EPJ Nuclear Sci. Technol. **8**, 38 (2022)

https://doi.org/10.1051/epjn/2022031

EPJ Nuclear Sciences & Technologies

Euratom Research and Training in 2022: challenges, achievements and future perspectives, Roger Garbil, Seif Ben Hadj Hassine, Patrick Blaise and Cécile Ferry (Guest editors)

Available online at: https://www.epj-n.org

REVIEW ARTICLE

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RadoNorm – towards effective radiation protection based on improved scientific evidence and social considerations – focus on RADON and NORM

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Received: 11 April 2022 / Received in final form: 28 June 2022 / Accepted: 26 September 2022

Abstract. RadoNorm aims to manage risks from exposures to radon and naturally occurring radioactive material (NORM) to promote effective radiation protection based on improved scientific evidence and social considerations. It supports the European Member States and the EU Commission (EC) in implementing the Basic Safety Standards for protection against ionising radiation hazards at the legislative, executive, and operational levels (Directive 2013/59/EURATOM). The project is grounded on (1) implementation of multidisciplinary and innovative research and technologies, (2) integration of education and training, and (3) dissemination of project results targeting a broad stakeholder community including the public, regulators, and policymakers. The objectives are achieved through scientific research-related topics (exposure, dosimetry, biology, epidemiology, societal aspects), cross-cutting topics (education and training, dissemination, ethics) and project management. The project will yield guidelines at legal, executive and operational levels. It will enable consolidated and harmonised decision-making in the field of radiation protection, considering societal aspects and sustainable knowledge transfer. The project contributes to EC activities to strengthen radiation protection in a consistent and joint manner, as has already been done through the establishment of radiation protection platforms, the promotion of projects (e.g., DoReMi, OPERRA) and the partnership CONCERT-EJP. The outcomes may also impact future recommendations.

1 Introduction

The European Basic Safety Standards Directive 2013/59/EURATOM widens the application of radiation protection practices to previously not affected fields, such as exposures to radon, thoron (including their progeny) and exposures to naturally occurring radioactive material (NORM), and demands that they are regulated in the same way as artificial sources. Implementing new regulations and related guidelines must be based on sound, scientifically based evidence currently missing. Many open questions remain regarding dosimetry, effects and risks of radon and NORM when occurring alone or in combination with other stressors such as smoking. Also, the increased awareness of radon and NORM hazards calls for better risk governance.

1.1 Objectives

The RadoNorm project, funded by EURATOM H2020 from August 2020 to July 2025, aims to provide the required knowledge and to significantly reduce scientific as well as technical uncertainties in all steps of the radiation risk assessment and management cycle for radon and NORM exposure situations, as illustrated in Figure 1. This calls for research and technological developments, education and training, as well as dissemination actions targeted to the public as well as regulators. RadoNorm

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thus provides a holistic umbrella framework for integrating all aspects of radon and NORM protection, including underpinning science, past experiences and societal needs that might be relevant for implementing effective practical actions to optimise the protection of humans and the environment as well as to further develop them in a holistic way. RadoNorm supports the implementation of the European Basic Safety Standards (BSS) and helps to cope with the new requirements on radon and NORM. It would also help to improve recommendations on an international level through the ICRP. The holistic approach by RadoNorm covers risk assessment and risk management, development of tools, methods and best practices to cope with the issues related to radon and NORM, as well as research on societal aspects, thus making major impacts on society and helping the decision-makers and authorities in regulation and guidance.

Thus, RadoNorm provides science-based recommendations and guidance on how to best implement the BSS. The focus is put on innovative and practical solutions that significantly improve the radiological situation and radiation protection practices by all stakeholders involved.

1.2 Implementation

The project is designed to initiate and perform research and technical development in support of European Union Member States, Associated Countries and the European Commission (EC) in their efforts to implement the European radiation protection BSS. It has a highly multidisciplinary and inclusive character, which targets all relevant steps of the radiation risk management cycle for radon and NORM exposure situations. RadoNorm aims to reduce scientific, technical and societal uncertainties by (i) initiating and performing research and technical developments, (ii) integrating education and training in all research and development activities, and (iii) disseminating the project achievements through targeted actions to the public, stakeholders and regulators. Steps addressed are the characterisation of radon and NORM exposures (WP2), improving dosimetry (WP3), assessing effects and risks for humans and the environment (WP4), refining mitigation technologies (WP5), raising the understanding of societal aspects (WP6), and disseminating achievements (WP8). Furthermore, an ambitious pan-European E&T programme contributes to competence building and sustainability of the project findings (WP7). Figures 2 and 3 demonstrate the relationship between work packages and how they intertwine to answer the question of radon exposure as an example.

At the start of the project, several risks were identified, the most significant of which were changes in beneficiaries, BREXIT, poor visibility and delays in work. The COVID-19 pandemic also presented an unforeseen risk. Measures have nevertheless been taken to avoid bottlenecks in work, where the coordination team has diligently worked to actively engage partners, foster healthy communication and ensure that deliverables and milestones are timely met.

2 Key areas (WORK PACKAGES; WPs)

2.1 Coordination, management and administration (WP1)

The RadoNorm project is a multinational and multidisciplinary project, spanning 57 partners across 22 European countries and collaborating with groups in the US and Canada. The project engages both the natural sciences and social sciences.

This enormous effort to improve radiation protection based on scientific evidence and social considerations for radon and NORM can only be competently realised with the help of a central coordination system. Therefore, the smooth and efficient running of the project is being managed by the project coordinator (PC), who is the single point of contact for the project as a whole for all exchange of information, reporting requirements and financial aspects.

2.1.1 Objectives

The main objectives of WP1 are mainly administrative, i.e., to ensure the smooth running of the project, establish smooth communication within the project and with external entities, and ensure that the scientific goals of the project are being reached.

Responsibilities of the PC include monitoring progress using milestones and deliverables, ensuring compliance with the Grant Agreement and Consortium Agreement and the collection and collation of reports and their subsequent handover to the EC. The PC is also tasked with maintaining clear lines of communication between participants and governing bodies in the project so that research is properly guided and arising issues are quickly resolved. Moreover, it is the PC's duty to administer the disbursement of funds to the consortium and subsequently monitor and report financial compliance.

2.1.2 Achievements

WP1 has successfully compiled the project's first periodic report to the EC and has so far ensured that the project's deliverables and milestones are on track.

To provide a medium for coordination and management of internal documents among project participants, a secure internal web-based workspace was integrated with the project's public website. This was done in collaboration with WP8, responsible for dissemination and communication activities. The workspace allows the exchange of various types of information, such as datasets, results, coordination decisions, timetables, presentations, materials, and reporting among partners. It allows each partner, the work package leaders, and the coordinator to regularly monitor progress in data collation, analysis, and accomplished deliverables.

A system of RadoNorm internal cascade communication was set up, which allows the PC to communicate directly with members of the Executive Board (ExB), consisting of all WP leaders, to further communicate with task leaders and personnel within their work packages. Meetings of the PC with the ExB are held regularly every

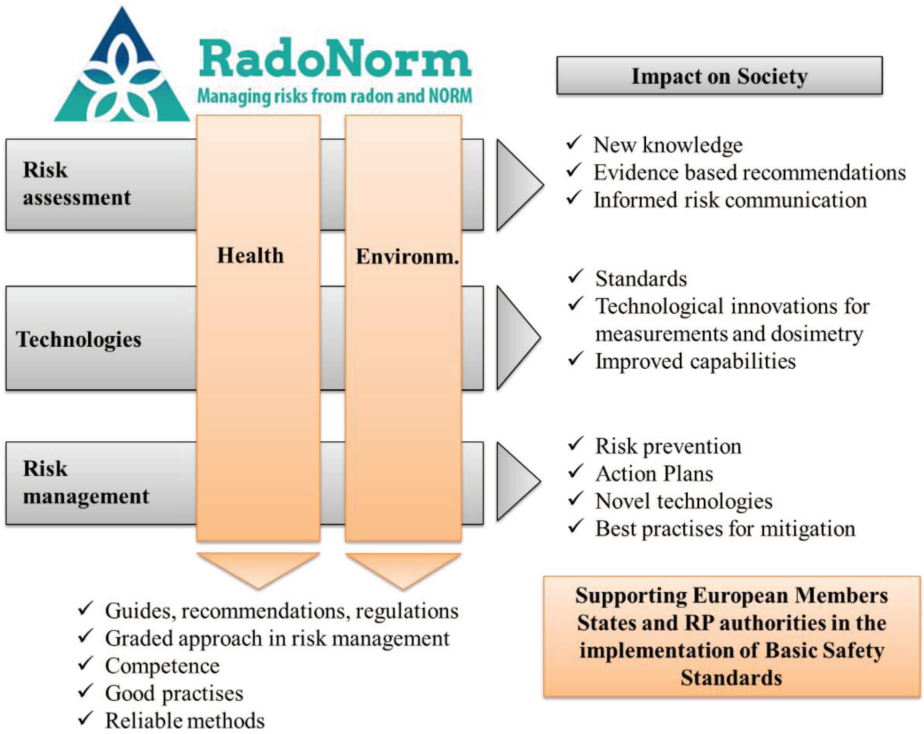

Fig. 1. Impact of RadoNorm on radiation protection.

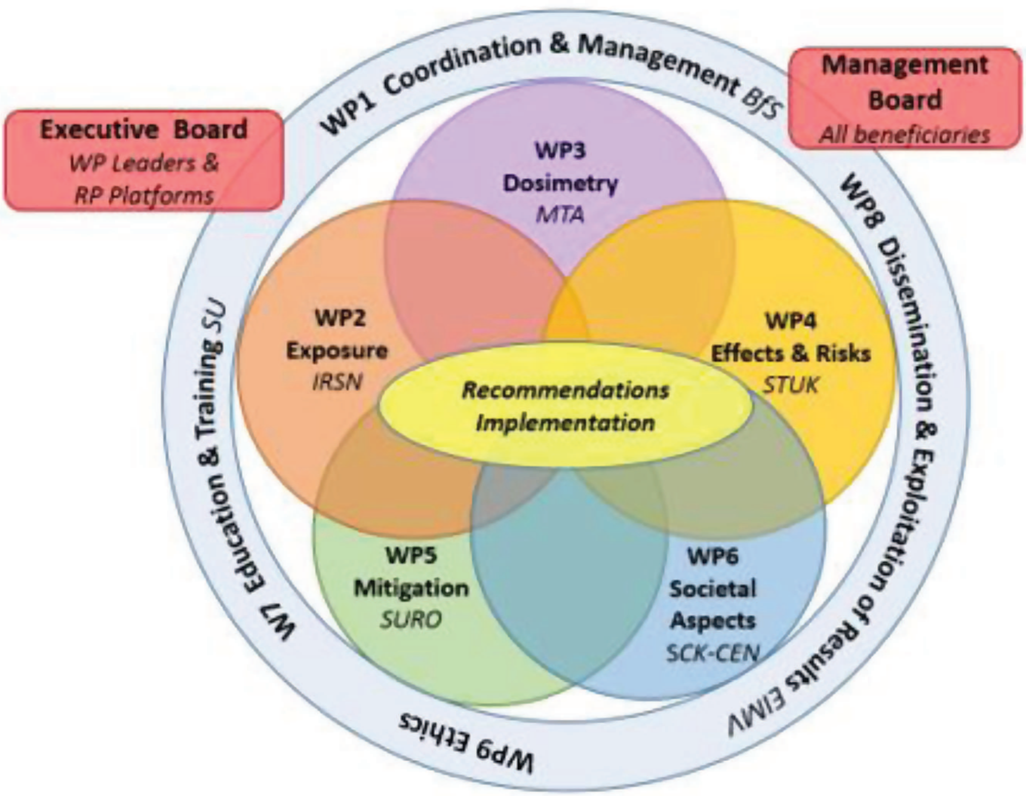

Fig. 2. Work package organisation in RadoNorm.

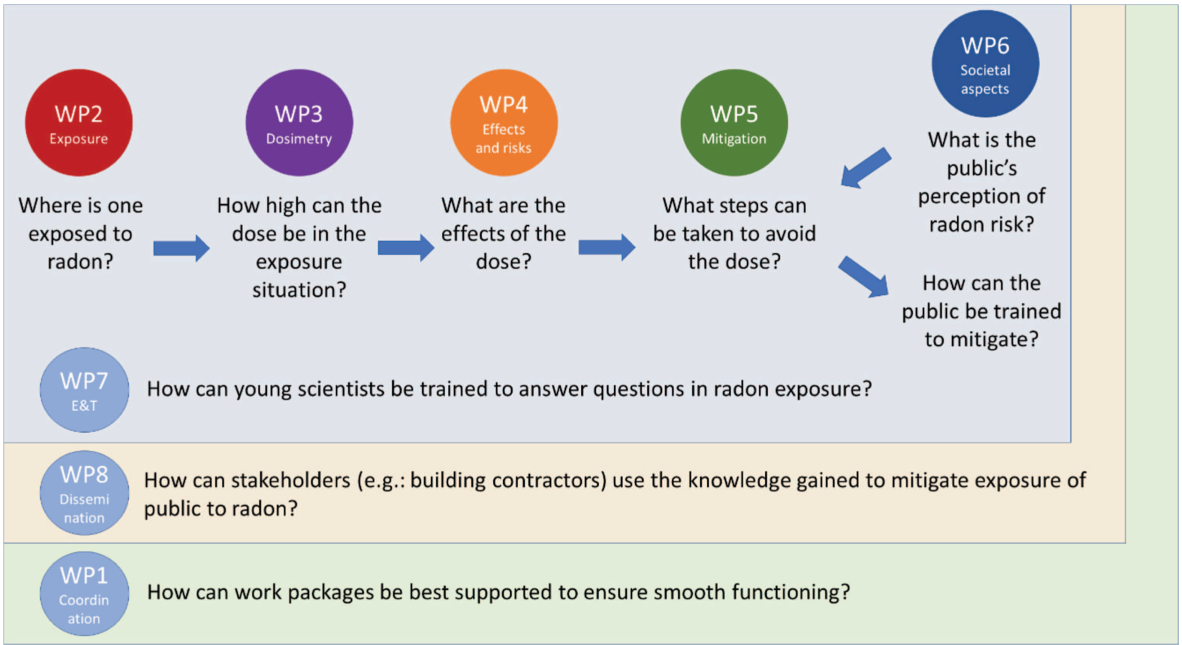

Fig. 3. How work packages contribute to the scientific process using radon as a case study.

three months. Moreover, the dissemination of information and results within the project was done through meetings of the General Assembly (GA) in the form of the Kick-Off Meeting and the 1st Annual Meeting. Due to the COVID-19 pandemic, both meetings had to be organised as online events.

Furthermore, the PC has clarified the ethics requirements of the project and made sure the necessary clearances have been obtained for the research to be carried out. This was done in the form of ethics reports that were submitted to the EC.

2.1.3 Perspectives

Another pillar of this work package is identifying project topics and results which could contribute to the Strategic Research Agenda (SRA) of the European Radiation Protection Platforms (RPPs). The PC has been in close contact with members of the European RPPs to identify relevant topics for research, especially as members of these platforms are part of the RadoNorm project. The research for RadoNorm is mainly based on their input, which is available to members of the platforms. Thus, the new findings benefit EU efforts not only in the development of BSS but also in the development of operational responses to local radioactive contamination, as well as aid the ongoing decommissioning of nuclear power plants across Europe and the subsequent storage of radioactive waste. It also increases public awareness of radiation protection measures.

2.2 Exposure situations (WP2)

When it comes to characterising and assessing the exposure of people and biota to radon and NORM, there still remain many uncertainties. As of now, there is great difficulty in radon metrology in determining (i) the average radon concentration level, which can be compared to the reference level, (ii) the fractionation between radon/thoron and their short-lived decay products, as well as (iii) the fraction of progeny attached to aerosols; which are all needed to assess the risk to radon exposure. Moreover, peculiarities in measurement can present themselves for specific sites (for example, in underground workplaces). Regarding exposure to NORM, the main uncertainties lie in understanding the different scenarios that can lead to an exposure event, not only due to the wide range of activities that use NORM but also due to the existence of natural areas with high background radioactivity, such as legacy sites. There is also difficulty in assessing the dispersion and transfer of NORM in the environment. Studying NORM dispersion and transfer is mainly done through the use of radioecological models, whose uncertainties can be reduced by a better understanding of the biological and geochemical processes governing the dispersion and transfer to various compartments of the environment.

2.2.1 Objectives

WP2 aims to provide a better characterisation of the exposure of people (public and workers) and biota to radon and NORM by fillings gaps of knowledge identified in previous European or National projects and those outlined as research priorities in SRAs of the European RPPs. Characterisation of exposure is to be done from the initial quantification of the radionuclide of concern at a given place and its contribution to the dose received by the people or the biota, to its dispersion and redistribution in the environment and finally to our capability of using models to predict this dispersion and transfer to assess the risk. For radon exposure situations, WP2 aims to improve upon detection and measurement methods for radon, thoron, and their progeny, assess the contribution of various natural and anthropogenic sources to radon exposure, aid in setting up workplace-specific radon measurement protocols and improve understanding of the processes and factors that contribute to the variability of outdoor amounts of radon, thoron and their decay products. For NORM exposure situations, WP2 will provide a systematic overview of exposure sites across Europe, investigate conditions and processes at NORM exposure scenarios that influence effects and risks, identify biological, chemical and geochemical parameters controlling the NORM migration in soil and transfer to plants, reviewing exposure pathways considered in radioecological models, and applying the new knowledge of exposure situations to models.

2.2.2 Achievements

Over the first 18 months, significant progress has been made. Methodologies and protocols have been established to compile or acquire new data for the (i) characterisation of temporal and spatial uncertainty of indoor radon measurement, (ii) characterisation of radon aerosols in underground workplaces, (iii) assessment of radon exposure in workplaces, (iv) assessment of building materials as a source of indoor radon exposure, (v) improvement of methods to identify high indoor radon levels, and (vi) assessment of radon and thoron outdoor concentrations and exhalation rate.

To collect information on NORM exposure sites at the European level, questionnaires and e-surveys were developed in collaboration with WP5. The initial experimental studies and the first set of field campaigns were started to better understand the influence of speciation, organic matter degradation, plant metabolites, earthworms or microorganisms on the mobility of uranium and radium in soils. These investigations would shed light on NORM transfer to plants and support the development of new modelling approaches to predict their reactivity in soils.

Finally, critical reviews of exposure pathways were carried out for dose assessment of public and biota at NORM industrial/legacy sites for three selected topics: (i) conventional waste disposal, (ii) the groundwater exposure pathways and the consideration of leaching and (iii) the use of sludge from sewer depuration systems of liquid effluents as fertiliser in agriculture.

2.2.3 Perspectives

This new scientific knowledge gained in WP2 will provide pragmatic and feasible recommendations or guidelines for radon-radon progeny measurements and workplace type-specific measurement protocols for the realistic assessment of radon exposure of the workers. Moreover, it will provide methods to support the EU Member States in the identification of high indoor radon levels at the European level, as well as give recommendations to support the revision of EC Radiation Protection guidelines (such as RPs guidance 122 and 135) in consideration of new types of industries involving NORM, processes, environmental standards and types of releases. WP2 outputs will also complement the risk assessment research for humans and biota as performed in WP4, as well as the assessment of remediation strategies in contaminated areas as in WP5.

2.3 Dosimetry (WP3)

Assessment of any dose-effect relationships requires reliable dose estimation. Therefore, it is highly important to obtain reliable data on doses, dose distributions, and their uncertainties in order to characterise the health and biological effects of radon exposure. These include data on absorbed doses and their uncertainties in epidemiological studies and on doses at different levels of biological organisation in biological experiments.

2.3.1 Objectives

Besides providing reliable dose estimation in different exposure scenarios, this area aims to identify specific human subpopulations potentially more sensitive to radon exposure than the general public since there are no two people alike. The effects of severe asthma on absorbed doses and dose distributions in the lungs have been quantified by computer models of airways of diseased patients considering anatomical, physiological, and histological differences.

While smoking increases lung cancer risk, it also induces changes in lung morphometry and respiratory physiology, affecting the deposition and clearance of radon progeny. In this way, the same environmental radon concentration may result in different absorbed dose rates in the lungs depending on smoking history. The final goal is to distinguish between smoking-induced and radon-induced lung cancers considering the differences in the spatial distribution of bronchial carcinomas and deposition patterns upon exposure to cigarette smoke and radon progeny.

While the highest fraction of a dose is absorbed in the lungs, other organs are also exposed to radon progeny and other sources of ionising radiation. Annual absorbed doses arising from exposure to radon gas, radon progeny, long-lived radionuclides (LLR) to the lung and to other organs will be calculated in individual miners. Calculations will be performed with standard biokinetic and dosimetric models published.

Another aim is to gain insights into the uncertainties arising from model parameters, which affect the dose attributed to cohort members, to define better the uncertainties affecting the dose-effect relationship. Biokinetic and dosimetric models will be applied in the dose calculations and uncertainty analysis. Uncertainties arising from exposure, biokinetic and dosimetric models will be studied separately and then combined.

It is an important question whether in vivo and in vitro experiments can mimic the real-life exposure scenario and to what extent. Therefore, computational microdosimetry will be performed in order to support the preparation and evaluation of biological experiments.

2.3.2 Achievements

Because of the widely differing experimental information on the effects of smoking, a thorough review of the existing literature was performed in order to establish reasonable modelling scenarios. A thorough review has been performed in order to develop a comprehensive model for the dose to embryo and foetus, considering a placental transfer, lactation, and age of children, among other factors. A literature review of the models and their parameter values has also been performed to quantify uncertainties deriving from prior distributions from which parameter values will be sampled for Monte Carlo simulations. In vivo dose distributions in human lungs (Fig. 4) have already been quantified in order to provide realistic exposure conditions for in vitro experiments with cell cultures and organotypic tissue models. Specific energy and hit distributions have also been quantified in the case of in vitro experiments with cells and organotypic tissue models exposed to solid alpha sources and charged particle microbeams.

2.3.3 Perspectives

The results of this WP will contribute significantly to the Multidisciplinary European Low Dose Initiative (MELODI) research platform by improving understanding of dose-response relationships for radiation-induced health effects and organ-specific cancer risk assessments, as well as to the European Radiation Dosimetry Group (EURADOS) platform by helping to refine, validate and implement new biokinetic models.

WP3 also address the question as to whether a new dose concept can be developed accounting for spatial dose inhomogeneity by generating new knowledge related to the role of spatial dose distribution in radiation risk, and exploring how intra-organ dose distribution can be considered in the system of radiation protection.

In order to explore ways how differences (if any) can be considered in the system of radiation protection, the consideration of the effects of spatial variation in dose delivery at other spatial scales has been reviewed. To complement that, the existing epidemiological and biological data about the biological and health effects of hot particles and other heterogeneous exposures, including exposure to radon progeny, will also be reviewed. In addition, particular attention will be paid to experimental results on the effects of spatially inhomogeneous dose distributions in state-of-the-art organotypic lung models. A biophysical model capable of predicting the relative biological effectiveness of various radiation types will also be applied to describe the carcinogenic potential of complex radiation fields in dependence on the dose. This will lead to an estimate of the effect of weighted dose dependent on the composition of the radiation field for carcinogenesis-related endpoints. Based on these studies, recommendations can be made on how to improve the system of radiation protection.

In the end, the results of this WP will contribute significantly to the MELODI research platform by improving understanding of dose-response relationships for radiation-induced health effects and organ-specific cancer risk assessments, as well as to the EURADOS platform by helping to refine, validate and implement new biokinetic models.

2.4 Effects and risk assessment (WP4)

2.4.1 Objectives

The general objective of WP4 is to generate new knowledge related to biological effects and responses after exposure to radon and NORM that have implications for risk assessment and radiation protection of humans and the environment. It also aims to reduce the existing uncertainties in risk assessment. To achieve this goal, WP4 is structured into tasks addressing major knowledge gaps in human health risk assessment of radon and NORM, such as the interaction between radon and smoking in lung cancer, risks of radon outside of the lung, risks associated with radon exposure during childhood, risks from radon and NORM in drinking water, mechanisms of radiation action in the disease processes, and quantification of various sources of uncertainties in risk inference. In addition to human health effects, we address the major knowledge gaps for the risk assessment of non-human biota with respect to the combined effects of NORM and other stressors and determine adverse outcome pathways (AOPs) leading to such effects.

2.4.2 Achievements

The methods used in WP4 include epidemiological studies and simulations based on epidemiological datasets, risk modelling, molecular epidemiology, experimental studies on combined effects carried out in realistic co-exposure conditions and determination of AOPs linking the mechanisms and effects after co-exposures. During the first 18 months of the project, all studies have been successfully initiated. Smoking risk models with temporal exposure window have been developed to include intensity and duration of smoking and time since quitting smoking, and geometric mixed models for interaction between cumulated radon exposure and smoking have been developed.

To study radon-related risks other than lung cancer among adults, detailed specification of analysis plans regarding outcomes, risk models and subgroups have been carried out. Aiming at pooled analyses of national studies on the association of radon and childhood cancers, leukaemia and brain cancer, studies on national cohorts have been continued. Moreover, mechanisms of radiation action in lung cancer are being studied among never-smokers exposed to radon. In addition to the molecular characterisation of non-small-cell-lung-cancer among 1000 patients, the genetic alterations found with the molecular phenotype in animals (rats) and humans exposed at work (miners) are being investigated.

Various sources of uncertainties in radon-induced lung cancer risk inference are studied. Developing and fitting Bayesian hierarchical models based on survival disease models and shared error structures may alleviate uncertainties in exposure and dosimetry. Biologically based models on lung carcinogenesis are being developed that

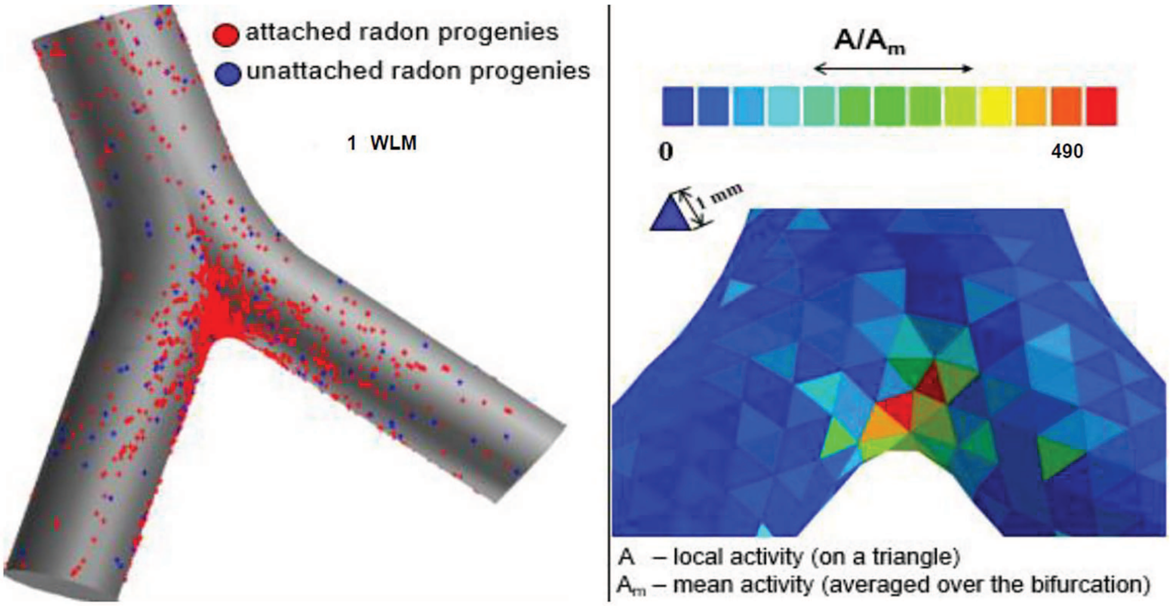

Fig. 4. Deposition pattern of the inhaled radon progenies in a central bronchial airway bifurcation (left) and colour map of the deposition enhancement factors (right).

integrate molecular data, calculate lifetime risk and contribute to the AOP development.

2.4.3 Perspectives

Even though it is well known that radon causes cancer, there are still major gaps in knowledge. Much less is known about the possible association between radon exposure and diseases other than cancer, like cardiovascular diseases. Furthermore, studies on radon risks have been carried out among adult populations, like uranium miners, and we need more information on the risks after exposure during childhood. The interaction of radon and smoking is also a major public health question. Smoking increases the lung cancer risk from radon, and in fact, quitting smoking is an effective way to reduce the risk of radon. We address this question by analysing datasets that have information on radon exposure and smoking, looking into the trends in smoking by age groups and experimental studies to gain a further understanding of the molecular mechanisms involved in the interaction of radon and smoking.

There are few studies focusing on the risk from ingestion of naturally occurring radionuclides such as radon, uranium and radium, and to this effect, better exposure characterisation from different drinking water sources is needed, which is planned to be undertaken during the course of the project.

Radon detectors that are sensitive to thoron (^{220}Rn) can over-estimate radon (^{222}Rn) exposure. This leads to an underestimation of lung cancer risk per radon exposure. To study this, the detectors used in previous epidemiological studies are being tested for their sensitivity to thoron.

Experimental studies on the effects and mechanisms of action of combined exposures to radon or NORM and other stressors relevant in true exposure situations of humans and biota have been started by reviewing and setting up co-exposure systems (cells, rodents, aquatic organisms). Based on the experimental data, predictive models will be established for the combined effects of multiple stressors for lung cancer caused by radon/tobacco and ecotoxicological relevant endpoints. Other stressors being considered are nanoparticles (e.g., carbon, silicate) and other NOR substances (e.g., U, Ra, Po-210).

In the end, the concerted effort of all tasks within the work package will help develop new methods for risk modelling, in particular, quantification of uncertainties for risk inference. It could potentially shed light on elucidating driver mutations for radon-induced lung cancer, which would be a major breakthrough in radiation carcinogenesis. But it would more likely be that several radon-related pathways leading to lung carcinogenesis are discovered. Contribution to public health will also be profound by providing predictive models on radon exposure and predictions on future lung cancer rates. Through its findings, WP4 is poised to close several knowledge gaps addressed in the MELODI, ALLIANCE and EURADOS research platforms.

2.5 Mitigation (WP5)

2.5.1 Objectives

The main goal of WP5 is to improve and optimise radiation protection of workers, the general public and the environment against the harmful effects of ionising radiation caused by the presence of natural radionuclides in nature and the work environment utilising innovative mitigation techniques, systems and strategies. In order to achieve the main goal, several key objectives were identified, and corresponding research activities were defined.

One main objective is the improvement of the efficiency of radon mitigation systems and their sustainability through the new developments and optimisation of current radon control systems. The innovative design of preventive measures and corrective actions applied in dwellings and workplaces involving NORM industries will use new knowledge on radon sources and radon entry pathways gained through experimental and theoretical work carried out specifically in WP2 and WP5 in close collaboration. The ongoing research is focused on the modification and optimisation of existing ventilation systems, such as described in Figure 5, the application of radon-resistant construction techniques and materials and the utilisation of continuous radon monitors for control of active operation elements of preventive measures and corrective actions.

Analysing information on lessons learned and experience gained during implemented actions for mitigation in buildings, workplaces and NORM industry facilities in the EU Member States is also undertaken as part of WP5. This information enables us to improve regulation tools and procedures, leading to a reduction of occupational and public exposures to ionising radiation reflecting the variety of exposure scenarios.

Another objective is the development of strategies for final treatment of NORM residues/waste based on preventive actions and mitigation methods with respect to existing circumstances corresponding to specific NORM-involving industries, technological processes, legacy sites and environmental conditions. This is based on the evaluation of remediation options using radioecological models from the legal perspective and general radiation protection principles (justification, optimisation, and dose limitation) based on industry-specific BATs (best available technologies) and/or LCAs (life cycle assessments).

2.5.2 Achievements

The methods used in WP5 include measurement campaigns in dwellings, workplaces, NORM industry facilities and legacy sites; field radiation surveys and environmental sampling and measurement; laboratory measurement and analysis; proficiency testing programs in radon/thoron calibration facilities; in situ comparison measurements; radioecological modelling and utilisation of case studies in specific NORM and legacy sites; radon-resistant construction techniques and materials testing; data processing and analysis software tools; information and data collection methods.

Over the course of the first 18 months, several questionnaires have been formulated and distributed. Two were done to get an overview of regulatory approaches and international standards for systems and methods (preventive measures, corrective actions) to control radon in workplaces and dwellings, formulated and distributed among relevant stakeholders. A third, more general questionnaire, in collaboration with WP2, was to gather specific information related to NORM aspects that would be needed later in the project. Other questionnaires are currently in preparation, such as collecting information about the measurement of radon and radon progenies and other relevant parameters that might be important from the point of view of dose from radon calculation and the evaluation of radon mitigation systems.

For radiation risk mitigation measures applied in NORM-involving industries and remediation of legacy sites, a workshop was organised with industry representatives and relevant authorities dealing with radioactivity in water. The workshop comprised invited introductory presentations on a legal context, research examples, case studies, already applied solutions and follow-up panel discussions.

A review of building materials and technologies with significant impact on indoor radon levels was also conducted. This was done by literature searches and asking partners about their experience with the material with elevated content of natural radionuclides or including residues of NORM industries.

Two specific NORM situations have been determined as case studies: (i) mixing of NORM residues with other residues during underground coal mining activities or for reuse/recycling and (ii) a NORM-affected legacy site in Norway. Key parameters needed for modelling and collation of relevant datasets for model application were carried out. The foreseen outcome of this would be a methodology and a procedure tested on the aforementioned cases for addressing solution effectiveness and identifying possible issues to obtain an appropriate, well-justified decision.

Laboratory experiments have commenced on exhalation rate measurement from a building material sampled during radon diagnosis. Additionally, other experimental and theoretical studies are underway on testing various methods of radon diffusion coefficient determination in radon-proof membranes.

The selection of active and passive dosimeters for testing purposes is also underway. This is done in order to prepare a large in situ inter-comparison measurement campaign focused on a dose assessment of workers from radon and radon progeny in selected underground workplaces. Measurement campaigns in dwellings and underground workplaces before and after the implementation of corrective actions and comparing measurement techniques are also planned. Installation of preventive measures based on a sub-slab depressurisation system for further testing purposes is also being carried out.

2.5.3 Perspectives

New findings will eventually lead to better software and measurement tools for air exchange rate determination and radon diffusion coefficient determination, among others. It will also help improve water treatment technologies by reducing the level of natural radionuclides and non-radioactive contaminants. Furthermore, it will strengthen mitigation efforts in NORM industries and legacy sites using site-specific radioecological models.

2.6 Societal aspects (WP6)

Radon, NORM and the risks they entail for humans and the environment are important societal issues. In this

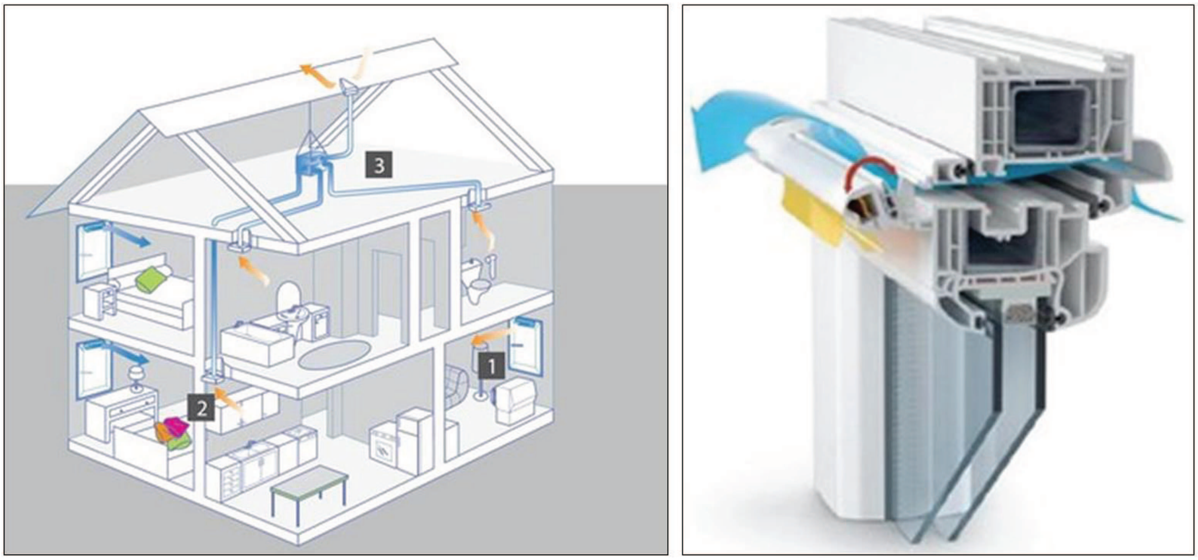

Fig. 5. Radon corrective measures – a hybrid ventilation system.

respect, they should not only be approached through a technical lens, but attention should equally be directed at the ways in which individuals, groups, organisations and institutions in society are perceiving, thinking about, and acting upon radon and NORM. When focusing on the societal aspects of radon and NORM, important questions arise, such as "what barriers are people experiencing to radon remediation?", "how can citizens be more actively engaged in radon measurement and remediation?" and "what factors influence companies' (un)willingness to use NORM-containing by-products in the production of construction materials?".

2.6.1 Objectives

Through a focus on the societal aspects of radon and NORM, WP6 aims to contribute to strategic, innovative, theory- and evidence-based governance of radon and NORM. Building on and addressing the gaps of past research, it proposes systematic and methodologically sounds social scientific approaches to study radon and NORM. More specifically, WP6 aims to improve public awareness of radon and NORM, evaluate methods to achieve behavioural change, and contribute to science-based policy support for radiation protection from Radon and NORM. This is done through five tasks, covering the development of a strong methodological base and toolbox for studying stakeholders' perceptions, attitudes, behaviours, motivations and opinions related to radon and NORM; the development and testing of health communication tools focused on achieving behaviour change; establishing and supporting citizen science initiatives on radon remediation; studying societal aspects in specific and understudied exposure situations; and formulating consolidated recommendations for science and policy. Integrating a work package dedicated to societal aspects, which builds on insights from social science and humanities research, demonstrates the strong holistic and multidisciplinary character of the RadoNorm project.

2.6.2 Achievements

In the first 18 months of the project, each task has been initiated with tangible outputs for all of them. With regard to the development of a strong social scientific methodological base and toolbox for studying radon and NORM, an elaborate literature review was conducted on methods used in published articles ($n = 142$) on the subject. Besides uncovering a strong underrepresentation of NORM as a subject in social science studies (being studied only in 19 articles), this review highlighted a dominant geographical focus on the US, the use of rather 'traditional' quantitative and qualitative methods, and the (lack of) reliability and validity of a range of variables and scales used in the past. Building on this state-of-the-art, a range of quantitative and qualitative methods have been selected, adapted and tested in various national and local contexts, gaining insight into how different publics perceive and act with regard to radon and NORM exposure. This will result in a database and methodological toolbox to be consulted and used by researchers and policymakers.

Some of the first results of WP6 have been published in various articles. Regarding citizen science, a paper titled "Evaluation of citizen science contributions to radon research" was published in the Journal of Environmental Radioactivity in October 2021. In that same journal, an article was published in April 2022 titled "Societal aspects of NORM: an overlooked research field". In that same month, the International Journal of Public Health published the article "Cure or Carcinogen? A Framing Analysis of European Radon Spa Websites".

Finally, various events have been organised in the context and with the support of WP6. A webinar titled "expert consultation on investigating the potential of citizen science for effective radon measurement and mitigation" was co-organised by RadoNorm, the Social Sciences and Humanities in Ionising Radiation Research (SHARE) platform and the International Atomic Energy Agency (IAEA) in the framework of the RICOMET 2020 conference in September 2020. During that same conference, a webinar on "Societal aspects and marketing challenges of NORM in building products" (co-organised by SHARE, the European NORM Association (ENA) and the RadoNorm project), and a webinar on "Radon air pollution: communication and protective behaviour" (co-organised by the Environment and Resources Authority (ERA), IAEA, the RadoNorm project and SHARE) was organised. A one-day hybrid conference on transdisciplinarity titled "Beyond scientific disciplinary boundaries: the future of radiation protection research and practice?" was organised by SCK CEN, MERIENCE, NMBU and the SHARE platform in September 2022.

2.6.3 Perspectives

These insights serve as a sound basis for developing communication strategies and tools, which might be used to tackle the identified gap between people's attitudes and values on the one hand and their actions on the other (e.g., knowing that radon is an issue and perceiving it as problematic, while not taking remediating actions). Through pinpointing behavioural objectives and change objectives for specific stakeholder groups and gaining insights into determinants of these behaviours, communication tools are developed and tested, both in the laboratory and 'field' settings. This hence provides a hands-on, scientifically consolidated means to achieve behaviour change, which is an important route towards increased radon testing, mitigation and/or remediation (Fig. 6).

An additional but partly complementary route to such an increase in testing, mitigation and/or remediation is also being investigated through setting up and testing a range of citizen science initiatives, where citizens take an active role in conducting measurements and designing strategies for increasing radon remediation. Through building on citizen science principles defined by the European Citizen Science Association and exchanging with previous radon-focused citizen science projects, four pilot initiatives have been prepared, of which the first (in Ireland) was launched in Spring 2022. Towards the end of 2022 and building on insights gained through the pilot studies, a call for citizen science initiatives on radon will be launched across Europe, thus establishing a network of initiatives and citizens engaged in radon governance.

One particular interest of WP6 also lies in investigating the understudied societal aspects related to specific radon and NORM exposure situations. These specific situations are radon and NORM in the context of geothermal projects, the use of NORM-containing industrial by-products in the construction industry, and the existence of radon spas in different European countries. Related to the first context, a socio-technical investigation is undertaken to describe radiological and chemical characteristics of geothermal by-products, uncover perceptions of workers and other stakeholders with regard to radiation issues, and identify – with the help of stakeholders – potential management strategies for these by-products. For the second context, interest is taken in the use of alternative cementitious binders made with NORM-containing by-products and how both industrial actors and end-users perceive the use of such binders in the construction industry. Finally, with regard to radon spas, a frame analysis has uncovered how such spas in their public communication frame radon is significantly different (and sometimes contradicting) ways from the framings encountered in public health communication, a finding which in the coming months will be further explored through interviews and/or observations with relevant stakeholders.

Overall, WP6 emphasises that radon and NORM are situated in complex and continuously dynamic societies and hence stresses that effective governance strategies should also uncover the interplay between the technical and natural aspects of radon and NORM on the one hand and their societal aspects on the other. As such, it contributes both to state-of-the-art research and to science-based policymaking.

2.7 Education and training (WP7)

2.7.1 Objectives

WP7 aims to organise the education and training program of RadoNorm focusing on Ph.D. students and early career researchers (ECRs). To this end, WP7 monitors and supports the progress of Ph.D. and ECR projects and contributes to their professional development by organising targeted courses and exchange visits.

2.7.2 Achievements

Approximately 24% of the project budget is dedicated to the salaries of Ph.D. students and ECRs. During the first 18 months of RadoNorm, 20 Ph.Ds. and 14 ECRs were recruited. A virtual meeting for Ph.D. students and ECRs was organised in 2021, where each young researcher presented his/her project and answered questions. Such meetings will be repeated regularly in order to foster collaboration between Europe's future radiation researchers. The coming meetings are intended as face-to-face events, where the researchers can get to know each other personally, this being an important element of team building.

Five courses were held in 2021: "Interdisciplinary radiation research on radon" organised by BfS (Germany), "The art of public opinion survey analysis: surveying the public on Radon and Norm" organised by the University of Antwerp and SCK-CEN (Belgium), "Naturally occurring radionuclides in work and natural environment – establishing the problem definition, finding sources and exposure assessment" organised by GIG (Poland), "NORM impact assessment toolkit: from microorganisms to human cells" organised by the University of Aveiro and University of Porto (Portugal) and "Cellular effects of high and low LET ionising radiation – introduction to radiation biology" organised by Stockholm University (Sweden).

Eleven travel grants were awarded in 2021, which was quite low and presumably due to the COVID-19 pandemic.

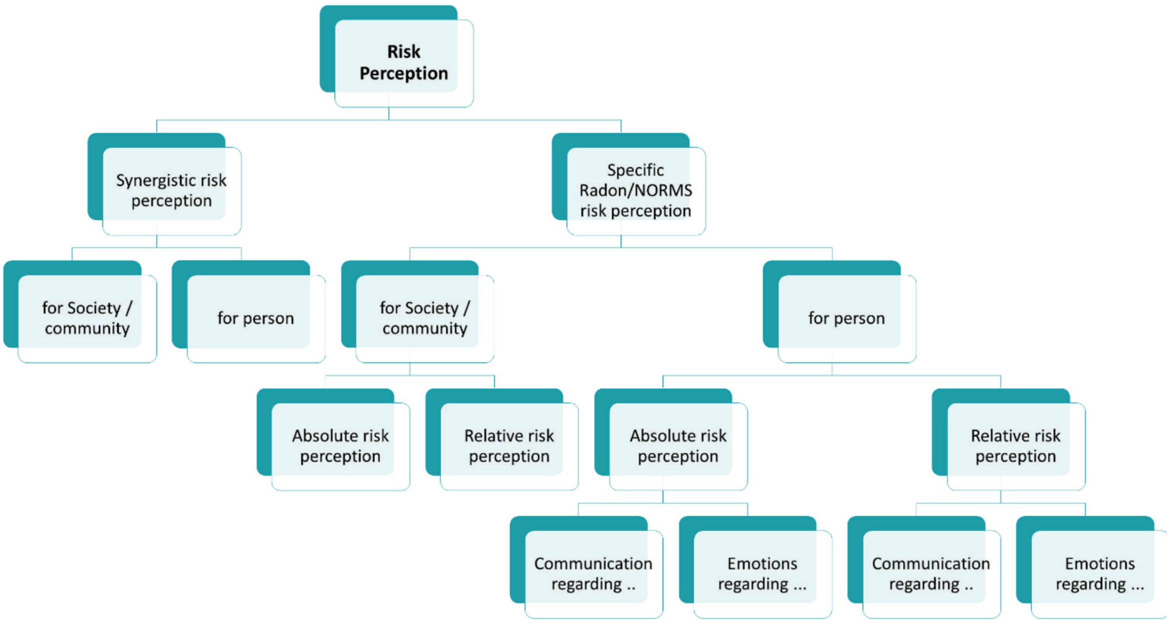

Fig. 6. Systematic overview of Radon/NORM risk perception.

2.7.3 Perspectives

There are still Ph.D. and ECR positions to be filled at a later stage, in accordance with the work planned for each task. Training and courses for these young investigators will also be conducted in the coming years, with various courses already planned for 2022. We expect that as the pandemic restrictions ease, we will be able to fund more travel grants to encourage young investigators to pursue scientific exchange in person.

At the end of the project, a new generation of scientists would be well-trained and willing to take on the challenges of radiation protection in their respective fields.

2.8 Communication, dissemination and exploitation of results (WP8)

2.8.1 Objectives

Among the aims of RadoNorm is also to disseminate the project achievements through special actions targeted at the public, other stakeholders including regulatory authorities and policymakers. In addition, one of the objectives of the project is to exchange and communicate with stakeholders, including the general public, affected populations, professional and regulatory organisations across Europe, as well as international communities of scientific, technical, legal, and other professional experts in radiation protection. Therefore, a specific cross-cutting work package in RadoNorm is devoted to communication, dissemination and exploitation of the RadoNorm results in the most effective way with the highest impact throughout the project lifetime and also beyond. To achieve the best results, all work package leaders are involved and contribute to the activities. The PC ensures resource optimisation to ensure consistency of the dissemination activities and maximise public outreach. The work package on communication, dissemination and exploitation objective is to: (i) enable two-way communication about the project and its results to multiple audiences and show its impact and benefits by addressing and providing possible solutions to challenges of radon and NORM exposures; (ii) make the results transferable for audiences that may use the new knowledge, data and information in their own work, enable use and uptake of results and maximise the impact of EU-funded research; (iii) utilise the RadoNorm results in developing, creating and marketing products, processes, services or other activities (policymaking) to effectively exploit the project's results for society.

2.8.2 Achievements

In order to achieve these objectives, the project adopted the strategy and plan for communication, dissemination and exploitation of results with the overview of stakeholders, their needs and expectations, different tools and channels for communication and dissemination and for involvement of target groups. Different means have been outlined for online communication and feedback, specific materials to promote key messages, events and participation in other relevant actions. Also support for other work packages in communication and dissemination of their research to scientific and non-scientific audiences is provided. The report of the strategy and plan provides the basis for both external and internal communication, dissemination activities and approach to the exploitation of results. RadoNorm's outreach activities aim at communicating and disseminating the project results during the project lifetime and increase the impact after the end of the project.

The external communication and dissemination strategy uses a synergetic combination of several channels and

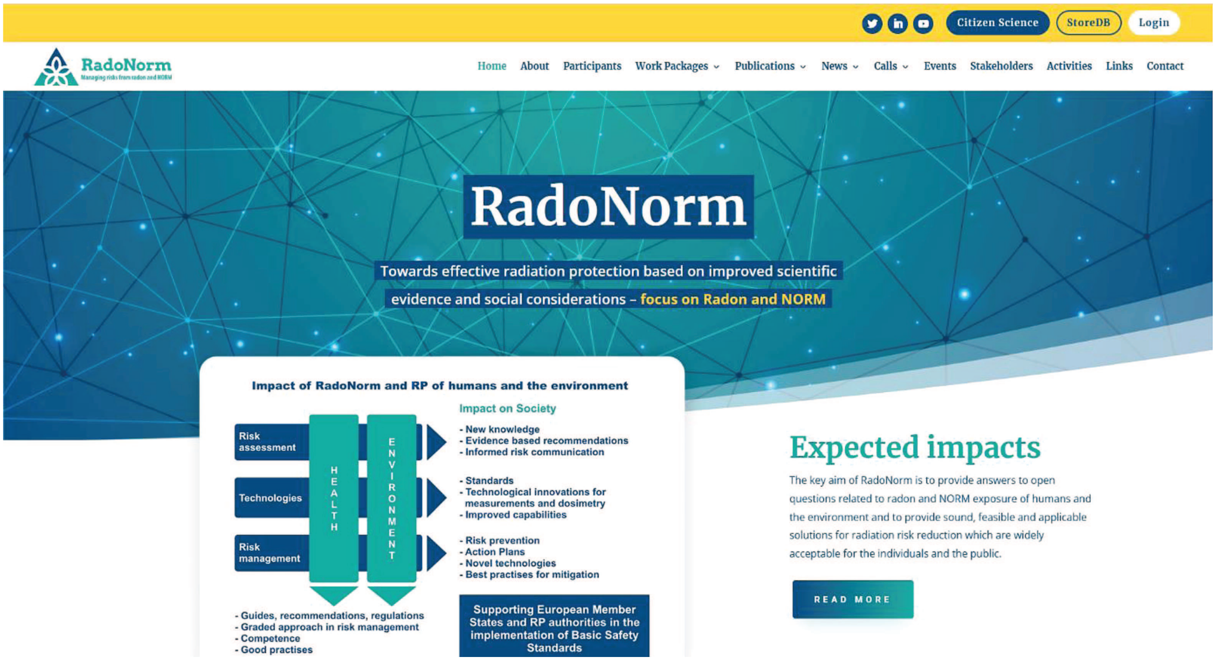

Fig. 7. RadoNorm website on public domain.

tools, such as a project website (Fig. 7) linked with social media networks, newsletters and other information materials, two-way interaction tools and channels with different stakeholder groups established in the project, conferences and other event opportunities and publications in various media including peer-reviewed scientific journals and popular science publications. All this information is available on the RadoNorm website https://www.radonorm.eu/ and is regularly updated.

The internal communication and dissemination plan defines responsibilities among project partners and consortium bodies and describes internal communication flows and monitoring instruments. Internal communications are conducted via emails sent out by the PC and work package leaders and periodic electronic or face-to-face meetings. Project communication and documentation (including project minutes, deliverables, etc.) are stored and shared in the internal repository on the RadoNorm webpage. The internal communication plan also provides information on templates made available to all partners.

2.8.3 Perspectives

The RadoNorm results will include reports, recommendations, new skills and knowledge, educational materials, publications, Ph.D. theses, new collected data and prototypes (like new pre-standards and measurement methods). RadoNorm uses the STORE^{db} platform (https://www.storedb.org) for secure storage of data and sharing and dissemination of data and information. In general, the RadoNorm results are public unless the decision to protect the outputs is taken (such as patenting or other forms of intellectual property protection). Green open access to the website's online project repository is assured, and also gold open access for a limited number of publications. Thus, the international guidelines for open data (FAIR) and transparent publication (TOP) are respected, and the availability and reuse of the primary scientific data further increase the value of RadoNorm output. It also assures that the public-funded RadoNorm output can become available to the broader research community. Published results would also be exploited by the scientific community and various stakeholders involved in radiation protection.

3 Conclusions

The RadoNorm project had a successful start and showed considerable and tangible output over its first 18 months, despite the COVID-19 pandemic. 12 out of 85 deliverables and 20 out of 99 milestones have been achieved. The project objectives have been fulfilled, especially in addressing knowledge gaps through scientific investigation, training personnel in radiation protection research, disseminating its findings to a broad audience, engaging and educating the public, and bringing together the radiation protection scientific committee at an EU level to coordinate research efforts.

Conflict of interests

The authors declare that they have no competing interests to report.

Acknowledgements

The authors thank Robbe Geysmans (SCK-CEN) and Árpád Farkas (EK) for their contributions to this article.

Funding

This project has received funding from the Euratom research and training programme 2019–2020 under grant agreement No. 900009.

Data availability statement

This article has no associated data generated and/or analysed.

Author contribution statement

Ulrike Kulka is the project coordinator, and Mandy Birschwilks is a member of the coordination team. Laureline Fevrier, Balázs Madas, Sisko Salomaa, Aleš Froňka, Tanja Perko, Andrzej Wojcik and Nadja Železnik are work package leaders. All authors contributed to the writing of this manuscript.

Cite this article as: Ulrike Kulka, Mandy Birschwilks, Laureline Fevrier, Balázs Madas, Sisko Salomaa, Aleš Froňka, Tanja Perko, Andrzej Wojcik, and Nadja Železnik. RadoNorm – towards effective radiation protection based on improved scientific evidence and social considerations – focus on RADON and NORM, EPJ Nuclear Sci. Technol. **8**, 38 (2022)