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RESEARCH ARTICLE

REVISED When citizen science meets radon building diagnosis: Synthesis of a French pilot project developed in the framework of the European RadoNorm research project

[version 2; peer review: 2 approved]

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Abstract

As part of the European RadoNorm research project, citizen science pilot projects focusing on the management of radon risk in houses have been implemented in four countries. This article describes the methodological basis, the development and the results of the French pilot project. Building on an initial review of existing literature, the pilot project aims to frame a 'participatory approach' aligned with the standards and recognized practices of citizen science. Particular attention was given to the management of data and the inclusion of ethical considerations.

The focal point of the project was the process of radon building diagnosis which is supposed to be carried out whenever (high) radon concentrations are measured and should be prerequisite to mitigation works. As experience shows, however, this diagnosis is hardly implemented in France. To help remedy this situation, the pilot project recruited citizens already aware about radon from Pays Vesoul Val-de-Saône (East of France) to test an existing online self-evaluation guide for radon diagnosis, report on their operational experience and meet with radon/building experts. This enabled citizens to contribute to improvements in form and content to the guide and to ensure that it would be better fit for purpose. Comparison of the guide with experts' practices offered additional perspectives on what building diagnosis should entail.

The pilot project produced rich and high-quality data that will nurture the evolution of the guide. The project demonstrated both the viability and the utility of applying the citizen science approach to radon post-measurement phases, with measurable benefits in bridging

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1. **Boris Dehandschutter**, Federal Agency for Nuclear Control, Brussels, Belgium

2. **Aaron Goodarzi**, University of Calgary, Calgary, Canada

Any reports and responses or comments on the article can be found at the end of the article.

knowledge gaps and in encouraging behavioural changes. The results of using a citizen science approach in the field of radon management and research are encouraging, and they far outweigh the challenges involved in the implementation.

Keywords
Radon at home, RadoNorm, citizen science, radiation protection, radon diagnosis, ethics

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REVISED **Amendments from Version 1**

Following the peer review reports, the comments and further proof-check of the manuscript, the major amendments are the followings:

- Improvements of the English of the abstract in plain language.

- Update of the § Literature analysis with inclusion of recent Canadian publications concerning the post-measurement steps and adjusting the text to modulate previous findings.

- Inverting Figure 1 and Figure 2; in Figure 2: separating the "research" and the "technical" results of the project.

- Updates in the § Discussion:

> Indicating that different metrics exist to assess what is citizen science and why the researchers selected the ECSA Principles then, below, discussing if applying all the ECSA Principles is viable for similar project.

> Displaying plainly the possible reasons that explain the low participation.

> Indicating that other projects (e.g. Canada) were more efficient in raising awareness with noting that the pilot project was a prototype not meant to raise broad awareness.

- Changing the title "Results" to "Synthesis of the results" in the Conclusions.

- Acronyms ECSA and CEPN included in the glossary.

- Local Health Contract (CLS) explained in footnote 2.

- References: including references proposed by Mr. Goodarzi, modifying the reference from Mrs. Berti Sulman and Mr. Stanley.

Any further responses from the reviewers can be found at the end of the article

Plain language summary

RadoNorm is a research project funded by the European Commission. Among its panel of research activities, one is dedicated to the testing of citizen science pilot projects on the the management of radon in houses. A pilot-project was developed in summer 2022 in France.

Radon is a naturally occurring radioactive gas created from some geological formations, it can travel to the surface, infiltrate buildings and accumulate. Radon exposure increases the risk of lung cancer. After an measurement showing (elevated) radon concentration in a house, a diagnosis (identify where the radon comes from) and mitigation (concrete actions to reduce radon) should follow, but evidence indicate that these are rarely performed in France. The authors thought it might be appropriate to focus the pilot project on the diagnosis step. From the point of view of citizen science, the project aimed to align with the recognized principles and practices in citizen science, include ethical considerations.

A pre-exiting on-line radon diagnosis guide was submitted to citizens recruited in the Pays de Vesoul (East of France) already aware about radon. The suggestions from the citizens were collected through questionnaires, meetings with radon/building experts and tests in real conditions. This 'participatory approach', positioning the citizen at the core of the project, produced technical suggestions that could help to improve the guide and, hopefully, increase diagnosis/mitigation intention.

Specific issues when merging citizen science and radon were identified (for example: a potential low participation and attention to plan the protection of the participants against radon from the onset) but these are manageable and should not prevent the launch other citizen science projects, which bring interesting and unexplored potentials for the citizens – and the experts – in radon management at home.

Introduction

Citizen science pilot projects in RadoNorm

Radon (^{222}Rn) is a radioactive gas produced by the decay of uranium and radium naturally present in the Earth's crust. Transported from the soil to the surface, radon can enter into buildings through cracks, holes and porous materials and accumulate indoors, thus presenting a health risk. Epidemiological studies have presented evidence of a linear increases in relative lifetime risk of lung cancer at $\geq$100 Bq/m^3 of repetitive, long term radon exposure (Darby *et al.*, 2005; Krewski *et al.*, 2005). Radon is recognized in many countries as the second cause of lung cancer deaths (IARC, 1998; WHO, 2009).

RadoNorm is a Euratom Horizon 2020 research project aiming to strengthen the scientific and technical basis of the management of exposure situations to radon and other naturally occurring radioactive materials (NORM). From 2020 to 2025, RadoNorm will federate 57 organizations including universities, research centres, radiation protection institutes, etc., under a multidisciplinary approach bringing together research, social science, technological development, education, and training activities, all structure into eight Work Packages (WP) (Kulka *et al.*, 2022).

One of the objectives of WP6 ('Social Aspects') is to investigate the perspectives offered by citizen science for the management of indoor radon in houses. Citizen science pilot projects were developed and tested in four countries: France (the pilot project being coordinated by the Nuclear Protection Evaluation Centre, CEPN), Ireland (by the Environmental Protection Agency, EPA), Hungary (by the Atomic Energy Research Centre, EK-CER) and Norway (by the Norwegian University for Life Sciences, NMBU). Each pilot project has its own specificities and organizational arrangements (Martell *et al.*, 2022).

The purpose of this article is to describe the methodological tenets of the French pilot project, to present how the project unfolded during the summer 2022, and to discuss the results obtained, both in technical terms and with respect to citizen science.

What is citizen science?

WP6 partners published a critical review of the literature on citizen science applied to radon research published until 2020 (Martell *et al.*, 2021). The first observation made by Martell *et al.* is that 'citizen science' is a flexible concept whose boundaries have evolved over time and as a function of the various topics, disciplines and promoters involved. These research dynamics have made it difficult to produce a single and definitive definition of "citizen science". Broadly, the term refers to any form of production of scientific knowledge where citizens actively

and deliberately participate along with the researchers (MESR, 2016). Yet even this broad definition fails to encompass the variety of methods applied in different disciplines (Haklay *et al.*, 2021; Heigl *et al.*, 2019). This situation has prompted several researchers to define distinct categories of citizen science. Among these, Martell *et al*. proposed to adopt Hacklay's typology (Haklay, 2013) based on the level of participation of citizens in the project (Table 1).

Citizen science has been employed in a variety of research fields, especially biodiversity, environmental research and natural sciences (MESR, 2016). The literature discussing its advantages and drawbacks is abundant. The most frequently mentioned advantages of citizen science include the volume of data collected and analysed, a favourable cost-time ratio, the development of innovative protocols (*ibid.*; Heigl *et al.*, 2019), an increase in awareness/education, and encouraging social innovation (*grassroots initiative*) (Butkevičienė *et al.*, 2021). But citizen science also has significant downfalls:

- From the researcher's perspective, citizen science challenges the principle of research autonomy, produces lower quality data, and may be exposed to an overall lack of rigor (Elliott & Rosenberg, 2019);
- From the perspective of the citizens, there are risks of instrumentalization, discrepancy between the answers provided by the project and actual needs, unbalanced expert-citizen relationships, and unsustainable motivation (Eleta *et al.*, 2019; MESR, 2016).

The management of data provided/produced by citizens as well as the implementation of ethical principles have been the topics of recent literature (Heigl & Dörler, 2018; Oberle *et al.*, 2019), including a special issue of *Citizen Science, Theory and Practice* entirely dedicated to ethics (Rasmussen & Cooper, 2019).

Several organizations offer recommendations and guidance on citizen science implementation. Martell *et al.* have adopted the 'Ten Principles of Citizen Science' developed by the European Citizen Science Association (ECSA, 2015; ECSA, 2020) as a metric to judge whether a participatory initiative can be considered citizen science, and if adequate resources and best practices have been included in the project.

State of the art on citizen science projects applied to radon management and research

The number of papers published on citizen science projects applied to radon management and research has been modest: less than 10 projects in the range 1984 to October 2020 have been identified by Martell *et al.* The role of the citizens has been generally low ('level 1' under Hacklay's typology) and none has met the Ten Principles fully. Martell *et al.* highlighted that these projects followed a top-down approach, with a clear separation of tasks between experts and citizens, the latter acting as 'data collectors' and not involved in the design of the project, the production of scientific knowledge or in the development of the findings. The authors showed that earlier projects focused only on the first steps of radon management – namely, information about radon and measurement at home – while the post-measurement stages focusing on reducing radon exposure were not tackled.

These results should be adjusted in considering recent publications. There have been several studies on citizen science applied to radon published since 2020 and some addressed post measurement stages, such as reaction to radon test results (Irvine *et al.*, 2022) and the effect of building codes and practices on radon concentration (Khan *et al.*, 2021). The effect of citizen scientists' psychology and behavioral choices with residential radon exposure (therefore providing means to reduce it) were also investigated recently (Cholowsky *et al.*, 2023; Simms *et al.*, 2021).

Objectives of the French pilot project

In France, no regulation regarding the management of radon in dwellings is currently in force[1]. For about 20 years, local stakeholders such as municipalities, communities/counties (groups of municipalities), Regional Health Agencies (ARS) and associations have decided on a voluntary basis to develop radon awareness initiatives and implement measurement campaigns (DGS, 2018). The Local Health Contract (CLS), which establishes a health strategy between a given community and the ARS, is sometimes an instrument used to formalize and implement radon initiatives for periods of a few years[2] (Réaud *et al.*, 2022).

[1] The current French national strategy is driven by the 4th French national radon action plan (2020–2024) and, when it comes to radon in houses, actions are concentrated on information and awareness The single regulatory requirement consists in an obligation to inform the buyers/tenants of real estate located in radon prone areas prior to a property transaction (article L. 125-5 of the French Environment Code). The radon prone areas are listed by the 27 June 2018 Regulatory Order.

[2] The local health contract (CLS) is a contractual document established between a local public administration (generally a group of communities) and the Regional Health Agency (ARS) which describe a local strategy intended for the improvement of the health of the population and include different objectives aligned with the local context (*e.g.* allergy, access to health care, …) and the means to achieve them. Experiences show that some administration can consider including an item about the measurement and the management of radon in houses within the CLS.

Table 1. Four levels of participation in citizen science (adapted from Haklay, 2013).

Level	Denomination	Role of the citizens
Level 1	Crowdsourcing	Citizens as sensors
Level 2	Distributed intelligence	Citizens contribute with data and help with basic interpretation
Level 3	Participatory science	Citizens participate in problem definition, data collection, and drafting of the conclusion and reports
Level 4	Extreme citizen science	Citizens are deeply engaged in most parts, including data analysis, conclusion and broadcasting the results

Following a measurement campaign, the 'mitigation works' (*e.g.* sealing the surfaces of the building in contact with the ground, limiting the transfer of radon in the building, ventilating the basement and/or the living areas) are presented to participating inhabitants. The mitigation is more effective when adequately combined with and adapted to the specificities of the building after a 'building diagnosis' performed by an expert (CEREMA, 2020; Lafage *et al.*, 2017). However, as a result of technical, financial, social and psychological obstacles (*ibid.*; Bourcier *et al.*, 2010; Hevey, 2017), the number of building diagnoses (even when the expense is covered) and of mitigation works (even in cases when radon concentrations are significant) remains very low (Nétillard *et al.*, 2013; Turcanu *et al.*, 2020).

Considering that post-measurement steps have been barely addressed by citizen science projects at the time of the development of the protocol and in view of the recurrent difficulties identified in France for this step in the radon management process, **the CEPN chose to focus the pilot project on the building diagnosis phase** performed after the measurement of elevated radon concentrations in houses.

A self-assessment guide for radon in buildings (hereafter called "the guide") was published on-line in 2019[3]. The guide was developed by the Centre for Studies and Expertise on Risks, the Environment, Mobility and Urban Planning (Cerema, a French public agency[4]), the School of Engineering and Architecture of Fribourg (HEIA-FR[5]) and the Romand Centre for Indoor Air Quality and Radon (croqAIR[6]) under the auspice of the JuradBat project[7]. Designed as a free-to-use interactive questionnaire, the guide provides information to facilitate the understanding of the radon penetration-and-transfer-phenomenon, and proposes specific mitigation solutions that respond to the main characteristics of the building, as indicated by the user.

The pilot project was designed to allow volunteer citizens to use the guide, report on their experience and take part in reflections on its form and the content, thus ensuring that future versions of the guide will be better fit-for-purpose. It is also hoped that the project will increase the visibility of the guide and the adoption of mitigation practices.

In marked contrast to projects with a top-down approach and the clear separation between the citizens and the experts, **the pilot project endeavoured to create the conditions for 'participatory science'. This meant putting citizens at the core of the project, especially in the production of scientific knowledge and involving them in every different step**, including data collection (*e.g.* the whole guide is submitted to their analysis), meetings (*e.g.* the views of the citizens and the experts are treated as equal) and in the overall organization (the development of the project and the conclusions are entirely based on the citizens' answers and proposals[8]). Therefore, the participants had to be already aware about radon and ideally, had already performed a measurement in their homes and had questions about mitigation—precisely the part of the process the guide is designed for.

To be deemed as 'citizen science' and to guarantee the incorporation of recognized standards and best practices in this field, **the project committed to alignment with the 'Ten Principles'**. While addressing ECSA Principle n°10 (legal and ethical issues surrounding copyright and confidentiality), it seemed necessary to **elaborate a Data Management Plan (DMP)** to delineate which data/results would be open access and which would be kept confidential.

Furthermore, as the ethical grounds of citizen science projects in the field of radon research could be questioned (as experienced by Stanley *et al.*, 2017 and Oberle *et al.*, 2019), **an application form intended for an ethical committee was considered necessary**. An important feature of the ethical considerations was to include in the project protocol the possibility for participants to have a radon diagnosis performed by an expert.

Methods

Recruitment of the participants

At the end of 2021, CEPN presented the concept of the pilot project to the Cerema and HEIA-FR experts who developed the guide and invited them to participate. CEPN then contacted the coordinator of the CLS of Pays Vesoul Val-de-Saône (PVVS county[9]) to discuss the possibility of recruiting participants among the citizens who took part in the winter 2020–2021 radon measurement campaign, where 168 radon measurements were performed in 24 municipalities in PVVS county (Rivière *et al.*, 2021). In May 2022, approval from the elected representatives of the county was granted and the coordinator sent out a leaflet (Annex 1 of the *Extended data,* Andresz *et al.*, 2023) presenting the project and the terms and conditions to participate, along with the results of the campaign. The researchers expected to recruit around 10% of the persons contacted - a judgement call based on the usual answer rate to survey experienced by the researchers - hence around 15–20 participants, and decided on a minimal value to

[3] https://jurad-bat.net/auto-evaluation (The guide is in French) [access in January 2023].

[4] https://www.cerema.fr/en [access in January 2023].

[5] https://www.heia-fr.ch/en [access in January 2023].

[6] https://www.croqair.ch (in French) [access in January 2023].

[7] The JuradBat project was a research project supported by European Interreg funding. From 2014 to 2019, it gathered more than 20 French and Swiss partners to develop a platform of information about indoor air quality and radon and set up a sustainable network aiming to share experience, expertise and competences notably through awareness and education and training programmes. The guide was one of the outputs of JuradBat.

[8] Additional research has shown that collaborative initiatives giving citizens the essential role of 'operating partner' and building the project based on their 'operating experience' is an emerging topic in the medical field, formalized by the *patient-as-partner* model (Karazivan *et al.*, 2015) with practical applications in hospitals Institut Curie.

[9] A county in eastern France gathering 176 municipalities, grouped into 5 communities, with around 70,000 total inhabitants. http://www.pays-vesoul-valdesaone.fr/fr/ (in French) [access in January 2023].

proceed of 6 participants, which was a bit lower than half the expected value and the size of the groups in Downs *et al.*, 2009; Downs *et al.*, 2010 whose topic of interest was close (air quality). The important consideration in the strategy (an opportunistic sampling) was to recruit a purposive group of motivated individuals to collect information on their experiences and perspectives on a topic of common interest (and not a group sufficient in size to allow statistical analysis of the answers, all the more so since the demographic characteristics of the initial group of 168 participants was not surveyed by PVVS and not known). To this regard, no exclusion criteria were used.

The partners of the pilot project, their relations and main tasks are schematically presented in Figure 1.

Data collection and analysis

In April-May 2022, the CEPN tested the guide repeatedly and to get accustomed and familiar with the content of the guide and the sequences of the questions depending on the previous answers. A flowchart provided by the developers was also used. The CEPN prepared a questionnaire with the objective to survey all the parts of the guide (the introduction, the questions, the answers provided, the report in .pdf format produced after each use and the section addressing the case where the radon concentration is below 300 $Bq.m^{-3}$) and from different angles (understanding, usability, suggestions). Due to the exploratory nature of the task, a mixed approach was selected with 24 closed questions, 7 open questions and 5 scaled questions (score from 1 to 5). The questionnaire was tested in-house by the CEPN (for the sake of independence and objectivity, the developers were not involved) and the final version (Annex 2 of the *Extended data,* Andresz *et al.*, 2023) was sent by e-mail to the participants. Quantitative and qualitative analyses of the answers were performed (by CEPN only) to prepare a slideshow for the in-person meetings, whose objective was to provide a forum for citizens and experts to exchange opinions about the guide and discuss possible modifications.

In order to test the guide in real conditions and to further explore its evolution, CEPN decided to compare the methodology established for the guide with that of an independent expert tasked with performing a radon diagnosis in the participants' homes. A protocol to compare the methodologies of the guide and the expert was prepared by CEPN (Annex 3 of the *Extended data,* Andresz *et al.,* 2023) considering all the questions in the guide and evaluating systematically if deviation in these questions and in the final results occur during the on-site diagnosis.

Demonstrating the feasibility of developing a citizen science project for radon management necessarily implies an evaluation of its implementation, the results acquired and the impacts. A feedback questionnaire was prepared on the basis of recommendations made in the evaluation of citizen science projects by RadoNorm partners (Martell *et al.*, 2022) and in the literature (Kieslinger *et al.*, 2018; Schaefer *et al.*, 2021 and the dimensions proposed by Phillips *et al.*, 2018). A key feature of the questionnaire (presented in Annex 4 of the *Extended data,* Andresz *et al.,* 2023) is a set of questions addressed to the experts. The value of this expert feedback appears to have been overlooked in earlier projects (*ibid.*).

Alignment with the principles of citizen science and the objectives of the project

Prior to its implementation, the above-described protocol was analysed for compliance with the 'Ten Principles'. The result of this evaluation is presented in Annex 5 of the *Extended data,* Andresz *et al.*, 2023. The consensus among WP6 partners was that the project should be assessed as level 3 'participatory science' on the Hacklay scale (Table 1).

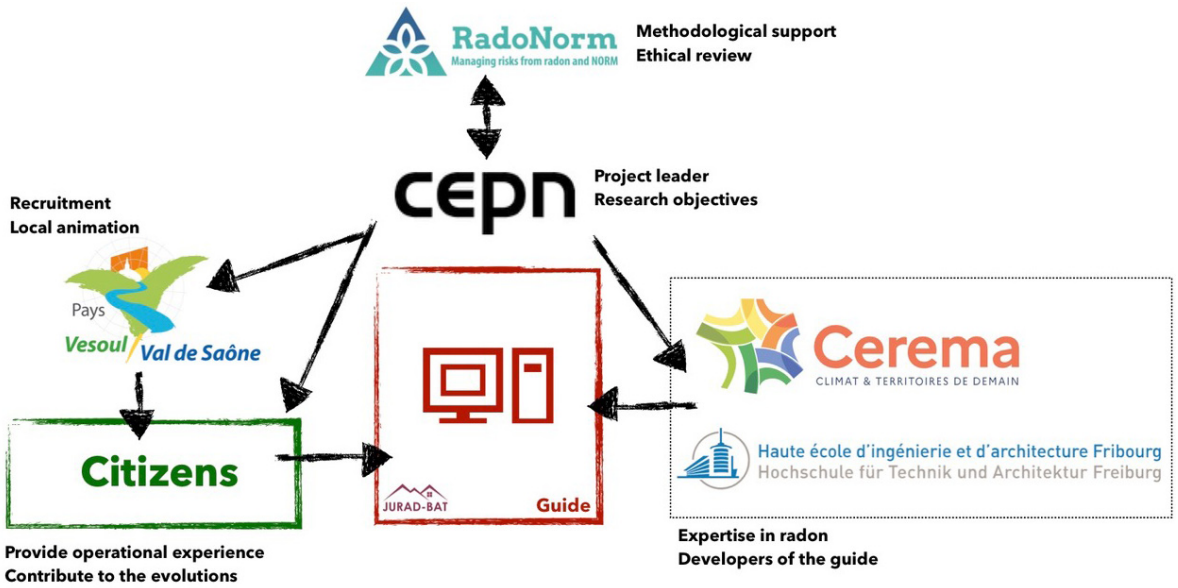


Figure 1. The partners, their relations and the main tasks.

An ethical application form, inspired by the standard model used by ethics committees in French universities, and a DMP, based on an existing document applicable for Horizon 2020 projects (CEA, 2021), were elaborated and completed on the basis of the literature review (Martell *et al.*, 2021), a corpus of recommendations and good practices (CNIL; Cohen & Doubleday, 2021; Durham, 2012; ECSA, 2020; Pierce & Evram, 2022), and especially those applicable to environment-related health and risk management (Berti Suman, 2020; Downs *et al.*, 2010; SHAMISEN-SINGS, 2020). The ethical application form and the DMP (Annexes 6 and 7 of the *Extended data,* Andresz *et al.*, 2023) were validated by the RadoNorm Ethical Committee 29 August 2022[10]. In accordance with these, each participant was given an information letter describing the project and the implications of participation from the outset, and was asked to sign a consent form (Annex 8 of the *Extended data,* Andresz *et al.*, 2023). All the participants signed the consent form.

Table 2 presents the connections between the objectives of the pilot project and their operational applications.

Results

Implementation

At the end of May 2022, because the number of citizens who had come forward was lower than the minimal value, the leaflet was sent to personnel aware about radon in several local public bodies: PVVS, Cerema, ARS and the Departmental Land Management (DDT). In early June, six participants had been recruited[11], and all their questionnaires were collected by mid-June. The analysis of these questionnaires was compiled in a slideshow presented during the first meeting (15 June 2022) and updated before the second meeting (16 June) to take account of the points of view expressed (the second slide show is presented in Annex 9). On 16 June, a building diagnosis was performed (with the help of the blueprints and pictures of the house) for one participant who had requested it and, on 20 July, a diagnosis was performed at the home of another participant (the report is provided in Annex 10).

A remote meeting with the citizens and the experts was planned (22 July 2022) to present and discuss a first version of the results and the final version (see Annex 11) was then sent to all participants. At the beginning of September, feedback questionnaires were sent to the citizens and the experts, and by the end of the month, six questionnaires had been collected.

The significant moments of interaction and the documents that have circulated are presented in Figure 2 and the number of citizens in the steps of the project is presented in Figure 3 (the number of experts has always been 2).

Results of the building self-assessment guide

Analysis of the questionnaires and the discussions during meetings revealed, first and foremost, the recognition by all of the usefulness of the guide and appreciation for its informative and comprehensive nature and the "*enormous amount of*

[10] The RadoNorm Ethical Committee confirmed that the pilot-project can start before its approval was granted (e-mail correspondence, 3rd March 2022).

[11] The characteristics of the participants were not surveyed by PVVS and not known. 4 participants were inhabitants engaged in the radon measurements campaign 2020–2021 and 2 from local public bodies with knowledge about radon.

Table 2. Objectives of the project and materials.

Objectives	Operational applications
Demonstrate the feasibility of a "citizen science" project on radon management in houses	• Check for adherence to the 'Ten Principles for Citizen Science' (Annex 5) • Collect formalized feedback data from citizens and experts about the project for future citizen science initiatives in this area (Annex 4)
Differentiate from projects focused only on radon awareness and measurement	• Focus on building diagnosis • Use the JuradBat building self-assessment guide for radon • Recruit citizens with prior experience and awareness in radon management (Annex 1)
Differentiate from the top-down approach and the clear separation between the citizens and the experts	• Put in place the conditions for citizens to be at the very core of the project, involved in all the different steps and using their answers and proposals to guide the project
Obtain results useful for the management of radon and radiation protection	• Produce specifications on the form and the content of the guide to ensure it is better fit-for-purpose • Use questionnaire (Annex 2), test in real conditions (Annex 3) and hold meetings • Increase the visibility of the guide
Incorporate ethical considerations	• Prepare an ethical application form (Annex 6) and a Data Management Plan (Annex 7) and submit them to the RadoNorm Ethical Committee • Provide an information letter for participants and a consent form (Annex 8) • Be able to offer a radon building diagnosis performed by an expert to interested participants

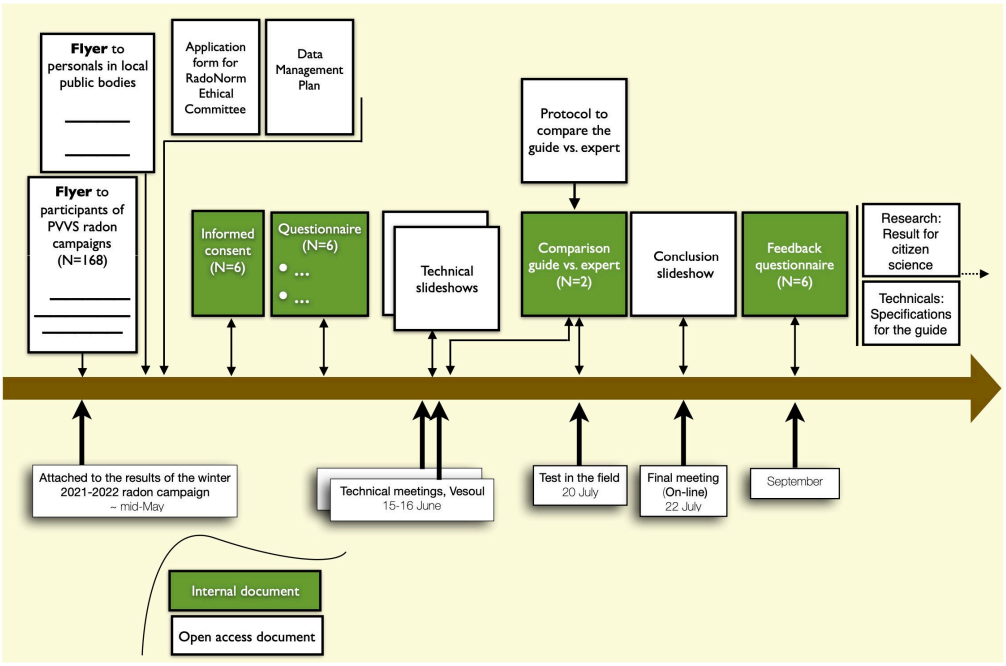


Figure 2. Significant interactions and documents in circulation.

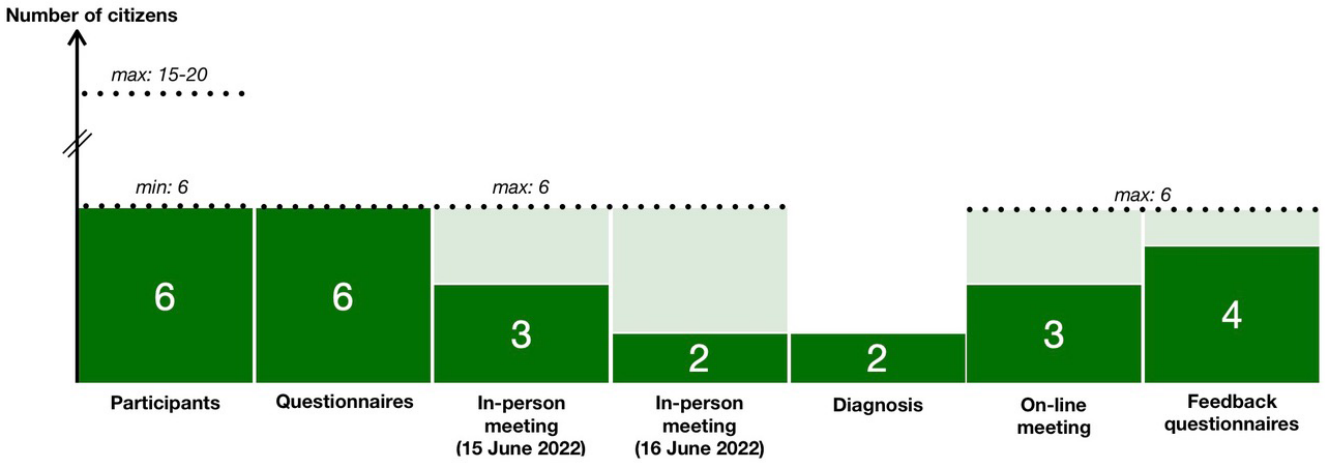


Figure 3. Evolution in the number of citizens in the project steps.

work" it embodies. That being said, several observations and suggestions for improvement were made.

Some suggestions involved the conciseness of the guide. Several parts of the guide were considered too long or detailed:

- The introduction: suggestions were made to split it up and distribute its content in the guide, to record a short introductory video or to design an interactive module using a schematic building to navigate in the guide.

- The pdf report could be shortened by removing repetitions and adding clarity by limiting the number of fonts, replacing line breaks, using colour coding to differentiate between works that are recommended and those to be avoided. No consensus on the ideal size (in pages) of the report was reached.

Other suggestions focused on the need for additional explanations, in particular with regard to ventilation and several technical terms (these were listed). Participants pointed out that technical terms (e.g. "*ventilation*" or "*air-tightness defect*") can be understood very differently by an expert and a citizen. Citizens highlighted that some concepts are better conveyed by image and video (rather than by text), and stressed that these media have become communication standards for the younger (if not for every) generation. All citizens were keen to provide illustrations if needed to replace existing ones.

Finally, whilst the ergonomics of the guide met consensus, some computer bugs and user interface adjustments (such as opening hyperlinks in another tab rather than in the same window) were listed.

Conceptual changes were also suggested by citizens such as incorporating other building configurations than the current ones (or indicating how to use the guide in the case of hybrid building configurations) and using the radon concentration value differently in the diagnosis process. Because the guide was developed by a Franco-Swiss team, it includes some national specificities that proved to be non-transferable between countries (for example: the radon reference level, several building peculiarities, and vocabulary). Participants recommended that the national specificities should be indicated.

The comparison of the guide with the expert confirmed that the guide is by no means a surrogate for the human expert. Only the latter can adapt the diagnosis process to the specificities of the building and decide to use devices (real-time measurement of radon or air renewal) to complete the picture of the radon transfer mechanisms in the house and to apprehend the diverse characteristics of the building (and their interrelationships), resulting in a diagnosis that is unique and inclusive of mitigation tuned to the situation and (possibly) ranked by cost or complexity.

Using the guide and consulting the report contributed to the adoption of diagnosis and mitigation measures by making users more aware of radon risks and how radon penetration/transfer mechanisms work, and by providing a large volume of information about diagnosis and mitigation adapted to broad categories of building configurations, all of which "*makes it possible to anticipate the need for mitigation work*". But several citizens indicated that these elements were neither necessary nor sufficient to act: "*it is imperative to meet a building professional before starting anything*". As the guide serves several objectives, including "*self-assessment*, *education*, *raising awareness*, *explanations of the work*, etc.", some users commented on the technical density of the document and suggested that the number of objectives be limited to the main one, which is (as one developer put it), "*introducing users to the topic of mitigation and to basic skills*".

Results of the citizen science project

The feedback questionnaires from four citizens (out of six) and two experts (out of two) were analysed. For the citizens, a startling result is that the pilot project had an impact on all tested aspects:

- The project raised citizen awareness about (a) radon risks in houses, (b) building diagnosis and (c) mitigation (impact on the *interest* dimension under Philips *et al.* typology (Philips, 2018));
- It increased the level of information citizens have on these 3 topics (*knowledge*);
- It encouraged citizens to look for further information (*skills of science inquiry*);
- It enabled citizens to talk about these 3 topics (*stewardship*);
- It motivated citizens to take actions (*self-efficacy*), to change their habits (*behaviour*) both at home and in their circle of family, friends, and neighbours.

The open comments emphasized the "*rewarding*" nature of the project, allowing a large volume of information to circulate from the experts to the citizens. It was observed that the citizen science approach allowed people to "*digest*" the information better.

For their part, the experts reported an improved awareness about citizen science applied to radon management efforts. They commented on their improved understanding of several knowledge and perception gaps between experts and citizens ("*the difficulty for individuals* [...] *to understand the issues*") and that other forms of support for diagnosis and mitigation are needed for action to occur after radon measurement. While the project did not change their technical knowledge about diagnosis and mitigation, "*the way of addressing these subjects*" in the future will be optimized by adapting the message and providing more room for explanations and pedagogy. Finally, the experts concluded that they were willing to talk about the pilot project in their organisations and beyond, via their networks[12].

Discussions

Project design and protocol

Citizen science is a flexible term and different metrics are available to design a 'citizen science' project be they quality criteria (Heigl & Dörler, 2018), best practices (EU, 2020) or research ethics board recommendations (Oberle *et al.*, 2019), although their applicability will depend among others: on the national regulations (on radon, ethics, data management), the targeted population, the objectives of the project and who is funding. In the context of the European RadoNorm project and previous publication of the partners (Martell *et al.*, 2021) choosing the ECSA 10 principles as indicators for the elaboration of the pilot project was the logical option.

At the design stage, the pilot project was confronted with the absence of a framework concerning the inclusion of ethical considerations for a citizen science project on radon: the literature review found that an ethics committee was not a systematic feature (*ibid.*), that its conclusions can be questioned (Oberle *et al.*, 2019) and that the content of the standard existing ethical application form did not align with the challenges of citizen science and radiation protection[13]. For the pilot project, it appeared necessary to adapt an existing file (for details about the adaptation, see Annex 7).

[12] Cerema published a summary of its participation in the project in October 2022 : When citizens attempt radon self-assessment, Cerema, https://www.cerema.fr/fr/actualites/quand-citoyens-s-essaient-autoevaluation-du-risque-radon (in French) [access in January 2023].

[13] For Larouche, 2019, the content of the standard ethical application form is a legacy of medical science practices.

If citizen science on radon were to develop, the pilot projects would benefit from a harmonized set of recommendations to decide whether approval from an ethics committee is needed. A template integrating the ethical principles of citizen science (*e.g.* ECSA, 2020) and possibly the ethical principles and procedural values of radiation protection (ICRP, 2018) would also be helpful in this respect.

Principle 7 (ECSA, 2015) invites project leaders to make data and results publicly available and to publish in Open Access and in citizen science databases, but this may conflict with the need to respect the confidentiality of the participants, who run the risk of facing a potential devaluation of their property or being targeted by radon solution commercial providers. In previous citizen science projects on radon, the results were anonymized (Tsapalov *et al.*, 2020).

For the pilot project, the following practices were integrated in the DMP (Annex 7) and these could form the basis for the data management of future citizen science projects applied to radon management in houses:

- A data protection impact assessment, expressing the risk/benefit balance for participating citizens;
- Integrating recommendations from citizen science practitioners (Cohen & Doubleday, 2021; Durham, 2012; Pierce & Evram, 2022) and the French National Commission for Data Protection and Liberties 'Six Key Practices' (CNIL);
- Consideration of the FAIR principles (EU, 2016);
- An informed consent to participate (Annex 8) describing how confidentiality is guaranteed and giving the possibility for participants to contact researchers at any time.

The researchers have endeavor to meet all ECSA 10 Principles in the pilot-project. However, their application from the onset on the management of radon in home proved to be challenging: some principles need adaptation, thematic could be missing and also applying all principles might be erring on the side of caution and potentially distracting resources and time from other benefiting goals of the project (recruitment, outcomes ...). The results of the other WP6 RadoNorm pilot-projects might confirm (or not) if applying all 10 Principles is a viable decision for citizen-science projects associated with radon management.

Participation

Citizen participation was an aspect that received constant attention. At the beginning, the challenge lays in the constitution of a group of sufficient size to generate discussions with the experts and to bring together different points of view (N.B. the characteristics of the population who participated in the radon measurement campaign were not known, so representativeness was not sought). Although the number of citizens was limited - which was considered "*most unfortunate*" by all – this count is not uncommon (Downs *et al.*, 2009; Downs *et al.*, 2010) and was ultimately quite convenient as it allowed for rich and inclusive discussions that are not necessarily possible with a large group.

Maintaining the level of participation throughout the project was another challenge (Figure 3). To counteract the potential for 'participation fatigue', the pilot project was concentrated in a short time frame (< 5 months) with meetings planned outside weekends and working hours (18:00 to 21:00). Regular follow-ups and reminders by email and telephone were sent out by CEPN and the CLS coordinator. Yet, if all the participants returned the questionnaire, only half of them attended the meetings (probably due to the inconvenience of the distance) and six feedback questionnaires (out of eight) were collected.

The researchers acknowledged that the participation during the project has been limited, especially in comparison with some projects identified in the literature review (Martell *et al.*, 2021) and recent Canadian projects gathering between two to four thousand participants (ex. Cholowsky *et al.*, 2023; Irvine *et al.*, 2022). It has however to be kept in mind that this pilot project was a prototype to test the feasibility of applying citizen science to improve radon diagnosis and remediation, and not meant to reach a broad scale. Among the possible (combining) reasons that explain the small participation: an opportunistic targeted sampling, an initial target of small size, a small team of researchers, the erosion of the interest of the inhabitants about radon (the measurement took place in winter 2020–2021), the complexity of the topic as well as social factors and behavioral reactions towards radon.

The motivations driving participants to join the project were surveyed orally. The "*European*" nature of the project, which gives it "*quite a dimension*" and "*appeal*" (because opportunities to participate in this type of project are rare) was highlighted. Citizens also indicated that the topic itself was "*interesting*" and "*important*". All these motivations relate to the concept of 'collective motivation' (under the classification established by Nov *et al.*, 2011 and recommended by Martell *et al.*, 2022). Several participants were also looking for information about diagnosis and mitigation ("*I wanted to know more*"), which corresponds to the concept of 'extrinsic motivation'. These are the two forms of motivation that were explicitly expressed.

To generate and sustain participation in future radon-focused citizen science projects, several scenarios could be explored in different combinations, depending on the topic:

- Emphasize the collective and extrinsic motivations identified in the pilot project;
- Discuss activating other forms of motivation, *e.g.* social interaction, reputation, and norm-oriented behaviour (see Nov *et al.*, 2011), but bearing in mind that the financial compensation of citizens (an intrinsic motive) is not an insignificant decision and could create difficulties (Tauginiene *et al.*, 2021);
- Consider the geographical extension of the project, but a large-scale-project does not facilitate plenary in-person meetings and remote meetings have their own challenges (Fouqueray *et al.*, 2023);

- Adapt the scope of the project in terms of the number and type of participants, for example by involving citizens who have not previously performed radon measurements (in which case, mass media can be used including printed media, municipal newsletters, social networks, microinfluencers (Cholowsky *et al.*, 2023) etc.);
- Mobilize pre-existing and well-established scientific organizations, ideally with experience in citizen science, *e.g.* a citizen laboratory. Platforms used for sharing citizen science projects (e.g. eu-citizen.science, scistarter.org) can be screened;
- Align the project's timetable with local initiatives (*e.g.* coordinate the start the project with a radon measurement campaign).

Results

The project generated a significant volume of comments and suggestions which, in the opinion of the experts, were "*constructive*", "*interesting*", of high quality and constituting a pool of modifications for the guide. While some suggestions can be implemented easily in the short term, others require a longer process of development and arbitration. It should be noted that at the time of writing, the transfer of the administration of the Jurad-Bat platform - which hosts the guide - to a new body was under negotiation. This transition is likely to delay the integration of the modifications proposed by citizens but will also strengthen the robustness and sustainability of the platform.

The results were collected through questionnaires and in-person/online meetings, which are quite 'classical' means for experts. For future citizen science projects (and if applicable), digital-methods including video, social media or smartphone applications could be implemented (the latter has already been applied in citizen science on ionizing radiation, Kim *et al.*, 2020; SHAMISEN-SINGS, 2020; Tsapalov *et al.*, 2020). The raw responses to the questionnaires can be found as *Underlying data* (Andresz *et al.*, 2023).

Merging citizen science and radon management

Citizen science initiatives are a way to federate citizens on the development of comprehensive and participatory approaches to radon risk management and strengthen their engagement in post-measurement actions, both being essential to fostering the radon management process (Turcanu *et al.*, 2020). However, the pilot project has shed light on some specific difficulties when citizen science meets radon.

Firstly, it is difficult to awaken the interest of citizens in radon: a complex, little-known, yet worrying subject that requires prior knowledge and familiarity with specific vocabulary and that may lack appeal in relation to other subjects. Other projects were much efficient in raising awareness yet after several interactions (2–5 over a year in general, or more interactions, Cholowsky *et al.*, 2023; Irvine *et al.*, 2022).

Secondly, as conceptualized for environment-related issues (Berti Suman, 2020; Ceccaroni *et al.*, 2021), citizen science focusing on a given health risk (be it air or soil pollution, invasive species, etc.) must be able to provide support for the management of the risk 'revealed' to participants. As a consequence, a citizen science project involving individuals exposed to radon in their homes should provide the (human) expertise, time and budget necessary to manage the risk. However, in France, this expertise is scarce, the effectiveness of the mitigation works is hard to predict and their costs difficult to determine. These issues should be considered by researchers when designing and framing future citizen science projects on radon management in houses.

A citizen science project should produce "*a genuine science outcome*" (in accordance with Principle 2 of ECSA, 2015), yet the implementation of the diagnosis and mitigation is based on know-how and a portion of empiricism. This observation does not impair their efficiency, yet there remains some level of interpretation on whether a citizen science project aiming to improve diagnosis and mitigation measures is 'scientific' or not. Without trying to discourage new projects from tackling the issues that arise post-measurement, the importance of correctly ascertaining the scientific aspects of the project should not be overlooked.

Beyond these difficulties, the participants in the pilot projects indicated that citizen science also brings new perspectives on ways to improve the management of radon. The following items were identified:

- Include a citizen science project in a Local Health Contract;
- Encourage established networks with an interest in indoor air quality and radon to start a citizen science project;
- Take advantage of the firm connections with actors in the field to improve the implementation of mitigation solutions and to collect feedback on their efficiency and cost (which are very rare data);
- Collect information about the expectations/difficulties faced by citizens;
- Introduce new ways to make people more aware and better trained in the area of radon management, contributing to (more) informed decision-making;
- Enlarge the circle of reflection beyond the experts.

Conclusions

Synthesis of the results

This experience demonstrates that it is possible to design a project that meets the established and recognized principles of citizen science, can be deemed 'participatory science', and whose focal point is the building diagnosis that follows a radon measurement at home. High standards for data management and considerations for ethical principles were

adopted and adapted to the specificities of the project. All these elements constitute notable methodological outcomes.

The technical results are rich and constructive. They will nurture modifications and developments to the guide at short and medium terms. The project confirmed the usefulness of the guide, which contributes to fostering action in the radon post-measurement phase. The project also increased the visibility of the guide and enlarged its initial audience.

Citizen participation was limited, but the project, being a pilot, was not designed to reach a large scale and it was not a barrier as the small group produced rich and inclusive discussions. Evaluation of the feedback highlights the benefits of the project for citizens in terms of the information received, how actionable this information can be, and how the citizens will disseminate it further and ultimately change behaviours in a wider population.

As for the experts (whose feedback is rarely collected after a citizen science project), this project has sharpened their awareness about the gaps that may exist between themselves and the citizens. Experts were thus enabled to adapt their approaches to the subject.

The pilot project encountered several specific issues that arise when citizen science meets radon, but in the end, these were found to be manageable. Both the citizens and the experts maintained that the citizen science approach has great unexplored potential to strengthen radon management at individual, local and potentially even bigger scales.

Perspectives

This pilot project is one of the four projects in the 'incubator of citizen science models' set up in the framework of RadoNorm WP6 which, at the time of writing, were being implemented in Ireland, Norway and Hungary. Each pilot project has different objectives and its own modalities (Martell *et al.*, 2022). In 2023, WP6 moved into the second phase by supporting organizations willing to carry out citizen science projects on radon management in houses. The organizations were selected after an open call which run from November 2022 to February 2023. In a third and final phase (post 2023), "citizen science toolkits" will be constituted by the RadoNorm partners on the basis of the experiences and elements – methodological, technical, tools, recommendations – identified in the projects. These toolkits will be made available to any actors wishing to set up a citizen science project applied to radon management in houses.

Acronyms

ARS: Regional Health Agency; **CEPN:** Nuclear Protection Evaluation Centre; **Cerema**: Centre for Studies and Expertise on Risks, the Environment, Mobility and Urban Planning; **CLS**: Local Health Contract; **DDT**: Department for Land Management; **ECSA:** European Citizen Science Association; **DMP**: Data Management Plan (Annex 7); **HEIA-FR**: School of Engineering and Architecture – Fribourg; **PPVS**: Pays Vesoul Val-de-Saône; **WP**: Work Package.

Data availability

Underlying data

Store^{DB}: STOREDB:STUDY1177 RadoNorm Subtask 6.3.1 - Citizen science pilot-project - Application in France - Documents - 2021~2022. https://doi.org/10.20348/STOREDB/1177 (Andresz *et al.*, 2023).

This project contains the following underlying data:

- Underlying data RadoNorm WP 6 3 1 Citizen Science French pilot project.xlsx
    - Tab 'Questionnaire': response to the questionnaires (see Annexe 2 of the Extended data)
    - Tab 'Feedback questionnaire': responses to the feedback questionnaire (see Annexe 4 of the Extended data)
- [Raw questionnaires associated with] Underlying Data RadoNorm WP 6 3 1 Citizen Science French pilot project.pdf (raw responses in French)

Extended data

Store^{DB}: STOREDB:STUDY1177 RadoNorm Subtask 6.3.1 - Citizen science pilot-project - Application in France - Documents - 2021~2022. https://doi.org/10.20348/STOREDB/1177 (Andresz *et al.*, 2023).

This project contains the following extended data

- Annexe 1 — Leaflet for the recruitment of participants (in French)
- Annexe 2 — Questionnaire about the building self-assessment guide
- Annexe 3 – Protocol to compare the building self-evaluation guide with an expert
- Annexe 4 — Feedback questionnaire about the participation to the pilot-project
- Annexe 5 – Adequation of the pilot-project with the ten principles in citizen science
- Annexe 6 — Application form for ethical committee and data management plan
- Annexe 7 — Data management plan
- Annexe 8 — Information document and consent form

- Annexe 9 —Slideshow prepared for and during the in person-meetings, 15 and 16 June 2022 (in French)

- Annexe 10 – Radon expertise report from the visit performed 20 July 2022 (Cerema document) (in French)

- Annexe 11 — Slideshow prepared for and validated after the final meeting, 22 July 2022 (in French)

Data are available under the terms of the Creative Commons Attribution 4.0 International license (CC-BY 4.0).

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✔ **Aaron Goodarzi**
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Having read the revisions, I am satisfied that this report is sufficiently well-described in terms of what was done and the outcomes that it is suitable for the scientific community to evaluate on it's merits, and learn from as progress is made within the space of increasing radon awareness and reducing high exposures.

No further comments or suggestions.

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Citizen science, radon exposure, radiation exposure, population health, radiobiology, building science

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Reviewer Report 08 August 2023

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✔ **Boris Dehandschutter**
Federal Agency for Nuclear Control, Brussels, Belgium

Thank you for the revision, I have no further comments to make.

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Environmental radioactivity expert at the Federal Agency for nuclear control, the radiation protection authority in Belgium

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Version 1

Reviewer Report 20 July 2023

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Aaron Goodarzi
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This study involves exploring the feasibility of carrying out a citizen science style radon awareness project in a French community. The study team attempt to apply all ten principles of citizen science into their research, which is an ambitious goal. While the study team have clearly learned a variety of valuable lessons regarding the implementation of a radon awareness project via a citizen science approach, regrettably the lack of participation by the community (6 responses) does detract from the outcomes. In my view, this lack of participation is, itself, a primary outcome that is indicative that the approach used here is problematic. I would like to see a more fulsome discussion of this, as it is valuable for others to understand. For example, I think a clear lesson from this work is that trying to apply all ten (academic) principles of citizen science (while a laudable goal) is now demonstrably not practical for this type of work, and appears to have interfered with the teams ultimate goal of promoting broad scale radon awareness, increasing understanding of local buildings as they relate to radon, and motivating health-seeking behaviour such as radon testing and exposure reduction.

This work could be improved by re-framing some of the discussion in terms of compare-and-contrast with other global jurisdictions where citizen science style work in radon awareness and exposure reduction are ongoing (e.g. Canada). I would recommend the authors be open to more boldly stating whether excluding certain principles of citizen science might be beneficial.

Within the discussion section, I would challenge the notion that it is universally "...difficult to awaken the interest of citizens in radon...". While this has been the experience of this team, there are now a variety of studies elsewhere that provide evidence that awakening this interest is achievable. Recent publication from citizen science centric research projects in Canada involve >30,000 households and achieve broad scale notoriety in the Canadian national press. While certainly there are many differences between Canada and France, the Canadian example is a valuable point of reference against which this can be compared to derive lessons.

Minor comments:

Reference "Fintan *et al*., 2017" is incorrectly labelled, as this should be Stanley *et al*., 2017 (Dr. Fintan Stanley being the first author).

Some additional references would be useful within the introduction, such as primary literature citations regarding exposure doses linked with increased lung cancer risk. I would also say it would be appropriate to provide a quick update on the information presented in Martell *et al*., 2021, as many additional studies involving citizen science and radon have emerged since then, making the statement that "number of papers published on citizen science projects applied to radon management and research has been modest: less than 10 projects over the last decades" out of date / untrue as of this time.

It is also incorrect to say that previous citizen science studies "focused only on the first steps of radon management – namely, information about radon and measurement at home – while the post-measurement stages focusing on reducing radon exposure were not tackled." There have been at least three studies since 2021 that addressed post measurement stages, citizen scientist psychology, reactions to information, behavioural choices, and more. So this section within the introduction would benefit from an update. Relevant PMID for these and other citizen science based radon publications include: 37029226[1], 36104382[2], 34475435[3], 34099826[4], 33762674[5].

References

1. Cholowsky NL, Chen MJ, Selouani G, Pett SC, et al.: Consequences of changing Canadian activity patterns since the COVID-19 pandemic include increased residential radon gas exposure for younger people.*Sci Rep*. 2023; **13** (1): 5735 PubMed Abstract | Publisher Full Text
2. Irvine JL, Simms JA, Cholowsky NL, Pearson DD, et al.: Social factors and behavioural reactions to radon test outcomes underlie differences in radiation exposure dose, independent of household radon level.*Sci Rep*. 2022; **12** (1): 15471 PubMed Abstract | Publisher Full Text
3. Khan SM, Pearson DD, Rönnqvist T, Nielsen ME, et al.: Rising Canadian and falling Swedish radon gas exposure as a consequence of 20th to 21st century residential build practices.*Sci Rep*. 2021; **11** (1): 17551 PubMed Abstract | Publisher Full Text
4. Cholowsky NL, Irvine JL, Simms JA, Pearson DD, et al.: The efficacy of public health information for encouraging radon gas awareness and testing varies by audience age, sex and profession.*Sci Rep*. 2021; **11** (1): 11906 PubMed Abstract | Publisher Full Text
5. Simms JA, Pearson DD, Cholowsky NL, Irvine JL, et al.: Younger North Americans are exposed to more radon gas due to occupancy biases within the residential built environment.*Sci Rep*. 2021; **11** (1): 6724 PubMed Abstract | Publisher Full Text

Is the work clearly and accurately presented and does it engage with the current literature?

Partly

Is the study design appropriate and is the work technically sound?
Partly

Are sufficient details of methods and analysis provided to allow replication by others?
Yes

Are all the source data and materials underlying the results available?
Yes

If applicable, is the statistical analysis and its interpretation appropriate?
Not applicable

Are the conclusions drawn adequately supported by the results?
Partly

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Citizen science, radon exposure, radiation exposure, population health, radiobiology, building science

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Author Response 28 Jul 2023

Sylvain Andresz

Dear Professor Goodarzi, Thank you very much for your review, positive feedback and helpful comments. We have implemented your comments (as well as elements coming from the comments until 24 July and further proof-checks) in a new version. In the following text, we would like to answer your comments in order of appearance in your report.

"*I would like to see a more fulsome discussion of this [the low participation of the citizen to the project], as it is valuable for others to understand*".

- We have included a § in the 'Participation' plaining detailing the possible reasons why the participation was low in the end.

"*For example, I think a clear lesson from this work is that trying to apply all ten (academic) principles of citizen science (while a laudable goal) is now demonstrably not practical for this type of work, and appears to have interfered with the teams ultimate goal of promoting broad scale radon awareness, increasing understanding of local buildings as they relate to radon, and motivating health-seeking behaviour such as radon testing and exposure reduction*" [...] *I would recommend the authors be open to more boldly stating whether excluding certain principles of citizen science might be beneficial*".

- The 10 Principles were the metrics used by the WP6 Leaders and Partners to assess

whether a project can be regarded as citizen science or not and (maybe erring on the side of caution) we decided to try to meet all the 10 Principles. It can be argued that this decision might have distracted resources/time from other aspects of the projects – maybe more beneficial. However, the Principles are a list of good practices, published almsot a decade ago, coming from the field and aiming to support the design and implementation of citizen science projects. It is not clear to the researchers which Principle(s) could have interfered (on a conceptual level) with the pilot project.

- The outcomes of the pilot project are limited anyway (this was prototype, limited in size, ...) and we are unsure they can be utilized to confront the 10 Principles. We then propose to see if the other RadoNorm pilot-projects also experienced that the application of the 10 Principles was not a viable option.

- We have added a § detailing these reasons in the 'Project Design and Protocol'. This was also the opportunity to indicate the existence of other metrics to decide if a project is CS and open a discussion on differences between countries (a comment of yours).

"*I would challenge the notion that it is universally "...difficult to awaken the interest of citizens in radon...*".

- Following the recent publications (not captured by the initial literature review), this statement is no longer true indeed. We have adjusted the statement by including results of 2 of the articles (among those with the highest citizen participation) you recommended.

"*Some additional references would be useful within the introduction, such as primary literature citations regarding exposure doses linked with increased lung cancer risk*."

- Inclusion of the "classical" publications of Darby and colleagues and Krewski and colleagues on the epidemiological results showing the dose-response relationship in the Introduction. Thanks for the recommendations.

"*I would also say it would be appropriate to provide a quick update on the information presented in Martell et al., 2021 making the statement that "number of papers published on citizen science projects applied to radon management and research has been modest: less than 10 projects over the last decades" out of date / untrue as of this time. [...] It is also incorrect to say that previous citizen science studies "focused only on the first steps of radon management*".

- The literature analysis performed by the Leaders and Partners of the RadoNorm WP6 project (the reference Martell et al. 2021) seek publications from 1984 to October 2020 (therefore could not capture later publications) and was published in June 2021 (at the very moment the team started the redaction of the protocol and make contact with the French experts).

- A new § has been included in the 'State of the art' part to indicate the existence and scope of the recent publications and experiences from Canada. Also, in the 'Objectives', we indicated that post-measurement steps were barely addressed by citizen science projects *at the time of the development of the protocol*.

Thanks again for your revision and comments. Sylvain Andresz, on behalf of the co-authors.

Competing Interests: No competing interests were disclosed.

Reviewer Report 13 July 2023

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Boris Dehandschutter
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The paper describes a pilot project of citizen science for radon management, where the authors attempted to recruit citizens in order to apply a bottom-up approach to radon management in dwellings, since this topic is of particular importance as radon affects peoples personal environment (their houses). Although it turned out to be very difficult to recruit sufficient candidates, because of the complexity of the topic, the amount of time needed to investigate, the paper can be of interest and importance for future research and attempts to imply citizen science in radon management programs. The context, framework and scientific basis on the citizen science approach are well elaborated, as is the overall methodology. The conclusions are rather limited, due to the limited number of citizen candidates recruited. This problem is well known and addressed in the paper in the section 'Participation' of the discussion. This pilot study provides a good basis for further initiatives and research for increasing public involvement in the radon programmes, and for using the input from those directly affected (the citizens) in their development and improvement.

Is the work clearly and accurately presented and does it engage with the current literature?
Yes

Is the study design appropriate and is the work technically sound?
Yes

Are sufficient details of methods and analysis provided to allow replication by others?
Yes

Are all the source data and materials underlying the results available?
Yes

If applicable, is the statistical analysis and its interpretation appropriate?
Not applicable

Are the conclusions drawn adequately supported by the results?

Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Environmental radioactivity expert at the Federal Agency for nuclear control, the radiation protection authority in Belgium

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Author Response 28 Jul 2023

Sylvain Andresz

Dear Mr. Dehandshutter, Thank you very much for your review and approval. Sylvain Andresz, on behalf of the authors.

Competing Interests: No competing interests were disclosed.

Comments on this article

Version 1

Reader Comment 25 Jul 2023

Yaela Golumbic, The Steinhardt Museum of Natural History, Israel

Having led a radon monitoring citizen science project in the past, I am very happy of the increased attention this area of research has received lately. Radon monitoring is indeed an under investigated area, with little public awareness. This paper criticizes previous radon citizen science projects, as having low participation roles, following a top-down approach and not meeting the Ten Principles of citizen science. I would ask authors to (A) provide the evidence for these claims, elaborating more about past projects and what can be learnt from them and (B) put this into context of citizen science projects globally which until recently were 95% contributory projects building on top-down approaches as their main model. Indeed recent developments in citizen science call for increased inclusion of participants in many steps of the project, yet this does not invalidate other participatory models. Authors claim the project “generated a significant volume of comments and suggestions”, this is confusing due to the low participation volume. Furthermore, due to the “longer process of development and arbitration” many of these comments were not integrated in the radon guide. This raises difficult questions about (A) the transparency and inclusivity of the decision-making process and the extent to which stakeholder input was genuinely considered and valued and (B) the sustainability of projects which aim at “putting citizens at the core of the project and involving them in every different step”. I would expect authors to consider these constraints and discuss how they can be managed. I would also like to see a critical appraisal of the low participation rate, including a discussion of the limitations this holds for generalization

of information. I would suggest to trial another 2-3 rounds of the same process to increase participation and information collected, before generating conclusions. I would also suggest to frame this work as a user centered/co design, rather than participation in all research steps. You may find the following references valuable in this context:

- Golumbic, Y.N., Fishbain B. & Baram-Tsabari, A. (2019). User centered design of a citizen science air-quality monitoring project. International Journal of Science Education, Part B 9(3), 195-213. https://doi.org/10.1080/21548455.2019.1597314

- Golumbic, Y.N., Peri, A., Shpak, M., Tsapalov, A., Kovler, K., Ben-Zvi, D., Baram-Tsabari, A. (2023) The radon home survey: A citizen science project for involving the public in authentic research combining science and society [in Hebrew, extended English abstract here - https://www.researchgate.net/publication/368882907_Citizen_science_and_public_involvement_in_research_c]. Israeli Sociology.

- Dalyot, K. & Golumbic, Y.N. (2023). Citizen Science in STEM education: Engaging students with real life science. In: International Encyclopedia of Education 4th Edition. 11, 224-233. https://doi.org/10.1016/B978-0-12-818630-5.13004-0 (see case studies section on radon project).

Competing Interests: No competing interests were disclosed.

Reader Comment 20 Jul 2023

Andrey Tsapalov, Technion Israel Institute of Technology, Haifa, Israel

It seems to me that any research project, especially a funded one, should be useful. Is it possible to benefit from offering citizens research, for example, on diagnosing and developing proposals for repairing their household appliances or cars as part of Citizen Science? If I'm not the only one who doubts getting such a benefit, why is it that in relation to the diagnosis and mitigation of indoor radon (as a very complex natural and anthropogenic factor, when there are no common approaches to measurements even among specialists) deep involvement of citizens is promoted, instead of simple and inexpensive indoor tests according to clear protocols like in the US. If the result of a simple test reveals a problem, then specialists, not citizens, should deal with it.

Competing Interests: No competing interests were disclosed.

Reader Comment 14 Jul 2023

Anna BERTI SUMAN, Digital Economy Unit, Marie Skłodowska-Curie Fellow at the European Commission's Joint Research Centre, Ispra, Italy

Not being an expert of radon measurement myself, but rather of environmental citizen science and of other forms of civic monitoring on complex and divisive environmental matters/risks, my review will focus on the accounting of the article of the citizen science experience, challenges and results.

The self-assessment guide for radon in buildings is a potentially interesting tool. It would have been useful to elaborate further on their uptake by citizens, eventual criticisms that emerged in drafting the guide and iterations for improvements. It could be also valuable to have the guide itself as annex for online consultation.

The article discusses the participative approach of the pilot being “in marked contrast to earlier projects with a top-down approach and low-level participation”. It would be in order to find references and examples to these earlier projects and why they are considered top-down.

Many acronyms as ECSA and CEPN are given with no much explanation. Perhaps, including them in the final glossary or providing an explanation in brackets would help?

Reflections on the reasons behind the lower participation than the expected would be also a relevant aspect to discuss. Albeit it is true that a small group of participants may foster closer discussions, the pool of volunteers is really low and this should be reflected in a disclaimer as it is difficult to draw results based on such a limited engagement. The article states that “the project generated a significant volume of comments and suggestions” but one wonders how is this possible with such a limited number of inputs, despite rich?

Figure 1 is informative but some entries are not clear like “Results for citizen science” (maybe of the citizen science pilot?). Table 1 is informative. Figure 2 talks about documents in circulation but it refers only to ‘the guide’.

The reflections on the role of the guide compared of that of a human expert and the need thereof is very relevant. Also the discussion of the ethical challenges encountered is valuable.

The results in terms of the difficulties of radon citizen science, and of recommendations are interesting. I would suggest an explanation of what a Local Health Contract is exactly. Under Conclusions, there is another Results section which is slightly confusing.

I thank the authors for the citation of Suman 2020 (Suman AB: Sensing the risks, A case for intergrating citizen sensing into risk governance. OpenPress Tilburg University, 2020). However, the correct citation is Berti Suman 2020 and 'integrating' is misspelled. Thanks for correcting it if you can.

Competing Interests: No competing interests were disclosed.

Reader Comment 04 Jul 2023

Andrey Tsapalov, Technion Israel Institute of Technology, Haifa, Israel

Unfortunately, I have almost no positive comments regarding the French pilot project, although the manuscript is well prepared and describes the Citizen Science study in detail. Probably, this study can be assessed as quality and validity of the research if well-known facts are not taken into account.

1. For example, the US has a strong indoor radon measurement and mitigation industry, in contrast to the very underdeveloped indoor radon regulation in France, as well as in the European Union as a whole. Indeed, less than 1% of buildings in Europe have been tested so far (IAEA Report, 2019). At the same time, according to the US Radon Action Plan (http://www.radonleaders.org/sites/default/files/2022-01/NRAP-2021-2025-Action-Plan-508.pdf), 3.8 million buildings have been mitigated by 2020 and 8 million buildings will be mitigated by 2025, with a total coverage of about 150 million buildings tested. Such a huge volume of measurements and mitigations means that the US has a rich experience of involving residents in conducting mass radon tests (in the short-term mode for 2-7 days), which are also paid for by residents, including mitigation (when necessary). However, mitigation, including preliminary diagnostics of the building, is carried out not by residents, but by experienced professionals with a license, since this is quite a difficult task. Unfortunately, the US (as well as UK and Sweden) experience is not discussed or even mentioned in the manuscript. Thus, instead of using decades-proven diagnostic technologies and installing reliable mitigation equipment (when necessary) by French radon professionals, residents are invited to participate in Citizen Science research (at Level 3 in Table 1) of a complex problem, but already solved in other countries. Most likely, the problem has arose again due to the low level of awareness of the indoor radon experts in France.

2. An internationally agreed protocol for measuring indoor radon to conformity assessment of a room with a normative at given reliability (usually at least 95%) is still missing. For example, the recommendation in the international standard ISO 11665-8 regarding the duration of measurements “at least two months” seems strange (and does not have a strict justification), while short-term tests are the main tool in the US, where radon regulation is much more effective than in Europe under the ISO standard. Moreover, a focus group created almost two years ago for the revision of ISO 11665-8 still continues to reject (without detailed discussion and alternative proposals) a rational criterion for conformity assessment that we proposed (https://doi.org/10.1093/rpd/ncad110). The rational criterion is based for the first time on the fundamental concepts of ISO/IEC, and harmoniously covers both short- and long-term measurements, providing a given reliability of decision making (https://doi.org/10.1111/ina.13098). For more than five years the Technion team has been developing and trying to promote the rational criterion (https://doi.org/10.1016/j.jenvrad.2017.12.003), including the necessary for this research (https://doi.org/10.1016/j.envc.2021.100204). However, the European Radon Community ignores all our proposals, judging by the results of the recently completed European metrological project MetroRADON (http://metroradon.eu), as well as the not quite adequate activity to study the spatiotemporal variations of indoor radon within the WP2 of RadoNorm project, which mentioned many times in the manuscript. Returning to the core of second fundamental comment, it must be emphasized that, due to the lack of rational regulation, it is impossible to organize mass measurements of indoor radon to effectively identify radon hazardous buildings, including their diagnostics necessary for mitigation. In our opinion, unfortunately, there is a very alarming defocusing of priorities in the European Radon Community (https://doi.org/10.1111/ina.13166), which significantly hinders the promotion of rational radon risk regulation, including educational programs, as well as the potential of Citizen Science. It is useful to add a few more specific comments. For example, the data in Figure 3 clearly shows the lack of interest among residents in the Citizen Science project in France, since only 6 of 168 initial participants agreed to participate in the study, and only two (about 1%) participated in all planned activities.

To conclude my comments, I would like to thank the authors for mentioning our study (Tsapalov *et al*., 2020) in the “Project design and protocol” and “Results” sections. In this context, it is useful to clarify that one of the most important results of the work of our team was the development of an on-line system with a mobile application that allows participants to control indoor radon measurements and, indeed, anonymously display their results on a web map. At the same time, any test participant can easily find their result on the map, in addition to the report sent to their e-mail. I would hope, the official reviewers, the manuscript authors and readers, including key coordinators and other contributors to the RadoNorm project, will appreciate the importance of the fundamental comments above as part of their further professional work in the field of research and regulation of indoor radon.

Competing Interests: No competing interests were disclosed.