Journal of Radiological Protection

Official journal of the Society for Radiological Protection



# The joint roadmap for radiation protection research: outreach and future

OPEN ACCESS
IOP Publishing | Society for Radiological Protection
Journal of Radiological Protection

J. Radiol. Prot. **41** (2021) S285–S296 (12pp)
https://doi.org/10.1088/1361-6498/ac1c96

# The joint roadmap for radiation protection research: outreach and future

**Nathalie R E N Impens**[1,*] **and Sisko Salomaa**[2,3]

[1] SCK CEN, Boeretang 200, 2400 Mol, Belgium
[2] University of Eastern Finland, Kuopio Campus, Yliopistonranta 1, 70210 Kuopio, Finland
[3] STUK—Radiation and Nuclear Safety Authority, P.O.Box 14, 00811 Helsinki, Finland

E-mail: nimpens@sckcen.be

Received 6 July 2021; revised 13 July 2021
Accepted for publication 11 August 2021
Published 27 September 2021

CrossMark

**Abstract**

During the last decade there has been remarkable integration of radiation protection research in Europe, driven by six research platforms. The platforms are associations of research centres, university research groups and funding bodies in Member States that are dedicated to specialised areas of research in radiation protection, such as health risks (MELODI), radioecology (ALLIANCE), radiological emergencies (NERIS), dosimetry (EURADOS), medical use of radiation (EURAMED) and societal aspects (SHARE). Recently these platforms established an umbrella organisation MEENAS, to endorse further integration and joint activities in research, education and training, and infrastructures. A milestone in this process of integration and priority setting was achieved in 2020 when the first edition of the joint roadmap for radiation protection research was finalised. In this paper we describe the various roles for research and development in the radiation protection context, ranging from basic scientific knowledge underpinning the system of protection to research supporting the development and application of international standards and research and development activities needed to ensure safety in radiation practices and in potential exposure scenarios. We describe the process of how the joint roadmap has been developed and how it could be implemented. Finally, we address the need to anticipate potential future exposure scenarios and to

* Author to whom any correspondence should be addressed.

systematically consider the impact of emerging technologies and global challenges in the context of radiation protection. The joint roadmap is a living document that needs to be regularly updated to cover both current and potential exposures of humans and the environment.

Keywords: roadmap, radiation protection research, human health, environmental health, medical exposure, energy mix

(Some figures may appear in colour only in the online journal)

## 1. Introduction

Ionising radiation is ubiquitous on Earth. The largest exposures of the public are resulting from natural radiation and from medical applications. Radiation protection exposure limits are mainly based on the knowledge of cancer risk and hereditary effects derived from epidemiological data, often obtained in much higher dose ranges than those typically encountered in the occupational context or medical diagnostics. The risks attributed to such higher dose ranges are related to the ability of radiation to cause DNA damage and to the well-established role of mutations in the development of cancer and hereditary effects. The linear extrapolation of risk calculations from the epidemiological studies towards the lower doses inherently assumes that similar mechanisms prevail. In the low dose range however, which is according to the UNSCEAR 2012 definition set at 100 mGy or 0.1 mGy min$^{-1}$, other mechanisms than DNA damage may prevail and determine the health outcome. There are still uncertainties in the health risk assessment from epidemiological datasets as well as gaps in knowledge on the mechanisms involved in the adverse health outcome pathways, especially for the events taking place between the initial exposure to radiation and the late health outcomes, as well as on the impact of dose rate and fractionation of dose. While the current radiation protection system is mainly based on the risk of cancer and hereditary outcomes extrapolated from the higher dose range, there is accumulating evidence on other adverse outcomes such as cardiovascular, neuro-cognitive, immune responses and lens opacities, as was discussed and reviewed in a MELODI workshop in 2019 [1–4]. There is also some variation in radiation responses between individuals due to individual characteristics. This may be true both for tissue reactions (individual sensitivity) and for the risk of developing late health effects like cancer (susceptibility) after radiation exposure, as discussed at a MELODI workshop in 2018 [5–8]. As about half of the exposure of humans is currently generated by medical applications of ionising radiation, it is very important to assess the adverse effects of the medical exposure of healthy tissues to better justify and optimise medical practices, in relevant dose and dose rate ranges, and for relevant ionising radiation energies and qualities. In medicine, there are growing expectations for personalised approaches taking into account the individual characteristics of a patient [9], as opposed to the population based approach practised in radiation protection.

Awareness of the need to protect the environment has emerged in the last decades of the 20th century: the reason is that in [10] this paradigm was stillvalid. It is only in the subsequent references that the point of view changed. UNSCEAR [11] reported responses of plants and animals to acute and chronic irradiation, both as individuals and as populations. ICRP decided to set up a task group, and a limited number of reference animals and plants was selected [12]. IAEA launched a work programme on the development of safety standards on the protection of the environment from the effects of ionising radiation. In its role to exchange and establish international consensus, the Third International Symposium on the protection of the Environment from Ionising Radiation was devoted to these topics [13]. A better understanding of the mechanisms initiated by molecular or chromosomal radiation damage to biota on the individual level or the population level of biological organisation is needed. As this is partially analogous to human health studies, enhanced collaboration between radiobiology and radioecology communities would be beneficial [14]. An update of the effects of ionising radiation on non-human biota was published by UNSCEAR in 2008 [15]. More recently, a consensus is emerging that a more holistic view is needed to describe effects to the ecosystem, taking into account the context of ionising radiation exposure, including other stressors and the complexity of the relation between effects on individual species and the ecosystem [16]. In the current COVID-19 pandemic, the understanding that human health is strongly interconnected to a healthy environment is also growing [17], and this insight might also impact the views on environmental radiation protection.

On the other hand, any over or under regulation of radiation protection comes at a high cost. A good balance between risk and benefit of the use of and exposure to ionising radiation should rely on a better understanding of human and environmental health effects. Radiation protection research may help to fine-tune this balance, which was one of the arguments for developing the joint research agenda and roadmap for radiation protection.

In this paper we describe research and development needs in various radiation protection contexts. We clarify the process how the joint roadmap has been developed and discuss how it could be implemented. Finally we address the need to anticipate emerging and potential exposure scenarios, as the joint roadmap is a living document that should be regularly updated to reflect relevant future research needs.

## 2. Role of research in radiation protection

Although the current system of radiation protection is considered robust, scientific progress may bring into light new paradigms that challenge the current understanding of radiation risks. Examples of those are the non-cancer effects or the new knowledge on cellular communication or epigenetic effects of radiation. On a more practical level, optimisation could still improve the balance between resources expended in protection efforts and the benefits arising from a practice. Therefore, uncertainties related to exposures and risks from such exposures need to be reduced. Research is the key to improve both the scientific knowledge base and operational radiation protection. In figure 1 the role of radiation protection research in the international radiation protection system is schematically represented.

Radiation protection research covers a very broad range of facets, each of them based on a broad range of scientific disciplines. European radiation protection research platforms have been established to gather and align the research and development efforts in different Member States in human health effects research (MELODI), dosimetry (EURADOS), radioecology (ALLIANCE), emergency management and response (NERIS), and later also in radiation protection research covering medical exposures (EURAMED) and social sciences and humanities (SHARE). The 7th Framework Programme of EURATOM supported through the OPERRA and COMET projects the establishment of strategic research agendas of the four already existing platforms MELODI, EURADOS, NERIS and ALLIANCE. Joint brainstorming sessions were organised between the four platforms to identify synergetic topics, but also to learn the needs of potential end users of the research. To activate multidisciplinary collaboration, the second research call of the OPERRA project was devoted to research topics requiring collaboration between research teams from the different platforms. A first Memorandum of Understanding (MoU) was signed in 2013 between the four existing platforms. Once EURAMED was also established, a second MoU was endorsed

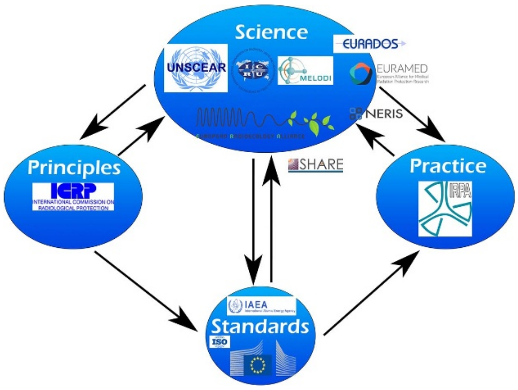


**Figure 1.** Role of science in the system of radiation protection. The joint roadmap aims to provide knowledge and technologies that can reduce uncertainties in the underpinning science and support the formulation of protection principles, development of standards and optimisation of radiation protection practices.

between EURAMED, MELODI and EURADOS. Then SHARE was also established, and the old MoUs were replaced and reinforced by the formation of an umbrella organisation called MEENAS in 2020, the acronym comprising the initials of the different platforms (https://eu-meenas.net/doku.php/home). MEENAS promotes integration and efficiency of European radiation protection research, encourages scientific education and training and fosters international collaboration.

## 3. Creating the joint roadmap for radiation protection research

In the framework of the European Joint Programme project CONCERT, the radiation protection research community in Europe prepared a joint roadmap for radiation protection research, available at the CONCERT website [18]. To start with, the different contexts in which exposure of humans and the environment take place were listed. Within these contexts, existing or realistic exposure scenarios groups were defined, each of them representing some needs for new knowledge, research and/or technologies. A limited list of high-level research challenges was developed, from which game changers were derived defined as *'Research that, when successfully executed, has the potential to substantially impact and strengthen the system and/or practice of radiation protection for man and/or the environment through (a) significantly improving the evidence base, (b) developing principles and recommendations, (c) developing standards based on the recommendations and (d) improving practice'*. As such, the authors consider that funding research as prioritised by the game changers will give maximal chance to address the most relevant topics, uncertainties and current issues in radiation protection. Graphical roadmaps have been prepared by the research community, projecting research topics in time for the next decades.

The game changers include topics in the different fields of radiation protection research, notably in health effects, medical, environmental, dosimetry, emergency, and social sciences, and support the development of principles, standards and practices as shown in figure 1. Radiation protection research addresses risk assessment and risk management and supports the development of improved measurements, dosimetry and technologies, all necessary for the better protection of human health and the environment. The societal impact of risk assessment

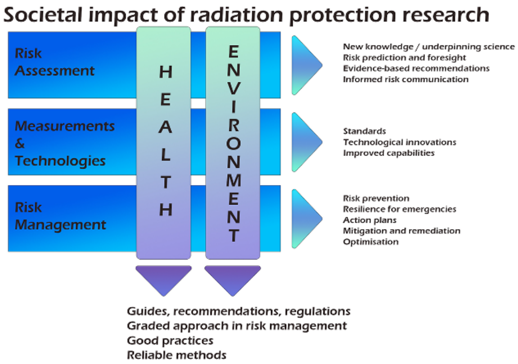


**Figure 2.** Radiation protection research aims to support the development of improved measurements and technologies, risk assessment and risk management in radiation protection.

arises from better knowledge that provides firm ground for evidence-based recommendations and informed risk communication. Improved understanding also enables assessment of potential future risks, risk prediction and foresight. Risk management encompasses society's actions to mitigate risks, ranging from risk prevention and resilience for emergencies to action plans, mitigation and remediation, keeping in mind optimisation between risks and benefits. Risk assessment and risk management would not be successful without research on metrology and dosimetry that support development of standards, new innovations and improved capabilities. The regulators and authorities in radiation protection make use of the improved knowledge on risk assessment and management and technological development when developing guidance, recommendations and regulations, considering a graded approach in risk management or developing good practices and reliable methods for their use and supervision. A schematic overview of the societal impact of radiation protection research in risk assessment, risk management and technological development is depicted in figure 2.

The development of the joint roadmap included several rounds of consultation, to gather the views of scientists from the different radiation protection research platforms and their stakeholders. Within the course of 2016–2017 also end users such as regulators, operators, the EC, governmental and non-governmental organisations, practitioners, patient and labour organisations were consulted. The first draft prepared in 2017 was distributed to these stakeholders, and their comments were again gathered during several workshops. This second consultation round ended in spring 2019. The information was taken into account by the Joint Roadmap Working Group to thoroughly revise the document. The new version currently available on the CONCERT website was approved by the Commission early in 2020. Once more the document was distributed to the different stakeholders to collect their comments and their views on prioritising the game changers. The collected comments will be considered in the future, as the joint roadmap is a living document. As such the authors, mainly scientists, try to take into account the end-users' values, views and needs as much as possible.

## 4. Implementing the joint roadmap for radiation protection research—what are the challenges?

Now that a first version of the joint roadmap is available, the implementation should start. A first challenge is to prioritise the game changers. A first attempt was undertaken by consulting the stakeholders on the latest version of the joint roadmap. However, the responses regarding priority setting depended heavily on the expertise, profession and/or the role of the respondents in the radiation protection field. Therefore, no one single priority list could be derived. The implementation of the different game changers will ultimately depend on the interest of the end users, such as governments and non-governmental organisations, regulators, industries and practitioners in medical applications, patients' and labour organisations.

Another way to prioritise radiation protection research could be to take into account the individual or collective doses and severity and type of the risks in certain exposure scenarios. This approach is like the graded approach used for categorisation of the need for supervisory activities by radiation protection authorities. Here we note that medical use of radiation and radon are the two main sources of radiation exposure to the population in Europe. Medical exposures of the public are responsible for about half of the average annual dose in the West [19, 20]. However, medical exposures are unevenly distributed so that part of the population does not receive any dose at all, and some undergo repeated diagnoses or treatments. The exposure of patients is significantly higher than the average value. In radiotherapy, healthy tissues may receive doses in the order of magnitude of 1 Gy, and some body regions in e.g. interventional or cardiological investigations or repeated three-or-four-dimensional imaging procedures may also result in high local exposures to healthy tissues.

From the ESOREX platform (https://esorex-platform.org/) it can be concluded that health care workers in many European countries also account for more than half of the cumulative occupational annual doses in their countries (checked for 2015). UNSCEAR 2008 [21] reports in detail doses to workers, showing that the average individual effective dose of health-care workers varies a lot. For example, in 2002 conventional radiologists received an average effective dose of 0.78 mSv $a^{-1}$, interventional radiologists 2.04 mSv $a^{-1}$ (data from the Netherlands), and interventional cardiologists in many European countries received up to 3–5 mSv $a^{-1}$ [22]. In the nuclear fuel cycle the measurably exposed workers received on average an effective dose of 0.79 mSv $a^{-1}$ in mining, 0.35 mSv $a^{-1}$ in milling plants, 0.34 mSv $a^{-1}$ in fuel fabrication and between 1 and 2 mSv $a^{-1}$ at pressurised water reactors in Germany in 2000–2002. For the NORM industry, France reported for 2015 an average effective dose of 1.94 mSv $a^{-1}$ to measurably exposed workers mainly from Rn inhalation. Germany reported average aircrew effective doses of 2 mSv $a^{-1}$, with maximal individual doses up to 6.5 mSv in 2015 [21].

A pragmatic approach in occupational monitoring is to use effective dose to take into account radiation qualities and doses to different organs. In many cases, however, exposures are highly inhomogeneous, and have different characteristics regarding type of radiation, organs exposed, and doses/dose rates. Therefore, no single dose-effect relationship will cover the stochastic effects in the long term, as both the dose and the risk for different organs and different types of adverse outcomes vary. Studies dedicated to the different exposure scenarios of patients and workers are needed to better understand the development of adverse outcomes. In addition, improvement of practices and setting of standards could result in reduction of exposures. The amount and type of individual or collective doses, or the risk or severity of the adverse outcomes in the different exposure scenarios could be used as indicators for research priority setting.

The increased evidence regarding non-cancer effects [1–4] suggests inclusion of such outcomes in the radiation protection system when more certainty regarding risk and dose-effect relationships becomes available. A better understanding of the underlying mechanisms can be obtained by means of collaboration between radiobiology, molecular epidemiology, systems biology and by describing adverse outcome pathways (AOPs). Dosimetry is of primary importance in any epidemiological study and monitoring. Also environmental exposures and effects on non-human biota, which are even more complex to unravel, deserve attention, along the growing consensus that human health is interrelated with the environment and that a holistic approach is needed for human and environmental protection [16, 17].

The multidisciplinarity of the research is another challenge to implementing the joint roadmap. The overarching goal of research is to study the exposure to and effects of radiation on human health (patients, workers and public) and the environment, taking into account planned, existing and emergency scenarios. Some non-exhaustive examples of disciplines are included in this paragraph. Metrology and dosimetry, modelling and development of various tools and technologies are needed to support radiation protection actions. Progress in artificial intelligence may support research and lead to innovations in medical applications of ionising radiation, in emergency management and recovery and in environmental studies. Last but not least, purely technological and scientific competences need to be complemented with social sciences and humanities, bringing the progress in science and technology to the end users, ensuring practical implementation, and creating a feed-back loop between the research and the societal needs covering political, social, economic and cultural viewpoints.

In addition, ionising radiation is only one of the stressors in the exposome, thus combined exposures will ultimately determine the resulting human health and environmental impact. Up till now, most exposome studies and reviews focus on chemical stressors, and do not describe or include ionising radiation as one of the stressors [22].

Many research questions in the joint roadmap can only be successfully addressed when human, technical and financial resources from different countries are combined. In the European Member States, there are national institutes and university groups carrying out radiation protection research. At European level, regulation of nuclear energy and radiation protection against ionising radiation, preparedness for radiological emergencies and surveillance of radiation in the environment are Articles of the Euratom Treaty. Therefore, Euratom also funds radiation protection research, with the aim to support networking and coordination activities and to align research in Europe, on top of the national resources. Euratom organises research calls to promote collaboration between the research actors in the different Member States. In the last decade, Euratom supported the setup of the research platforms MELODI, ALLIANCE, NERIS, EURAMED and SHARE, each of them covering specific fields of radiation protection research on low dose risks, radioecology, emergency management and preparedness, medical applications and social sciences and humanities, respectively. Collaboration between these platforms and the already existing EURADOS platform on dosimetry was established during the last decade through various MoUs. Some research calls with support of Euratom in the field of radiation protection research were specifically dedicated to focus on synergistic, multidisciplinary research topics to promote the research collaboration between the different scientific communities. These platforms were the drivers developing the joint roadmap for radiation protection research. This roadmap will be used by Euratom as a source of research needs, to inform the Member States' representatives that are responsible for designing the research calls in the future. Though the Euratom was initially established to unite Member States' activities related to nuclear energy (fission and fusion) and radiation protection, it is clear that radiation protection also covers medical exposures and NORM, which by far are the two largest sources of radiation exposure in Europe. Therefore, it is important to reach out and engage with the health and environmental research communities, and organise information exchange, discussions, cooperation and coordination of research programmes outside Euratom, to seek mutual benefit. The authors consider that inclusion of ionising radiation in multiple stressors studies is essential. However, a further complication is that the division at European level into Euratom Treaty and non-Euratom Treaty responsibilities is typically mirrored by funding silos at the national level, with divided responsibilities that impact national co-funding arrangements.

## 5. Global scientific and societal outreach

Some of the research challenges in the joint roadmap would benefit from reaching out outside Europe and even to global scale. There are radiation protection issues where global harmonisation is needed, or where large cohorts for epidemiological research are required, or research questions that simply cannot be tackled without gathering the critical mass of human expertise or financial resources available in the world. Such a global organisation can only be launched with the support from the governments and responsible national, regional and international agencies, organisations, and research platforms. Organisations such as COHERE in Canada (www.cnsc-ccsn.gc.ca/eng/resources/research/cohere/index.cfm), the Health Physics Society [23] and the Electric Power Research Institute (EPRI, www.epri.com/) in the US, the Japan Society for the Promotion of Science committee on the utilisation and biological effects of radiation organises research to assess biological effects and the medical use of ionising radiation are also active in radiation protection research and could be key players for global collaboration with the European platforms. Last but not least the Organisation for Economic Co-operation and Development's Nuclear Energy Agency (OECD/NEA) has organised a High-Level Group on Low-Dose Research to work on approaches and tools to better understand effects of low dose exposures in humans and wildlife through global coordination of epidemiology, radiobiology and radiotoxicological research. The OECD-NEA Committee on Radiological Protection and Public Health launched the idea to develop AOPs related to low dose effects. This could be done considering the experience of the Extended Advisory Group for Molecular Screening and Toxicogenomics, that has already developed the AOP approach to organise published evidence on mechanisms of toxicity overarching multiple levels of biological organisation in the chemical and ecological fields. In April 2021 MELODI organised a scientific workshop to support the development of various AOPs related to exposure to ionising radiation, gathering experts from within and outside the radiation protection area from Europe, Canada, Japan and the US, and in connection with ALLIANCE. It is expected that the participants will set up and publish their findings most probably in the next 2 years.

Initiatives such as the European Radiation Protection Weeks (organised by the European radiation protection research platforms with support from Euratom), the annual IDEA workshop (organised by EPRI) and the international workshop on the biological effects of radiation (BER 2018) in Japan are essential milestones bringing together the relevant research communities. Following the BER 2018 workshop, the co-chairs published the Osaka Call-for-Action [24] to bring together healthcare and radiation sciences for an optimal use of ionising radiation in medicine, and strengthened radiation protection of patients and the public. Although the Osaka Call-for-Action focuses only on the link between radiobiology and the medical use of ionising radiation, many of the challenges described in the paper may be translated to other fields of radiation protection research.

Last but not least, the translation of research results tailored to the needs within the society is very important but challenging. This challenge relies on expertise in social sciences and humanities, good communication and active involvement of regulators, decision-makers and relevant end users. Initiatives such as the RICOMET workshops (www.ssh-share.eu/ricomet2021/) can be an essential bridge to fill the gap between science and policy and society.

## 6. Environmental, societal and technological changes may impact exposure scenarios, pathways and radiation protection practices: a look forward

The world around us is changing and this will impact the operational environment in radiation protection as well. It is therefore important to proactively consider the research needs by updating the joint roadmap as a living document. Climate change is progressing and calls for major changes in the production and use of energy. Shortage of natural resources and concern over loss of biodiversity have promoted the move towards circular economies. Digitalisation and artificial intelligence will change technologies used in e.g. medical imaging and reduce the workload of many professionals. All these changes will impact the radiation protection practices, exposure scenarios and research needs in the future. Here we highlight some exposure scenarios that may gain importance, and that may call for attention and research to evaluate the consequences for radiation protection. Communication with actors in these areas would be useful to prepare the research community for the coming changes.

### *6.1. Evolution of energy production towards renewables and emerging nuclear technologies*

The principles of energy conservation and mass conservation are important concepts when considering energy production and circular economies. Natural nuclear energy and radioactivity play a key role as initial sources of energy in many if not all renewable (and fossil!) energies. The Sun is a gigantic fusion reactor; the solar energy is trapped in chemical form via photosynthesis (biomass), temperature differences create winds, etc. The Sun is also warming the Earth's crust and, in addition, the radioactive decay of uranium creates the heat that is used as geothermal energy.

On one hand, the nuclear phase-out in many countries is becoming reality: decommissioning of nuclear power plants, eventually with return to green-field conditions as well as nuclear waste management activities will be needed in the next decades. Environmental impact assessment of these activities may need radiation protection research specifically focusing on the individual cases.

On the other hand, global interest in low carbon energy systems is growing rapidly due to climate change. Whereas the debate regarding the ideal energy mix in each country is out of scope of this paper, the potential technologies are renewables such as hydroelectric, solar, wind, and geothermal energy production in combination with electric power storage, but also small modular reactors (SMR). SMRs are gaining attention in various countries all over the world as stated in [25] and on the website of OECD-NEA (www.oecd-nea.org/jcms/pl_26297). All these renewable and nuclear technologies rely on natural resources, such as uranium and rare earth metals that need to be mined and that result in a disturbed Earth's crust and a materials life cycle including naturally occurring radioactive materials (NORMs). Considering that NORM industries are responsible for an important share of industrial radiation exposure, it is important to proactively investigate the radiation protection aspects of all potential energy sources that may result in NORM. Both environmental impact assessment and effects to humans as workers or public need to be investigated in a holistic way, taking into account the full materials cycles from mining towards decommissioning and long-lived waste. UNSCEAR [26] has summarised the radiation exposures that different existing energy systems generate. However, data for the full cycles are available only for the coal cycle and the nuclear cycle. The same exercise would be needed for all renewables that will be part of the energy mixes.

The research needs regarding the full life cycle environmental impact assessment in normal operation require a similar approach independently from the type of mine, but tailored to the dimensions, the geography, the environment and population density and climate conditions. Such environmental impact studies include the release and transport in the biosphere, impact on workers and humans living near the plants and the food chain, waste management as well as safety, security and emergency management. When choices need to be made as to which energy mix will be needed, socioeconomic and political debate will be important, but correct and complete information on the environmental and health impact of each energy mix component is essential to the society to make informed decisions. Informed decision-making on the energy mix in each country should rely partially on the full radiological impact assessments of the different energy alternatives. Therefore, and also for the sake of global harmonisation of standards and principles, such research programmes should start simultaneously with the future energy mix debates on national and international level.

### *6.2. Zero waste economies (circular economies)*

What previously was called waste is now raw material for somebody else. Zero waste or circular economies make use of recycling of waste materials. Efficient use of materials is beneficial from economic point of view and good for the nature. The principle of mass conservation also means that some elements that exist in low concentrations in the raw material can be accumulated during processing, whereby elevated levels of harmful substances like radioactive agents, appear in certain fractions. For example, caesium ends up mainly in the ash when burning wood or peat that is contaminated by caesium from radioactive fallout. Another example is scrap metal containing radioactivity that ends up in a metalwork furnace, whereby the radioactivity is released or contained in some fraction. NORMs exist in the Earth's crust and in building materials. Mining as well as geothermal energy production or oil pumping release radon and NORM. Recycling means less mining but increase of NORM in re-used materials.

### *6.3. Environmental changes*

Climate change brings about major changes in the ecosystems. This, in turn, is likely to impact the transfer of radioactive elements in the environment too, and therefore the exposure of humans and the wildlife. Climate change may affect exposure due to flooding, drought and extreme weather conditions. Exposure risks by extreme wheather conditions may increase in the future [27], and ionising radiation might be a confounding factor on how climate change affects ecosystems [28]: there are already and will be more changes in biodiversity, ecosystems and food chains. Radio ecological models should be adapted accordingly.

### *6.4. Medical exposures*

Last but not least the medical applications of ionising radiation is a very dynamic area of patient and workers exposure. In particular, there are growing expectations for personalised approaches taking into account the individual characteristics of a patient and allowing individual risk-benefit assessment. The EURAMED Rocc-n-roll project (https://cordis.europa.eu/project/id/899995) supported by Euratom will produce a strategic research agenda and roadmap for medical applications of ionising radiation. These documents will cover synergies from the areas of radiation protection, health research and digitalisation, and will guide the European Commission and stakeholders on future research. The roadmap will include a part on radiation protection in the evolving medical field and will be available in 2022. Medical radiation protection research will support policy makers, national healthcare, health practitioners, patients and comforters on optimisation strategies, by providing knowledge and knowhow, to allow informed decision making and adjust/harmonise protocols, to maximise treatment outcome and optimise radiation protection. Also basic research on dose-effects is needed, bringing together epidemiologists, radiation scientists and medical professionals. Vice versa, low dose research may benefit from the large patient cohorts receiving various diagnoses and therapies.

## 7. Conclusions

The Joint Roadmap is a major output from the CONCERT European Joint Programme on Radiation Protection Research. It brings together the Strategic Research Agendas developed by European research platforms MELODI (health risks), ALLIANCE (radioecology), NERIS (radiological emergencies), EURADOS (dosimetry), EURAMED (medical use of radiation) and SHARE (societal aspects of the use of radiation), with the aim of identifying joint research priorities and developing roadmaps that capable of addressing research challenges in a range of exposure scenarios in a multidisciplinary way, thus enhancing the societal impact. The joint roadmap is a living document. Reaching out beyond the radiation protection community will be needed to contribute to major societal questions like climate change, zero waste economies, combating cancer and technological innovations.

## Acknowledgments

The EJP CONCERT project has received funding from the Euratom research and training programme 2014–2018 under Grant Agreement No. 662287. This publication reflects only the authors' view. Responsibility for the information and views expressed therein lies entirely with the authors. The European Commission is not responsible for any use that may be made of the information it contains.

The graphics were kindly edited by Michael Neys.

## ORCID iD

Nathalie R E N Impens https://orcid.org/0000-0001-5058-1550

## References

[1] Tapio S, Little M P, Kaiser J C, Impens N, Hamada N, Georgakilas A G, Simar D and Salomaa S 2020 Ionizing radiation-induced circulatory and metabolic diseases *Environ. Int.* **146** 106235

[2] Ainsbury E A *et al* 2021 Radiation-induced lens opacities: epidemiological, clinical and experimental evidence, methodological issues, research gaps and strategy *Environ. Int.* **146** 106213

[3] Pasqual E 2020 Neurodevelopmental effects of low dose ionizing radiation exposure: a systematic review of the epidemiological evidence *Environ. Int.* **136** 105371

[4] Lumniczky K *et al* 2021 Low dose ionizing radiation effects on the immune system *Environ. Int.* **149** 106212

[5] Averbeck D *et al* 2018 Progress in low dose health risk research: novel effects and new concepts in low dose radiobiology *Mutat. Res. Rev. Mutat. Res.* **776** 46

[6] Seibold P *et al* 2020 Clinical and epidemiological observations on individual radiation sensitivity and susceptibility *Int. J. Radiat. Biol.* **96** 324

[7] Kalman C and Oughton D 2020 Ethical considerations related to radiosensitivity and radiosusceptibility *Int. J. Radiat. Biol.* **96** 340

[8] Gomolka M, Blyth B, Bourguignon M, Badie C, Schmitz A, Talbot C, Hoeschen C and Salomaa S 2020 Potential screening assays for individual radiation sensitivity and susceptibility and their current validation state *Int. J. Radiat. Biol.* **96** 280

[9] Rehani M 2019 Looking for solutions: vision and a call-for-attention for radiation research scientists *Int. J. Radiat. Biol.* **95** 793

[10] ICRP 1977 Recommendations of the ICRP. ICRP Publication 26 *Ann. ICR* **1** 3

[11] United Nations Scientific Committee on the Effects of Atomic Radiation 1996 *Sources and Effects of Ionising Radiation* (New York: United Nations)

[12] ICRP 2007 The 2007 recommendations of the interenational commission on radiological protection. ICRP Publication 103 *Ann. ICRP* **37** 2–4

[13] International Atomic Energy Agency 2003 Protection of the environment from ionising radiation *Proc. of the Third Int. Symposiuim on the Protection of the Environment from Ionising Radiation (SPEIR 3) (Darwin, Australia, 22–26 July 2002)* (Vienna)

[14] Hinton T G, Bedford J S, Congdon J C and Whicker F W 2004 Effects of radiation on the environment: a need to question old paradigms and enhance collaboration among radiation biologists and radiation ecologists *Radiat. Res.* **162** 332

[15] United Nations Scientific Committee on the Effects of Atomic Radiation 2008 *Sources and effects of ionising radiation* Volume II Scientific Annex E (New York)

[16] Mothersill C *et al* 2018 When a duck is not a duck; a new interdisciplinary synthesis for environmental radiation protection *Environ. Res.* **162** 318

[17] WHO 2018 *Preventing Diseases through Healthy Environments. A Global Assessment of the Burden of Disease from Environmental Risks*

[18] Impens N R E N and Salomaa S 2020 Second joint roadmap for radiation protection research (available at: www.concert-h2020.eu/Document.ashx?dt=web%26file=/Lists/Deliverables/Attachments/206/D3.7_Second%20joint%20roadmap_draft_reviewed_%20052020_approved03062020.pdf%26guid=01b5ac77-b2ec-4cda-9c98-917dba396f0f)

[19] Schauer D A and Linton O W 2009 Ionizing radiation exposure of the population of the United States, medical exposure—are we doing less with more, and is there a role for health physicists? *Health Phys.* **97** 1

[20] United Nations Scientific Committee on the Effects of Atomic Radiation 2000 *Sources and Effects of Ionising Radiation Volume I* (New York)

[21] United Nations Scientific Committee on the Effects of Atomic Radiation 2008 *Sources and effects of ionising radiation. Volume I Annex B, excel tables attachment 2 available at the UNSCEAR website* (available at: www.unscear.org/unscear/en/publications/2008_1.html)

[22] Vermeulen R, Schymanski E L, Barabási A-L and Miller G W 2020 The exposome and health: where chemistry meets biology *Science* **367** 392

[23] Davis J, Dewji S A, Abelquist E and Hertel N 2019 Synopsis of the oak ridge radiation protection research needs workshop *Health Phys.* **116** 69

[24] Weiss W and Yonekura Y 2019 International co-operation in biological research to address low dose radiation risk: Osaka call-for-action *Int. J. Radiat. Biol.* **95** 1351

[25] International Atomic Energy Agency 2020 Advances in small modular reactor technology developments *A supplement to IAEA Advanced Reactors Information System (ARIS)* (Vienna, Austria)

[26] United Nations Scientific Committee on the Effects of Atomic Radiation 2016 *Sources, effects and risks of ionising radiation, Annex B (corrected)* (New York)

[27] Contessa G M *et al* 2016 Climate change and safety at work with ionizing radiations *Ann. Ist. Super. Sanita* **52** 386

[28] Møller A P and Mousseau T A 2019 Interactive effects of ionizing radiation and climate change on the abundance of breeding birds *Ecol. Indic.* **99** 178