JERA

RESEARCH PAPER

Similarities and differences between radon surveys across Europe: results from MetroRADON questionnaire

Giorgia Cinelli[1]*, Francesco Bochicchio[2], Peter Bossew[3], Carmela Carpenteri[2], Marc De Cort°[1], Valeria Gruber[4], Federica Leonardi[5], Tore Tollefsen°[1], and Rosabianca Trevisi[5]

[1]European Commission, Joint Research Centre (JRC), Ispra, Italy °retired; [2]Italian National Institute of Health, National Center for Radiation Protection and Computational Physics, Rome, Italy; [3]German Federal Office for Radiation Protection, Berlin, Germany; [4]Department for Radon and Radioecology, Austrian Agency for Health and Food Safety, Linz, Austria; [5]National Institute for Insurance against Accidents at Work – INAIL, Rome, Italy

Abstract

***Background*:** As a major cause of lung cancer after smoking, indoor radon is a hazard for human health. Key steps of radon surveys are numerous and include metrology, survey design, development of maps, communication of results to stakeholders, etc. The Council Directive 2013/59/EURATOM introduced new challenges for European Union Member States, such as the identification of radon priority areas, which calls for efforts to improve all the key steps involved in radon surveys.

***Objective*:** This study aims to compare existing radon measurement procedures between different European countries and to use the results to optimize the consistency of indoor radon data across Europe.

***Design*:** A questionnaire was developed and sent to more than 70 European institutions working in this field to collect information on indoor radon surveys carried out in the respective countries, in order to identify the rationale and methodologies used.

***Results*:** A total of 56 questionnaire forms on indoor radon surveys were completed and returned by universities, research institutions, and competent authorities on national and regional surveys from 24 European countries. The replies have been analyzed, and the main findings have been reported, although these replies did not allow to answer all the questions about comparability.

***Conclusions*:** From the replies given by the respondents, there is evidence that European indoor radon surveys are comparable regarding measurement methods but not comparable regarding the survey design. Comparability regarding data management, statistical treatment, aggregation, and mapping is unclear on the basis of the replies putting in evidence the need of further information.

Keywords: *indoor radon surveys*; *questionnaire*; *comparability*; *Europe*

Among the natural sources of ionizing radiation, particular attention is given to radon, since it is responsible for half of the natural dose received by the global population (1) and is a major cause of lung cancer after smoking (2).

Radon is a radioactive noble gas with three naturally occurring isotopes, ^{222}Rn, ^{220}Rn, and ^{219}Rn, which originate, respectively, from the primordial decay series of ^{238}U, ^{232}Th, and ^{235}U. Due to its short half-life (3.98 s), ^{219}Rn is neglected here, and only ^{222}Rn ($T_{1/2}$ = 3.82 d), hereafter called radon, and ^{220}Rn ($T_{1/2}$ = 55.8 s) hereafter called thoron, are considered.

Council Directive 2013/59/EURATOM (hereafter EU-BSS) (3) contains detailed provisions on the protection from all natural radiation sources, including radon. The EU-BSS introduced new challenges for European Union Member States to reduce both the individual and collective risks attributable to radon exposure. These goals can be reached by the countries moving their radon concentration distributions toward lower radon levels, in line with the principle of optimization of protection, one of the principles of the system of radiation protection (3).

As a result, one of the first steps for a national radon control strategy is the evaluation of the radon concentration distributions, which has to be representative of the population exposure to radon (2). This can be obtained with radon surveys conducted with certain criteria recently reviewed in IAEA reports (4, 5).

Therefore, an effort is requested to improve all key steps of the radon survey chain from metrology (measurements and calibrations) to the development of maps, from survey design to communicating results to stakeholders like doctors, health personal, building sector, regional regulators, teachers, employers, media, the public, etc.

Citation: Journal of the European Radon Association 2022, **3**: 7605 http://dx.doi.org/10.35815/radon.v3.7605

In 2005, a first overview of indoor radon surveys in Europe was performed (6). Most European countries carried out radon measurement campaigns, mainly to identify regions in which high radon levels occur frequently. It showed that no two countries had used the same approach, in terms of survey design, measurement techniques, and mapping strategies. Subsequently, the Joint Research Centre (JRC) of the European Commission decided to develop a harmonized European map of indoor radon concentration. As a result, more than one million measurements of long-term indoor radon concentration in ground-floor rooms of dwellings from 36 countries, including EU Member and non-Member States, were collected, aggregated into 10 km × 10 km grid cells and mapped. The last version was updated in December 2020 and is available online (7). The achievement of this map was a fundamental step to proceed with the creation of the European Atlas of Natural Radiation (8). To our knowledge, few international questionnaires on radon have been carried out, focusing mostly on radon legislation and national guidelines (9), aspects of radon programs (10), radon reference levels (RLs) and measurement techniques and protocols (11), or radon awareness of the population (12, 13).

Comparability and interpretability

One of the specific objectives of the MetroRADON Research Project (14) was to compare existing radon assessment (from measurement to mapping) procedures between different European countries and to use the results to optimize the consistency of indoor radon data across Europe. To this end, a literature review was performed (15, 16), and a questionnaire on indoor radon surveys in European countries was set up. This questionnaire aimed to gather information about the rationale and methodologies used in indoor radon surveys, to identify suitable approaches for reducing inconsistencies and improving harmonization of indoor radon data.

This paper presents the main outcomes from the analysis of the replies and discusses three main topics: 1) design characteristics of indoor radon surveys, 2) measurements methods, and 3) data management, statistical treatment, aggregation, and mapping. These analyses have helped to answer the question of whether the results of existing indoor radon measurement procedures (including rationale, design, measurement methods, data analysis, etc.) in different European surveys are comparable. That is, (I) whether the same objective quantity, submitted to different measurement and evaluation procedures, leads to the same numerical result; (II) reversely, whether given numbers, for example, the means of radon concentrations in two different municipalities acquired by different procedures, reflect the objective situations in these municipalities, and not a measurement effect. The concept is visualized in Fig. 1. (I) is checked through methodical intercomparisons. (II) is more difficult to verify, since the true A and B are unknown. To ensure comparability, methods a and b must be reliable, that is, they must be quality assured and their differences are well understood; the latter was one of the objectives of the questionnaire.

As an example, in municipality A, applying method a, a mean indoor radon concentration (IRC) of 100 Bq/m³ has been found, while in municipality B, applying method b, it is 50 Bq/m². The values are comparable, if they refer to the same measurand (e.g. annual mean IRC in ground floor living rooms) and if the difference is caused by the objective different radon situations, but is not an effect of different methodology.

Investigation of comparability is fundamental in the discussion going on about harmonization of indoor radon data at European level (17). Comparability is crucial for joint interpretability of results acquired by different methods.

The replies have been collected between December 2017 and July 2018; therefore, this study discusses the results with status mid-2018.

Materials and methods

In December 2017, the questionnaire was sent to more than 70 European institutions working in this field (not only national authorities but also regional administrations,

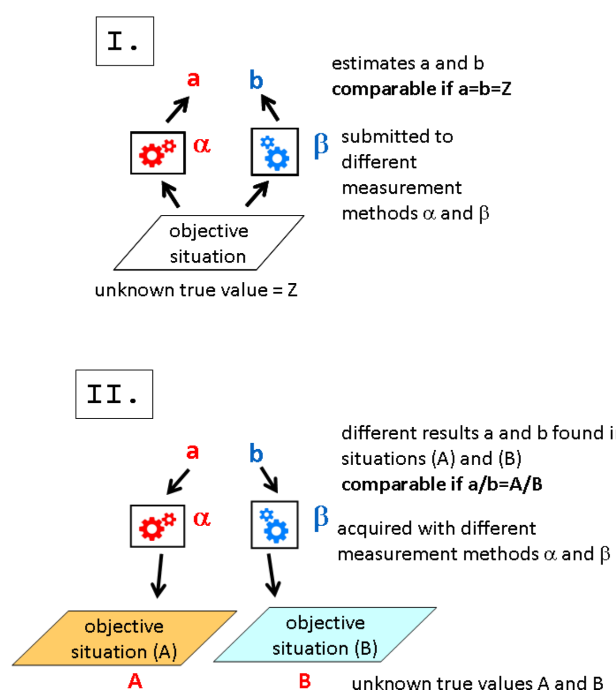

Fig. 1. The concept of comparability. Upper part (I): true quantity Z must lead to same measured values a = b; lower part (II): ideally, different measurement results must reflect the difference of the objective situation in which they have been acquired, but not the different acquisition methods.

universities, and research centers), inviting them to fill in a separate questionnaire for each survey they had carried out and/or to forward it to the person, who could best answer these questions. The questions about indoor radon policy in the countries (see section 5 of questionnaire 'Policy on indoor radon') were asked to be filled only by representatives of the national authorities. The replies were collected until July 2018.

The questionnaire has been structured in five different sections: 1) Information about respondent; 2) Design characteristics of indoor radon surveys; 3) Measurement methods; 4) Data management, statistical treatment, aggregation, and mapping; 5) Policy on indoor radon.

Different types of questions were proposed in the questionnaire form: free text, single choice, multiple choices, matrix, and table with the possibility to add additional information if needed.

Fifty-six replies were collected from 37 respondents in 24 countries: seven countries reported information about more than one survey, for example, Austria 8 and Italy 19 surveys (Fig. 2).

Many respondents have a role in public institutions (as regulators, policy decisions makers, etc.) but most of them are experts or researchers.

The questionnaire form and all replies given by the respondents are provided in a report (18).

EUSurvey, an online tool of the European Commission, was used to design the questionnaire, which was shared with the participants and collected the replies. Microsoft Excel 2016 software was used for statistical analysis and for creating graphs and tables.

Results and discussion

Characteristics of indoor radon surveys – design, purpose, and target population

One section of the questionnaire was intended to gather general information about the indoor radon survey (i.e. if other surveys have been carried out, if the survey is ongoing or finished, the timeframe, and coverage) and its rationale (purpose, target population, and strategy).

Eighty-seven percent of the respondents from 20 out of 24 participating countries indicated that they performed more than one indoor radon survey, even if only seven countries filled more than one questionnaire form to report about different surveys (see earlier). The number of surveys performed by each institution (and country) is very variable as well as the degree of coverage of territory:

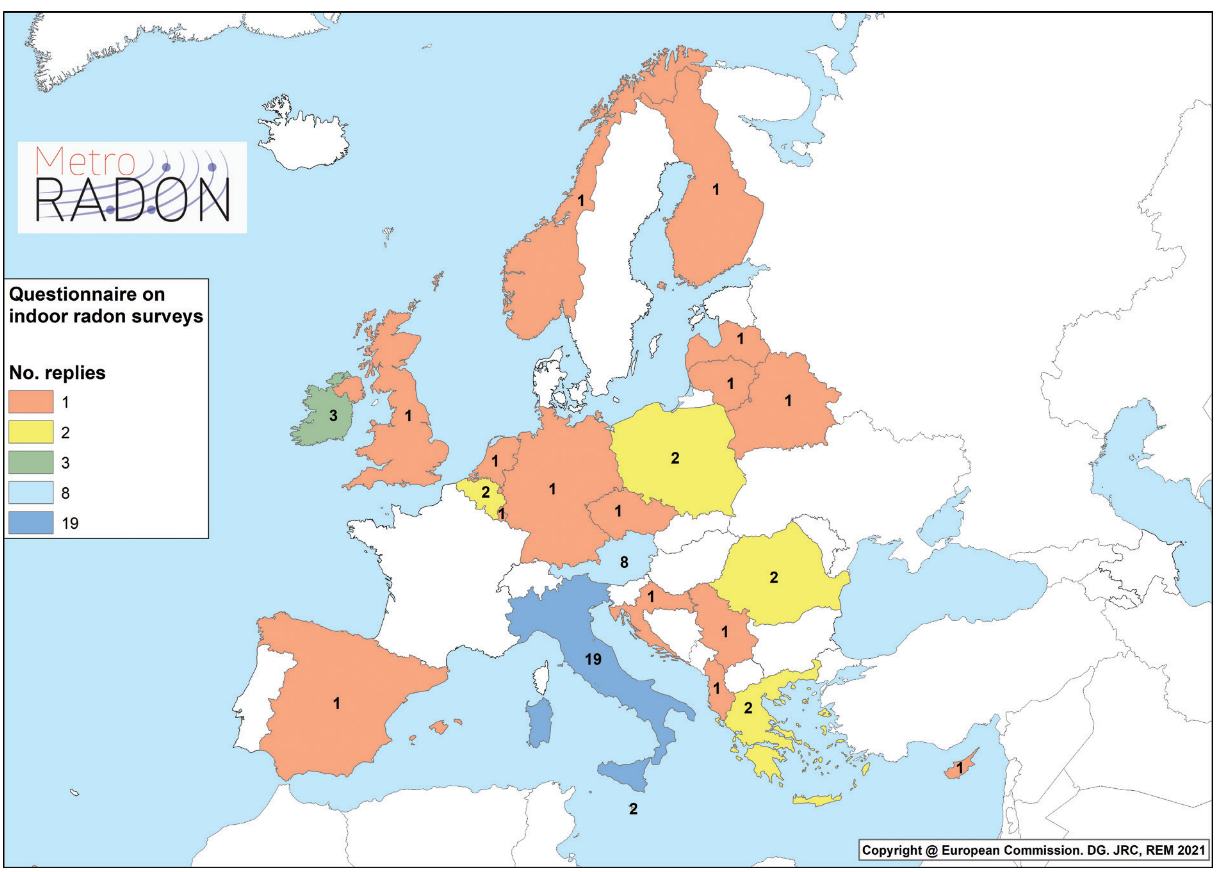

Fig. 2. Map of Europe showing the number of replies on indoor radon surveys given by each country.

most of them are on regional or subregional scale. Indeed, about 65% of respondents carried out 2–5 surveys, with two important exceptions: Public Health England replied that 20 partial surveys were merged and the German Federal Office for Radiation Protection reported that 28 partial surveys were conducted in Germany.

Most of the indoor radon surveys (81%) were carried out and concluded between 2000 and 2010, four were conducted in the 1980s, and 12 in the 1990s. Only one was in its beginning and nine (17%) were still on-going.

An indoor radon survey can be designed to reach different goals: depending on it, the sampling strategy, the targeted population, the sampling locations, the duration of measurements, and the measurement techniques are selected. Typically, important goals are to produce an indoor radon map (i.e. to determine the geographical distribution of indoor radon levels), to determine national average indoor radon concentration, to identify radon priority areas (RPAs), or to assess the dose caused by indoor radon to the population or a specific population group.

Table 1 shows the distribution of replies about the main purposes of the surveys: more than 60% of surveys have more than one goal. It can be observed that all purposes were quite uniformly selected: in particular, in 25% of replies, the main purpose was the evaluation of the indoor radon average concentration, especially in case of surveys performed on a national scale (18% out of 25%). Among the 'other' purposes, the risk assessment of particular categories of workers (i.e. underground tourist routes and caves workers, administrative buildings workers, etc.) and of a specific population group (such as students or children in kindergartens) were reported. Regional surveys were often designed with the aim to gather information to identify RPAs.

Figure 3 puts the wide range of sampling strategies in evidence, on which the surveys were based. Notably, 50% of the surveys had adopted more than one strategy. When 'To evaluate the indoor radon average concentration' was selected as purpose, about 50% of nationwide surveys used a sampling strategy based on population-weighted sampling, and 40% of them used random sampling. For the identification of RPAs or generally for mapping, a geographically based sampling strategy was generally adopted: in recent surveys, the territory is divided into geographical units, such as rectangular grids of certain area or considering the administrative boundaries. In most of the surveys with a geographically strategy, the random sampling has been preferred. Among the 'other' strategies, systematic surveys in a specific type of buildings/locations (e.g. schools and caves) are taken into account.

The selection of the building type in which radon measurements are performed depends on the main goal of the survey. In surveys where more than one building type was considered, dwellings and multifamily buildings (in total

Table 1. Distribution of purposes of indoor radon surveys indicated in the replies

Proposed purposes	Selected purposes		Notes
	n	%	
To have a first idea of radon distribution in a given area	20	17	
To evaluate the indoor radon average concentration	29	25	
To identify radon priority areas (RPAs)	23	20	
For mapping	21	18	
Others	23	20	Risk assessment of workers and/or of a limited population group

Note: It was possible to select more than one option. Number of replies = 56.

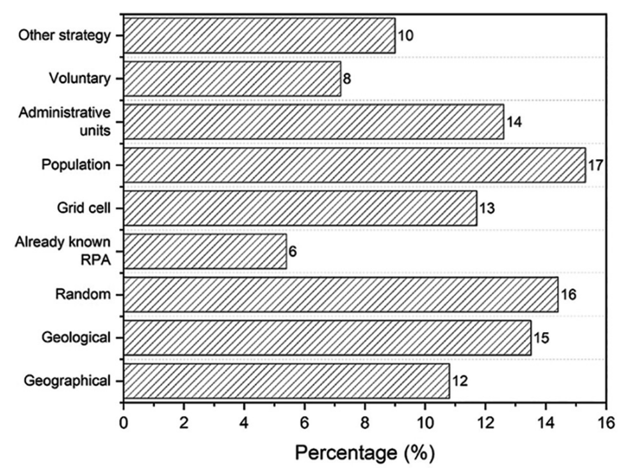

Fig. 3. Distribution of sampling strategies on which the surveys were based.

43%) were generally preferred. Other preferred measured building types are schools and kindergartens (27%), general workplaces (10%), public buildings (11%), and underground touristic mines and caves (7%). In case of radon measurements in dwellings, 65% of them were carried out in rooms located at ground floor, 7% located at first floor, 3% in the basement, and 25% in 'other' locations (second or higher floor, etc.).

In almost 90% of the surveys, a questionnaire was used to collect metadata, that is, information about the measurement site (house type, building materials, heating system, remedial action performed, etc.) and anthropogenic factors (number of inhabitants, ventilation habits, smoking and living habits, etc.). Figure 4 shows the percentages of the selected metadata categories asked for in questionnaires that accompanied indoor radon surveys.

Among 'other' category, corresponding to 9% of the replies, respondents provided additional information about metadata asked, such as year of construction of the

Citation: Journal of the European Radon Association 2022. 3: 7605 http://dx.doi.org/10.35815/radon.v3.7605

building, on floor-soil contact, number of floors, occupancy rate, etc.

An important aspect of a survey design is its representativeness: according to the questionnaire results, only in 61% of the reported surveys, this issue was taken into account when the radon survey was planned.

Measurement methods

Many detector techniques have been established to measure the concentration of radon and its decay products in indoor air. Methods requiring an electric source are termed active; otherwise, they are called passive. Some widely used passive techniques are as follows: 1) solid state nuclear track detectors (SSNTD; available with different materials – LR-115, CR-39, and polycarbonate) (19), 2) active charcoal canisters (20), and 3) electret ion chambers (21, 22).

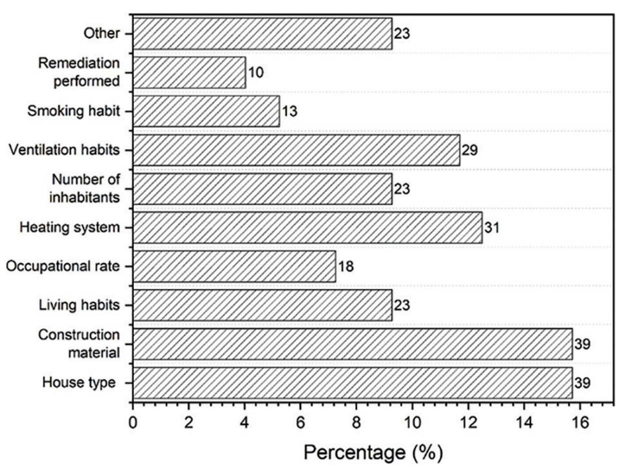

Fig. 4. Distribution of metadata that have been asked for in questionnaires that accompanied indoor radon surveys.

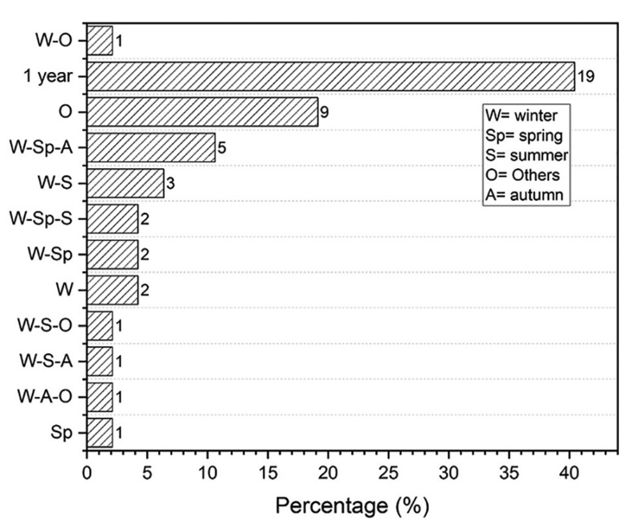

Fig. 5. Seasons in which indoor radon measurements have been performed. Percentage and number or replies are indicated.

Active systems in common use are ionization chambers, proportional counters, Geiger Muller tubes, Lucas cells, scintillators, solid state detectors, and more (2, 8).

Moreover, radon measurements are often discussed in terms of either a short-term or long-term test. Since environmental radon concentrations are subject to temporal variability, the duration of a measurement (i.e. the time over which radon concentration is averaged) and the time of the year when it was performed are crucial for assessing its accuracy and precision as estimate of a long-term mean.

The choice of measurement technique used in a survey and the duration of the measurements are highly affected by survey goals and sampling strategies, as well as by logistic constraints.

The analysis of the replies reveals that most of the surveys used passive devices (≈95%) for radon monitoring. Among the passive detectors, the most used are SSNTD based mostly not only on CR39 (more than 50%) but also on LR115 (around 25%). For the SSNTD detectors, 44% of respondents performed 1-year measurements. In the other cases, measurements were performed mostly during the winter (≈ 25%) but often covering more than one season. Figure 5 shows detailed information about the duration of the surveys.

Only in few cases was seasonal normalization applied in order to estimate an annual average radon concentration from measurements whose duration is less than 1 year. In most cases, radon concentration is highest in winter; therefore, using raw, that is, non-normalized winter values is a conservative approach. In 'other' category, the respondents provided additional information: 6 months measurement (half winter-half summer), winter for short-term measurements; winter/summer for long term; two subsequent measurements each at 6 months; 3 months measurement period when seasonal correction factors are close to 1; from September to June; from October to May; heating season; November to June and June to November; average of two measurements, first measurement in heating season (duration 1–2 months), second in non-heating season.

The influence of thoron on the devices used to measure radon was considered in very few surveys. About 22% of the respondents know that the measurement methods used were affected by thoron, but most of them (around 45%) did not correct the results. About 17% of the respondents seemed not to be aware of the effect.

Data management, statistical treatment, aggregation, and mapping

As a common practice, once indoor radon measurements have been carried out, results need to be collected together with meta-information related to the measurements, that is, measurement duration, geographical position, building characterizes, and living habits (4, 5).

Then, data should be checked and normalized if required (i.e. seasonal normalization, floor normalization, usually to ground floor). The last step is to process the data by aggregating them into mapping units (municipalities and grid cells) or submit them to geostatistical procedures to produce maps and to communicate the results to decisions makers, authorities, scientific community, and the public (23).

In almost all surveys analyzed, the interest and involvement of the participants (population or employer) was very high. The return rates1 are higher than 80% in more than 80% of the surveys. The evaluation rates2 are higher than 75% in more than 70% of surveys.

Only in seven surveys, the results have been corrected for lost detectors (12%); more than 80% replied that this was not done, or they did not reply at all to this question. Among the answers given by some respondents on how the results were corrected for lost detectors, it was reported that if more than one detector was positioned at one location, the remaining ones that could be recovered were used for estimating the value.

In case of parallel measurements at the same location-measurement point, arithmetic mean (AM) was chosen as representative value in 60% of the replies. When more than one measurement were performed at the same dwelling/house/building, the value chosen to be reported in databases was equally distributed between AM, raw data, no answer, and other.

Considering the SSNTD detectors, more than 90% replied that no normalization linked to building characteristics, in particular to floor levels, was applied.

Forty-six percent of the replies reported that data were aggregated using simple target descriptive statistics of raw data, and some aggregation methods specified by responders are reported as follows:

- AM for the building;
- maximum per building (for assessment of necessary remediation measures);
- AM mean per season (or simple AM) per mine/cave;
- AM and standard deviation (SD) per dwelling types, year of construction, ventilation types, smoking (yes/no), volume of measurement space, and type of space/room;
- AM, maximum, median, median absolute deviation, geometrical mean (GM), SD, cumulative frequency for municipality, or other geographical unit; and
- use of parametric and non-parametric tests, assume log-normal distribution and by means of Geographic Information System.

1. The return rate is defined as the fraction of deployed detectors that could be collected.

2. The evaluation rate is definded as the fraction of deployed detectors that could be evaluated and have plausible results (e.g. detectors that were returned but obviously not exposed or damaged are excluded).

Only 37% of the replies responded positively to the question if the surveys included aggregation or modeling of raw data (standard house, applying geostatistical techniques such as kriging,3 average within municipality, etc.). Description of some methods reported by the responders is listed as follows:

- target quantities: indoor radon concentration or radon potential (annual radon concentration for standard room or house; not to be confused with the geogenic radon potential);
- geostatistical methods for mapping: aggregation into geographical units (e.g. municipalities), moving averages or methods of the kriging family including advanced versions (24); regression approaches that take advantage of existing predictor data; combinations (25); target statistics: mean or probability to exceed a RL within regions;
- Variants include population weighing and correction of the variance of short-term radon input data.

Considering only the replies concerning national databases, for about 50% of the countries, data were aggregated in some ways: eight of them reported that at least simple statistics of raw data were calculated; six of them reported also a sort of modeling of the data (e.g. using geostatistics or simply performing averages within municipalities).

To the question about the mode in which the data were presented to the public or the authority, the majority replied 'other' (Fig. 6). This is because between the options proposed in the questionnaire, several important ones were missing; according to the respondents, these are as follows:

- direct communication (result letter) to the managers of the administrative buildings, kindergartens, and schools;
- result letter or simple report to all households;
- reports and scientific papers;
- reports for authorities; and
- maps on web sites.

Indoor radon policy

In this section, 13 questions were addressed to national authorities only and 19 countries answered them. The questions were related to national databases, including details about data aggregation and modeling, and some information about the status of the implementation of the requirements of the EU-BSS.

However, the results of this study may not provide the full picture after transposition of the EU-BSS

3. Kriging method is the main estimation procedure used in geostatistics. It predicts unknown values using known value and a variogram model to estimate the spatial correlation.

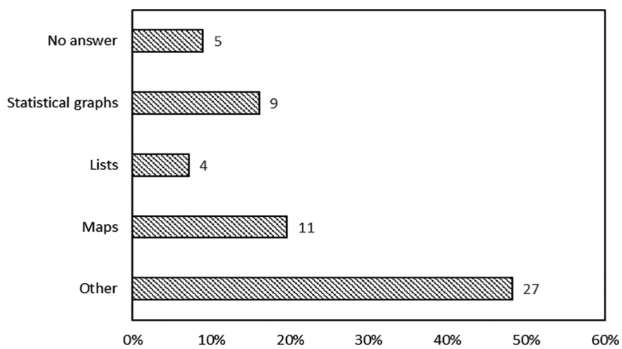

Fig. 6. Number and percentage of the different options selected by the respondents to the question: how data are presented to the population/authority.

requirements into all EU national legislations because the replies of the questionnaire were collected between December 2017 and July 2018, just before or just after the transposition deadline of the EU-BSS (February 6, 2018).

Subsequently to the collection of information through the questionnaire-based survey described in the present paper, WHO has recently conducted an update to the survey performed in 2007 on radon guidelines, programs, and activities (10, 26).

In 2020, the European Commission published a report on regulatory control of radon in workplaces implementing the requirements of the EU-BSS (27). The report also provides some practical examples of regulatory control of radon exposure at workplaces from five European countries, which covers information summarized in the present paper.

National databases

Almost 60% of the countries have merged data from different surveys in a national database. From these databases, it results that the number of dwellings/buildings with radon concentration measurements in the countries varies from few hundreds to about 600,000, with half of the respondents reporting more than 12,000 dwellings. Based on these data, the percentage of the dwelling-building stock with radon concentration measurements is generally lower than 1% for each country, with the exception of Finland where this percentage is about 8%.

Implementation of requirements of the 2013/59/Euratom Directive

Reference levels. The institutions reported the RLs and the actions that should be taken if it is exceeded, separately for dwellings (new and existing ones), public buildings, and workplaces.

Most countries (11 out of 19) reported 300 Bq m^{-3} as RL for all four situations described earlier. For the remaining countries, the answers are more varied: in few cases, the RL chosen (100 or 200 Bq m^{-3}) for new and existing dwellings is lower than the one for workplaces or public buildings, which is generally equal to 300 Bq m^{-3}, the maximum allowed by the EU-BSS.

According to the EU-BSS, the action taken by the countries in case of exceedance of RLs is remediation, but it is different for dwellings and workplaces: generally, for dwellings, remediation is recommended, whereas for workplaces and public buildings, it is mandatory (27).

Radon priority areas. Almost 60% of the countries have identified RPAs or said that the identification was ongoing at the time when they responded to the questionnaire. In all cases, the input data used for the identification of these areas are the indoor radon concentrations. However, eight countries have also reported to use information about the geology, and among them, five countries have included also other input data (such as radon in soil and gamma dose rate) as additional predictors.

The definition used to classify RPAs is mostly based on the percentage of dwellings exceeding RL: this percentage varies from 1% (UK) to 30% (Czech Republic) according to the different radon distributions of the countries. Norway chose to define all its territory as RPA.

According to the requirements of the EU-BSS, five countries reported that measurements in ground floors and basements of workplaces are mandatory in RPAs. Moreover, information campaigns to increase the public awareness (in five countries) and preventive measurements in new dwellings (in four countries) have been taken.

Conclusions

In the framework of the MetroRADON project, an indoor radon surveys questionnaire was designed and addressed to more than 70 European institutions working in this field, such as national authorities, regional administrations, universities, and research centers.

The main objective of the questionnaire was to collect information on rationales and designs of indoor radon surveys in Europe, as well as about measurement procedures and data processing. This information is the base for analyzing comparability and joint interpretability of radon surveys.

From the 56 replies from 24 countries collected between December 2017 and July 2018, it can be concluded that European indoor radon surveys are

1. *comparable* for the measurement methods. In almost all surveys (95%), passive devices were used for radon measurements, and among them, more than 80% were SSNTD. Almost 50% of measurements had a duration of 1 year. Of the remaining, most tried to cover all seasons to represent the meteorological variability of the year, which is one of the main controls of indoor radon concentration, or include winter for conservative

measurement results, as usually, radon concentration is highest in winter.
2. *not comparable* for the design characteristics of indoor radon surveys related to their objectives. Indeed, the majority of the surveys had more than one purpose as well as more than one sampling strategy. Consequentially, great heterogeneity in building types and methods chosen for distributing the detectors was evidenced.
3. *too varied* to enable easy comparability with respect to data management, statistical treatment, aggregation, and mapping. The high return rates reported in all surveys can be highlighted, but little information was provided about data normalization. A great heterogeneity was found on the methods and models for aggregating data. Replies were too vague (due to questions too vague too) to be conclusive for this matter, and further information is needed.
4. Reference levels had been already established by most responding countries, whereas RPAs delineation was still under way. Regarding the radon policies, it is worth noting that their long-term goal should be the reduction of the number of lung cancers attributable to radon, which can be achieved by preventing radon entry in new dwellings and by reducing radon in existing ones. From the present work, it emerges that, for nearly all the countries, the percentage of the housing stock with radon concentration measurements is lower than 1%, despite the huge number of radon surveys carried out up to now.

Acknowledgements

The author would like to acknowledge all the persons that filled or has been consulted for filling the questionnaire. A special thanks go to Stephan Mundigl for his revision and suggestions and to two anonymous reviewers.

Conflict of interest and funding

The authors declare no conflict of interest. This work was supported by the European Metrology Programme for Innovation and Research (EMPIR), JRP-Contract 16ENV10 MetroRADON (www.euramet.com). This project has received funding from the EMPIR programme co-financed by the Participating States and from the European Union's Horizon 2020 research and innovation programme.

References

1. United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). Source and effects of ionizing radiation – Volume I, Annex B. New York: United Nations; 2008. Available from: https://www.unscear.org/unscear/en/publications/2008_1.html [cited 15 June 2021].
2. World Health Organization (WHO). WHO Handbook on Indoor Radon: a public health perspective. World Health Organization; 2009. ISBN 978941547673. Available from: https://www.who.int/publications/i/item/9789241547673 [cited 15 June 2021].
3. European Commission (EC). Council Directive 2013/59/Euratom of 5 December 2013 laying down basic safety standards for protection against the dangers arising from exposure to ionising radiation, and repealing Directives 89/618/Euratom, 90/641/Euratom, 96/29/Euratom, 97/43/Euratom and 2003/122/Euratom. OJEU 2014; 57(L13): 1–73. Available from: https://eur-lex.europa.eu/eli/dir/2013/59/oj [cited 12 August 2021].
4. International Atomic Energy Agency (IAEA). National and regional surveys of radon concentration in dwellings. Review of methodology and measurement techniques. IAEA analytical quality in nuclear applications. Series n. 33; 2013. Available from: https://www-pub.iaea.org/MTCD/Publications/PDF/IAEA-AQ-33_web.pdf [cited 1 February 2021].
5. International Atomic Energy Agency (IAEA). Design and conduct of indoor radon surveys, Safety Report Series n. 98; 2019. Available from: https://www.iaea.org/publications/12351/design-and-conduct-of-indoor-radon-surveys [cited1 February 2021].
6. Dubois G. An overview of radon surveys in Europe. Report EUR 21892 EN. Scientific and Technical Research Series. 2005. ISBN 92-79-01066-2. Available from: https://op.europa.eu/en/publication-detail/-/publication/30b38f3c-200f-43e4-a829-438c55d921ac/language-en/format-PDF/source-186562756 [cited 22 January 2021].
7. Digital European Atlas of Natural Radiation. Available from: https://remon.jrc.ec.europa.eu/About/Atlas-of-Natural-Radiation/Digital-Atlas [cited 28 January 2021].
8. European Commission (EC), European Commission, Joint Research Centre, Cinelli G, De Cort M, Tollefsen T (Eds.). European Atlas of Natural Radiation. Luxembourg: Publication Office of the European Union; 2019. Printed version: ISBN 978-92-76-08259-0; doi: 10.2760/520053; Catalogue number: KJ-02-19-425-EN-C; Online version: ISBN 978-92-76-08258-3; doi: 10.2760/46388; Catalogue number: KJ-02-19-425-EN-N. Available from: https://remon.jrc.ec.europa.eu/About/Atlas-of-Natural-Radiation/Download-page [cited 12 August 2021].
9. Åkerblom G. Radon legislation and national guidelines. Swedish Radiation Protection Inst.; 1999. Available from: https://inis.iaea.org/collection/NCLCollectionStore/_Public/31/004/31004182.pdf?r=1&r=1 [cited 22 January 2021].
10. World Health Organization. International radon project: survey on radon guidelines, programmes and activities: final report. World Health Organization; 2007. Available from: https://apps.who.int/iris/handle/10665/331770 [cited 22 January 2021].
11. Synnott H, Fenton D. An evaluation of radon reference levels and radon measurement techniques and protocols in European countries. A report of the ERRICCA 2 European project (European Commission Contract FIRI-CT-2001-20142). Dublin: Radiological Protection Institute of Ireland; 2005.
12. Share, Team up, Engage, Analyse, Monitor (STEAM) project Joined Radon Population Opinion Survey, Part of IAEA TC Project RER9153 – 'Enhancing the Regional Capacity to Control Long Term Risks to the Public due to Radon in Dwellings and Workplaces'. Available from: https://www.iaea.org/projects/tc/rer9153 [cited 4 February 2021].
13. Bartzis J, Arvela H, Bochicchio F, Collignan B, Fojtikova I, Gray A, et al. Radon Prevention and Remediation (RADPAR). Final Scientific Report. 2012. Available from: https://radon.iss.it/wp-content/uploads/2019/06/European

Commission_RADPAR-FinalScientificReport.pdf [cited 12 August 2021].

14. MetroRADON project (2017–2020). Available from: http://metroradon.eu/ [cited 12 August 2021].
15. Pantelić G, Čeliković I, Živanović M, Vukanac I, Nikolić JK, Cinelli G, et al. Qualitative overview of indoor radon surveys in Europe. J Environ Radioact 2019; 204: 163–74. doi: 10.1016/j.jenvrad.2019.04.010
16. Pantelić G, Čeliković I, Živanović M, Vukanac I, Nikolić J, Cinelli G, et al. Literature review of indoor radon surveys in Europe. EUR 29613 EN. Luxembourg: Publications Office of the European Union; 2018. doi: 10.2760/977726
17. Bossew P, Čeliković I, Cinelli G, Ciotoli GC, Domingos F, Gruber V, et al. On harmonization of radon maps, submitted to JERA 2021.
18. Cinelli G, Bochicchio F, Carpentieri C, Venoso G, Trevisi R, Leonardi F. Results of analysis of MetroRADON questionnaire data on indoor radon surveys. Annex 3 of Deliverable 3 of MetroRADON project; 2019. Available from: http://metroradon.eu/wp-content/uploads/2017/06/16ENV10-MetroRADON-D3_accepted.pdf [cited 12 August 2021].
19. Durrani SA, Bull RK. Solid state nuclear track detection. Principles, methods and application. Oxford: Pergamon Press; 1987. doi: 10.1016/C2013-0-02771-5
20. Cohen BL, Nason R. A diffusion barrier charcoal adsorption collector for measuring Rn concentrations in indoor air. Health Phys. 1986 Apr; 50(4): 457–63. doi: 10.1097/00004032-198604000-00002. PMID: 3957669.
21. Kotrappa P, Dempsey JC, Hickey JR, Stieff LR. An electret passive environmental ^{222}Rn monitor based on ionization measurement. Health Phys. 1988 Jan; 54(1): 47–56. doi: 10.1097/00004032-198801000-00002. PMID: 3335440.
22. Kotrappa P, Dempsey JC, Ramsey RW, Stieff LR. A practical E-PERM (electret passive environmental radon monitor) system for indoor ^{222}Rn measurement. Health Phys. 1990 Apr; 58(4): 461–7. doi: 10.1097/00004032-199004000-00008. PMID: 2323927.
23. Baumann S, Bossew P, Celikovic I, Cinelli G, Ciotoli G, Domingos F. Report and Guideline on the definition, estimation and uncertainty of radon priority areas (RPA). Deliverable 5 of MetroRADON project. 2020. Available from: http://metroradon.eu/wp-content/uploads/2017/06/16ENV10-MetroRADON-D5-with-Annexes_Accepted.pdf [cited 12 August 2021].
24. Raspa G, Salvi F, Torri G. Probability mapping of indoor radon-prone areas using disjunctive kriging. Radiat Prot Dosimetry. 2010 Jan 1; 138(1): 3–19. doi: 10.1093/rpd/ncp180
25. Miles JC. Mapping the proportion of the housing stock exceeding a radon reference level. Radiat Prot Dosimetry. 1994 Dec 1; 56(1–4): 207–10. doi: 10.1093/oxfordjournals.rpd.a082454
26. WHO Global Health Observatory data repository. Available from: https://apps.who.int/gho/data/node.main.RADON?lang=en [cited 12 August 2021].
27. European Commission. Radiation Protection RP193. Radon in workplaces – implementing the requirements in Council Directive 2013/59/Euratom. Luxembourg: Publications Office of the European Union; 2020. Available from: https://op.europa.eu/en/publication-detail/-/publication/93cc4aff-47c5-11ea-b81b-01aa75ed71a1/language-en?WT.mc_id=Searchresult&WT.ria_c=37085&WT.ria_f=3608&WT.ria_ev=search [cited 12 August 2021].

***Giorgia Cinelli**
European Commission, Joint Research Centre (JRC)
via E. Fermi 2749
IT-21027 Ispra (VA)
Italy
Email: giorgiacinelli@gmail.com