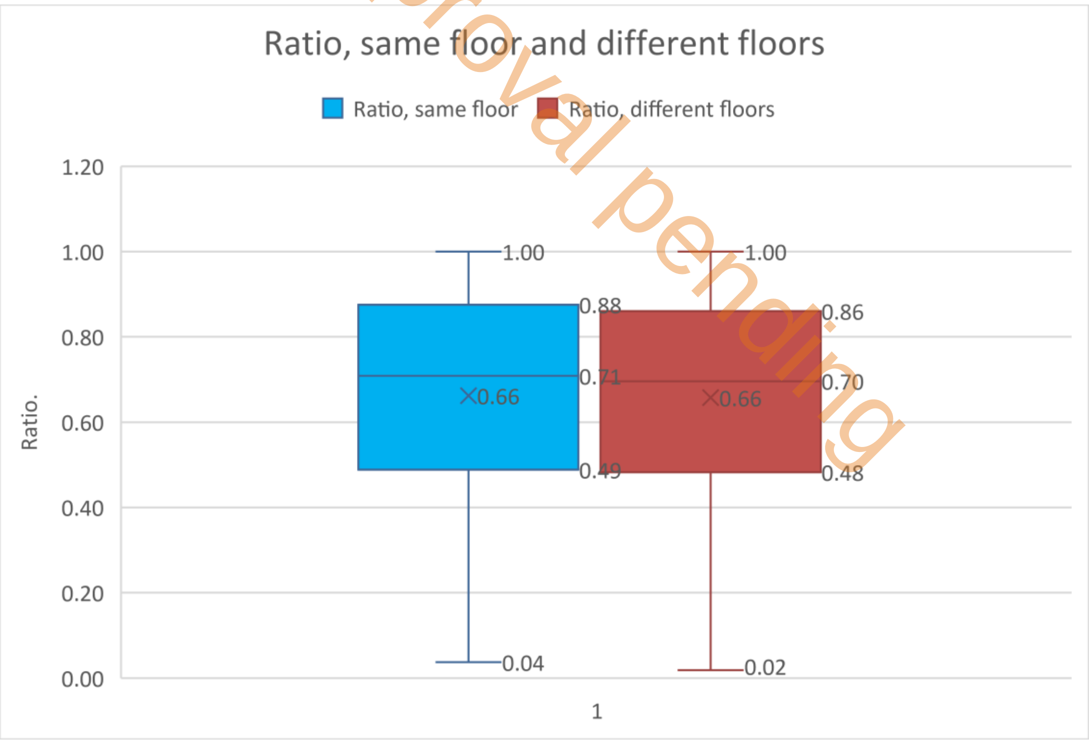


Figure 24: Ratios for two measurements measured at the same floor and different floors are. For homes with two measurements at the same floor: N=1418. For homes with measurements at different floors N=1321.

The ratios of measurements measured at the same floor and different floors are very much the same. As may be seen from the Table 27, the difference in ratio differs more from survey to survey than between measurements at the same floor and different floors in the combined survey.

As can be seen from Table 26, the ratios of the RnC in the bedroom and the living room (bedroom divided by living room) have been calculated for detached houses and apartments in block of flats in the 2013 and 2019 surveys combined, when the bedroom and the living room are at the same floor and at different floors. In detached houses, different floors and same floors, and in apartments in block of flats (only one floor) the ratios are 1, 0.82 and 1, respectively. To gain a closer understanding of these differences, it may be necessary to study in more detail which floors bedrooms and living rooms are usually located on, as well as ventilation habits.

D. How often does one measurement, compared to two measurements, fail to find a homes above RL?

In the WHO Handbook on indoor radon (WHO, 2009) the recommended reference level is 100 Bq/m^3. For EU member states the Basic Safety Standards Directive (2013), article 74, states that national reference levels for indoor radon concentrations shall be established and further stating that the reference level for the annual average radon activity concentration in air shall not be higher than 300 Bq/m^3. As shown in Table 21, 200 and 300 Bq/m^3 seem to be common national reference Levels (RL) for new and existing dwellings in countries investigated in the RadoNorm WP 5 (RadoNorm, 2022, Deliverable 5.1, Table 3). In most of the participating EU member states (eleven out of 15), a RL in dwellings of 300 Bq/m^2 has been implemented.

It is assumed that the extent to which national measurement protocols have been established, and the content of these, varies from country to country. For example, is there a requirement for more than one measurement per home, and what would be the consequence of measuring in only one room? In the following tables (Table 28, Table 29, Table 30 and Table 31) it is investigated with the present data set whether one measurement, as opposed to two measurements, in the home fails to determine whether the home has a radon concentration above the national reference level, or not.

Table 28: How often, in percentage, was the RnC$_{low}$ below the RL at the same time as the average of the two measurements was at or above?

	Different floors (N=1321)	**Same floor (N=1418)**
RL= 300 Bq/m^3	0.9	0.6
RL=200 Bq/m^3	1.7	1.3
RL=100 Bq/m^3	6.2	3.7

Table 29: How often, in percentage, was the RnC$_{low}$ below the RL at the same time as the RnC$_{high}$ was higher?

	Different floors (N=1321)	**Same floor (N=1418)**
RL= 300 Bq/m^3	2.6	1.5
RL=200 Bq/m^3	5.1	2.5
RL=100 Bq/m^3	10.7	7.5

Table 30: How often, in percentage, was the $RnC_{bedroom} < RL$ *and the* $RnC_{livingroom} > RL$*?*

	Different floors (N=720)	Same floor (N=719)
RL=300 Bq/m^3	1.4	0.7
RL=200 Bq/m^3	2.9	2.5
RL=100 Bq/m^3	8.2	6.3

Table 31: How often, in percentage, was the $RnC_{livingroom} < RL$ *and the* $RnC_{bedroom} > RL$*?*

	Different floors (N=720)	Same floor (N=719)
RL=300 Bq/m^3	1.0	0
RL=200 Bq/m^3	2.1	0.3
RL=100 Bq/m^3	2.6	0.7

The tables show that one measurement, as opposed to two measurements, in the home fails to determine whether the home has a radon concentration above the national reference level in 0-7.5% of the homes when the measurements are at the same floor and in 0.9-10.7% when the measurements are at different floors.

However, it is important to be aware that how to measure and calculate a value to be compared with the reference level varies from country to country probably depending on national measurement procedure or established custom. As an example, it can be mentioned that the reference level in Sweden and Norway is for both countries 200 Bq/m^3. In Sweden the reference level refers to an average of measurements in the dwelling. The average of the home is calculated by first finding the average of each floor and then calculate the average of floors. In Norway the reference level refers to each single room (occupied rooms, like living- and bedroom). This means that if, in a two-storey home, 250 and 150 Bq/m^3 are measured in occupied rooms on the lowest floor and 50 and 80 Bq/m^3 are measured in occupied rooms on the upper floor, the home in Sweden will be below the reference level (((250+200)/2+(80+50)/2)/2 Bq/m^3=145 Bq/m^3), while in Norway it will be interpreted as above the reference level.

2.1.4.3 Conclusions

The aim of this study was to investigate whether within the same dwelling, is the room-to-room variability greater between rooms on different floors if the dwelling is on several levels than the variability between rooms in a single-level dwelling? To investigate this data from three surveys with randomly selected homes across the nation, and two measurements in each home was used. Not directly answering the research question, but anyway interesting was the descriptive statistics revealing that, on average, both the highest and the lowest radon activity concentration in the homes, as well as the median and geometric mean, are higher in the homes where the measured rooms are at different floors than when they are at the same floor. Likewise, the descriptive statistics shows that the radon activity concentrations, on average, are higher in the living rooms and bedrooms when those are located on different floors than when they are located on the same floor. Since the number of floors on average was different with an average of floors of 2.1 and 2.6 in the homes with the two measurements at the same floor and different floors respectively, a hypothetical explanation is the chimney effect. However, this has not been investigated further in this study. In apartments with only one floor the radon activity concentration in living rooms and bedrooms was equal with respect to AM, GM and median.

All housing types taken together, the absolute difference between the two measurements was on average 24 and 32 Bq/m^3 for measurements on the same floor and different floors, respectively. Correspondingly, the median differences between the two measurements were 8 and 11. Nevertheless, the differences between the two measurements in some of the dwellings were quite large and even above 1000 Bq/m^3. However, the ratios of measurements measured at the same floor and different floors are very much the same (on average 0.66). The difference in ratio differs more from survey to survey than between measurements at the same floor and different floors in the combined survey.

Ratios of the radon activity concentrations in the bedroom and the living room (bedroom divided by living room) was calculated for detached houses and apartments in block of flats in the 2013 and 2019 surveys combined, when the bedroom and the living room are at the same floor and at different floors. In detached houses, different floors and same floors, and in apartments in block of flats (only one floor) the ratios are 1, 0.82 and 1, respectively. To gain a closer understanding of these differences, it may be necessary to study in more detail which floors bedrooms and living rooms are usually located on, as well as ventilation habits.

Finally, it was investigated whether variation within a dwelling would result in dwellings above the reference level not being found if only one measurement, as opposed to two measurements, was performed. One measurement, as opposed to two measurements, in the home failed to determine whether the home had a radon concentration above the national reference level in 0-7.5% of the homes when the measurements were at the same floor and in 0.9-10.7% when the measurements were at different floors.

2.1.5 References

Abd-Elzaher M. (2012). Measurement of indoor radon concentration and assessment of doses in different districts of Alexandria city, Egypt. Environmental geochemistry and health. 35.

Antignani S., Venoso G., Ampollini M., Caprio M., Carpentieri C., Di Carlo C., Caccia B., Hunter N., Bochicchio F. (2021). A 10-year follow-up study of yearly indoor radon measurements in homes, review of other studies and implications on lung cancer risk estimates. Sci Total Environ. 762: 144-150.

Cucoş Dinu A., Cosma C., Dicu T., Begy R., Moldovan M., Papp B., Niţă D., Burghele B., Sainz C. (2012). Thorough investigations on indoor radon in Băiţa radon-prone area (Romania). Sci Total Environ. 431: 78-83.

Daraktchieva Z. (2021). Variability of indoor radon concentration in UK homes. J Radiol Prot. 18.

Faheem M., Mati N., Matiullah. (2007). Seasonal variation in indoor radon concentrations in dwellings in six districts of the Punjab province, Pakistan. J Radiol Prot. 27: 493-500.

Fisher E.L., Field R.W., Smith B.J, Lynch C.F., Steck D.J., Neuberger J.S. (1998). Spatial variation of residential radon concentrations: The Iowa Radon Lung Cancer Study. Health Phys. 75: 506-13.

Ghany H.A.A. (2006) Variability of Radon Levels in Different Rooms of Egyptian Dwellings. Indoor and Built Environment. 15: 193-196.

Harley N.H., Chittaporn P., Roman M.H., Sylvester J. (1991). Personal and home ^{222}Rn and gamma-ray exposure measured in 52 dwellings. Health physics 61(6): 737-744.

ICRU (2012). ICRU Report 88. Measurement and reporting of radon exposures. J. of ICRU. 12:2.

Li L., Stern R.A., Blomberg A.J., Kang C.M., Wei Y., Liu M., ... & Koutrakis P. (2022). Ratios between radon concentrations in upstairs and basements: A study in the northeastern and midwestern united states. Environmental Science & Technology Letters 9(2): 191-197.

Matiullah A.A., Rehman S., Mirza M.L. (2003). Indoor radon levels and lung cancer risk estimates in seven cities of the Bahawalpur Division, Pakistan. Radiat Prot Dosimetry 107: 269-76.

Ptiček Siročić A., Stanko D., Sakač N., Dogančić D., Trojko T. (2020). Short-term measurement of indoor radon concentration in Northern Croatia. Applied Sciences 10(7): 2341.

RadoNorm (2022). D5.1 - Report on regulatory approaches and radon control technologies used in dwellings, workplaces and large buildings. https://www.radonorm.eu/wp-content/uploads/file_exchange/D5.1_Report-on-regulatory-approaches-and-radon-control-technologies-used-in-dwellings-workplaces-and-large-buildings_approved17052023.pdf

Sannappa J., Chandrashekara M.S., Paramesh L. (2006). Spatial Distribution of Radon and Thoron Concentrations Indoors and their Concentrations in Different Rooms of Buildings. Indoor and Built Environment 15: 283-288.

WHO (2009). WHO handbook on indoor radon: a public health perspective. World Health Organization.

Žunić Z.S., Ujić P., Nađđerđ L., Yarmoshenko I.V., Radanović S.B., Petrović S.K., ... & Bossew P. (2014). High variability of indoor radon concentrations in uraniferous bedrock areas in the Balkan region. Applied Radiation and Isotopes 94: 328-337.

2.2 Spatial variability within buildings

(Contributors: ISS, STUK, DSA)

2.2.1 Background and literature review

(Authored by ISS)

2.2.1.1 Methods

This section is aimed at studying indoor radon variability from dwelling to dwelling inside the same building. There are few studies on this aspect. However, this information is essential to determine whether each dwelling in a building requires individual measurement or if radon levels can be inferred from a neighbouring dwelling. Protocols for radon mapping purposes (i.e., to identify high radon areas) typically focus on the ground and lower floors of buildings, assuming that radon levels on the upper floors are consistently lower within the same buildings. However, there is some evidence to suggest that variations can be substantial between adjacent dwellings. In subtask 2.1.1 of the RadoNorm project, a review of literature and initial analyses are being conducted on this issue.

A search of papers studying indoor radon activity concentration was conducted using as resources the Web of Science, Scopus, Elicit and Semantic Scholar search engines. The keywords used in the search were: “radon”, “concentration”, “levels”, “dwelling(s)”, “same”, “building”, “variability”, sometimes used all together, sometimes in subgroups.

The search was limited to articles published in English. Papers not extensively analysing variability, with limited sample (only one or two buildings measured) or focusing on building types other than dwellings were excluded (see flowchart in Figure 25).

The search was updated until January 2025.

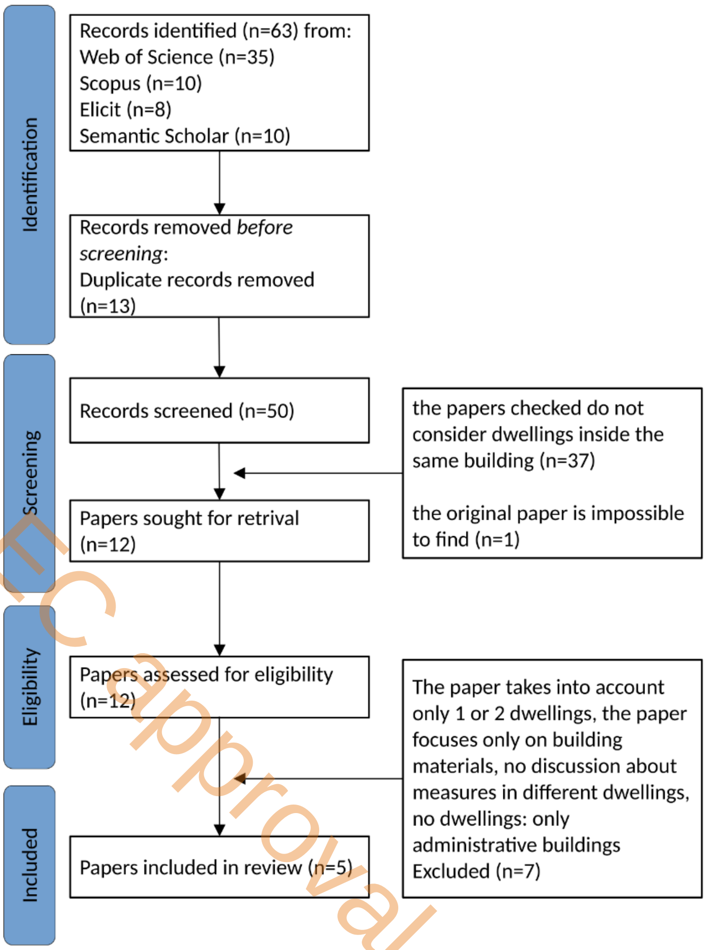


Figure 25 Flowchart for the review on spatial variability within buildings

2.2.1.2 Discussion of the selected papers

All the selected papers state that the average Indoor Radon Concentration (IRC) varies considerably from dwelling to dwelling inside the same building, suggesting that radon levels are affected by factors other than just building type and location. Most of the research works focuses on finding out the reasons of this phenomenon, in some cases confronting the size of the effect in different kinds of buildings (Tchorz-Trzeciakiewicz & Olszewski, 2019) or the seasonal dependence of the IRC variations (Senitkova & Kraus, 2019) or chimney effect (Florică et al., 2024). In all cases the measurements were performed using passive detectors. In most cases (Senitkova & Kraus, 2019; Tchorz-Trzeciakiewicz & Olszewski, 2019; Borgoni et al., 2014) the data were analysed all together and the analysis results showed collectively, while in Vukotic et al. (2019) and Florică et al. (2024) the buildings were both considered separately and collectively.

From a careful reading of the articles as a whole, the common knowledge that increasing the dwelling floor IRC should decrease, does not turn out to be a firm and clear rule. In Tchorz-Trzeciakiewicz & Olszewski (2019) the authors, among a general IRC decreasing with increasing floor number, noticed that IRC differed 4 to 6 times even among dwellings located in these same types of buildings, on these same soil types or these same floors. In Senitkova & Kraus (2019) the maximum values of radon concentration are observed in the first and second-floor rooms probably due to the contribution of radon emanation from the soil.

In Vukotic et al. (2019), measures in the studied multi-storey buildings are highest in dwellings on the ground floor. A decrease of radon concentration is observed from the ground floor to the 1st floor, with a ratio of the arithmetic means 1.20. A gradient of changes in radon concentrations from the 1st floor upward cannot be noticed because the mean and median values of radon concentrations oscillate irregularly.

In Borgoni et al. (2014), within the sample of 676 rooms in 358 buildings two distinct strata were identified: underground+ground floor, and first+second+third. The floor effect tended to be more variable at lower floors where concentrations were higher although the variability was found to increase again at the top floor, possibly due to the scarcity of the sample measures taken at this level.

In Florică et al. (2024), 455 apartments in 30 multistorey buildings (from 4 to 13 floors) were selected for the analysis. In this sample radon concentration at upper floors were mostly higher that those measured at lower floors, the authors explain such a behaviour as consequence of the chimney effect and poor ventilation.

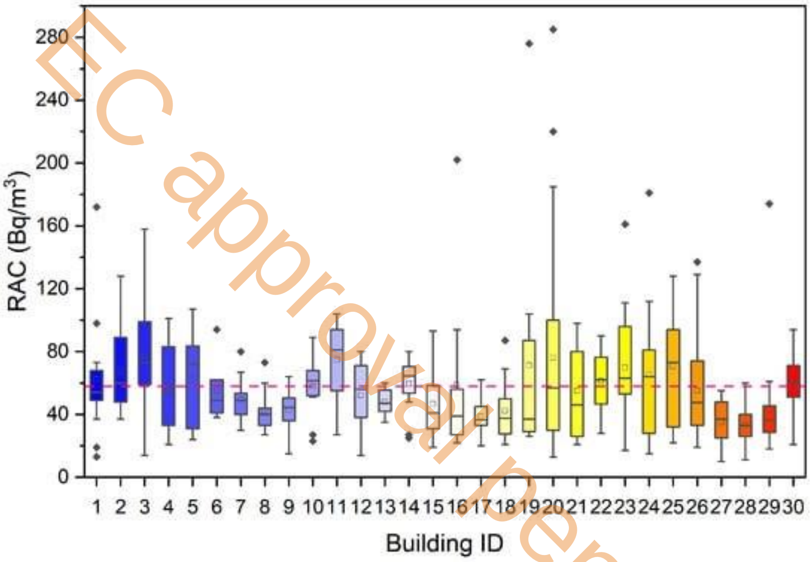


Figure 26: Radon Average concentration boxplot, taken from Florică et al. (2024)

Finally, in Vukotic et al. (2019), in the 6 buildings taken into account, even the ratio between average IRC measured in the winter season, with respect to the one measured in the summer is the opposite to the awaited result.

There is no preferred analysis method among the papers: both Tchorz-Trzeciakiewicz & Olszewski (2019) and Senitkova & Kraus (2019) do not analyse variability directly, while different approaches were adopted in the other three articles.

- As of Vukotic et al. (2019) the analysis of variance (ANOVA) shows that the difference of mean radon concentrations between the 1st and the 2nd, 3rd, and 4th floor is not statistically significant at a significance level of 0.05 (p = 0.91, p = 0.64, and p = 0.98, respectively). All this means that radon from the ground has an effect, albeit weak, only on the radon concentrations on the ground floor.

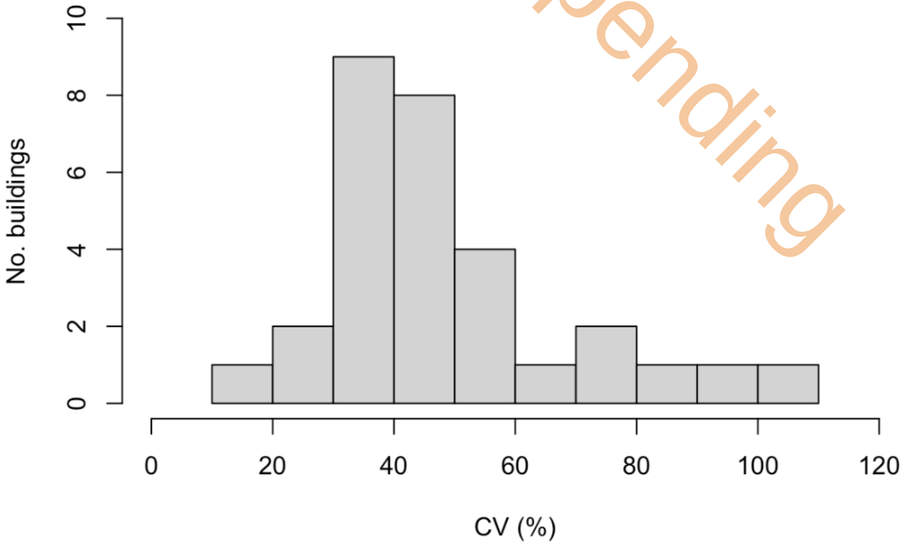
  The coefficient of variation values within each building are summarized in the following Table 32.

Table 32: Coefficient of variation values within each building, derived from Vukotic et al. (2019)

Building ID	No. dwellings measured per building	CV(%) within building
1	6	16%
2	6	29%
3	6	22%
4	6	11%
5	6	25%
6	4	5%

The average value of CV in Vukotic et al. (2019) is 19%. Such a low value is easily explained by the general low radon level in the monitored dwellings, due to (as explicitly explained by the authors) a scarcely radogenic geology, a good isolation from the ground and low radon emissions by the building materials.

- In Borgoni et al. (2014), an extensive dataset of radon measures, lithology and building features was analysed adopting a mixed effects model to account for the hierarchical nature of the data, quantifying the extent to which different factors manage to explain the variability of indoor radon concentration. The dataset was stratified within lithologies, within buildings in the same lithology, and within different measures in a single building. The overall analysis reinforces the idea that, in the interplay between lithology and building influence, the latter has a much higher impact on the indoor concentration variability.
- In Florică et al. (2024), the coefficient of variation (CV) showed an average value of 48% ranging from 19% to 96%, eliminating from the analysis one of the apartments that was not in use during the monitoring period, which led to the accumulation of high radon concentration. More details about the CV distribution are available in Figure 27.



N	min	Q1	AM	SD	Med	Q3	max
30	19%	33%	48%	20%	44%	52%	103%

Figure 27: Distribution of CVs within buildings, derived from Florică et al. (2024)

2.2.2 Overview of the analyses

To investigate the issue of spatial variability within buildings, four datasets were used:

- two Italian datasets: one extracted from a larger dataset collected as part of the Italian epidemiological study on radon and lung cancer (begun in 1996), consisting of 215 dwellings in 103 buildings, and the other collected within the framework of the RadoNorm project, involving 23 apartments distributed in 8 buildings;
- one Finnish dataset, consisting of 15,893 predominantly earth-contact dwellings spread across 3552 housing cooperatives;
- one Norwegian dataset, derived from a survey conducted in four blocks of flats and 14 terraced houses within a housing cooperative in Oslo.

The results of the analyses are presented separately in the corresponding sections.

2.2.3 Analysis of Italian data

(Authored by ISS)

To investigate the variability between separate apartments within the same building, two distinct datasets were used:

1. A subset of data from the Italian epidemiological study, which was already available prior to the start of the RadoNorm project.
2. New data collected within the framework of the RadoNorm project.

The datasets are analysed separately.

To assess within-building variability, two parameters were used:

- The coefficient of variation (CV), calculated as the ratio between the standard deviation and the arithmetic mean of the measurements (mostly annual) across the different apartments within each building. A correction for small sample sizes was applied, since in most buildings only 2–3 apartments were measured.
- The geometric standard deviation (GSD) of the measurements across the apartments in the same building, assuming a log-normal distribution of values within buildings. This assumption could not be verified due to the limited number of measurements per building.

Since in some buildings the measured apartments were located on the same floor, while in others they were on different floors, the analysis was conducted separately for these two groups of buildings to investigate potential differences.

2.2.3.1 Analysis of Italian data already available, from the Italian epidemiological study on radon and lung cancer

This dataset originates from the Italian epidemiological case-control study on residential radon exposure and lung cancer, which involved approximately 2,000 dwellings. In each dwelling, two rooms were measured, ideally on different floors. Measurements were conducted using passive devices over two consecutive 6-month periods (Bochicchio et al., 2005).

The residential history of each subject enrolled in the study was reconstructed, tracing back the addresses where they had lived during the 5 to 34 years preceding enrolment. In cases where it was not possible to contact the current resident of a specific apartment, radon concentration was measured in a proxy dwelling within the same building. Preference was given to proxy dwellings on the same floor as the target apartment; if unavailable, the nearest dwelling above or below was selected.

As a result of this measurement strategy, multiple dwellings within the same building were monitored. In total, 103 buildings included more than one dwelling with a valid measurement, amounting to 215 dwellings in 103 buildings (Table 33).

Table 33: Buildings included in the Italian analysis, by number of dwellings measured

No. dwellings per building	No. buildings	Total No. of dwellings
Two	95	190
Three	7	21
Four	1	4
Tot	103	215

It is evident that, in most cases, two different apartments were measured within the same building.

On average, the radon concentration measured in the 215 dwellings was 100 Bq/m³, with values ranging from 20 Bq/m³ to 402 Bq/m³ (Table 34).

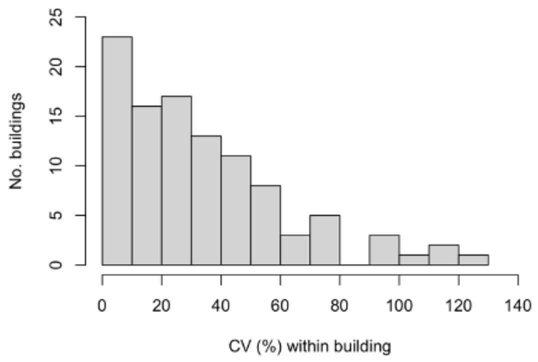
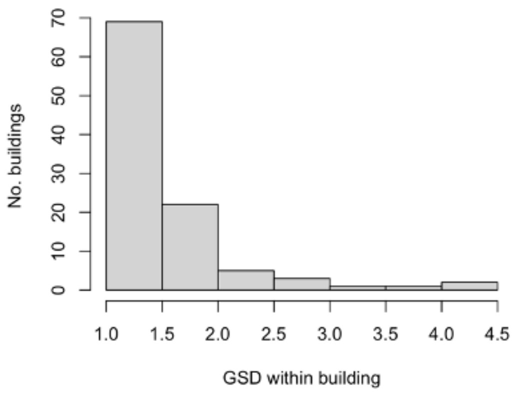
Table 34: Radon concentration summary statistics of the measurements in dwellings and in the buildings.

No.	Min (Bq/m³)	Q1 (Bq/m³)	AM (Bq/m³)	SD (Bq/m³)	Med (Bq/m³)	GM (Bq/m³)	GSD	Q3 (Bq/m³)	max (Bq/m³)
Dwellings									
215	20	48	100	77	73	80	1.9	121	402
Buildings									
103	20	54	100	67	81	83	1.84	127	353

For each building, both a coefficient of variation (CV) and a geometric standard deviation (GSD) were calculated based on the measurements across apartments within the building.

Figure 28 shows the histograms and summary statistics of these values.

Overall, the average within-building CV is 34%, and in 75% of cases, it is below 45%. The average GSD is 1.5**.**

CV distribution	GSD distribution
	

	CV
No.	103
Min	1%
Q1	11%
AM	34%
SD	28%
Med	28%
Q3	45%
max	121%

	GSD
No.	103
Min	1.01
Q1	1.11
AM	1.52
SD	0.64
Med	1.33
Q3	1.60
max	4.42

Figure 28: Within-building variability, assessed through the distributions of the coefficient of variation (CV) and geometric standard deviation (GSD).

Out of the 103 buildings, 69 buildings have 2 (or 3 or 4) apartments measured on different floors, while 26 buildings have 2 apartments measured on the same floor.

Within-building variability was analysed separately for these two groups.

For 8 buildings, floor information was missing for at least one of the measured apartments, so they were excluded from this part of the analysis.

As shown in Figure 29 and Table 35, radon variability (in terms of coefficient of variation) between apartments located on the same floor tends to be slightly lower than that observed between apartments on different floors within the same building.

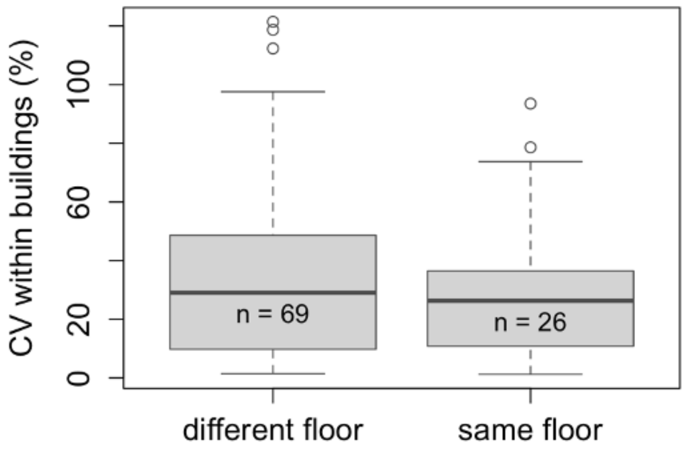


Figure 29: Box-plot of the CVs in the buildings with apartments at different or at the same floor.

Table 35: Summary statistics for the CVs in the buildings with apartments at different or at the same floor

	No.	Min	Q1	AM	SD	Med	Q3	Max
Flats at different floors	69	1%	10%	35%	29%	29%	49%	121%
Flats at the same floor	26	1%	11%	29%	23%	26%	36%	94%
Total	103	1%	11%	34%	28%	28%	45%	121%

In Figure 30 and Table 36, radon variability between apartments within the same building is investigated in terms of geometric standard deviation (GSD).

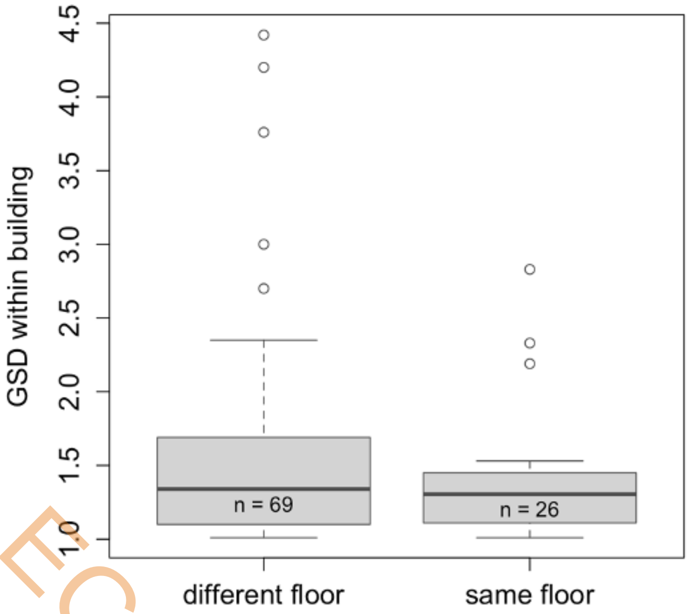


Figure 30: Box-plot of the GSDs in the buildings with apartments at different or at the same floor.

Table 36: Summary statistics for the GSDs in the buildings with apartments at different or at the same floor

	No.	**Min**	**Q1**	**AM**	**SD**	**Med**	**Q3**	**Max**
Flats at different floors	69	1.01	1.10	1.55	0.69	1.34	1.69	4.42
Flats at the same floor	34	1.01	1.12	1.45	0.51	1.30	1.51	3.28
Total	103	1.01	1.11	1.52	0.64	1.33	1.60	4.42

Although a greater spread in the values of CVs and GSDs appears to be present when apartments are located on different floors, the non-parametric Wilcoxon test comparing the medians of the two groups does not reject the hypothesis that the median CVs or GSDs are equal.

The limitation of this analysis is that measurements are not available for all floors of the surveyed buildings.

2.2.3.2 Analysis of Italian data: Radon levels across building floors

Finally, we investigated whether, in the 69 buildings where apartments on different floors were measured, radon concentrations were systematically higher on lower floors compared to upper floors.

The distribution of apartments by floor is shown in the following Table 37.

Table 37: Distribution by floors of the apartments involved in the Italian analysis

Floor level	**No. of dwellings**
Basement	7
Ground floor	24
Raised ground floor	17
1st floor	48
2nd floor	30
3rd floor	32
4th floor	27
5th floor	20
6th floor	7
7th floor	2
8th floor	1
Tot	215

To investigate this, the ratio between the average annual radon concentration in the apartment on the highest floor and the radon concentration in the apartment on the lowest floor was calculated. The summary statistics of these ratios are reported in Table 38 and the corresponding boxplots are shown in Figure 31.

Among the 69 buildings, 27 buildings have their lowest floor located in the basement, ground floor, or raised ground floor. The histogram of the Higher floor/Lower floor ratios for these buildings is shown in Figure 32, with the summary statistics provided in Table 38. The distribution of ratios for these 27 buildings was compared to the distribution of ratios in the 43 buildings where the lowest measured floor was above the raised ground floor. The table includes the statistics and summary statistics for the entire set of buildings.

Table 38: The distribution of ratios between radon concentration in the apartment on the highest floor vs. radon concentration in the apartment on the lowest floor

	No.	**No. of ratios >1 (%)**	**Min**	**Q1**	**AM**	**SD**	**Med**	**Q3**	**Max**
Lower floor ≤ raised GF	27	15%	0.19	0.42	0.73	0.09	0.54	0.89	2.10
Lower floor > raised GF	43	60%	0.20	0.89	1.11	0.38	1.05	1.37	1.95
Total	70	43%	0.19	0.56	0.96	0.46	0.93	1.31	2.10

GF= ground floor; Q1= first quartile; Q3=third quartile

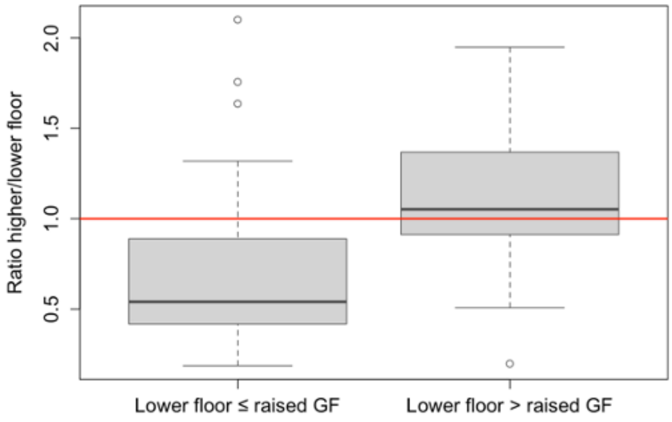


Figure 31: Box-plot of the higher floor/lower floor ratios.

It can be observed that, compared to the average value recorded in the apartments on the ground floor (or basement or raised ground floor), the average measurements in the apartments on upper floors are lower in 85% of the cases. However, if the comparison is made with an apartment on a floor higher than the raised ground floor, this percentage drops to 40%.

The histogram of the ratios is shown in Figure 32.

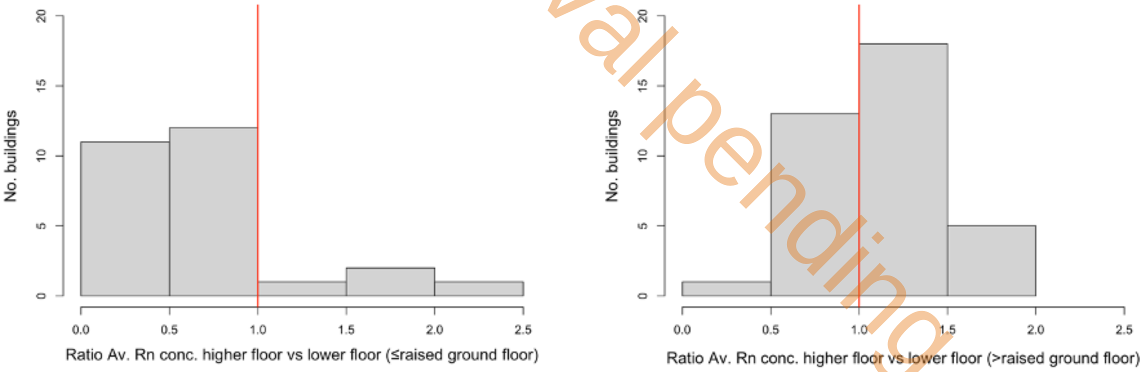


Figure 32: Higher floor/lower floor ratios where i) lower floor is a raised ground floor or lower (on the left), ii) lower floor is higher than a raised ground floor (on the right)

From this analysis, we can conclude that although in most cases radon concentrations measured on the ground or lower floors of a building are higher than those measured on the upper floors, this is not always the case. In our sample, 15% of the buildings showed lower radon concentrations on the ground or lower floors compared to the upper floors.

2.2.3.3 Analysis of Italian data acquired in RadoNorm

A total of 8 buildings were involved, each with two or more apartments measured, preferably stacked, for a total of 23 inhabited apartments and 3 cellars**.** Usable data for analysis: 21 apartments in 8 buildings**.**

The measurements were performed using electronic radon monitors, preferably placed in the living areas of each apartment.

The first detectors were installed in October 2022, with the last ones placed in May 2024.

For most of the apartments, measurements were taken over the course of one year. In a few cases, the measurement duration was only for a few months. Summary statistics for each building involved in the analysis are shown in Table 39.

Table 39: Summary statistics for each building involved in the Italian analysis

Building ID	No. dwellings	AM Rn (Bq/m^3)	SD Rn (Bq/m^3)	SD Rn corr small samples (Bq/m^3)	GM (Bq/m^3)	GSD	Intra-building CV (%)
1	3	99	39	44	94	1.58	45%
2	2	104	2	3	103	1.03	3%
3	2	40	8	11	40	1.31	27%
4	3	77	45	51	69	1.84	67%
5	3	249	94	107	239	1.49	43%
6	3	56	31	35	51	1.76	62%
7	2	85	69	86	69	3.18	102%
8	3	144	67	76	135	1.65	53%

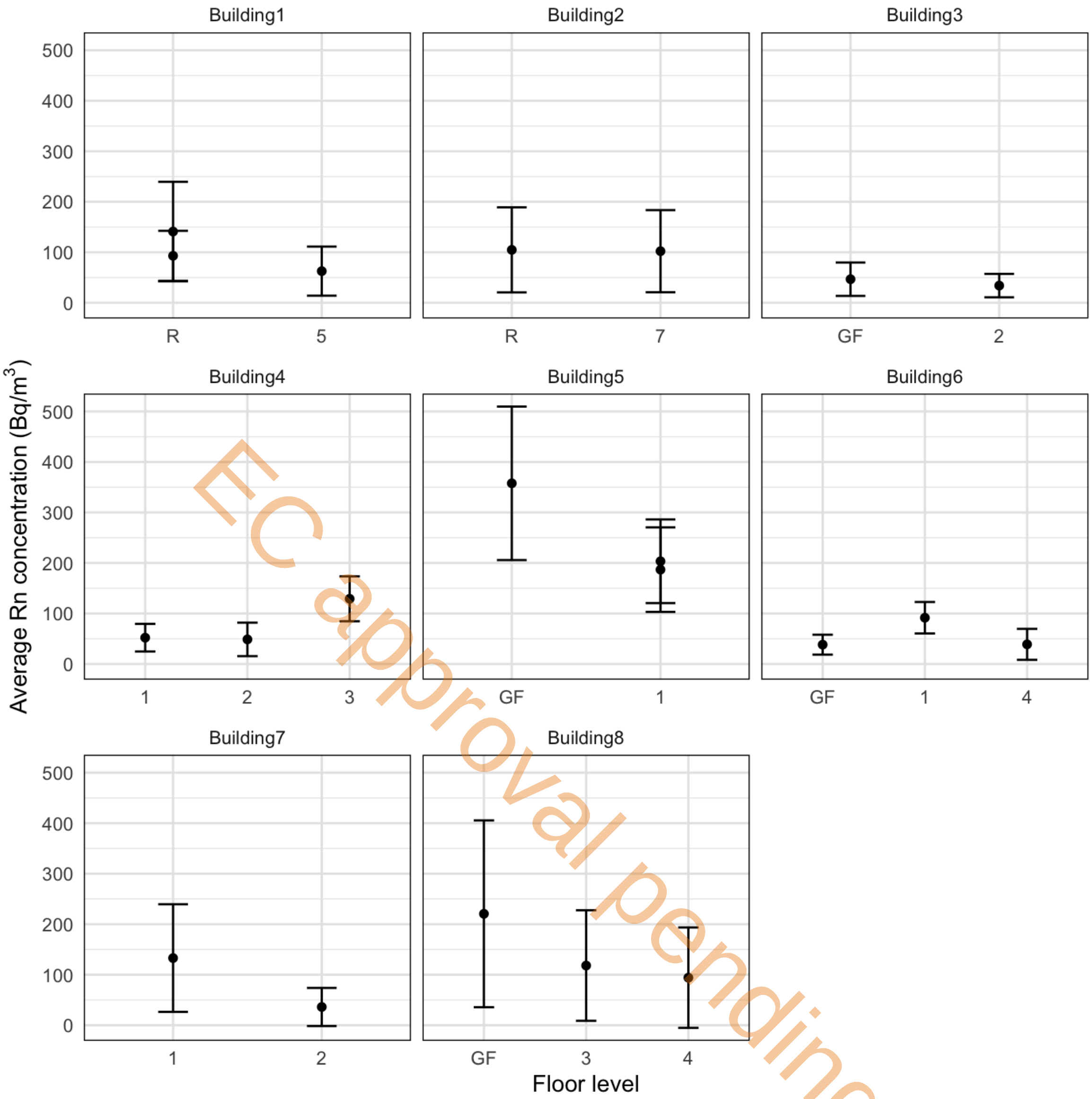
Note: All the buildings were monitored for 12 months except for building 3 and 7, that was monitored for 3 and 7 months, respectively.

The variability between apartments within each building, hereafter referred to as intra-building variability, was measured using the coefficient of variation (CV) of the annual average values of the dwellings within the same building. Summary statistics for the intra-building CV distribution are reported in the following Table 40.

Table 40: Summary statistics of the intra-building coefficient of variation (CV)

No.	min	Q1	AM	median	SD	Q3	max
8	3%	39%	50%	49%	29%	63%	102%

In the following Figure 33, separately for each building, annual radon concentration (± standard deviation) with respect to the floor of the measured dwelling is shown. A systematic decreasing trend in radon concentration with increasing floor level is not always observed.



R= raised ground floor; GF= ground floor; 1=first floor; 2= second floor; ...

Figure 33: Average annual radon concentration for each measured apartment (± standard deviation) in each building

In two buildings out of eight (25%), we found that there was no consistent trend of radon concentration decreasing with higher floors (specifically, in building 4, the radon concentration on the third floor was higher than on the first floor, and in building 6, the radon concentration on the first floor was higher than on the ground floor).

The limitation of this analysis is that measurements are not available for all floors of the surveyed buildings.

2.2.4 Analysis of Finnish data

(Authored by STUK)

The Finnish analysis of spatial variation of radon concentration between apartments covered 3552 housing cooperatives and 15 893 predominantly earth-contact dwellings. These housing companies were typically apartment blocks, terraced houses, semi-detached or detached housing cooperatives. The results are presented in detail in Turtiainen *et al*. (2025), available at https://www.mdpi.com/2073-4433/16/2/118, and need not be repeated here.

2.2.5 Analysis of Norwegian data

(Authored by DSA)

To investigate how much the radon activity concentration varies between dwellings on the same and different floors of the same building a survey was conducted in four blocks of flats and 14 terraced houses in a housing cooperation in Oslo, Norway. Both 2-month and a one-year measurements were carried out in the homes because the survey was designed to provide data on both spatial variation and temporal variation of radon concentration (see chapter 1.2.4). The one-year measurements were chosen for the analysis of the spatial variation. The datasets from the blocks of flats and the terraced homes are analysed separately.

2.2.5.1 Dataset no. 1: dwellings in 4 blocks of flats

The four blocks of flats are shown in Figure 34. Building A and C have two entrances and apartments at three floors. Building B has three entrances and apartments at four floors. Building D is almost identical to Building B, but since the Building D is built into a hill, it has one apartment in a lower ground floor as well (Figure 34). Table 41 is providing an overview of the distribution of apartments in the buildings.

Figure 34: The four blocks of flats (A, B, C and D) with entrances numbered from one to ten in roman numerals, and building D with an extra apartment at a lower ground floor. Pictures: Google Maps and Google Street View.

Table 41: Number of apartments in the different buildings, entrances and floors

Building:	A		B			C		D		
Entrance:	**I**	**II**	**III**	**IV**	**V**	**VI**	**VII**	**VIII**	**IX**	**X**
3rd	-	-	2	2	2	-	-	2	2	2
2nd	2	2	2	2	2	2	2	2	2	2
1st	2	2	2	2	2	2	2	2	2	2
Ground floor	2	2	2	2	2	2	2	2	2	2
Lower ground floor	-	-	-	-	-	-	-	-	-	1
Total apartments per entrance	6	6	8	8	8	6	6	8	8	9
Total apartments per building	12		24			12		25		
Total apartments in the four buildings	73									

Homeowners of all the 73 apartments were offered one-year measurements with integrating track etched detectors. Measurements were carried out in 41 apartments, but in two apartments the measurements were more than two months shorter than a year and were therefore excluded. Further 6 apartments were excluded because the homeowner only returned one detector, and 2 apartments because floor information were missing. After the exclusions, the range of days measured in the 31 (42%) remaining homes was 337-398 days, with an arithmetic mean of 361. All the remaining participants started the measurements within the first two weeks of February 2022 and ended in the period 28th January – 13th March 2023.

The distribution of measurements in the buildings is shown in Table 42. The number of measurements varies between zero and 75% of the apartments at each floor in a building, except for the lower ground floor where one of one apartment was measured.

Table 42: Number of measurements at different floors, entrances and buildings

Building	A		B			C		D		
Entrance	**I**	**II**	**III**	**IV**	**V**	**VI**	**VII**	**VIII**	**IX**	**X**
3rd	-	-	2	-	1	-	-	2	1	1
2nd	0	0	0	0	0	2	1	0	0	0
1st	1	1	1	1	1	1	1	2	0	1
Ground floor	2	1	1	2	0	1	1	0	2	0
Lower ground floor	-	-	-	-	-	-	-	-	-	1
Total per entrance	3	2	4	3	2	4	3	4	3	3
Total per building	5		9			7		10		
Total	31									

All the mean radon activity concentrations (Bq/m^3) in the apartments, as well as arithmetic means (AM) at different floors, entrances and buildings are given in Table 43.

Table 43: Mean radon activity concentration (Bq/m^3) in all apartments, as well as arithmetic (AM) means at different floors, entrances and buildings.

Building	**A**			**B**				**C**			**D**			
Entrance	**I**	**II**	**AM, I+II**	**III**	**IV**	**V**	**AM, III+IV+V**	**VI**	**VII**	**AM, VI+VII**	**VIII**	**IX**	**X**	**AM, VIII+IX+X**
3rd	-	-	-	25 24	- -	49 -	**33**	-	-	-	35 24	24	13	**24**
2nd	- -	- -	-	- -	- -	- -	-	38 13	38	**30**				-
1st	19 -	47 -	**33**	28 -	25 -	31 -	**28**	59	48	**54**	43 31		24	**33**
Ground floor	41 20	20 -	**27**	42	28 27	- -	**32**	114 -	34 -	**74**	- -	20 10	- -	**15**
Lower ground floor	-	-		-	-	-		-	-		-	-	104	**104**
AM, entrance	**27**	**34**		**30**	**27**	**40**		**56**	**40**		**33**	**18**	**47/19***	
AM, building	**29**				**31**			**49**				**33**		
AM, all buildings								**35/33***						

*Without the lower ground measurement

The ratio between the dwellings with the highest and the lowest radon activity concentration at the same floor and building varies between 0.11 to 0.81 (Table 44). This means that the lowest radon activity concentration was between 11 and 81% of the highest. However, the radon activity concentrations are generally quite low and therefore has high uncertainty. Consequently, the ratios have high uncertainties too. As an example, the ratio calculated for the first floor of building D comes from radon activity concentrations of 10 and 20. With a ratio of 0.5, it may seem like there is a big difference between the two measurements. However, in practice, the two concentrations are the same, within the measurement uncertainty.

Table 44: Radon activity ratios at different floors and within buildings. Ratios are calculated based on the lowest and the highest measured radon activity concentration at each floor or building.

Building	A	B	C	D
3rd		0.49		0.37
2nd	-	-	0.34	-
1st	0.40	0.81	0.81	0.56
Ground floor	0.49	0.64	0.30	0.50
All building	0.40	0.49	0.11	0.23*/0.09

*Without the lower ground measurement

Another way of looking at the variation is to calculate the Coefficient of Variation (CV). However, to calculate CV for only two or three measurements can be misleading. Consequently, CVs have only been calculated for the entire buildings as a whole, with 5 to 10 apartments measured per building (Table 45).

Table 45: The Coefficient of Variation (CV) of the radon activity in the buildings as a hole, and all four buildings together.

Building	A		B		C		D		A, B, C, D	
	N	CV (%)	N	CV (%)	N	CV (%)	N	CV (%)	N	CV (%)
All floors	5	47	9	28	7	65	10*	82*	30/31*	42/65*

*Including the measurement in the lower ground floor apartment

The CVs are quite high (>30%), which mean that the variations in radon activity concentrations are quite high as well. However, the radon activity concentrations are in general quite low, and only two apartments have a mean radon activity concentration >100 Bq/m^3, which is the WHO recommended reference level as well as the recommended action level in Norway. The two apartments with radon activity concentrations above 100 Bq/m^3 are both situated on the lowest floor in building C and D.

To conclude, the variation between apartments at the same floor and the variation across floors in building A and B does not seem to differ much, and the mean radon activity concentrations in the apartments are generally low (< 50 Bq/m^3). If we disregard the high measurement in the apartment on the lower ground floor in building D, the same applies to this building. However, the lower ground floor apartment has high radon activity concentrations both in the bedroom (103 Bq/m^3) and the living room (104 Bq/m^3). Unfortunately, we do not have measurements in the two apartments located on the floor above (same entrance) which could possibly provide an answer to whether radon moves from the ground and upwards in these building. Unlike building A, B and D, a high mean radon activity concentration is found at ground floor in building C (125 Bq/m^3 in the living room and 103 Bq/m^3 in the bedroom). At 1st floor in this building, compared to 1st floors in the other buildings, slightly higher than average radon activity concentration are found (54 Bq/m^3, compared to 28, 33 and 33), which raises suspicions that radon to some extent moves from the ground up the floors of this building.

This survey supports much of what have been reported in the literature previously and the experience from Norway. The radon concentrations on higher floors (above the 1st floor) are normally low and below the WHO recommended reference level. On the lower floors, the concentration can reach higher values, indicating that radon is seeping in from the ground.

It would have been a strength for the analysis if all apartments in the buildings had been measured. This should be strived for in any future surveys of a similar type. Furthermore, it may be advantageous to include several nearby buildings of the same type.

2.2.5.2 Dataset no. 2: 63 dwellings in 14 terraced houses

The 14 terraced houses (A-O, Figure 35) consist of 4 or 5 apartments each, altogether 63. One-year measurements with integrating track etched detectors were offered to the homeowners in all 63 apartments. Measurements were carried out in 41 apartments, but in five apartments the measurements were more than two months shorter than a year and were therefore excluded. The range of measured days were 347-405 with an average of 360. The first measurements started 1.02.2022 and the last measurements ended 12.03.2025. Table 46 provides an overview of the distribution of buildings, apartments, floors, radon activity concentrations (RnC). The 35 apartments with white numbers indicate the homes where measurements were carried out and not excluded.

Figure 35: Houses and apartments where one-year measurements were offered. Numbers in white indicate apartments where the measurements were performed.

All the terraced homes in the survey were built in 1955/56 and are part of the same housing cooperative. According to Geological Survey of Norway´s bedrock map, all the homes are located on the same type of bedrock - tonalitic gneiss. Further, In the national map indicating the probability of finding homes with high radon activity concentrations, the area is classified as "low to moderate". This means that it is assumed that <20% of homes have > over 200 Bq/m^3 in living spaces in the basement or on the ground floor.

The buildings are not identical. They vary in terms of the number of floors, among other things. Some are built on flat ground while others are built into the terrain, some have a garage as part of the bottom floor while others do not have a garage. In some of the apartments, the homeowner has converted basement rooms into occupied rooms, and in some cases the basement was excavated several years after the home was completed.

In buildings B, C, E, I, J, L and O, measurements were taken in each apartment (with the exception of one) on the first floor, on the ground floor, and in the basement in a bedroom, the living room and an "other" room, respectively. These buildings will be comparable in this respect. The owner of one apartment that deviated slightly in terms of measurement pattern stated that measurements had been taken in a bedroom on the first floor and a living room and an "other" room on the ground floor.

Other comparable buildings are G, H, K, M and N, where the measurements have been done, with a few exceptions, in a room on the first floor and in two rooms on the ground floor.

The pattern of measurements in building F stands out from the other apartments with one measurement at ground floor and two at the basement floor.

All the radon activity concentrations (RnC) are provided in the following Table 46.

Table 46: All measured radon activity concentrations (RnC) as well as arithmetic means (AM), standard deviations (SD) and coefficient of variation (CV) for apartment and buildings. The AM, SD and CV for a building are based on the AMs of the apartments. Buildings with measurements mainly at first floor, ground floor and basement are coloured pink. Buildings with measurements mainly in a room on the first floor and in two rooms on the ground floor are coloured blue. The last building is coloured green.

Building				**Apartment**						
Letter	**AM (Bq/m^3)**	**SD (Bq/m^3)**	**CV (%)**	**No.**	**AM (Bq/m^3)**	**SD (Bq/m^3)**	**CV (%)**	**Floor**	**Room type**	**RnC (Bq/m^3)**
B	241	86	36	6	239	163	68	First	Bedroom	116
								Ground	Living	177
								Basement	Other	424
				7	156	55	35	First floor	Bedroom	116
								Ground	Living	133
								Basement	Other	219
				8	328	262	80	First	Bedroom	146
								Ground	Living	208
								Basement	Bedroom	628
C	263	-	-	9	263	122	46	First	Living	384
								Ground	Bedroom	267
								Basement	Other	139
E	153	-	-	18	153	98	64	First	Living	134
								Ground	Bedroom	66
								Basement	-	260
F	249	75	-	20	117	24	21	First	Living	90
								Basement	Living	137
								Basement	Bedroom	124
				21	381	195	51	Ground	Living	174
								Basement	-	561
								Basement	Bedroom	407

G	66	2	-	24	65	22	34	First	-	55
								Ground	Bedroom	50
								Ground	Living	91
				26	67	9	14	First	Bedroom	73
								Ground	Other	57
								Ground	Living	72
H	44	22	22	27	40	1	3	First	Bedroom	41
								Ground	Other	39
								Ground	Living	39
				28	54	9	17	-	Bedroom	43
								Ground	Other	61
								Ground	Living	58
				29	33	4	12	First	Bedroom	29
								Ground	Other	33
								Ground	Living	36
				30	53	11	21	First	Bedroom	45
								First	Living	66
								Ground	-	49
				31	38	6	15	First	Bedroom	32
								Ground	Living	42
								Ground	Other	40
I	108	96	89	33	220	71	32	First	Bedroom	172
								Ground	Living	186
								Basement	Other	301
				34	52	10	20	First	Bedroom	55
								Ground	Living	40
								Basement	Other	60
				35	53	6	11	First	Bedroom	53
								Ground	Other	60
								Ground	Living	47
J	36	7	19	36	39	11	28	First	Bedroom	37
								Ground	Living	29
								Basement	Other	50
				37	39	23	59	First	Bedroom	27
								Ground	Living	24
								Basement	Other	65
				38	26	8	32	First	Bedroom	20
								Ground	Living	23
								Basement	Other	35
				39	41	17	40	First	Bedroom	30
								Ground	Living	33
								Basement	Other	60

K	34	16	48	41	21	6	31	First	Bedroom	15
								Ground	Living	28
								Ground	-	19
				42	30	4	13	First	Bedroom	30
								Ground	Other	25
								Ground	Living	33
				44	52	8	16	First	Bedroom	49
								Ground	Living	47
								Ground	Other	62
L	51	8	-	46	57	21	36	First	Bedroom	58
								Ground	Living	36
								Basement	Other	77
				48	45	16	36	First	Bedroom	33
								Ground	Living	39
								Basement	Other	63
M	58	6	-	52	52	11	21	First	Bedroom	45
								Ground	Living	60
				53	61	5	8	First	Other	57
								Ground	Living	66
								Ground	Other	61
N	45	26	58	55	30	2	8	First	Bedroom	27
								Ground	Other	30
								Ground	Living	32
				56	30	4	14	First	Bedroom	29
								First	Other	26
								Ground	Living	35
				58	76	23	31	First	Bedroom	56
								Ground	Living	70
								Basement	-	102
O	60	18	31	59	39	17	43	First	Bedroom	26
								Ground	Living	34
								Basement	Other	58
				60	60	27	45	First	Bedroom	44
								Ground	Living	46
								Basement	Other	91
				61	57	16	27	First	Bedroom	47
								Ground	Living	49
								Basement		75
				62	84	52	62	First	Bedroom	53
								Ground	Living	55
								Basement	Other	144

From Table 46, the CV within buildings was computed for 7 buildings, with values ranging from 19% to 89% and a median of 36%.

2.2.5.3 Conclusions on the Norwegian dataset no. 2

The CVs for buildings with only one apartment measured cannot be calculated. Further CV calculated from a small number of apartments could be misleading. For the buildings with at least three apartments measured, CV varies from 19 to 89%. If CV > 30% based on at least 3 apartments is defined as large variation, then there is large variation between apartments in five out of seven buildings in this survey.

Looking at the variability between these 13 close buildings the range of building AM was 34-263 Bq/m^3 with mean value of 108 Bq/m^3, SD=88 Bq/m^3, and CV=81%. Hence, it is obvious that the variation between buildings in this area is large.

2.2.6 Conclusions

(Authored by ISS, DSA, STUK)

Radon variability within a building cannot be considered low, although it is not extremely high.

Considering both Italian datasets (a total of 111 buildings), a median intra-building CV of 28% was observed (interquartile range: 11%–48%). A similar magnitude of variability is also found in the Norwegian dataset, where a median intra-building CV of 36% was observed in the surveyed buildings.

The difference in variability between apartments within the same building (over a total of 103 buildings) appears to be quite small, whether the apartments are located on the same floor (from the Italian data: median = 26%, IQR: 11%–36%) or on different floors (from the Italian data: median = 29%, IQR: 10%–49%). Although a slightly greater spread in the values of CVs appears to be present when apartments are located on different floors, the medians cannot be considered statistically different. Analyses for the Norway data appear to support this finding, although based on only two buildings, concluding that the variation between apartments at the same floor and the variation across floors does not seem to differ much.

All the analyses indicate that, as expected, radon concentrations are generally higher on ground or lower floors, given that soil is one of the main sources of indoor radon. However, radon concentrations are not *systematically* lower on upper floors than on lower floors. In the two Italian datasets, 15% and 25% of the sampled buildings showed lower radon concentrations on the ground or lower floors, compared to the upper measured floors.

Spatial variability within buildings in the Finnish analysis was computed between apartments belonging to the same housing cooperative. Housing cooperatives are common in Nordic countries and can include multiple nearby buildings rather than a single building, which means that the apartments within the same housing cooperative may be located in different buildings, although on the same plot of land. The Finnish dataset reported a median Rn concentration GSD of 1.5 for two apartments within the same housing cooperative, whereas in the Italian dataset, with two apartments measured within the same building, a slightly lower median GSD of 1.3 was observed. This difference may be explained by the fact that housing cooperatives can include nearby but distinct buildings, therefore the GSD estimate of 1.5 may reflect not only within-building variability but also some variability between close buildings

Finally, the Norwegian and Finnish analyses were also conducted in nearby buildings, revealing considerable variability between close buildings and therefore supporting the conclusion that low radon levels in one building cannot be assumed to imply low levels in nearby buildings.

2.2.7 References

Bochicchio, F., Forastiere, F., Farchi, S., Quarto, M., & Axelson, O. (2005). Residential radon exposure, diet and lung cancer: A case-control study in a Mediterranean region. *International journal of cancer 114*(6): 983-991.

Borgoni, R., De Francesco, D., De Bartolo, D. Tzavidis, N. (2014). Hierarchical modeling of indoor radon concentration: how much do geology and building factors matter? *Journal of Environmental Radioactivity* 138: 227-237.

Florică, Ș.; Lupulescu, A.-I.; Dicu, T.; Țenter, A.C.; Moldovan, M.-C.; Dobrei, G.-C.; Copaci, L.; Cucoș, A. (2024). Radon Concentration Assessment in Urban Romanian Buildings: A Multistory Analysis. *Atmosphere* 15: 1267. DOI: https://doi.org/10.3390/atmos15111267

Senitkova, I. J., & Kraus, M. (2019). Seasonal and Floor Variations of Indoor Radon Concentration. IOP Conf. Ser.: *Earth Environ. Sci*. 221: 012127

Tchorz-Trzeciakiewicz DE, Olszewski SR. (2019). Radiation in different types of building, human health. *Sci Total Environ*. 667: 511-521.

Turtiainen, T., Kaipainen, V., Kojo, K., Perälä, M., Holmgren, O., Kurttio, P. **(2025).** Variation in Radon Concentration Between Apartments in Housing Cooperatives. *Atmosphere* 16(2): 118.

Vukotic, P; Zekic, R; Antovic, NM; Andjelic, T. (2019). Radon concentrations in multi-story buildings in Montenegro. *Nuclear Technology & Radiation Protection* 34 (2): 165-174.

2.3 Spatial variation of radon concentration in non-residential buildings

(Contributors: STUK, GIG,)

2.3.1 Background and literature review

(Authored by, STUK, GIG)

This review addresses spatial variability within buildings other than dwellings. The followed methodology is described in section 2.1.1.

The majority of published data which can be considered a somehow contributing to the discussion about spatial radon activity concentration in workplaces located in above ground buildings are collected in schools, kindergartens and hospitals, to some extent (22 articles). For all remaining options of aboveground workplace 24 research reports were found and 8 ones dealing with radon exposure in waterworks. There are only a few articles somehow dealing directly with the problem of the variation of radon activity concentration in workplace located in different rooms at the same level of an above ground parts of buildings. Differences in radon activity concentration however are expressed in different manner, as percentage of individual measurements result in one building exceeding the reference level (Denman et al., 2002), direct comparison measurements done in separate rooms (Carpentieri et al., 2011; Madureira et al., 2016; Ivanova et al., 2014, 2021; Leonardi et al., 2021; Loffredo et al., 2024). Quite well documented spatial variation is provided for specific workplaces such as a radon spa where significant differences, up to four times, are observed between offices and therapeutic rooms (Kavasi et al., 2019). Another workplace often considered in terms of exposure to radon are water treatment plants. The facilities of a waterworks differ in terms of size and structure. High radon activity concentrations tend to occur at those parts of a waterworks with high water flow rates and a small air volume, e.g. the tapping of a spring. The further a facility is located from the spring, the more radon could already have been outgassed or decayed. Like in dwellings, the radon activity concentrations in waterworks are subject to diurnal and seasonal variations, also tending to higher concentrations in the cold season (Stietka et. al., 2017).

The reported radon concentration variability pattern in workplaces is similar as in flats and apartments (Alharbi and Akber 2015) however, the total volume of a space contributes to the variation. Workplaces having smaller volume are similar to a house. The most often noticed are differences between the rooms on the ground floor and those on the upper floors, usually on the first floor as upper levels are rarely reported (Ivanova et al., 2021; Loffredo et al., 2024). The variations observed in the rooms at the same level are usually attributed to the differences in ventilation and room use (activity performed inside) (Dixon et al., 1996).

Similarly to apartments, relationships with properties of local ground (geology) as well as construction materials, the overall construction of a building and its current technical condition are reported as sources in differences in radon activity concentration (Dixon et al., 1996; Alharbi and Akber 2015; Bode et al., 2018; Stojanovska et al., 2019) however generally considered as spatial variability much more notable among the buildings than within the buildings themselves (Ivanova et al., 2021). Considering the building-to-building relation radon activity concentration variations are also considered as affected by practices carrying on inside (schools, hospitals workshops, offices etc.) (Dixon et al., 1996). However, variations observed from this perspective are rather short-temporal nature determined by working time (Durcik et al., 1997). It was showed that there is a possibility to overestimate the annual dose even more than 3 times, using average radon activity concentration for a whole day instead of the average value measured for working hours for air-conditioned workplaces. Differences are lower during the heating especially due to energy saving reasons are limiting indoor-outdoor air exchange (Tokanami et al., 2003).

Some reports underlined the fact that average radon activity concentration in air in public and commercial buildings are nearly an order of magnitude lower than in flats/apartments (Cohen et al., 1984), due to, probably, more efficient ventilation system and more rigorous building maintenance practices with regard to quality of indoor air in workplaces (Tokanami et al., 2003). However, other authors are concluding differently as there is no significant variations between workplaces and homes, however erected in the same area (Denman et al., 2002). It is also important to note that high levels radon activity concentration may be found at some sites chosen arbitrarily and initially not considered to be of any particular risk, such as shops, theatres, schools, offices, cathedrals, building material firms, etc. Martín Sánchez et al. (2012) confirmed in his study caried out in Spain that 16% of these workplaces tested presented levels above 400 Bq/m^3.

The temporal variation reported are sometimes bigger in workplaces especially day to day as the ventilation system is usually switched off after working hours, hence radon activity concentration is significantly bigger during the night and weekends. However, it is not a strict rule as radon activity concentration also depends on the activities performed during a working day, usually between 8-17, as it was already mentioned above (Alharbi and Akber 2015; Dimitrova et al., 2025).

In summary, 5 papers providing quantitative data on spatial variability in non-residential buildings were identified by analysing the references of the selected papers in addition to 6 articles selected through the literature review described in Section 2.1.1.

A brief summary of each of all the 6 + 5 selected articles is provided below.

- In Campania, southern Italy, Loffredo et al. (2022) measured the radon concentration in 39 public kindergartens and primary schools. The measurements took place from February 2021 to February 2022 and a total of 525 classrooms were tracked, distributed on 13 classrooms in the basement, 492 on the ground floor and 20 on the second floor. The radon concentrations ranged from 11 Bq/m^3 to 1416 Bq/m^{3}with a geometric mean of 77 Bq/m^3 and a median of 74 Bq/m^3. An unusual finding in this study was that the concentrations in the spring-summer semester were higher than those measured during the autumn-winter period. The authors explained this difference to the fact that the schools were closed in the summer period and thus the concentrations were accumulated. The largest concentrations were found in the basement and ground level. The coefficient of variation of radon concentrations (CV) was determined for each floor and school to examine the room-to-room variation on the same floor within each school. For the basement, ground floor and second floor, the mean CV was 11%, 9% and 43%, respectively. The differences were explained with varied practice regarding open windows during the day.
- In Salento, Italy, Leonardi et al. (2021) performed a survey in 54 buildings at the University of Salento. The aim of this study was to evaluate radon distribution pattern in buildings placed in an Italian karst area. Measurements were performed in 963 rooms; below ground floor, ground floor, first floor, second and upper floor. The annual average radon concentration in all rooms varied from 38 Bq/m^3 to 1848 Bq/m^3 with a geometric mean of 120 Bq/m^3. The CV`s of the distribution of radon levels for all rooms was 117%, for floors average 100% and rooms average 92%. CV below ground floor, ground floor, first floor, second and upper floor was 168%, 94%, 97% and 130% respectively. In this study the spatial variations were greater between rooms than floors, which is explained because of differences of construction materials.
- As an attempt to optimize measurements protocols in two floors buildings, Curguz et al. (2020) performed radon concentration measurements in 50 schools, where 141 rooms were measured. The radon concentration at the ground floor were generally higher than the first floor with a range between 90 Bq/m^3 to 4200 Bq/m^3. The CV radon concentration was estimated separately for the ground- and first floor with a median variability of 27% and 14% respectively. For the ground floors, some buildings had a CV higher than 100%. From these results the authors emphasize that it is

not necessary to monitor upper floor when the concentration at the ground floor is low. Due to the high radon spatial variability of rooms at ground floor, they recommend a high number of measurements.

- In a pilot study, Bochicchio et al. (2014) carried out a systematic survey in 327 schools in 13 municipalities in Serbia. Radon concentration in 639 classrooms was measured, and concentration and CV within rooms and floors for each municipality was computed. The CV vas calculated as a measure of relative variation in radon concentration between schools in each municipality. The variation between schools within municipalities was ranging from 37% to 89% with a total CV for the 13 municipalities of 65%. In schools where at least two rooms were analysed, the median CV was 26%, ranging from 0% to 110%. The median CV between floors were 24%. The authors emphasize that there was a considerable variability of radon concentrations between schools, and to a minor extent within schools.
- In a research institute in Rome, Antignani et al. (2009) evaluated radon indoor spatial variation between buildings and within buildings with focus on floors and rooms in the same floor. 558 rooms in 29 buildings were monitored. Arithmetic mean of average floor means of radon concentration was 121 Bq/m^3 for all buildings with a CV between the buildings of 88%. The arithmetic mean CV within buildings was 57%. The CV variation between floors was 42%, where higher CVs occur in the same building where the ground level is characterized by a high radon concentration level compared to the other floor levels. The arithmetic mean CV between rooms at the same floor were 45%, 48%, 41% and 25% for underground, basement, ground floor and 1st floor, respectively. The authors emphasize that there is a significant radon concentration variation among workplace buildings. In addition, they also emphasize the importance of performing measurements in the same floor in buildings due to the high floor-to floor variability of the same buildings.
- In Greece, Papachristodoulou et al. (2010) measured indoor radon and natural gamma radiation in 42 public workplaces. The workplaces were distributed in five detached high-rise buildings and included various offices, research laboratories and students` classrooms. The radon concentration ranged between 19 and 278 Bq/m^3 with an arithmetic mean of 95 Bq/m^3 and geometric mean of 82 Bq/m^3. The radon concentrations in basement and ground floor workplaces were significantly higher than those measured in the first and upper floors. This variation is explained with the pressure driven flow of gas from the underlying soil and bedrock. No seasonal variation was observed, which is explained by ventilation and heating practices pertaining to the buildings.

Additional articles:

- In Bulgaria, Ivanova et al. (2014) measured indoor radon concentrations in 296 kindergartens in Sofia, using CR-39 detectors over a 3-month period. A total of 922 measurements were conducted, with concentrations ranging from 9 to 1415 Bq/m^3. The geometric mean was 101 Bq/m^3 (GSD: 2.08), and the arithmetic mean was 132 Bq/m^3 with a standard deviation of 118 Bq/m^3. Within-building variability, assessed in 256 kindergartens with at least two measurements, showed a wide range of CV, from 1% to 156%, with a median CV of 28%. This suggests moderate to high room-to-room variability, influenced mainly by room location and occupancy. The variability was comparable to that reported in similar surveys of schools in Serbia.
- In Bulgaria, Ivanova et al. (2021) investigated the spatial variability of indoor radon concentrations in 331 rooms across 16 school buildings in five municipalities of Plovdiv province. Measurements were conducted over an 8-month period. The arithmetic mean radon concentration was 160 ± 175 Bq/m^3, and the geometric mean was 108 Bq/m^3 with a geometric standard deviation (GSD) of 2.35, indicating high variability. Within-school variability showed that horizontal (room-by-room) differences were more pronounced than vertical (floor-to-floor) ones. Classroom and office variations, measured by CV and GSD, were found to be similar on ground and first floors. Between-

school variation was significantly influenced by the year of construction, which reflects the general technical condition of the buildings.

- Carpentieri et al. (2011) analysed radon concentration variability within 75 schools as part of a study aimed at assessing the precision of long-term radon measurements under field conditions in Serbian schools. The analysis showed median CV of 26% and 25% for the first and second 6-month periods, respectively—notably higher than the variability observed in repeated measurements within individual rooms.
- In the largest public hospital in southern Italy, "AORN Cardarelli" Loffredo et al. (2024) has conducted radon measurements campaign from May 2021 to March 2024. A total of 20 buildings were monitored, and in 589 rooms. Measurements were carried out in all the underground and ground floors, while in only three buildings, measurements were also carried out on mezzanines. The different premises monitored included analysis laboratories, operating rooms, doctors' offices, emergency rooms, warehouses and reception areas. Annual average concentration was determined from the time-weight average radon concentration from two consecutive six-month periods using exposure time as the weight. Radon concentration measurements in all rooms ranged from 4 Bq/m^3 to 424 Bq/m^3, with a median of 24 Bq/m^3. The geometric mean of radon concentrations was 29 Bq/m^3 with a geometric standard deviation of 2. The mean value of radon concentration was 45 Bq/m^3. The average radon activity concentration measured in all buildings was found to be lower than the Italian National average, as well as the Campanian average. In each building, the radon concentration variation among rooms of the same floor, was also studied. The average CVs of the annual radon measurements per floor obtained were equal to 66%, 60% and 53% for the measurements carried out on the underground floors, ground floor and mezzanine floor, respectively. As observed, the variability between rooms is not negligible and decreases as the floor increases, although the differences are not statistically significant. This variability can be associated with the different characteristics of the rooms and with the different behavior of the occupants. In fact, rooms belonging to the same floor and buildings were often intended for very different purposes.
- Madureira et al., 2016 measured radon concentrations in 45 classrooms from 13 public primary schools located in Porto, with the highest occupational density per classroom and located on higher radon risk areas. Measurements were carried out using CR-39 passive radon detectors for about 2-month period. A single radon detector for each room was used, provided that the measurement error is considerably lower than the variability of radon concentration between rooms. In all schools, radon concentrations ranged from 56 to 889 Bq/m^3 (mean = 197 Bq/m^3). The limit of 100 Bq/m^3 established by WHO IAQ guidelines was exceeded in 92% of the measurements, as well as 8 % of the measurements exceeded the limit of 400 Bq/m^3 established by the national legislation. The analysis of radon variability within schools was mainly oriented in studying two different aspects: (1) variation within the same floor (room-to-room variation) and (2) between floors (floor-to-floor variation). To evaluate room-to-room variation, the CV of the radon concentrations was calculated and summarized for each floor with more than one monitored room. Taking into account all the measured classrooms, the total CV was 73.1 %. The variation between classrooms in a school ranges from 6.9% to 96.5%. Authors concluded that from the obtained results, no correlation was detected between the indoor radon concentrations and the geological bedrock.

A summary table of the main relevant results of these studies is the following Table 47.

Table 47: Comparison of the spatial variations observed in different studies

Study	Country	N	Type	Variability
Antignani et al. (2009)	Italy	29	Research institute	CV between buildings = 88% CV within buildings = 42% CV between rooms = 25% 48% (depending on the floor)
Bochicchio et al. (2014)	Serbia	327	School	CV between schools = 65% Median CV within school = 26% Median CV between floors = 24%
Carpentieri et al. (2011)	Serbia	75	School	Median CV 25%
Curguz et al. (2020)	Serbia	50	School	Median CV 25 %
Ivanova et al. (2014)	Bulgaria	256	Kindergarten	Median CV 28% (range 1–156%)
Ivanova et al. (2021)	Bulgaria	16	School	Median GSD 1.84, range 1.28–3.62 (ground floor)
Leonardi et al. (2021)	Italy	54	University	Within building CV=92%-117%
Loffredo et al. (2022)	Italy	39	Kindergarten	Median CV 9% (ground floor)
Finnish study (present report, see section 2.3.3)	Finland	13 190	Various types	Median GSD 1.35–2.78 depending on number of detectors
Madureira et al., (2016)	Portugal	45	School	CV between schools = 73.1% Median CV within school = 16.2% range 6.9-96.5%
Loffredo et al., (2024)	Italy	589	Hospital	Undergroundd median CV =66%; range 4-125% Ground median CV = 60%; range 9-144% Mezzanine median CV =53%; range 10-126%

2.3.2 Overview of the analyses

To investigate the issue of radon concentration spatial variability within workplace buildings, two datasets were used:

- One Finnish dataset, with radon measurements in Finnish workplaces;
- One Polish dataset, with radon measurements from surveys conducted in 34 public facilities: kindergartens, schools, town hall buildings and 1 hospital.

2.3.3 Analysis of Finnish data

(Authored by STUK)

2.3.3.1 Data selection

Spatial variation of radon in Finnish workplaces has been reported by Turtiainen *et al.* (2025a). The report is in Finnish and a summary is given here. The data selected from the Finnish national radon registry maintained by STUK covered all workplaces and their radon measurements between 2014 and 2024, amounting to 25 161 workplaces and 116 466 radon measurements. The dataset was filtered using the following criteria:

- Measurements taken between September 1 and May 31.
- Measurement duration of at least 60 days.
- If the measurement continued beyond May 31, it was terminated within three days of each other.
- Measurements started within 30 days of each other.
- Only the first measurement results were selected if multiple measurements were taken at different times at the same workplace.
- These criteria applied to at least two measurement results.

Criteria 1–2 ensured the reliability of sampling, ensuring measurements were made when radon concentration variations were minimal and measurements were sufficiently long. Criteria 3–4 ensured the representativeness and comparability of the measurement results. Criterion 5 aimed to exclude workplaces that had undergone radon remediation and subsequent re-measurements. The final dataset included 18 421 workplaces and 87 850 radon measurements.

2.3.3.2 Handling of low-level results

In some cases, measurements recorded very low values, which were disproportionately represented in the dataset. This occurred due to the smallest measurable concentration limit in the radon registry. All four laboratories (STUK, Radonova, AlphaRadon, Eurofins) offering radon measurements have different lower detection limits, which can be influenced by factors such as the size of the postal background (radon exposure during return mailing), measurement duration, and how many times the detector casing was used. Unfortunately, the database does not consistently include values below the detection limit, leading to inconsistencies. Results below the detection limit (whether recorded or simulated) should not be included in the analysis of the spatial variation of concentrations.

2.3.3.3 Spatial Variation Analysis

Spatial variation was examined based on the results from workplaces with a geometric mean radon concentration >20 Bq (N=13 190). Spatial variation was described using geometric means (GM) and associated geometric standard deviations (GSD). The geometric mean was chosen because workplace radon concentrations typically follow a log-normal distribution, as observed in previous studies. Several statistical measures were calculated, including geometric mean, standard deviation, minimum, median, maximum, interquartile range (IQR), and percentiles (16th and 84th, 5th and 95th), based on the data with a GM >20 Bq/m³. The data was classified according to the number of measurement points and the geometric mean radon concentration.

2.3.3.4 Measurement uncertainties

All measurement results include measurement uncertainty, which consists of random uncertainty components as well as uncertainty components that are the same for all detectors. Random uncertainty affects the reproducibility of the results, while systematic uncertainty affects the accuracy of the results. For example, systematic errors from the calibration fixture and the uncertainty of the calibration of the reference measuring device used for calibration are the same for all detectors and do not contribute to variation in the measurement results. On the other hand, random uncertainties cause variability in the results. When comparing two measurement results, only the random uncertainty components are considered in the uncertainty assessment.

All integrated radon measurements in Finland are based on alpha track detectors. However, STUK's database does not store uncertainty associated with individual results, only the measurement result itself. By reviewing test reports, it can be observed that the uncertainty estimates from all four laboratories are similar for the same radon concentrations and measurement durations. The uncertainty components of STUK's own detector are well-known (Turtiainen *et al.*, 2024), so they can be used as a basis for estimating measurement uncertainties for detectors from other laboratories as well. Technique for subtracting detector-borne variation from the observed variation is presented by Turtiainen *et al*. (2025b).

2.3.3.5 Analyses

All analyses were performed using open-source software, RStudio (Posit PBC). Monte Carlo simulations and reductions of variation due to the measurement method were carried out using MS Excel.

2.3.3.6 Radon concentration statistics for measurement points and workplaces

The results of the point-specific radon measurements from the entire dataset (N = 87 850 measurements) followed a log-normal distribution. The arithmetic mean (AM) of the dataset was 107 Bq/m³ and the geometric mean (GM) was 38.6 Bq/m³. The GSD of the dataset was 3.72. The jittering of concentrations below 10 Bq/m³ had a small effect: the GM and GSD of the radon concentrations were 37.2 Bq/m³ and 3.99, respectively. The workplace-specific geometric means (GM) (N = 18 421 workplaces) primarily followed a log-normal distribution. The geometric mean of the workplace-based measurements was 40.2 Bq/m³, which is slightly higher than the GM of all the measurement results.

2.3.3.7 Factors affecting the spatial variability

No statistically significant correlation was observed between the geometric means and geometric standard deviations of the workplace-specific radon concentrations. Spearman’s tests indicated that no statistically significant correlation could be observed between radon levels and GSD from which the variability due to the detector uncertainty was subtracted. The only exception was for the case with three measurement points, which was most probably a fluke. In contrast, a statistically significant, strong positive correlation was observed between the number of measurement points and the GSD due to concentration variation (Spearman’s r = 1, p = 0.002) (Figure 36).

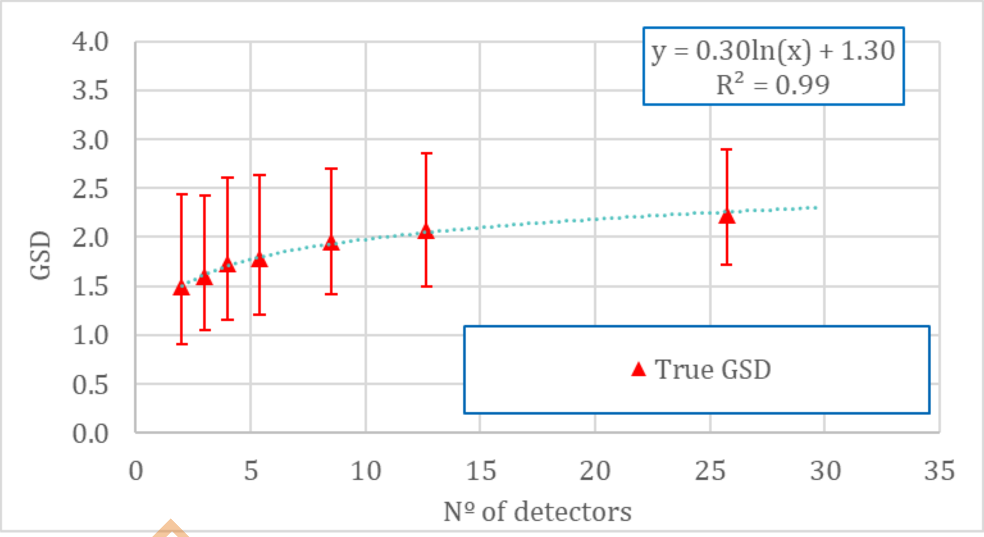


Figure 36: Correlation between the number of measurement points at the workplace and the geometric standard deviation of the workplace-specific radon concentrations. The data is from grouped GSD-data from which GSD due to measurement technique has been subtracted.

In Figure 37, a box-and-whisker plot is presented showing observed workplace-specific GSDs categorized solely by the number of measurement points, without accounting for the variability caused by measurement techniques. Sometimes, measurers place instruments in locations like electrical cabinets or under access hatches to crawlspaces, which are not workspaces. These measurement results often significantly deviate from others and do not reflect workers' radon exposure. Outliers identified from the categories divided by the number of measurement points were removed, averaging 1.6% (ranging from 0–2.6%).

When there were only two measurement points, the distribution of the measured GSD values was highly skewed to the right. The removed GSD values ranged from 11 to 92. In one case where the GSD was 92, one of the radon concentrations stored in the database was 1.7 Bq/m³, and the other was 1001 Bq/m³. It is clear that at least the former result is erroneous, as outdoor air typically has more than 5 Bq/m³.

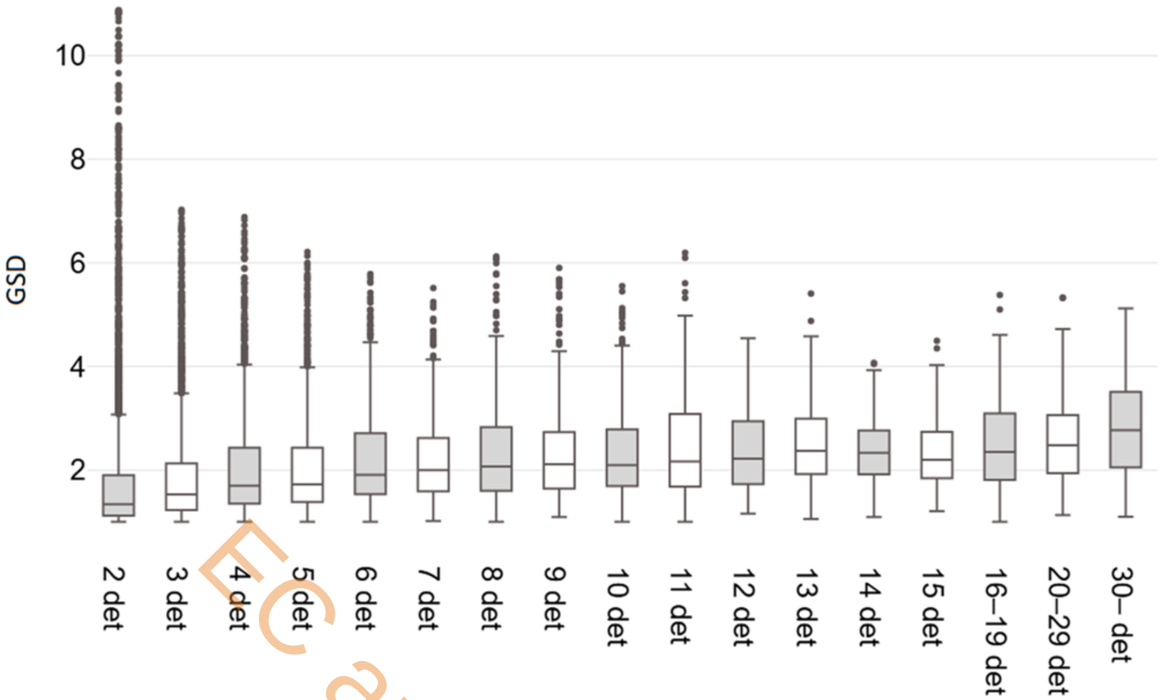


Figure 37: Observed GSD of radon concentration in workplaces with different number of measurement points.

2.3.3.8 Computing probabilities

Let's simulate radon concentration in workplaces with 5 measurement points and >30 measurement points when GM is 200 Bq/m^3 using empirical GSD data. Higher GSDs lead to larger spread of the results and higher probability of exceeding the reference level (Figure 38).

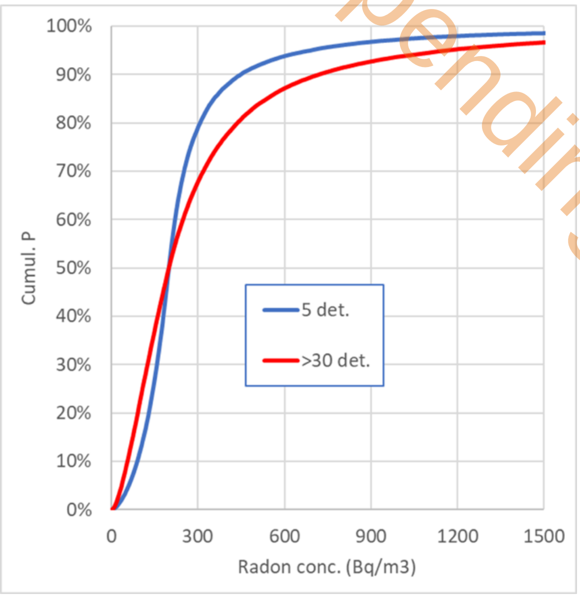


Figure 38: The cumulative probability distribution of radon concentration based on the empirical distribution of the observed GSD values, when there are 5 or more than 30 measurement points at the workplace. The figure shows that the distribution of concentrations is noticeably narrower when there are fewer measurement points. The distributions were generated using a Monte Carlo simulation.

Based on the empirical distributions, Monte Carlo simulations can be used to calculate the probabilities that the radon concentration at a measurement point exceeds (Table 48) the reference value, or that the reference value is exceeded at one or more measurement points at the workplace (Table 49).

Table 48: Probabilities that the radon concentration at a measurement point exceeds the reference value of 300 Bq/m³, when 2, 3, 5, 10, 20 or 50 measurements had been carried out in a workplace building at different geometric means (GM) of radon concentration.

GM	**2**	**3**	**5**	**10**	**20**	**50**
30 Bq/m³	1%	1%	1%	1%	1%	1%
50 Bq/m³	2%	2%	2%	3%	3%	5%
100 Bq/m³	5%	6%	7%	9%	10%	14%
150 Bq/m³	10%	11%	14%	18%	20%	24%

Table 49: Probabilities that the radon concentration at one or more measurement points exceeds the reference value of 300 Bq/m³, when 2, 3, 5, 10, 20 or 50 measurements had been carried out in a workplace building at different geometric means (GM) of radon concentration.

GM	**2**	**3**	**5**	**10**	**20**	**50**
30 Bq/m³	2%	2%	3%	6%	10%	41%
50 Bq/m³	5%	6%	10%	24%	38%	92%
100 Bq/m³	11%	17%	30%	60%	80%	100%
150 Bq/m³	19%	31%	53%	86%	96%	100%

2.3.4 Analysis of Polish data

(Authored by GIG)

In Poland, measurements were conducted inside one of the towns located in the northern part of the Upper Silesian Coal Basin (USCB) in the Silesian Voivodship, within the Bytom Basin geological unit. Mining of zinc and lead ores developed in the region from the 13th century and, from the 19th century onwards, also coal mining.

Surveys were conducted in 34 public facilities: kindergartens, schools, town hall buildings and 1 hospital. Detectors were placed at the level of basement and ground floor.

The duration of observations: measurements were performed in years 2021-2022 and were repeated three times; in each campaign the detectors were exposed for about six months. The measurements were performed using passive detectors RADOSYS type with CR-39 foil. Results are presented in Table 50 below.

Table 50: The results of radon measurements in kindergartens, schools, properties of the municipality, Piekary Śląskie, Poland.

Location in the building / Geology of bedrock		Number of buildings	Number of measurements	Min Bq/m^3	Max Bq/m^3	Avg Bq/m^3	Mdn Bq/m^3	SD Bq/m^3
All buildings	Basement	34	88	8	2110 ± 477	143	60	315
	Ground floor		87	8	1702 ± 386	91	37	207
Quaternary	Basement	10	49	8	441 ± 99	85	48	102
	Ground floor			8	183 ± 41	49	32	45
Triassic	Basement	22	117	8	2110 ± 477	175	72	383
	Ground floor			8	1702 ± 386	128	46	259
Carboniferous	Basement	2	11	19 ± 10	127 ± 29	71	64	41
	Ground floor			19 ± 10	107 ± 24	53	52	33

The radon concentrations in buildings range from the lower limit (LLD) of the currently used method, i.e. 8 Bq/m^3, to 2110 ± 477 Bq/m^3. In general, higher concentrations were measured in the basements: the arithmetic average, calculated for all obtained values is 143 Bq/m^3, median 60 Bq/m^3, standard deviation (SD) 315 Bq/m^3. On ground floors radon concentrations varied from LLD up to 1702 ± 386 Bq/m^3, with an arithmetic average of 91 Bq/m^3, a median of 37 Bq/m^3 and a standard deviation of 207 Bq/m^3.

For a deeper analysis of the results obtained, in the context of spatial variations in radon concentration, the locations of the buildings in which the research was conducted were divided due to the geological structure of the underlying strata:

- a layer of Quaternary sediments, over 10m thick.

- Triassic outcrops;

- outcrops of the Coal-Bearing Carboniferous;

Figure 39 presents the results of measurements performed in buildings built on Quaternary sediments. The following figures (Figure 40 and Figure 41) present the results for a group of buildings located on the Triassic outcrop and built on Coal-Bearing Carboniferous outcrops sediments.

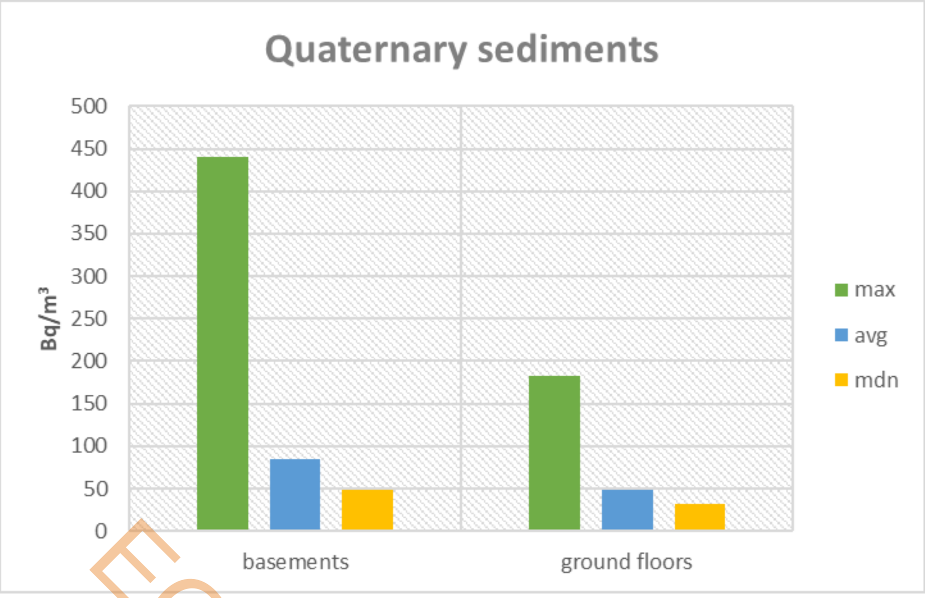


Figure 39: Radon concentrations in buildings located on Quaternary sediments.

In basements in buildings, built on Quaternary sediments, the maximum of measured concentrations of radon was 441 ± 99 Bq/m³, the average value was 88 Bq/m³, the median – 48 Bq/m³ and SD 102. The results showed, that in the rooms located on ground floors, the reference value (300 Bq/m³) was not exceeded in this location. In case of basements, the reference value may be exceeded.

Figure 40: Radon concentrations in buildings located on Triassic outcrops.

In basements of buildings built on Triassic carbonate formations, both the maximum value of radon concentrations (2110 ± 477 Bq/m³) and the calculated average (175 Bq/m³) are higher than those obtained on Quaternary sediments. The median of measured radon concentration is 72 and SD 383 Bq/m³. Also, in the rooms on the ground floor, the maximum radon concentration (1702 ± 386 Bq/m³) and the average value (128 Bq/m³), are higher than in the other geological area. Analysing the results of measurements in the Triassic sites, it should be concluded that by continuing the measurements a high variability of radon concentrations in buildings can be expected. Consequently, the reference value will be exceeded in a certain percentage of buildings.

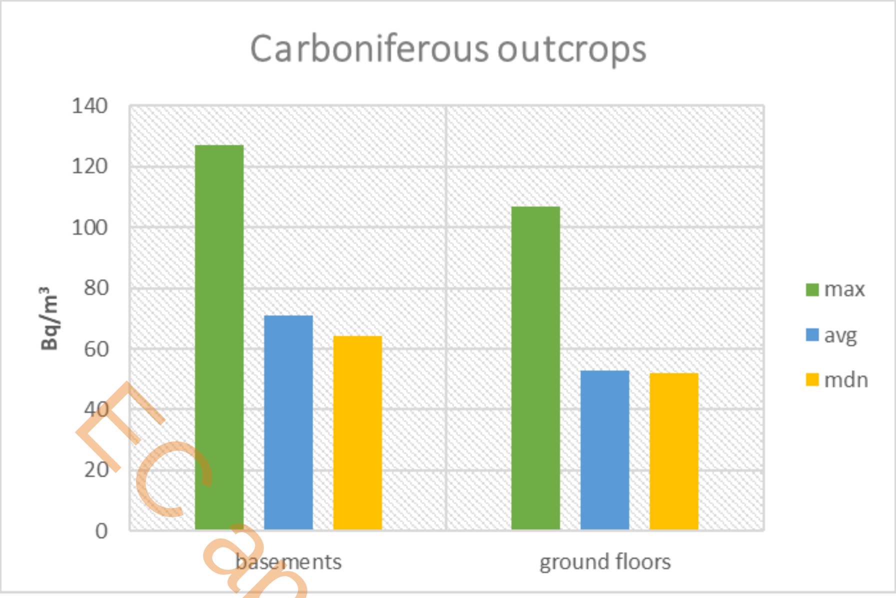


Figure 41: Comparison of radon concentrations in buildings located on Carboniferous outcrops.

In buildings built on Carboniferous deposits, at both levels, the maximum and mean values (127 ± 29 Bq/m^3, 71 Bq/m^3 in the basements and 107± 24 Bq/m^{3t}, 53 Bq/m^3 on the ground floors) are lower than in other geological outcrops. Median and SD values indicate that most measured values are comparatively low and in general below the reference value of 300 Bq/m^3.

2.3.5 Discussion

(Authored by STUK, GIG)

STUK records the radon concentrations of 1 500 to 5 000 new workplaces annually. Depending on the year, 13–17% of workplaces have radon concentrations exceeding the reference value of 300 Bq/m^3 in one or more workspaces. However, these workspaces are usually not continuously occupied (occupancy >600 hours per year), so they do not require radon remediation unless the worker's radon exposure reference value (0.5 MBqh/m^3) is exceeded. The observed exceedance percentages are in good agreement with the probabilities obtained from the Monte Carlo simulations presented in Table 48. The average radon concentration in workplaces, based on integrated radon measurements, is also approximately 40 Bq/m^3, according to a national sampling study (Kojo et al., 2023).

Comparing with studies conducted in other countries is challenging, as they primarily focus on schools and kindergartens (Table 47). In addition, it has typically been assumed that the spatial variation of radon concentration follows a normal distribution, with the coefficient of variation used as the parameter to describe the variability. However, there is one study in the literature that identified a log-normal distribution within a building (Ivanova *et al.*, 2021). In their study, which covered 16 Bulgarian schools, the GSD of radon concentrations in ground-floor rooms ranged from 1.28 to 3.62, with a median of 1.84. The results are very similar to those of this study.

Overall, the studies on spatial variability in non-residential buildings show that the spatial variation of radon concentration, especially in large workplace buildings, is very high. Even if radon concentrations are generally low across the workplace (GM radon concentration 50 Bq/m³), the probability of finding a radon concentration exceeding the reference level in at least one workspace becomes significant (>20%), if 10 or more measurements are needed at the workplace. Therefore, it is very important to ensure sufficient measurement density within the building's indoor spaces, for example as specified in ISO 11665-8 (ISO, 2019).

The Polish analysis of the results of measurements, conducted in Piekary Śląskie, show the spatial variation of radon concentration in workplaces such as kindergarten, schools and offices of town hall. The measured radon concentrations varied in the range from 8 Bq/m³ to 1702 Bq/m³. The observations confirmed the hypothesis about the primary influence of the local geological structure on the distribution of radon levels in buildings. Results confirm that even in small areas, significant spatial variability of radon concentrations in buildings is observed. In the analysed area, the main factor determining the possibility of radon transport and migration is the geological structure of the bedrock. The limestones and dolomites building up the area are highly fractured and cavernous. Quaternary and Carboniferous sediments are less permeable, less fractured, more compact. Nevertheless, the fact that some of the buildings built over the post-mining voids are damaged facilitates gas penetration. The analysis of the results obtained should be expanded to include verification of mining, construction and technical information.

In general, the available data about spatial radon activity concentration variations do not justify any approach based on calculation of a correction factor for dose evaluation based on this variability. The observed data are determined by many parameters site specific not subject parametrisation mainly determined by the way of use a workspace subject evaluation. Moreover, the spatial variability, if exist may be masked by the temporal variability. Considering the number of workplaces type it is difficult, even impossible to separate these effects. Moreover, the overall tendency is that modern buildings are equipped with dedicated ventilation system focussed on energy saving. The air quality rules are strictly followed (ISO 2019a), e.g. the air in a working space is exchanged few time per hour. Depending on the number of people inside that is by the solving the problem of exposure to radon, as actually risk is caused by radon progeny not by the radon gas itself.

Possible suggestion on monitoring campaign organisation inside a building is to try to carry out measurement on the first three floors and in rooms used in significantly different manner, if exits (in some schools, differences are reported for classroom and is staff rooms, Ivanova et al., 2021).

2.3.6 References

Alharbi, S. H., Akber, R. A. 2015. Radon And Thoron Concentrations In Public Workplaces In Brisbane, Australia. Journal Of Environmental Radioactivity 144 (69): 76.

Antignani, S., Bochicchio, F., Ampollini, M., Venoso, G., Bruni, B., Innamorati, S., ... & Stefano, A. (2009). Radon concentration variations between and within buildings of a research institute. Radiation measurements 44(9-10), 1040-1044.

Bochicchio, F., Žunić, Z.S., Carpentieri, C., Antignani, S., Venoso, G., Carelli, V., Cordedda, C., Veselinović, N., Tollefsen, T., Bossew, P. 2014. Radon in indoor air of primary schools: a systematic survey to evaluate factors affecting radon concentration levels and their variability. Indoor Air 24: 315-326.

Bode, K., Reci, H., Daci, B., Bylyku, E., Bërdufi, I., Kiri, E. 2018. Indoor Radon Concentration Related To Geological Areas At Different Workplaces Of Albania. Rad Conference Proceedings 3: 111–114.

Carpentieri, C., Zunic, Z.S., Carelli, V., Cordedda, C., Ferrighno, G., Veselinovic, N., Bossew, P., Tollefsen, T., Cuknic, O., Vojinovic, Z., Bocchiccio, F. 2011. Assessment of long-term radon concentration measurement precision in field conditions (Serbian schools) for a survey carried out by an international collaboration. Radiation Protection Dosimetry 145(2–3): 305–311.

Cohen, B., Kulwicki, D., Warner, K., Grassi, C. 1984. Radon Concentrations Inside Public And Commercial Buildings In The Pittsburgh Area. Health Physics 47(3): 399-405.

Curguz, Z., Venoso, G., Zunic, Z.S., Mirjanic, D., Ampollini, M., Carpentieri, C., Di Carlo, C., Caprio, M., Alavantic, D., Kolarz, P., Stojanovska, Z., Antignani, S., Bochicchio, F. 2020. Spatial variability of indoor radon concentration in schools: implications on radon measurement protocols. Radiation Protection Dosimetry 191(2): 133–137.

Denman, A., Lewis, G., Brennen, S. 2002. A Study Of Radon Levels In Nhs Premises In Affected Areas Around The Uk. Journal Of Environmental Radioactivity 63(3): 221-230.

Dimitrova, I., Todorov, V., Georgiev, S., Mitev, K. 2025. Real Time Monitoring Of Rn-222 In Workplaces And Estimation Of Working Time Correction Factor. Radiation Measurements 181: 107359.

Dixon, D., Gooding, T., Mc Cready-Shea, S., 1996. Evaluation And Significance Of Radon Exposures In British Workplace Buildings. Environment International 22: 1079-1082.

Durcik, M., Havlik, F., Vicanova, M., Nikodemova, D. 1997. Radon Risk Assessment In Slovak Kindergartens And Basic Schools. Radiation Protection Dosimetry 71(3): 201-206..

ISO, 2019 ISO 11665-8:2019 Measurement of radioactivity in the environment — Air: radon-222 Part 8: Methodologies for initial and additional investigations in buildings. Published (Edition 2, 2019)

ISO, 2019a. ISO 16000-40:2019 Indoor air Part 40: Indoor air quality management system, edition 1Ivanova, K., Stojanovska, Z., Tsenova, M., Badulin, V., Kunovska, B. 2014. Measurement of indoor radon concentration in kindergartens in Sofia, Bulgaria. Radiation Protection Dosimetry, 162(1–2): 163–166.

Ivanova, K., Stojanovska, Z., Djunakova, D., Djounova, J. 2021. Analysis of the spatial distribution of the indoor radon concentration in school's buildings in Plovdiv province, Bulgaria. Building and Environment, 204: 108122.

Kavasi, N., Csordas, A., Nagy, K., Beltran, S., Kikaj, D., Vaupotic, J., Kovacs, T. 2019. Occupational Exposure Assessment At A Therapeutic Radon Spa Facility In Hungary. Radiation Protection Dosimetry 184(3-4): 470-473.

Kojo, K., Turtiainen, T., Holmgren, O., Kurttio, P. 2023. Radon Exposure Concentrations in Finnish Workplaces. Health Phys. 125(2): 92–101.

Leonardi, F., Botti, T., Buresti, G., Caricato, A., Chezzi, A., Pepe, C., Spagnolo, S., Tonnarini, S., Veschetti, M., Trevisi, R. 2021. Radon Spatial Variations In University's Buildings Located In An Italian Karst Region. Atmosphere 12(8): 1048.

Loffredo, F., Opoku-Ntim, I., Meo, G., Quatro, M. 2022. Indoor Radon Monitoring in Kindergarten and Primary Schools in South Italy. Atmosphere 13(3): 478.

Loffredo, F., Capussela, T., De Martino, F., Quarto, M. 2024. Indoor Radon Measurement In Buildings Of Aorn Cardarelli, The Largest Hospital Of National Relevance In Southern Italy. Atmosphere 15(7): 815.

Madureira, J., Paciencia, I., Rufo, J., Moreira, A., Fernandes, E.O., Pereira, A. 2016. Radon In Indoor Air Of Primary Schools: Determinant Factors, Their Variability And Effective Dose. Environmental Geochemistry And Health 38(2): 523-533.

Martín Sánchez, A., de la Torre Pérez, J., Ruano Sánchez, A.B., Naranjo Correa, F. L. 2012. Radon in workplaces in Extremadura (Spain). Journal of Environmental Radioactivity 107: 86-91.

Papachristodoulou, C. A., Patiris, D. L., Ioannides, K. G. 2010. Exposure to indoor radon and natural gamma radiation in public workplaces in north-western Greece. Radiation Measurements 45(7): 865-871.

Stietka, M., Baumgartner, A., Kabrt, F., Maringer, F. J. 2017. Measurement strategies for radon in indoor air of waterworks - a review. Radioprotection 52(2): 101 – 107.

Stojanovska, Z., Boev, B., Zunic, Z. S., Ivanova, K., Sorsa, A., Boev, I., Curguz, Z., Kolarz, P. 2019. Factors Affecting Indoor Radon Variations: A Case Study In Schools Of Eastern Macedonia. Romanian Journal Of Physics 64: 1-2.

Tokonami, S., Furukawa, M., Shicchi, Y., Sanada, T., Yamada, Y. 2003. Characteristics Of Radon And Its Progeny Concentrations In Air-Conditioned Office Buildings In Tokyo. Radiation Protection Dosimetry 106(1): 71-76.

Turtiainen, T., Laine J-P., Rantanen, S., Oinas, T. 2024. Nonlinear calibration and temperature sensitivity of makrofol solid-state nuclear track detectors for radon measurement. Atmosphere 15(10): 1179.

Turtiainen, T., Kaipainen, V., Kojo K., Perälä, M., Kurttio, P. 2025a. Radonpitoisuuden spatiaalinen vaihtelu työpaikkarakennuksissa. STUK-B 333. Vantaa: Säteilyturvakeskus, 2025.

Turtiainen, T., Kaipainen, V., Kojo K., Perälä, M., Holmgren, O., Kurttio, P. 2025b. Variation in Radon Concentration Between Apartments in Housing Cooperatives. Atmosphere 16(2): 118.

2.4 Spatial radon variability in relation to geology

(Contributor: GIG)

2.4.1 Introduction

(Authored by GIG)

The major source of radon lies beneath buildings, in the soil or rock, which always contain certain concentrations of uranium and thorium—the parent radionuclides of radium isotopes (Ra-226 and Ra-228) and radon isotopes (Rn-222 and Rn-220, although usually only the former is recognized as radon). Soil characteristics are a critical factor determining the gas's movement toward the surface. Radon atoms present in the soil or rock can enter buildings through cracks in floors and walls, openings around sump pumps and drains, cavities in walls, joints in construction materials, gaps around utility penetrations, and crawl spaces that open directly into the building.

Investigations, for example in the Upper Silesian Coal Basin, have shown that increased radon migration and its entry into buildings are caused by changes in the geological environment resulting from the exploitation of mineral resources (Wysocka et al., 2010). In the investigated post-mining areas, mining-induced changes in the rock body are among the main factors influencing radon's ability to migrate over longer distances. It has been observed that local changes in the geology of the ground strongly affect radon transport capacity and its penetration into buildings. Subsoil disintegration caused, for example, by mining activities also significantly alters the radon potential of specific areas.

2.4.2 Review

(Authored by GIG)

The worldwide literature describes the spatial variability of radon concentrations in buildings in the context of different geological settings or technical building conditions. For instance, in the study by Wysocka et al. (2022), based on data from 160 buildings, it was concluded that the local geological structure and the effects of mining operations significantly impact radon concentration levels in buildings. Even among buildings in close proximity, radon levels vary widely.

Seasonal variability in radon concentration has been observed in all surveyed buildings, each showing individual fluctuation patterns. A general correlation with outdoor temperature was noted. Most of the examined buildings exhibited a negative correlation between radon concentration and outdoor temperature; however, some showed a positive correlation, and some showed none. This again underlines the significant influence of the subsoil's geological structure—even for buildings located close to each other (Karpińska et al., 2004).

The study of Zalewski et al. (1998), also included buildings typical for the region: 66% made of brick, 5% of wood, and 29% of prefabricated materials ("large panel" blocks). Under Polish climatic conditions, all buildings are centrally heated and lack air-conditioning. Measurements were taken in 122 uninhabited basements (cellars), with the remaining 290 measurements taken in the inhabited parts of the buildings. Results were analysed by geographical distribution (i.e., geology) and vertical location within the buildings (basement vs. upper floors). Another data analysis considered both the geographical distribution (reflecting the underlying geology) and the vertical positioning of the rooms within buildings (basement vs. upper floors) (Bochicchio et al., 2014).

Data derived from international agencies and monitoring bodies—including ICRU, ICRP, UNSCEAR, WHO, and IAEA—enable cross-national comparisons involving countries such as Austria, Italy, Finland, and Germany (Trevisi et al., 2022). Radon measurements in residential and occupational buildings were typically carried out on ground floors. Statistical analysis of data from 3815 workplaces and dwellings in Lombardy, Italy where the mean value of radon concentration was recorded at the level of 124 Bq/m^3

ranging from 9 Bq/m^3 to 1,796 Bq/m^3, suggests that radon exposure in these environments varies significantly by region and is heavily influenced by local geological conditions (Borgoni et al., 2011).

It has also been shown that even buildings located close together but constructed on different rock types can exhibit significant differences in radon levels. Long-term measurements generally produce lower average results than short-term ones (46 vs. 70 Bq/m^3), as indicated in studies such as Wysocka et al. (2002).

In schools, large variability in radon concentrations between and within buildings has been reported. For instance, a study conducted in 13 Portuguese schools revealed considerable differences in radon levels, though no direct correlation with geological bedrock was detected (Madureira et al., 2016). However, another study by Ivanova et al. (2021) found that differences in CRn (concentration of radon) between schools were related to geographic location and geology. Older buildings, especially those with structural degradation such as cracks or enlarged pores, tend to accumulate more radon, particularly in areas in direct contact with the soil. The role of building materials was found to be minor compared to soil influence. Ventilation and energy efficiency also played a role, albeit less significant.

Curguz et al. (2020) emphasized the importance of conducting radon measurements in multiple ground-floor rooms, as considerable spatial variability was observed within individual school buildings in Bosnia and Herzegovina. Similarly, Wysocka et al. (2022) showed that in public buildings in post-mining areas, radon levels were significantly higher today than in the 1990s—particularly in basements of buildings situated on Triassic dolomites and limestones. These differences are attributed to geological changes from mining activities, such as erosion, fault rejuvenation, subsidence, and karst formation, which create migration pathways for radon.

Kozak et al. (2011) demonstrated significant seasonal and spatial variations, with notably higher concentrations found in buildings located in the Sudety Mountains, due to the specific geology of the area. Regional climate (thermal-precipitation zones) also influences the spatial variability.

Sannappa et al. (2006) found that indoor radon and thoron progeny concentrations are influenced by ventilation, surface materials, and structural characteristics. Thoron concentrations generally decrease with height, while radon concentrations remain relatively constant. Old buildings exhibited slightly higher concentrations due to poorer ventilation, although granite flooring in new buildings could contribute to higher radon due to ^{226}Ra content.

A study at the University of Salento (Leonardi et al., 2021) analysed 963 rooms across 54 buildings. About 11% exceeded the reference level of 300 Bq/m^3, with values ranging from 38 to 1849 Bq/m^3. Despite expectations, no significant difference in radon levels was observed between ground and upper floors, suggesting other factors—such as construction materials and usage patterns—could affect indoor radon behaviour. Greater variation was observed across rooms than floors, indicating the need for spatial comprehensive sampling strategies.

2.4.3 Conclusions

(Authored by GIG)

To conclude, the spatial variations of radon concentrations in buildings is influenced by geological, architectural, seasonal, and human factors, which is briefly summarised in the groups below.

Geological and Environmental Influences

Local geology is one of the strongest determinants of radon presence. Areas with uranium-rich bedrock, such as granites or metamorphic formations, often show elevated radon levels. In Poland, for instance, the Sudety Mountains and Upper Silesia are known for high radon potential (Przylibski, 2004; Wołkowicz, 2007; Wysocka et al., 2002). Similar patterns are noted in other European contexts, such as Italy and Bulgaria (Ivanova et al., 2021; Leonardi et al., 2021).

Geogenic factors are further modulated by soil permeability and moisture, which affect radon migration. Seasonal variation due to environmental temperature and atmospheric pressure also plays a role (Karpińska et al., 2004).

Building Design and Construction Materials

The spatial distribution of radon within buildings is influenced by architectural layout, construction materials, and insulation. Buildings with basements or in contact with the ground typically exhibit higher radon levels in lower floors (Sannappa et al., 2006; Madureira et al., 2016). Construction defects, floor cracks, and poorly sealed foundations serve as entry routes for radon.

Materials such as concrete, granite, and gypsum may themselves emit radon, further contributing to indoor variability (Przylibski, 2004).

Ventilation and Occupant Behavior

Ventilation systems, whether natural or mechanical, play a pivotal role in modulating radon levels. Rooms with insufficient airflow often accumulate more radon, while increased air exchange reduces concentrations (Madureira et al., 2016). Daily human activities and window-opening patterns also contribute to intra-building variation.

2.4.4 References

Bochicchio, F., Zunic, Z. S., Carpentieri, C., Antignani, S., Venoso, G., Carelli, V., Cordedda, C., Veselinovic, N., Tollefsen, T., Bossew, P. (2014) Radon in indoor air of primary schools: a systematic survey to evaluate factors affecting radon concentration levels and their variability. INDOOR AIR Volume 24 Issue3 Page315-326 DOI10.1111/ina.12073

Borgoni R, Tritto V, Bigliotto C, de Bartolo D. (2011) A geostatistical approach to assess the spatial association between indoor radon concentration, geological features and building characteristics: the case of Lombardy, Northern Italy. Int J Environ Res Public Health. 2011 May;8(5):1420-40. doi: 10.3390/ijerph8051420. Epub 2011 May 6. PMID: 21655128; PMCID: PMC3108118.

Curguz Z., Venoso G., Zunic Z.S., Mirjanic D., Ampollini M., Carpentieri C., Di Carlo C., Caprio M., Alavantic D., Kolarz P., Stojanovska Z., Antignani S., Bochicchio F. (2020). *Spatial variability of indoor radon concentration in schools: implications on radon measurement protocols.* Radiation Protection Dosimetry, 191(2), 133–137. https://doi.org/10.1093/rpd/ncaa137

Ivanova K., Stojanovska Z., Djunakova D., Djounova J. (2021). *Analysis of the spatial distribution of the indoor radon concentration in school's buildings in Plovdiv province, Bulgaria.* Building and Environment, 204, 108122. https://doi.org/10.1016/j.buildenv.2021.108122

Karpińska M., Mnich Z., Kapała J. (2004). *Seasonal changes in radon concentrations in buildings in the region of northeastern Poland.* Nukleonika. https://doi.org/10.1016/j.jenvrad.2004.02.005

Kozak K., Mazur J., Kozłowska B., Karpińska M., Przylibski T.A., Mamont-Cieśla K., Grządziel D., Stawarz O., Wysocka M., Dorda J., Zebrowski A., Olszewski J., Hovhannisyan H., Dohojda M., Kapała J., Chmielewska I., Kłos B., Jankowski J., Mnich S., Kołodziej R. (2011). *Correction factors for determination of annual average radon concentration in dwellings of Poland resulting from seasonal variability of indoor radon.* Applied Radiation and Isotopes, 69(10), 1459-1465. https://doi.org/10.1016/j.apradiso.2011.05.018

Leonardi F., Botti T., Buresti G., Caricato A.P., Chezzi A., Pepe C., Spagnolo S., Tonnarini S., Veschetti M., Trevisi R. (2021). *Radon spatial variations in university's buildings located in an Italian Karst region.* Atmosphere, 12(8), 1048. https://doi.org/10.3390/atmos12081048

Madureira J., Paciencia I., Rufo J., Moreira A., de Oliviera Fernandes E., Pereira A. (2016). *Radon in indoor air of primary schools: determinant factors, their variability and effective dose.* Environ Geochem Health, 38, 523–533. https://doi.org/10.1007/s10653-015-9737-5

Przylibski T.A. (2004). *Concentration of ^{226}Ra in rocks of the southern part of Lower Silesia (SW Poland).* Journal of Environmental Radioactivity, 75(2), 171–191. https://doi.org/10.1016/j.jenvrad.2003.12.003

Sannappa J., Chandrashekara M.S., Paramesh L. (2006). *Spatial distribution of radon and thoron concentrations indoors and their concentrations in different rooms of buildings.* Indoor and Built Environment, 15, 283–288. https://doi.org/10.1177/1420326X06066323

Trevisi R., Leonardi F., Buresti G., Cianfriglia M., Cinelli G., Gruber V., Heinrich T., Holmgren O., Salvi F., Seri E., Bossew P. (2022). *Radon levels in dwellings and workplaces: a comparison with data from some European countries.* Journal of the European Radon Association, 3. https://doi.org/10.35815/radon.v3.758

Wołkowicz S. (Ed.) (2007). *Radon Potential of Sudetes with Determination of Potentially Medicinal Radon Water Areas.* Państwowy Instytut Geologiczny, Warszawa (in Polish).

Wysocka M., Chałupnik S., Skowronek J., Mielnikow A. (2002). *Comparison between short- and long-term measurements of radon concentration in dwellings of Upper Silesia (Poland).* J. Min. Sci., 40(4), 417–422. https://doi.org/10.1007/s10913-004-0026-4

Wysocka M., Kozłowska B., Dorda J., Kłos B., Chmielewska I., Rubin J., Karpińska M., Dohojda M. (2010). *Annual observations of radon activity concentrations in dwellings of Silesian Voivodeship.* Nukleonika, 55, 369–375.

Wysocka M., Nowak S., Chałupnik S., Bonczyk M. (2022). *Radon concentrations in dwellings in the mining area—Are there observed effects of the coal mine closure?* Int. J. Environ. Res. Public Health, 19, 5214. https://doi.org/10.3390/ijerph19095214

Zalewski M., Karpińska M., Mnich Z., Kapała J. (1998). *Radon concentrations in buildings in the north-eastern region of Poland.* Journal of Environmental Radioactivity, 40(2), 146–154. https://doi.org/10.1016/S0265-931X(97)00077-5

3 Conclusions

This report examines various aspects of the spatial and temporal variability of indoor radon concentrations, providing insights into various factors affecting these levels, primarily in residential environments but also touching on workplaces in some instances. It begins by addressing the temporal variability of radon, focusing on how concentrations can change from year to year. It also explores the differences between radon levels measured over a few months versus those observed annually, taking into account the influence of seasonal changes. Additionally, the report examines the fluctuations in radon concentrations over very short periods, such as a few days, compared to those observed on an annual basis. A particular emphasis is placed on daily variability, highlighting how radon concentrations can fluctuate within a single day.

The report also investigates the spatial variability of radon within residential settings. It looks at the distribution of radon concentrations within a single dwelling, considering room-to-room variation on the same floor and between different floors of the same building. Further, it explores how radon concentrations can differ from one dwelling to another within the same building, both on the same floor and across different floors—an aspect that remains largely under-researched, although it is highly relevant for designing measurement strategies to identify buildings with elevated radon levels.

Workplace environments are also considered, with a focus on spatial variability within these settings. Finally, the report addresses the role of geology in shaping spatial radon variability, examining how geological factors can influence radon levels in both residential and workplace environments.

These various aspects of the spatial and temporal variability of radon concentration are analysed based on data from multiple datasets collected across different countries, namely Italy, Finland, Norway, Switzerland, and Poland. These datasets exhibit notable differences, such as the types of dwellings and workplaces measured and the climatic zones involved. The performed analyses reflected also the specific needs or interests of each country in addressing particular issues related to radon. As a result, drawing overarching conclusions is challenging due to the diversity of the datasets analysed across different countries and the variety of issues addressed. However, this diversity represents a strength, as it provides valuable insights that can serve as a foundation for further research, offering a starting point for exploring specific aspects of radon variability in greater depth.

For detailed conclusions of the individual analyses, reference can be made to the specific sections of the report where each investigated topic is discussed extensively. Key conclusions are reported below.

Overall, radon concentration shows significant temporal and spatial variability, with important implications for measurement protocols. Year-to-year variability in Finland is moderate (16% CV), and the previously reported higher variation may have been due to shorter measurement durations. Short-term seasonal effects appear limited in some regions, such as Switzerland, likely due to mild winters, while in Norway, seasonal variability appears to be quite large, resulting in high variability in the calculated seasonal correction factors (CV = 56%). Very short-term variability remains too high to replace long-term protocols. Daily fluctuations in Italy show radon levels about 30% lower during daytime hours (9:00-19:00) compared to night-time hours.

On the spatial scale, within-dwelling variability in Norway reveals that room location (e.g., different floors) can influence radon levels, with less variability when rooms are on the same floor. Within-building variability is somewhat elevated (CV ~28–36%) and not always floor-dependent—Italian data show 15–25% of buildings with higher radon levels on upper floors. Between-building variability is even more pronounced, as low concentrations in one unit do not guarantee low levels nearby. In housing cooperatives, radon concentrations in one apartment cannot reliably predict those in another, as concentrations follow a log-normal distribution with a GSD of 1.5–2.0, depending on the number of apartments. In workplaces, spatial variability is particularly high: even with low average levels (e.g., 50 Bq/m³), there is a >20% chance of exceeding the reference level in at least one room when multiple measurements are taken. Polish data confirm that geological conditions and building integrity (e.g., post-mining damage) play a key role in local radon distribution.

It is essential that measurement protocols do not overlook radon variability, as this may lead to exposure misclassification, potential underestimation of health risks, and inadequate implementation of radioprotection measures.