Deliverable 2.11

Overview of NORM exposures sites in Europe and characterization of most relevant NORM exposure scenarios

Work Package 2

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

Document information

Project Acronym	**RadoNorm**
Project Title	**Towards effective radiation protection based on improved scientific evidence and social considerations - focus on radon and NORM**
Project Type	**RIA**
EC grant agreement No.	**900009**
Project starting / end date	**1st September 2020 – 31 August 2025**
Work Package No.	**2**
Work Package Title	**Exposure**
Deliverable No.	**2.11**
Deliverable Title	**Overview of NORM exposures sites in Europe and characterization of most relevant NORM exposure scenarios**
Lead Beneficiary	**DSA**
Contractual Delivery Date	**29.02.2025**
Actual Delivery Date	**31.05.2025**
Type	**Report**
Dissemination level	**PU**
Authors	**Jelena Mrdakovic Popic (DSA), Alla Dvorzhak (CIEMAT), Boguslaw Michalik (GIG), Hallvard Haanes (DSA), Cristina Nuccetelli (ISS), Gennaro Venoso (ISS), Federica Leonardi (INAIL), Rosabianca Trevisi (INAIL), Flavio Trotti (ARPAV), Raffaella Ugolini (ARPAV), Nathalie Vanhoudt (SCK CEN), Lea Pannecoucke (ASNR), Pascale Blanchart (ASNR), Danyl Perez-Sanchez (CIEMAT), Almudena Real (CIEMAT), Alicia Escribano (CIEMAT), Antti Kallio (STUK), Laureline Fevrier (ASNR).**

To be cited as:

Mrdakovic Popic, J., Dvorzhak, A., Michalik, B., Haanes, H., Nuccetelli, C., Venoso, G., Leonardi, F., Trevisi, R., Trotti, F., Ugolini, R., Vanhoudt, N., Pannecoucke, L., Blanchart, P., Perez-Sanchez, D., Real, A., Escribano, A., Kallio, A. Fevrier, L. (2025): Overview of NORM exposures sites in Europe and characterization of most relevant NORM exposure scenarios. Deliverable D 2.11 of project RadoNorm.

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Acknowledgement

This document is a deliverable of the RadoNorm project. This project has received funding from the Euratom research and training programme 2019-2020 under grant agreement No 900009.

Status of deliverable		
	By	Date
Delivered (Lead Beneficiary)	Jelena Mrdakovic Popic (DSA)	20.05.2025
Verified (WP Leader)	Laureline Février (ASNR)	22.05.2025
Reviewed (Reviewers)	WP Leader, PC	27.05.2025
Approved (PC)	PC	28.05.2025
Submitted to EC (PC)	PC	28.05.2025

Executive Summary

Naturally occurring radionuclides (NOR) are ubiquitous in the natural environment from the Earth origin. In most of the rocks, minerals and soils, NOR are not of radiation protection concern since they are present at low activity concentrations. However, there are certain rocks and minerals as well as activities (e.g., mining, chemical mass reduction, high temperature and pressure processes) that may lead to accumulation of NOR. Finally, naturally occurring radioactive materials (NORM) may emerge in the facilities of certain industries or in the environment, potentially giving raise to the radiation exposure of workers, public and the environment. Such situations should be considered with regards to radiation protection aspects and principles of justification, optimisation and dose limits or constraints.

In task 2.5 - *Overview of NORM sites and exposure scenarios in Europe and their characteristics* of the WP 2 *Exposure* of the RadoNorm project, a detailed investigation of various NORM exposure situations (planned and existing) was conducted according to designed work plan that included (a) development of an identification methodology for NORM, (b) development of Tools for information and data collection in a systematic and harmonised way, (c) conducting an electronic NORM survey (with three developed parts for regulators, industry operators and waste managers) across European countries, (d) collecting detailed information and data about NORM exposure situations using developed tools from RadoNorm task 2.5 participant countries, and finally, (e) conducting a literature review for missing information.

The main outcomes presented in this report include:

- Compiled information for an overview of the different NORM sites across Europe,
- Description of the main identified planned exposure situations – NORM involving industries, and existing exposure situations – NORM affected legacy sites,
- Consideration of legislative frameworks and regulatory practices in different countries with respect to NORM,
- Improved data on NORM matrices in different industries, per different exposure categories, updated quantitative data on NOR in different materials – raw materials, main and by-products, residues, discharges and wastes,
- Overview of exposure scenarios and pathways considered in different countries for estimation of radiation dose magnitude for workers, public and environment, including non-human biota,
- Overview of other simultaneously present hazards that are not radioactive and application of radiation protection but also occupational, health and safety measures,
- Consideration of approaches to NORM classified as residues and waste, and
- Identified challenges and directions for future work.

In the Deliverable Appendices, abstracts for manuscripts, to be submitted & under review for peer review publication, are provided related to detailed description of NORM exposure situations in mineral processing industries and energy production sectors across European countries.

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1. Introduction

Naturally occurring radioactive material (NORM) is material containing no significant amount of radionuclides other than primordial radionuclides such as ^{238}U, ^{232}Th and their radioactive decay products and ^{40}K. Material in which the activity concentrations of naturally occurring radionuclides (NOR) have been changed by a technological process or other human activity is also included under the term NORM (IAEA, 2022a; ICRP, 2019).

Many industries that process raw materials, containing NOR in a wide range of activity concentrations, produce a variety of NORM matrices in form of products, by-products, residues, and wastes, liquid effluents and atmospheric discharges. After mining, industrial extraction, processing and technical manipulation, the activity concentrations of NOR can be elevated or unevenly distributed between the various NORM arising from the different processes. This may give rise to an elevated radiation exposure to workers, public and the environment (ICRP, 2019). The main activities leading to accumulation and increased levels of NOR are identified as mining and milling of ores, oil and gas industry, extraction and purification of water, coal combustion for energy generation, use of geothermal energy, industrial exploitation of minerals, including for instance monazite, phosphate, ilmenite. Furthermore, NORM can also be present in agricultural fertilisers, soil amendments, construction and building materials, commodities, drinking water, certain food and feed (IAEA, 2014). In addition to numerous NORM involving industries, there is a number of NORM affected legacy sites, i.e. old, historically neglected sites with presence of various form of NORM with elevated activity concentration of different NORs and currently outside the proper radiation protection regulatory control (ICRP, 2019).

Due to increased exposure to ionising radiation, presence of NORM may pose potential health risks for workers, public and the environment. Over the last decades, the interest in NORM, both in terms of regulation and research, has raised from scarce publication on industries and NORM (e.g. oil and gas) to development of the standing conferences on NORM and intensive EC and IAEA work (EC, 2002, EC, 2003; IAEA 2003, 2006, 2008). Research activities related to NORM have been intensified in parallel with the introduction of regulatory requirements in the international standards for protection against ionising radiation, the EU Basic Safety Standards Directive (EU BSS) (EC, 1996; EC 2014) and the IAEA Basic Safety Standards (IAEA BSS) (IAEA, 2003; IAEA 2014).

The main features of NORM, leading to the globally elevated attention and interest include (Turcanu et al., 2022):

- NOR are radiotoxic radionuclides either long-lived, or subject of successive decay constituting decay series,
- Occurrence in geological formations worldwide,
- Historically neglected issues related to NORM as the focus has been only on artificially produced radionuclides,
- Occurrence in different industrial processes and environmental media, depending on a variety of ambient and environmental conditions,
- Worldwide, there are still large quantities of NORM residues being deposited, and discharged, in the environment, in a way unaccepted for waste containing artificial radionuclides,
- Due to NORM abundance, higher probability for workers, the public and biota to be exposed exists, in comparison to other radiation source types,
- Difficulties in communication of risks related to NORM.

Therefore, information, updated qualitative and quantitative data about the actual and potential sources and extent of NORM and related issues (abundance, different NORM sources, radionuclide activity concentrations, mobilization and concentration processes, exposure scenarios, impact assessment, dose modelling, etc.) is of high importance for getting an accurate perspective of problems that may encounter regarding radiation exposure and radiation protection (IAEA, 2003; IAEA MODARIA I Programme, 2015; IAEA, 2018; IAEA MODARIA II Programme, 2019; IAEA, 2021; Michalik, 2009; Vandenhove et. al., 1999).

The main objectives of the work in the RadoNorm task 2.5. of WP 2 Exposure were to:

- compile information for an overview of the different NORM sites across Europe and their characteristics,
- improve understanding of mobilisation processes, from source - via transport - to human & biota and environmental dose/risks at NORM exposure situations, which would facilitate the regulatory decision-making and potentially contribute to the development of a holistic and integrated management of NORM,
- identify commonalities and shared issues between the main NORM sites,
- obtain an overview of challenges (scientific and regulatory) identified at these sites,
- provide most relevant exposure scenarios for workers and the public, and fully characterise important exposure situations, with respect to NOR and possibly other simultaneously present hazards.

2. Study design

Directive 2013/59/Euratom (EC, 2014) clearly requires from EU member states identification of practices involving NORM (*Article 23*) and developing the graded approach to regulatory control commensurate with the impact that regulatory control may have in reducing such exposures or improving radiological safety (*Article 24*), while *Annex VI* provides List of industrial sectors involving NORM. Early in the RadoNorm project, during experts' discussions, it became clear that despite the deadlines given for a transposition of EU BSS requirements, countries may have been at different levels of NORM requirements implementation, for example regarding NORM inventory and proper developed regulatory control. It was assumed (and confirmed in a preliminary project task activity), that various reasons for different stages of EU BSS implementation – from (a) limited or lack of knowledge, such as those about methodology for identification of NORM exposures (taking into account EU BSS Annex VI list and wider considerations) and tools for systematic data collection for preliminary screening or further impact assessments or licensing where needed, (b) slow legislation changes and implementation,(c) lack of human and other resources for proper NORM identification and further control where needed – may be relevant for different countries.

To provide the most updated, panoramic overview of NORM exposure situations across the European countries, it was decided to collect all available information and data from RadoNorm participant countries, but also wider, from as many as possible European countries. To be able to do this, it was further decided to develop a methodology and proper tools that would allow a systematic (and from the scratch) NORM exposure identification, and subsequently, consistent data collection. It was foreseen that in first instance, methodology and tools will be applied for data gathering from the RadoNorm project participant countries, while later – both methodology and data collection tools could be shared wider for purposes of exposure situation screening, NORM inventory making, research purposes, E&T etc. In parallel, to be able to get information and data from European countries that do not participate in the RadoNorm project, an electronic survey on NORM was prepared and disseminated. Further details on used approaches are presented in sections 2.1., 2.2., and 2.3.

2.1 Methodology for identification of NORM involving practices

Naturally occurring radionuclides present in the natural environment (in contrast to the living and working environment), unless disturbed by any human activity, are appraised as a component of natural background and not subject to regulatory control regardless the activity concentration, and so, no actions are necessary from a radiation protection perspective (*Article 2*, EU BSS, EC 2014). In contrast, NOR emerging in a living or work environment should be considered as a possible source of non-negligible exposure, and therefore, subject to regulatory control.

A tiered approach has been developed (Michalik et al., 2023) to systematically identify situations when exposure to NOR cannot be neglected from a radiation protection perspective (*Figure 1*). The developed approach, assumes an initial position of limited knowledge of the situation and proposes four tiers for determining the NORM inventory as follows:

I. Analysis of the presence of natural mineral resources (the content of NOR is an inherent feature of all materials of mineral origin),

II. Identification of ongoing and any former mining industries (including other underground workplaces),

III. Identification of ongoing and former mineral and fossil fuel processing industries,

IV. Analysis of commodities and products life cycle, including their application, final disposal and secondary wastes generated.

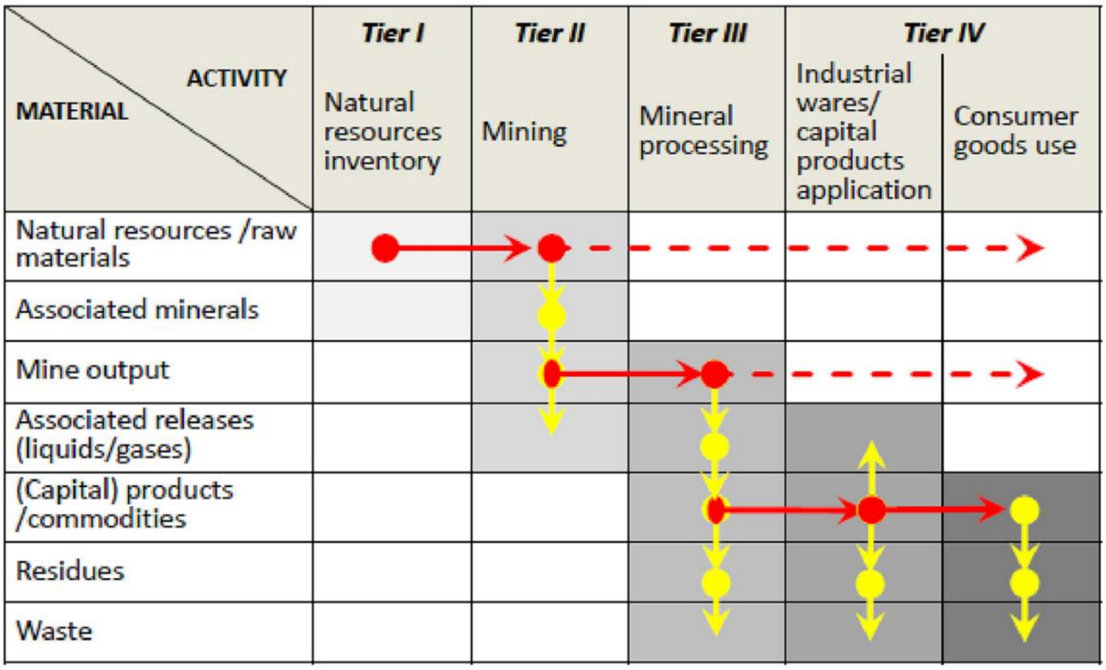

Figure 1 - Matrix of NORM identification tiers (Michalik et al., 2023).

The proposed approach follows the line of subsequent processes or activities, and sequence of emerged materials at each level, therefore the likelihood that an important component is overlooked is minimised. Meticulous application of the methodology allows the development of complete national and regional inventories of NORM affected sites and exposure situations.

The proposed system of information collection is flexible and can be launched at any tier (any point of the matrix in *Figure 1)* and carried out even in reverse. However, if applied from tier I to tier IV, there is a high probability that all cases and situations, in which NOR occurrence could be important from a radiation protection perspective, will be identified and situations of concern will not be overlooked (*Figure 2*), what may not be the case in case-by-case identification following the existing international regulatory lists.

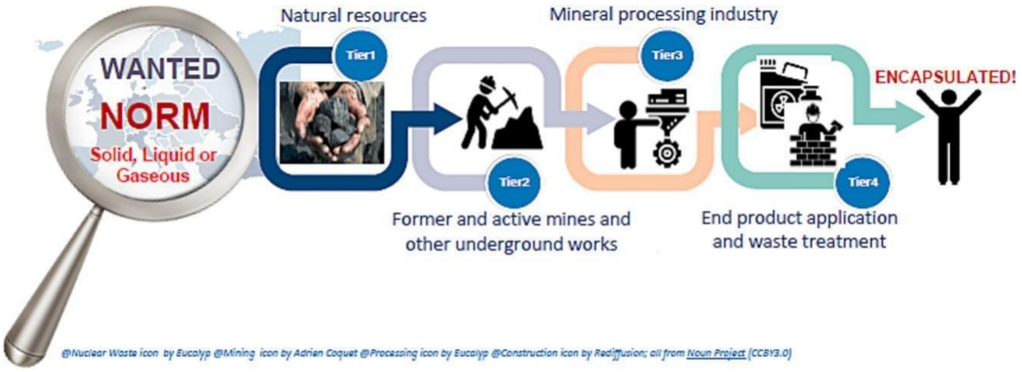

Figure 2 - A systematic tiered methodology facilitating initial or periodic review of NORM inventories. (Michalik et al., 2023).

Tier 1 – Inventory of natural resources

Information and data from geological surveys and lists of raw materials are commonly available in national registers. Features of minerals identified in raw materials should be considered regarding NOR content using literature data or widely available national and international databases. The qualitative information concerning specific minerals of potential radiological protection concern should be completed with quantitative data on radionuclide activity concentrations, if available. Where no such data are available, screening measurements are recommended to verify predicted situations.

Tier 2 – Inventory of ongoing/former mining industry

In this tier, mining activities dealing with raw materials with enhanced activity concentration of NOR should be considered first. However, also other mining activities (even those of raw materials with no elevated NOR) should be the subject of analysis due to the radiation risk-favourable circumstances that may be created during the mining. These may include local hydrological conditions and occurrence of formation water, mining method, ventilation systems applied (considering circumstances influencing radon exhalation (Chen, 2022; Skubacz et al., 2019)), type of ore treatments, generated residues as well as related dust, leachates and physical hazards (Angadi et al., 2015; Bahari et al., 2007; Garcia-Tenorio et al., 2018), mine tailings, drainages storage and treatments, considering possible impact on workers, environment and public as well as NOR accumulation in residues emerged after treatment (Michalik et al., 2020; Santos et al., 2015; Skubacz et al., 2011; Skubacz et al., 2019; Wysocka et al., 2021).

Tier 3 – Inventory of mineral processing industries

Various mineral processing industries recover the element or mineral of interest enclosed in a matrix of inert material. Applied processes may be, in general, divided on chemical reaction or physical treatment. Additionally, a specific process to be considered is energy generation from fossil fuels. Regardless the underlying principles of a process, streams of materials occur that are differentiated from used feedstock in mass, volume, chemical composition, or even aggregate state as well as the radionuclide activity concentration. At this level of analysis, attention should be paid not only to the parent radionuclides of a decay series, but also the decay products including the ^{228}Ra, ^{228}Th or ^{210}Pb and ^{210}Po as well as radon isotopes (^{222}Rn and ^{220}Rn). Even if no NORM is identified, workplaces should be checked for radon and radon progeny, especially in confined poorly ventilated spaces. There is a wide range of materials where NOR can be elevated, from formation (production) waters, scale, sludge, filter materials, residues and wastes. The dominant radionuclides and their activity concentrations can be variable depending on industry – technology and processes.

Tier 4 – Inventory of end-product application and waste utilisation

The last tier for identification of possible NORM exposure situations is focused on industrial materials, by-products, and tools as well as commodities, which are present directly in the working or living environment and potentially containing NORM. The probability of finding products containing NORM is higher in:

• industrial materials and tools (such as welding rods, refractories, abrasive materials, ceramics),

• construction and building materials (such as tiles, glaze, natural rocks, products with waste origin),

• fertilisers.

In practice, in industrial sectors as well as in individual technological processes, enhanced NOR is not the only hazard. Such industries commonly give rise to multiple hazards, among which the radiological hazard may not be necessarily the dominant one. Therefore, to be able to completely characterise exposure situations in the different NORM involving industries, the identification of non-radiological hazards is also necessary. However, as overall circumstances are very similar when both radiological and non-radiological hazards are present, use of the life cycle approach (LCA) methodology and tools already developed in the context of non-radiological hazards, with adaptation to NOR related effects, is an optimal choice.

More details about each of the tiers, their inter-connection and illustrative application in certain situations can be found in Michalik et al., 2023.

2.2 Tools for a systematic, consistent data collection

Once the identification methodology for NORM exposure situations was made, tools (in form of Excel registers) for information and data collection at identified sites were developed (see Mrdakovic Popic et al., 2023a, registers available as Supplementary Material). Registers are focussed on industries and consist of a set of predefined records, reflecting NORM specific features identified through analyses of technological processes, inventory of materials present in such processes, emerging waste streams, performed work and workplaces characteristics as well. A possibility was also included to expand the predefined structure to cover still unpredicted situations, however in a coherent way with the entire register.

It was foreseen that use of such tools should facilitate an ongoing comprehensive collection of qualitative and quantitative data from NORM affected sites across Europe, in a systematised and harmonised way. The overall gathered data should then allow making an updated European overview of NORM exposure sites that will represent a step forward for future work to make an international database for information on NORM, with relevant data of comparable quality. Moreover, the collected data were expected to significantly improve characterisation of the NORM sites and scenarios with respect to NOR behaviour, accumulation or mobilisation in different conditions, exposure pathways, exposure doses for workers, public and non-human biota.

Efficient and user-friendly tools were developed for most relevant NORM exposure situations as follows:

1. High Background natural Radiation Areas (HBRA),
2. Oil and gas production,
3. Geothermal energy production,
4. Phosphate fertiliser production,
5. Zircon industry, tiles; 5b Zircon industry, refractories,
6. Cement production
7. Phosphoric acid production,
8. TiO_2 production,
9. Primary iron production,

10. Non-ferrous metals smelting,
11. Coal fired power plants,
12. Ground water filtration facilities,
13. Mining industry (including Coal mining),
14. Legacy sites (NORM affected), and

Additionally, a generic register (No. 15) for other NORM involving activities was prepared as compilation of most probably occurring details based on the previous 14 specific registers. Developed tools allow gathering the data – qualitative and quantitative – in different ways, to the different levels of details that may be needed, for instance for an initial screening of identified NORM exposure in regulatory control case, for research data collection, for operators' inventory making etc. As shown in *Figure 3*, the tools ensure consideration of production site processes and materials (raw materials, main products, residues and/or wastes), and consideration and evaluation of different exposure scenarios for workers (production site) but also for public and the environment, including non-human biota in cases of soil pollution with NORM, air NORM discharge and liquid NORM effluents.

NORM tools are made with a level of flexibility as they are intended to be used as generic tools for collecting available general information and data on specific industrial sectors or NORM exposure category identified on the level of a country, but also as site specific tools where data from a specific facility can be gathered, when available. Each register contains three parts: 1) descriptive data, 2) quantitative data, and 3) predefined information to support characterization of technological or other processes of concern.

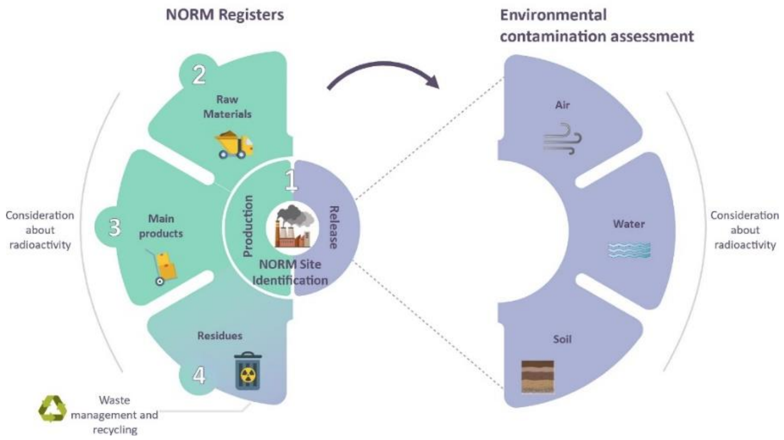

Figure 3 - Data collation flow process by NORM registers at identified NORM involving industries (Mrdakovic Popic et al., 2023a).

Main issues-topics that were subject of information and data collection by tools were:

- Legislative aspects of NORM management and regulatory approaches in the country,
- Occurrence of NOR in different materials in industries and existing exposure situations,
- NOR mobility and transport in the environment, monitoring programmes,
- Presence of non-radioactive hazards,
- Dose assessment for workers, public and non-human biota,
- Activity concentration of relevant radionuclides (^{238}U and ^{232}Th and respective progeny and considering possible disequilibria in the series, ^{40}K) in different material categories, and,
- Destination and treatment of NORM residues and wastes.

Both open questions and questions with proposed answers in the form of a drop-down menu were used, in order to obtain as many consistent and comparable results as possible. More details on developed tools can be found in the Mrdakovic Popic et al., 2023a.

2.3 Electronic NORM survey

An international electronic NORM survey has been developed to collect data on NORM exposure situations from target-audience, (a) regulators, (b) industry operators and (c) waste managers in a unified manner, and, with focus on countries which are not directly involved in the RadoNorm project (Mrdakovic Popic et al., 2023b). It is expected that an improved overview, better knowledge and understanding of NORM-involving exposure situations in Europe can provide a benefit to all involved parties and can support the optimisation of management and regulatory approaches to deal with NORM, also in light of the Circular Economy Plan Goals (EC, 2020). In addition, the structure and type of information included in the NORM survey may be valuable for practical use for initial or periodical characterisation of NORM involving exposure situations and sites worldwide, especially in countries that still need support for these activities.

The formulation of questions was based on the main objectives of the survey:

- providing an updated overview of the NORM-involving situations in Europe as well as their improved exposure characterisation,
- updating approaches for modelling NOR transfer in the environment and dose assessment,
- gathering an overview of measures to mitigate overall risk applied in NORM-involving industries as well as types of remediation activities at NORM affected legacy sites.

The process for information and data collection in survey was structured in a way that qualitative data were collected using open, closed and multiple-choice questions, while for quantitative data - collection was conducted using provided tables to be filled in.

The exposure situations considered in the survey included:

- wide categories of NORM involving industries,
- NORM affected legacies,
- high background natural radiation areas (HBRA), and,
- NORM waste disposal sites.

Survey was comprehensive, including questions related to different aspects of management and regulation (from legislative and regulatory approaches, NORM inventory, information about non-radioactive hazards and applied mitigation measures, approaches for dose modelling, optimisation methods etc.) of a range of materials (raw materials, main and by products, residues and wastes, discharges etc.). Additionally, questions about scientific and regulatory challenges identified at NORM exposure situations were included as open questions, to give the respondents a chance to articulate their own perspectives on the topic.

The survey was developed in the English language. The implementation of the NORM survey was done via the RadoNorm webpage. The potential participants were informed about benefits and negligible potential risks, and it was explained that replies to the survey would be analysed in an anonymised form and kept in accordance with the European Data Protection Regulations. Additional information about the goals of the survey and foreseen outcomes were also made publicly available in the form of a report on the RadoNorm webpage. The NORM survey was implemented on the EU survey platform. Before launching, the survey was tested by members of the RadoNorm project, experts in NORM issues. The invitation to participate in the survey was sent directly to >400 contacts/stakeholders in European countries. A contact list was produced using the stakeholder list of the RadoNorm project, existing professional network connections and Google searches.

Moreover, a web survey link was shared to a wider audience via social media. The survey was launched on the 10 January 2022 and was open until 31 May 2022. The responses were received from 19 countries, i. e., from 17, 7 and 3 countries, for regulators, industry operators and waste operators, respectively. More information and comprehensive overview of results from e-NORM survey are available in Mrdakovic Popic et al., 2023b.

3. Main features of NORM exposure situations

In the following sections, outcomes – information and data obtained by the tools (Excel registers) and e-NORM survey are presented with respect to the particular topics, main features of NORM exposure situations.

3.1 Legislative framework and regulatory approaches to NORM

The Council Directive 2013/59/EURATOM lays down the basic safety standards (EU BSS) for protection against exposure to ionising radiation (EC, 2014). It states that industries processing materials containing NORM should be managed within the same regulatory framework as other practices. Member states may decide to exempt justified practices from notification, or to clear material emerging in frame of an authorised practice from regulatory control, based on exemption and clearance levels (EL and CL, respectively) laid down in Annex VII of the EU BSS (EC, 2014), in terms of activity concentrations of natural radionuclides from ^{238}U and ^{232}Th series and ^{40}K for solid materials, or in terms of annual effective dose.

Most European countries adopted ELs and CLs for solid NORM from the EU BSS (EC, 2014), certain countries adopted the values from the EC report 'Radiation Protection 122, part II' (RP 122 part II) (EC, 2002) (Table 1), while in some countries a combination thereof is used. It is important to note that ELs and CLs reported in EU BSS and RP 122 part II are calculated for different dose criteria, respectively 1 mSv y^{-1} and 0.3 mSv y^{-1} (Table 1).

Table 1 - EL and CL provided in EU BSS and RP 122, part II used in various countries across Europe for solid NORM

Radionuclide	Values for solid materials, EU BSS (kBq kg^{-1})	Values for solid materials, RP 122, Part II (kBq kg^{-1})
^{238}U-series	1	0.5
^{232}Th-series	1	0.5
^{40}K	10	5
^{226}Ra		0.5
^{228}Ra		1
^{228}Th		0.5
^{210}Pb		5
^{210}Po		5
^{238}U		5
^{232}Th		5

As illustration, based on this study data, Belgium and Spain use EL and CL values based on EC Radiation Protection 122, Part II (EC, 2002), while in Italy values for ^{238}U and ^{232}Th series adopted from the EU BSS are in use together with the specific ELs and CLs for ^{210}Pb and ^{210}Po (5 kBq kg^{-1}) adopted from the RP 122, part II. In France, on the other hand, no terms ELs and CLs are used, but equivalent numerical values, adopted from the EU BSS are applied. In Germany, a set of ELs and CLs starting at 0.2 kBq kg^{-1} to 0.5 and 1 kBq kg^{-1}, for ^{238}U and ^{232}Th series, as the sum of the highest specific activity of radionuclides of the ^{238}U and ^{232}Th series are applied. Moreover, in Belgium and Germany, landfill specific CLs were derived, which depend on the total mass of waste delivered annually at the landfill. In Norway and Denmark, a set of numerical values in terms of activity concentrations for all radionuclides in ^{238}U and ^{232}Th series are defined, and a summation rule is applied in the regulatory control, which are also in line with the approaches and values given in the EU BSS and RP 122, part II. The main dose criterion for workers and public is in most countries set at 1 mSv y^{-1}, although depending on country and case, lower dose criteria in use are notified (0.1 and 0.3 mSv y^{-1}). More details about developed national approaches can be found in a report by HERCA, 2021; Mrdakovic Popic et al., 2023a and b.

Regarding discharge of radioactive effluents and gases, EU BSS gives more flexibility to member states to develop proper control measures, since it provides no numerical authorization values for deliberate discharges. Still, qualitative requirements are provided for examination and approval of plans for establishment of appropriate authorised limits, estimation of doses to public proportionate to the risk involved, monitoring of radioactive discharge (EU BSS, *Articles 65-67*), and use of up-to date best scientific knowledge in the exposure assessment (*Figure 4*). Based on the current study analysis of national regulatory approaches in European countries, the main criterion used in these situations is the annual dose of 1 mSv as a maximal allowed dose for the public exposure from all authorized sources. However, there are some countries that adopted own national numerical values of maximal NOR concentrations for liquid NORM effluents (this study, HERCA, 2021).

For example, in Belgium, the Netherlands, Norway and UK specific authorized discharge levels of NOR are available for liquid effluents (this study, HERCA, 2021). However, for most of European countries, the dose criteria, as general exemption criteria for members of the public, are commonly set in national legislations, in range 0.3 mSv y^{-1} to 1 mSv y^{-1}. These dose criteria are widely used together with ELs and CLs for the development of graded regulatory approaches.

Figure 4 - Process of decision-making at investigated planned exposure situations.

3.2 Overview of NORM exposure situations in Europe

Detailed information and data were obtained from the RadoNorm participants in a form of filled out Excel tools (registers). Additional information and data were obtained by countries (both the RadoNorm participants and non-RadoNorm participants) through the e-NORM survey. Twenty-one European countries, which provided information and data (qualitative and quantitative), are presented in *Figure 5.*

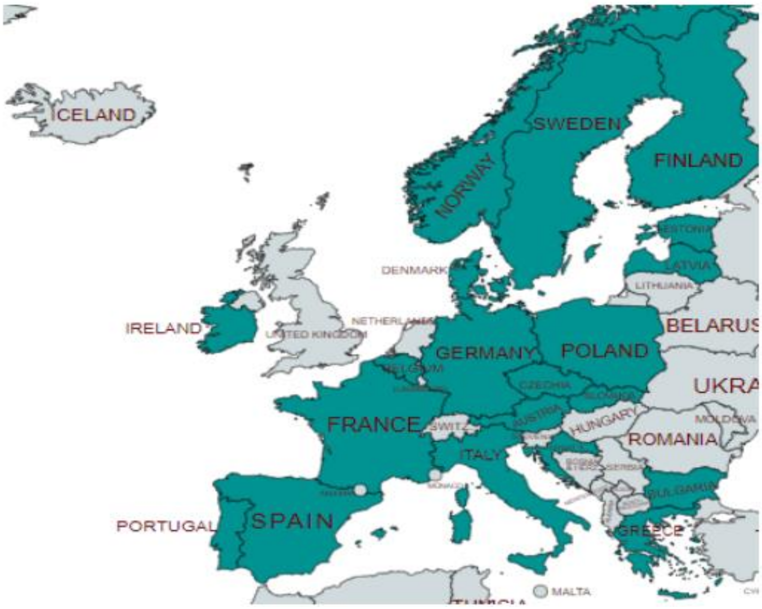

Figure 5 - Map of European countries where data on NORM exposure situations were collected from.

Pooling available information on occurrence of NORM exposure situations provided several issues for further consideration:

- High Background natural Radiation Areas (HBRA) – at the beginning of project, participants of task 2.5. discussed criteria that should be used to consider a site as HBRA. In the end, sites enriched with ^{238}U, ^{232}Th, undisturbed by human activities in the past or present days and those showing high $^{220,222}Rn$ (because of e.g., elevated mother radionuclide activity concentrations, disturbance of secular equilibrium due to natural processes, background anomalies etc) were decided to be considered as HBRA. However, only few countries reported data for such exposure sites, while challenges in distinguishing these sites from other NORM sites and no existence of proper formulation in the national legislations were highlighted by many countries.
- Legacy sites affected by NORM – after data collating, it was clear that different countries may define *Legacy sites* differently. In contrast to HBRA, it was easier to understand that this term is used for historical, old sites, often with questionable ownership and no responsibility assignment, no regulatory control, while complex contamination including NOR exist. However, in some countries, legacy sites are also parts of the operational facilities, e.g. old disposal sites that are not properly controlled at time being, while in others this is not the case.
- The majority of NORM involving industries from the Annex VI; EU BSS (EC, 2014) is present in investigated countries, but beside these industries, some that are not included neither in the EU BSS nor in the IAEA list are identified (*Figure 6*). These are for example potash mining, pulp and paper mills, radon spas, geothermal spas, bauxite processing, etc.
- In some countries, there is an approximate knowledge on present NORM-involving industry, but a comprehensive identification and NORM inventory making is still missing, due to lack of practical NORM related issues/understanding of EU BSS requirements, lack of human resources and time needed for such activity etc.

Still, the overview of NORM exposure situations across European countries, including certain industries that are non-active at present time, but might have same issues and challenges as active ones, are presented in *Figure 6.*

Abundance index presents the ratio between the number of countries where we identified NORM involving facilities and the number of countries that were investigated.

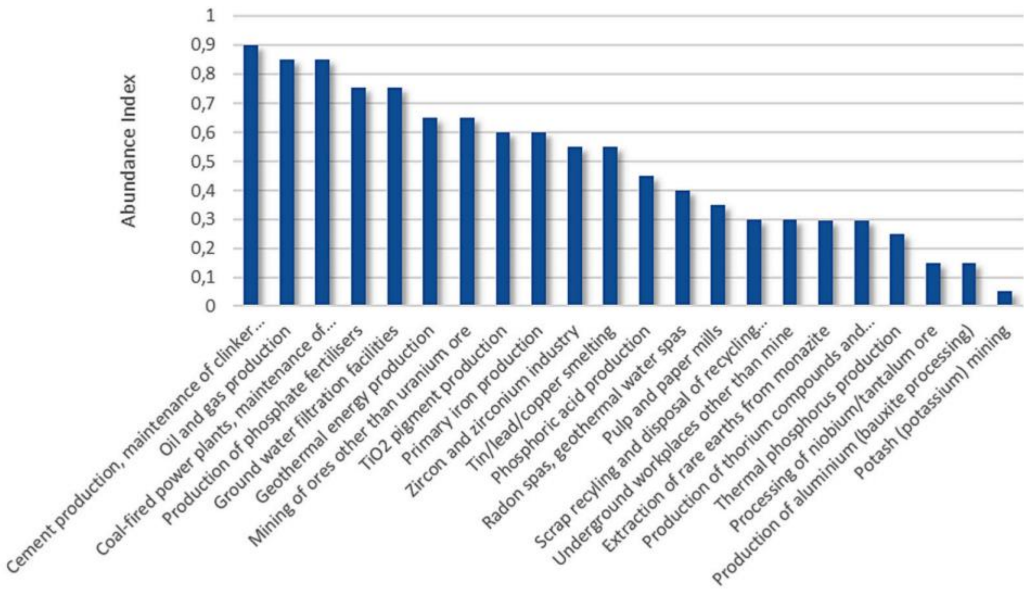

Figure 6 - Presence of NORM involving industries/practices in European countries.

The NORM involving industries, present in most of countries are cement industry, oil and gas industry and coal fired power plants. At somewhat lower abundance level are the production of mineral fertilisers and ground water filtration facilities, but these industries together with the geothermal energy production, mining of ores, production of TiO_2, primary iron production, zircon and zirconium production, tin/lead/copper smelting are all present in > 50% investigated countries in Europe in this work. Beside NORM-involving activities, NORM affected legacy sites and HBRA site were reported, although in a lesser extent.

3.3 NORM involving industries across the European countries

3.3.1 Raw materials containing NOR

Generally, the activity concentrations of the radionuclides in rocks and soil in the nature are low (UNSCEAR, 2000; 2008). However, certain minerals, contain uranium, thorium and their progeny, or potassium at enhanced levels. These can be commercially exploited due to fissile characteristics of minerals, but also due to their other elements content or particular characteristics. In the latter case, there is a wide range of NORM involving industries, which include various technological processes (e.g. chemical mass reduction, high temperature, pressure etc.) that may lead to accumulation of NORM with elevated radionuclide concentrations, what further imply necessity of radiation protection control.

In this report, certain raw materials with elevated activity concentrations of ^{238}U, ^{226}Ra, ^{210}Pb, ^{210}Po, ^{232}Th, ^{228}Ra and ^{228}Th (> ELs and CLs of EU BSS, EC 2014), used in identified NORM involving industries across European countries, are presented at *Figure 7*. It should be, however, highlighted that ranges of NOR in raw materials are broad, often below 1 kBq kg^{-1}, and that there are numerous identified different raw materials in use, which do not express elevated NOR activity concentrations (Mrdakovic Popic et al., 2023b), but still imply need for a careful consideration of each category and case by case industrial screening approach.

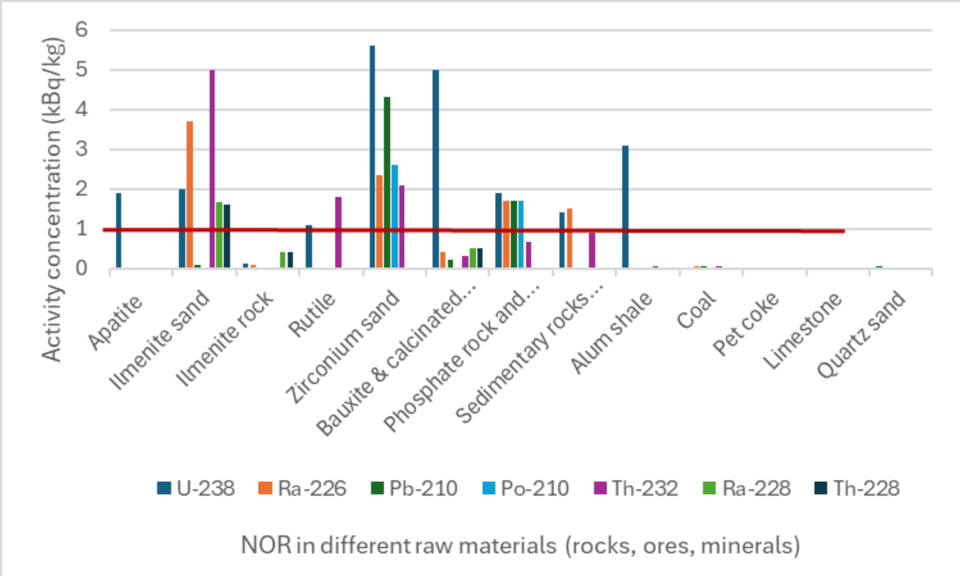

Figure 7 - Raw materials (minerals, sand, rocks) used in NORM involving industries.

Apatite, ilmenite sand, rutile, zirconium sand, bauxite, phosphate and sedimentary rocks as well as alum shale have been reported to exhibit activity concentrations higher than 1 kBq kg^{-1} of at least ^{238}U and ^{232}Th, but also of certain progeny radionuclides. Here presented raw materials and NOR values are in good accordance with data given in IAEA, 2006 and UNSCEAR, 2008. These materials are used in many industries – e.g., production of phosphate fertilisers, zircon and zirconium industry, TiO_2 production and others – and thus, it calls for caution and application of radiation protection measures, regarding potential further increase of NOR concentration and their accumulation during technological processes in facilities, and potential exposure of workers, but also in certain cases exposure of the surrounding environment and non-human biota. A special case is potassium salts (potash) used also for fertilizers production often together with phosphate rocks. In this case potassium is an element of interest, hence there is no case of enhanced radioactivity as content of ^{40}K isotope in the total potassium is stable. However, in some pure potassium compounds used (KCl, K_2O) ^{40}K activity exceeds the relevant CL and when used intentionally must be considered in terms of radiation protection.

Based on available data, it was also noticed that even raw materials with NOR activity concentrations < 1 kBq kg^{-1} (many identified industrial cases, see Mrdakovic Popic et al., 2023b; *Dvorzhak et al., 2025a, in prep., Mrdakovic Popic et al., 2025, under review for peer-review publication; in Appendices)* may potentially give accumulation of NORM with elevated radionuclides depending on production processes. Therefore, in consideration of NORM involving industries and regulatory approaches – all steps of the main technological process and all materials (raw materials, but also products, by-products, residues in different forms, discharges and effluents and finally waste) should be controlled for their NOR activity concentration levels. Based on that, proper radiation protection, occupational, safety and health measures should be considered, i.e. based on evaluated risk from ionising radiation, a proper graded regulatory control developed, commensurate with such risk.

3.3.2 NORM in mineral processing industries

Some of mineral processing industries use raw materials with different activity concentration levels of NOR. Accumulation or mobilisation of certain radionuclides can happen, as above mentioned, due to different processes, conditions and materials.

To investigate that, information and data were collected and then compared for the following mineral processing industries:

- phosphoric acid production,
- phosphate and potassium fertilisers industry,
- cement industry,
- TiO_2 production,
- zircon and zirconia production.

Details on each industry, including general description, overview of raw materials, main and by products, residues, discharges and wastes and activity concentration of NOR are provided in *Dvorzhak et al., 2025a, in prep*., (abstract available in Appendix A).

Activity concentrations of NOR in raw materials in the investigated industries, such as sedimentary rocks, phosphate and potash sands, zircon sand and zirconium oxide are in many cases higher than ELs & CLs, although the values are, as above mentioned in 3.3.1., found to be in a wide range, greatly depending on the origin of used raw materials.

Main products in all investigated industries are commonly of no radiation protection concern, although some countries reported NOR activity concentrations for certain main products, such as phosphoric acid, mono- and diammonium phosphate fertilisers, potassium fertilisers, refractory slurry, slightly elevated, up to 3 kBq kg^{-1} for ^{238}U and ^{232}Th decay chains.

The highest level of accumulation of NOR was, as expected, in residual materials and waste, where depending on raw material and features of the technological processes it can reach hundred-levels of kBq kg^{-1} for certain radionuclides (e.g., fusion furnace dust in zirconium industry reaches levels of 130 kBq kg^{-1} for ^{210}Po and 40 kBq kg^{-1} for ^{210}Pb; filter residue material in TiO_2 production reaches levels of 200 kBq kg^{-1} for ^{210}Pb and 140 kBq kg^{-1} for ^{210}Po). Still, most of the residue NOR activity concentrations were reported to be below 100 kBq kg^{-1}.

Phosphogypsum (PG) was found to be produced as largest volume of NORM, however NOR activity concentrations in it are usually not high, although it can sometimes exceed the ELs & CLs. The most dominant radionuclides present in variably enhanced levels are ^{226}Ra, ^{228}Ra, ^{210}Pb and ^{210}Po in scales, sludges, filter materials, and liquid and gaseous effluents including dust (particulate matter) (*Table 2*).

Table 2 - Overview of main products, residues and waste per mineral industries with elevated NOR activity concentrations and main accumulated radionuclides

Industry	Main products	Residues and waste	Main NORM isotopes
Phosphoric acid production	Phosphoric acid 54% P_2O_5 (merchant grade)	Phosphogypsum	^{226}Ra
		Scale	^{238}U, ^{226}Ra
		Liquid sludge	^{238}U
		Solid sludge	^{238}U, ^{226}Ra, ^{210}Pb
		Filter materials	^{226}Ra, ^{210}Pb

Fertilisers production	Monoammonium phosphate Diammonium phosphate	Scale Calcium fluoride sludge	^{226}Ra ^{226}Ra
Zirconium industry	Refractory Refractory slurry	Fusion furnace dust Hydrated lime General air exhauster dust Scrap grinding dust Sludge Scrap refractory residues	^{210}Pb, ^{210}Po ^{210}Po ^{238}U, ^{226}Ra, ^{210}Pb ^{238}U, ^{226}Ra, ^{210}Pb, ^{210}Po ^{238}U, ^{226}Ra, ^{210}Pb, ^{210}Po ^{238}U, ^{226}Ra,^{232}Th
TiO_2 production	-	Scale Sludge Brick lining of tanks Ilmenite mud Filter residue Metal hydroxide	^{238}U,^{226}Ra,^{210}Pb, ^{232}Th ^{226}Ra,^{228}Ra, ^{228}Th ^{226}Ra,^{210}Pb,^{228}Ra,^{228}Th ^{238}U,^{226}Ra, ^{228}Ra, ^{228}Th ^{238}U,^{226}Ra,^{210}Pb, ^{210}Po, ^{232}Th, ^{228}Ra ^{238}U, ^{232}Th
Cement industry	-	Clinker dust	^{210}Pb, ^{210}Po

3.3.3 NORM in energy production sectors

Naturally occurring radioactive material in the oil and gas industry, coal mining and coal-fired power plants and geothermal energy production facilities were investigated and compared, regarding natural radionuclides and main RP aspects being considered, within all consecutive segments of their energy production lines. While all the details are provided in *Mrdakovic Popic et al., 2025*, under review (preprint link available in Appendix B), the main conclusions were as follows:

- Raw materials (oil formation rocks, crude oil, coal) commonly contain low activity concentrations of NOR, which are in secular equilibrium with mother radionuclides ^{238}U and ^{232}Th, and of no concern for radiation protection as such. Nevertheless, in certain cases geothermal fluids may have elevated levels of ^{226}Ra, ^{210}Pb and ^{210}Po depending on the system conditions. This information calls for a cautious approach with proper protection measures even at these early stages.
- Energy carriers' pre-treatment and transportation in all sectors, led to the accumulation of NOR in the residues - scales, sludge and filter deposits with high concentration of $^{226,228}Ra$, ^{210}Pb and ^{210}Po.These radionuclides, with the addition of ^{222}Rn in certain situations, were identified as the main dose contributors in all energy sectors.
- Combustion process and energy generation itself produce residues containing NOR mainly in coal-fired power plants (fly and bottom ash), since the use of oil shale in the EU is limited.
- Maintenance and cleaning processes were found to be the most concerning exposure scenarios for workers from an RP standpoint, with external radiation as the main exposure pathway for all investigated sectors.

- The oil and gas industry as well as coal mining are mainly responsible for the release of significant volumes of produced water containing ^{226}Ra and ^{228}Ra. Energy generation from coal is the source of the biggest waste stream when considering solid waste from coal mining and coal combustion products from coal fired power plants. However, the average NOR activity concentration is only slightly enhanced, and a high proportion of solid waste is reused. Thermal energy use is responsible for creation of scales and sediments due to similar processes as in case of formation water released from coal mining and oil and gas exploitation.

3.3.4 NORM in groundwater filtration facilities

As approximately 50% of the drinking water in the EU originates from groundwater (GW), data collected by tools from only a few countries, represented a small number of answers. No obvious reasons for such scarce reporting were found, and data was then complemented by responses from e-NORM survey and literature data geographically belonging to Europe. Types of materials listed to be of radiological concern included liquids - raw GW, leaving GW (drinking water), and solid materials - activated carbon filter, alumina filter, sand filter, sand and anthracite filter, backwash sludge, decantation sludge, aeration sludge and concentrate from osmosis.

It is known that in some cases the concentration of ^{222}Rn, ^{238}U and ^{226}Ra can be significantly elevated in raw groundwater in Europe. The activity concentrations in raw GW (up to 130 Bq L^{-1}, 0.17Bq L^{-1} and 0.06 Bq L^{-1} of ^{222}Rn, ^{238}U and ^{226}Ra, respectively) and leaving GW (up to 4 Bq L^{-1}, 0.1 Bq L^{-1} and 0.03 Bq L^{-1} of ^{222}Rn, ^{238}U and ^{226}Ra, respectively) were significantly lower in the tools collected answers, and may be considered as not representative of European groundwater in general. Values obtained by the e-survey for GW were lower but of comparable magnitude, up to 50 Bq L^{-1} for ^{222}Rn and one order of magnitude higher, up to 2 Bq L^{-1} for ^{226}Ra, ^{228}Ra. Higher number of data is, therefore, necessary to draw the proper conclusions about NOR activity concentrations and possible implied risks.

The solid materials of concern (*Table 3*) were almost either filter materials that had accumulated radionuclides (activated carbon/alumina, sand and sand and anthracite filters), or solid residues removed from filters during filter washing (e.g. backwash sludges). Aeration sludge, decantation sludge and concentrate from reverse osmosis were also listed. In addition to this, it is known from literature that at least ion-exchange resins can also be of concern at water treatment facilities.

Table 3 - Naturally occurring radionuclides in solid residues from groundwater treatment facilities (kBq kg^{-1})

Material type	^{238}U	^{226}Ra	^{210}Pb	^{228}Ra	^{228}Th
backwash sludge[a]	0.001 – 2.8	0.3– 4.3	0.27 – 1.2	0.28 – 1.2	0.47 – 1.1
sand filter[a]	0.04 – 0.12	0.02 – 0.6	0.001 – 0.02	0.05 – 0.24	0.04 – 0.12
sand+anthracite filt[a]	0.46 – 0.55	4.4 – 5.2	0.16 – 0.18	1.5 – 1.9	1.3 – 1.4
activated carbon[a]	0.1 – 0.46	0.03 – 0.08	0.2 – 1	0.01 – 0.04	0.03
aeration sludge[b]	6.5	0.32	0.22	0.280	0.09
alumina filter[b]	0.03	0.29	0.02	0.51	No available data

decantation sludge[b]	0.1	8.8	1.7	7	No available data
limestone filter[b]	0.11	0.35	0.1	0.13	0.05
precipitate in raw water pipe[b]	0.94	0.8	0.11	0.9	0.7

[a]Ranges of activity concentrations of NOR, [b]Maximal values of activity concentrations of NOR.

3.3.5 NORM in non-ferrous metal smelting

In total fifteen facilities for non-metal smelting made qualitative and quantitative data available for this work. Most facilities were related to nickel (Ni), cobalt (Co), copper (Cu) or zinc (Zn) -production, but also to tin (Sn), germanium (Ge), molybdenum (Mo) and lead (Pb).

Activity concentration ranges of NOR in different material types from non-ferrous smelting are shown in *Table 4*. The highest concentrations are reported from raw materials - cassiterite (up to 3 kBq kg^{-1} of ^{226}Ra and 24 kBq kg^{-1} of ^{232}Th) and hardhead (FeSn) (up to 11 kBq kg^{-1} of ^{238}U and 6 kBq kg^{-1} of ^{232}Th), by- product Cu-concentrate (up to 7 kBq kg^{-1} of ^{238}U) and residue filter dust (up to 35 kBq kg^{-1} of ^{210}Po).

The analysis showed that the maximum concentrations in individual samples from raw materials are not directly transferred into equally high concentrations in residues, as typically these types of smelters get raw materials from many sources. The mixtures of different raw materials combined with other chemicals in the processes result in mixing and dilution so that the maximum concentrations in residues are less than the maximum in individual raw materials. Moreover, the metal content in ore is usually merely very few percent, hence feedstock mass reduction after metal sourcing is negligible, that is why no accumulation of NORM in the main waste stream is observed. An exception to this is ^{210}Po in the filter dust where the mass concentration factor is very large (i.e. polonium gets concentrated in a high temperature process from a large mass of raw materials into a very small mass of dust fines

Table 4 - Activity concentration (kBq kg^{-1}) ranges of natural radionuclides in materials from non-ferrous smelting facilities

Type of material	^{238}U	^{226}Ra	^{210}Pb	^{210}Po	^{232}Th
Raw material	0.03 – 11	0.01 – 3.20	-*	-*	0.01 – 24
Main Product	0.001 – 0.03	0.0001 – 0.02	0.0001 – 0.005	-	0.001 – 0.004
Side Product	0.024 – 7.30	0.001-0.002	0.003 – 0.008	-	<0.001 – 0.01
Residue	0.02 – 2.70	0.005 – 0.11	0.003 – 0.7	5 – 35	<0.001 – 0.8
Effluent	< 0.004	<0.001	<0.001	-	<0.0005

**- nuclide specific data are not provided, however considering untreated chemically raw materials secular equilibrium in the whole decay series can be assumed, so even not reported must be considered in the related hazard evaluation.*

In general, maintenance operations are the most critical, but often protection measures against non-radioactive hazards applied in frame of the overall occupational health and safety (OH&S) systems (e.g., ventilation, respiratory protective equipment) are sufficient to efficiently protect against significant radiation exposures.

3.4 Exposure scenarios, pathways and effective doses

To be able to estimate possible exposure radiation doses for humans and non-human biota, the exposure scenarios for particular type of exposure situation must be considered. An approach to the exposure scenario definitions with respect to NORM was first provided by the European Commission in 2002, in the guidance RP 122 Part II (EC, 2002).

According to gathered information, RP 122, Part II-given exposure scenarios and pathways are commonly still in use in Europe, but countries also use tailor-made exposure scenarios i.e., scenarios adapted to the site-specific conditions in various industries or at legacy sites. Numerous exposure scenarios related to NORM mineral processing industries and NORM in energy production sectors are provided in detail in *Dvorzhak et al., 2025b, under prep*., and *Mrdakovic Popic et al., 2025, under review* (Appendices A and B).

Some of the illustrative examples of reported considered exposure scenarios and pathways are:

- For workers
  - exposure of workers to NOR that may happen during prolonged and close contact with raw materials while doing manual or semi-manual transportation, unpacking, and other work that include proximity and contact with large quantities of raw materials, in closed or open spaces, due to inhalation of dust or gamma radiation exposure,
  - exposure of workers in oil and gas industry during maintenance, when handling waste materials and surface-contaminated objects, potential exposure during the cleaning of contaminated equipment; during the decommissioning of oil and gas platforms,
  - exposure scenarios for workers in groundwater treatment facilities are reported during handling of NORM sludges/filters and working near sludges/filters (incl. activated carbon filters),
  - exposure to radon, especially radon progeny in workplaces located in confined spaces with poor ventilation, typical in any kind of underground mining regardless of exploited raw material.

- For public
  - exposure of members of public living in the vicinity of NORM involving industrial facilities which discharge the liquid effluent containing NORM to water bodies (e.g. streams or small lakes), emit gaseous NORM or produce solid NORM waste that is unproperly disposed of in the environment (see illustration of the complexity of the exposure pathways and processes relevant for potential public and environmental exposure due to coal fired power plants air dispersion and solid and liquid waste from oil and gas industry improperly disposed of, *Figure 8*).
  - exposure of the population due to activities in groundwater treatment facilities evaluated on the assumptions that all the radioactivity from the water treatment plant is transferred to the river or retained by the sewage sludge, which is subsequently used as fertilizer in agriculture.
  - exposure of members of the public due to living in the vicinity of disposal sites for NORM waste where leakage is possible due to unproper construction or disposal measures.
  - exposure of members of public during recreational time spent in the vicinity of old NORM-affected legacy sites.

In the given exposure scenarios, workers and members of the public may be exposed to ionising radiation from NOR through different exposure pathways. Relevant exposure pathways that are commonly considered are as following (in brackets percentage of answers for workers and members of the public, respectively):

- exposure due to inhalation of radon and/or radon progeny (46 %, 36 %),
- exposure to external gamma radiation (46 %, 36 %),
- exposure due to (inadvertent) ingestion (18 %, 36 %),
- exposure due to inhalation of dust containing natural radionuclides (55 %, 36 %).

Dermal contact is also reported as less significant, but possible for workers when handling high-activity materials or residues without protective gear (e.g., in oil and gas industry).

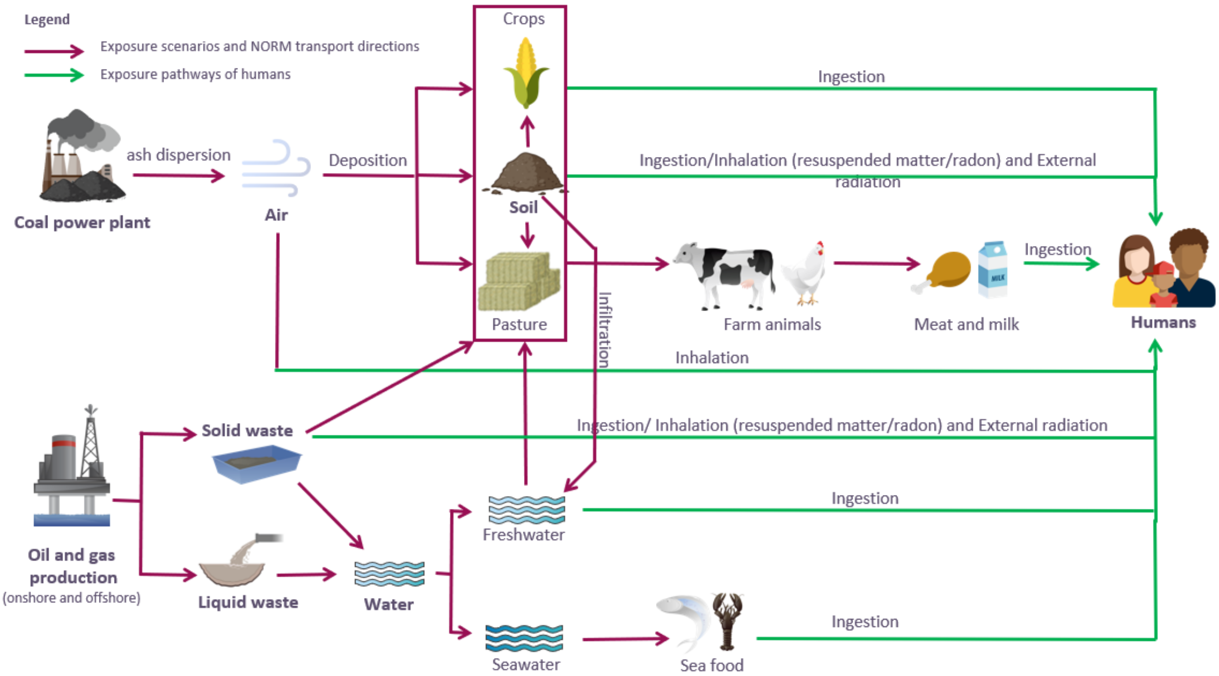

Figure 8 - Exposure scenarios, with transport directions and exposure pathways, for atmospheric NORM discharge from coal-fired power plants, and NORM solid and liquid waste from oil and gas facilities, considered in calculating the dose for the represent person.

3.4.1 Exposure of workers to NORM

Workers involved in the industrial processes containing NORM can be occupationally exposed to radiation. Usually, exposure to NORM in industrial processes is not of radiological concern, however, to ensure the safety of workers, protective actions, including monitoring and dose assessments are required. Maximal reported values of radiation effective dose exposure to NORM in here investigated NORM involving industries, main exposure pathways of exposure and exposure control measures are presented in *Table 5*.

Collected annual exposure doses of workers in this study were in general lower than those published in the peer-review literature, but still in accordance with the lower part of the ranges worldwide reported for the different industries (Garcia-Tenorio et al., 2012; Gazquez et al., 2021; Elghawi and Elammari, 2024; Fall et al., 2023), UNSCEAR reported values (UNSCEAR, 2021)). Annual doses above 1 mSv y^{-1} were noticed in few cases - up to 1.32 mSv in zirconium industry, 2.02 mSv in TiO_2 production industry and 1.74 mSv in coal mining, while doses of workers in other NORM mineral processing industries, NORM energy production sectors, groundwater water treatment and metal smelting were all below the dose criterion of 1 mSv y^{-1} (EU BSS), approximately one to two orders of magnitude lower. Indoor Rn is by far the biggest concern of natural radiation for workers at groundwater treatment facilities, if groundwater comes into contact with indoor air (e.g. Jantsikene et al., 2014; Tyrväinen et al., 2023,). In our study, values for workers exposure doses up to 0.52 mSv y^{-1} were reported for external and internal exposure to NOR, excluding Rn inhalation. In a recent study from Finland, Kallio et al., 2023., found similar workers exposure dose of 0.3 mSv y^{-1} for same exposure pathways; in the same study it was also concluded that workers exposure dose from NORM at groundwater treatment facilities will be < 1 mSv y^{-1} when U-series and Th-series concentrations of solid residues are < 10 kBq kg^{-1}. This is affected by the type of work done at groundwater treatment facilities, i.e. only short times are spent very close to the materials.

During the operations in all investigated industries, including handling and management of high NOR-containing scales, workers are equipped with personal protection equipment (PPE), and other OH&S measures and equipment, generally used for other hazardous substances, such as contact time limitation, ventilation systems, rotation of workers on duties. These measures highly reduce the risk of external gamma exposure, ingestion and inhalation of all hazardous substances, which is sufficient to protect against radiation exposure too (this study, Gellermann et al., 2018).

Table 5 - Overview of workers exposure doses due to NORM (mSv y^{-1}), exposure pathways and commonly applied protective measures

Industry	Main exposure pathway[a]	Maximal reported exposure dose (mSv y^{-1}) – RadoNorm project	Exposure control measures (listed for all industries pooled)
Phosphoric acid production	Ext	0.62	Shielding Ventilation Time control Personal protective equipment Monitoring Training
Fertilisers production	Ext, In	0.69	
Zirconium industry	Ext, In	1.32	
Cement production	Ext, In	0.14	
TiO_2 production	Ext	2.02	
Oil and gas industry	Ext, In, Ig, Rn	0.35	
Coal mining	Ext, In, Rn	1.74	
Coal fired power plants	Ext, In	0.17	
Geothermal energy production	Ext, In, Ig, Rn	< 0.10	
Groundwater filtration facilities	Ext, In, Rn-excluded	0.52	
Non-ferrous metal smelting	Ext, In, Ig	0.30	

[a]*Ext: external exposure; In: inhalation; Ig: ingestion; Rn: radon inhalation.*

3.4.2 Exposure of public and environment to NORM

Understanding the physical and chemical processes that influence the accumulation of contaminants within the production site is essential for estimation and mitigating of potential radiation exposure. When features of technological processes and important parameters are known, the prediction of radionuclide behaviour, and consequently occupational and public radiation exposure dose, in each situation is possible. However, it is more complex when NOR are present, due to human activities, in enhanced concentration in the environment, and when further transported and mobilised in different environmental compartments depending on prevailing environmental conditions. The main processes leading to further transportation and distribution of NOR in the different environmental compartments and potentially reaching non-human biota are identified as numerous, first as going on in abiotic environment: wind and water erosion, surface creep, leaching, seepage, precipitation, sedimentation, Rn exhalation, diffusion, convection, atmospheric dispersion, dry and wet deposition, then leading to the transfer to biota as high plants primary production, interception and inhalation or ingestion to some extent, and finally directly related to biota activity as bioturbation or organic mass decomposition (Mrdakovic Popic et al., 2023a).

Depending on NORM involving industry or activity and exposure scenarios of concern, the exposure pathways of public to NORM can be (a) external irradiation from deposited radionuclides, (b) external irradiation from immersion in air contaminated by radionuclides, (c) inhalation of radionuclides contaminated air, (d) ingestion of food products contaminated by radionuclides. However, in general, the estimations showed relatively low doses for public for various considered scenarios that countries from Europe reported for different situations involving NORM. Exposure doses to public reported regarding mineral processing industries were in range 0.1 mSv y^{-1} to 0.5 mSv y^{-1}. The highest dose of 0.5 mSv (still below a dose criterion of 1 mSv y^{-1}) was obtained in certain public exposure to external gamma irradiation and dust inhalation related to living in the vicinity of zirconium industry facilities. Phosphoric acid production, fertilisers production and TiO_2 production are not known to give elevated doses to the public, while cement, although seen as environmental burden due to carbon footprint, neither is a source of an additional exposure in the stage it's production nor connected with increased risk when used in constructions.

The evaluation of exposure dose to the public from groundwater treatment facilities was carried out using values established by RP 135 (EC, 2003). The exposure scenario with population living near the river included consideration of exposure pathways - internal river water ingestion and fish consumption and external radiation from sediments near riverbanks. The calculated exposure doses to public were negligible, in range 8.4E-6 – 1.1E-5 mSv y^{-1}. In other relevant exposure scenario - exposure of the population is considered when all the radioactivity is retained by the sewage sludge, further used as fertilizer in agriculture. This scenario regards a population that eats vegetable grew on the soil fertilized with sludges or eats meat (milk) from livestock that grazes on that soil. From the surveys conducted in the framework of Task 2.5, low estimated effective doses, ranging from low 6.4E-6 mSv y^{-1} to 1.34E-2 mSv y^{-1} have been found. Nevertheless, for sludge directly obtained from water treatment plants, recent research indicates that effective doses exceeding 0.3 mSv y^{-1} can arise when $^{226+}$Ra and $^{228+}$Ra decay segment concentrations approximate 1 kBq kg^{-1}, a level that literature confirms is exceeded in certain sludge samples from drinking water treatment facilities (Venoso et al, 2024).

Public exposure doses were evaluated based on collected data, also for energy production sectors including NORM: oil and gas, coal fired power plants and geothermal energy productions. Results, taking into consideration different exposure scenarios, showed doses in low range of 0.001 to 0.013 mSv y^{-1}, for oil and gas and coal fired power plants energy production, while doses from the geothermal energy production were lower for several orders of magnitude, i.e. negligible (*Mrdakovic Popic et al., 2025*, *under review,* Appendix B).

Only limited information was available on potential radiological impact of NORM to environment and non-human biota in case of mineral processing industries. In Norway, there are limited emissions to air and sea due to handling of raw material and industrial processes emissions. The maximum weighted absorbed dose rates, exceeding 3 µGy h^{-1} for the most highly exposed organism, lichen and bryophytes, have been estimated, which are above the natural background dose rates from primordial radionuclides, but would still remain below natural exposures from radon gas and certainly below the ERICA screening benchmark (10 µGy h^{-1}) (Brown et al., 2008) and UNSCEAR (2000, 2008) benchmark dose rate of 40 µGy h^{-1}. Even accounting for the considerable uncertainties in this calculation, the maximum dose rates remain far below the no-observed-adverse-effect level (NOAEL).

It should be, however, highlighted that there are substantial uncertainties (e.g. design of monitoring programs, sampling sites and frequency type of organisms, measurement methods, modelling programs applied) in the reported estimates of impact. Further research is still needed, regarding offshore and onshore installations as well as during decommissioning activities (Gilbin et al., 2021; Hosseini et al., 2012; MacIntosh et al., 2022).

4. NORM affected legacy sites

The general definition of legacy sites can vary from country to country (RadoNorm exercise, 2021), but generally, in the context of radiation protection can be most properly expressed as: '*an area contaminated by residual radioactive material deriving from past activities or events that may pose risks to health and safety or the environment, and present technical or administrative challenges to timely remediation*' (IAEA, 2022b).

Typical NORM affected legacy site examples that were reported in task 2.5 activities include former mining sites (uranium, radium, iron, niobium, coal, pyrite mines), decommissioned phosphate fertilisers production facility, ferro-niobium production sites, CaF_2 sludge heaps, phosphogypsum stacks and radium containing CaF_2 (from the phosphate industry) discharge into small rivers. Different complex NORM situations exist in the context of management of legacy sites as multiple exposure of environmental compartments (waste- or contaminated soils, rocks, rivers, contaminated equipment) is commonly observed.

In most of the NORM affected legacy sites, the whole area of an affected site is covered by contaminants. Therefore, alteration (detriment) on local environment caused directly by huge mass of disposed materials as well as all derived supporting activities (e.g. transport) must be considered when formulating the problem. When a huge amount of such kind of material is exposed to environmental conditions, different processes leading to the dispersion of disposed material into neighbourhoods must be considered as soil or water erosion, at least. NORM affected legacy site as an objective of monitoring or remediation may be considered as constituting of two parts - extremely different in properties and subject to different actions (a) on-site where NORM is directly disposed, and (b) off-site where certain effects of NORM disposed on-site may occur.

Among the possible solutions for reducing exposure of members of the public or environment, the following are considered in collected information:

- no actions towards mitigation or prevention, only monitoring of existing situation is expected,
- temporary solutions are applied based only on-site seclusion and limited access,
- temporary solutions are applied based on engineering (including phytotechnology) to limit radionuclides dispersion/migration from the site,
- land reclamation/revitalisation is obligatory taking into consideration the further use of the land, for derived waste the same methods are applied as in the case of residues released from ongoing NORM involving industry
- presence of other non-radioactive pollutants is an issue, while NORM is considered as a side effect to be solved by case-specific approach.

Some challenges reported for the legacy sites include: the clear definition (already mention), development of proper methodology for a consistent characterisation of complex multiple contaminants pollution sites, development of proper tools for consideration of overall risk related to multiple contaminants and considering humans but also environment per se and non-human biota.

On the other hand, while many European countries are paying a lot of attention and spending many efforts for post-industrial areas inventories and remediation, what in the light of ongoing civilization changes is common process in EU, contamination by NOR is rarely considered even in case of legacies from well-defined NORM involving industries.

5. NORM residues and waste – handling and disposal

Industrial activities involving NORM, as any kind of industry, leads to the creation of a desired product but also residues which may be classified as waste if no further use for material is foreseen, or as material subject to recovery. Decision on possibility for reusing or recycling the material is commonly made considering a large set of factors and constraints, such as environmental, health and safety, economical, technical, infrastructure, etc. Enhanced activity concentration of NOR in residues may hinder the reuse and recycling of a given material, due to regulatory considerations and radiation protection.

Managing waste in an environmentally sound manner and making use of the residues are key elements of the EU's general environmental policy that should also be applied to NORM residues through reprocessing, recycling and recovery solutions while guaranteeing radiation safety (HERCA, 2021), and in light of circular economy and European Circular Economy Action Plan (EC, 2020) and in accordance with the 2030 Agenda for Sustainable Development (UN, 2015) and European Green Deal (2019).

NORM waste can be present in big volumes and masses, in different aggregated states as well as in complex chemical/physical form. Therefore, application of rules developed for 'typical' radioactive waste to NORM is not always justified from an economical and applicable technical solutions perspective. In about 40% of obtained information, NORM is never classified as radioactive waste, slightly above 10% declare the use of same limits for NORM as for radionuclides used as radioactive sources (e.g. radium), whereas above these limits, waste is considered as radioactive waste regardless of the purpose of use, physical and chemical form. However, in 50% of the responses, a special limit, expressed as a radionuclide activity concentration, has been established above which NORM waste is classified as radioactive waste. Moreover, a specific approach was noticed where NORM formally is not classified as radioactive waste, however, must be disposed of in the radioactive waste repository when dose evaluation indicates an excess of dose limits set either to workers or members of the public. It must be highlighted that such heterogeneous approaches among countries, however, can lead to equivocal situations in case of transboundary actions related to NORM. Final destinations and fate for NORM, considered from legal perspective, were for most of the investigated countries conventional waste disposal site (inert, non-hazardous, hazardous), followed by NORM dedicated disposal site, nuclear waste repository.

Only few countries reported reuse or recycling of NORM, in particular NORM residues coming from coal combustion products from coal fired power plants, extraction of rare-earth elements and red mud in building materials or civil engineering. More future work is needed on understanding of clearance levels and reuse of different NORM.

6. Life Cycle Assessment approach to NORM – first steps of application

LCA is a standardized methodology for evaluating the environmental sustainability of materials and processes across their entire life cycle. As defined by ISO 14040:2006 (ISO, 2006), LCA provides a structured framework to assess environmental impacts at every stage, from raw material extraction, manufacturing, and transportation to usage, disposal, or recycling. This methodology involves defining the goal and scope of the study, collecting inventory data (Life Cycle Inventory - LCI) on resource use and emissions, assessing potential environmental impacts (Life Cycle Impact Assessment - LCIA), and interpreting the results to identify sustainability challenges and opportunities, generally considering three areas of protection: human health, natural environment, and issues related to natural resource use (Figure 9 (Sala et al, 2016)). In currently used LCIA, ionising radiation is considered mainly for nuclear industry (especially nuclear fuel cycle) as one of agents - impact category - that can impact only on humans and rarely the environment (Paulillo et al., 2018; Solberg-Johansen et al., 1997).

Conventional LCA models would struggle to assess NORM due to insufficient radiological data within existing LCI and LCIA for human health and ecosystems. The absence of specific datasets on radioactivity limits the accuracy of sustainability assessments for NORM. Moreover, models applied in currently used LCIA modules are too general and using them makes it impossible to consider all NORM features. A review and necessary adaptations of existing LCA functionalities in terms of emerging needs must be prioritised in further NORM invetsigations.

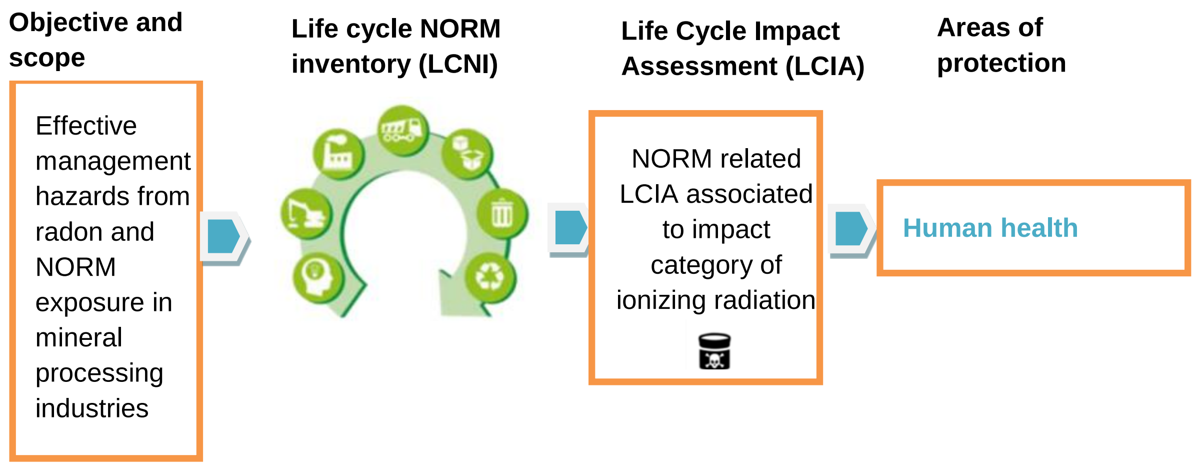

Figure 9 - Life Cycle Assessment steps related to NORM in mineral processing industries associated to the impact category of ionising radiation (Figure adapted from Sala et al, 2016).

The collected NORM data and their analysis, presented in this report, can be considered as the first steps to take into account the impact category of NORM ionising radiation in Life Cycle Assessment for a specific industry or product. For each stage of an industry activities (raw material or natural resources extraction, manufacturing, use, wastes management, etc.), relevant NORM-related data such as NOR activity concentration in raw materials, main products, by-products, wastes, etc., as well as information about emissions into the environment, the destination of the residues, and possible doses during different stages of processes can be considered as the *Life Cycle NORM Inventory* (LCNI).

The next step in Life Cycle Assessment related to NORM is the ***impact assessment*** associated with ionising radiation. The risk of developing adverse health effects depends on the radiation dose and the higher the dose is, the higher will be the risk of adverse effects. Therefore, the assessment of impact in category of ionising radiation – human health is proposed to be evaluated in dose loads for workers and members of the public, measured in mSv y^{-1} as the most appropriate and understandable functional unit. Although it is not a direct health effect, it is a term that directly connect to health effects. The dose assessment for workers and the public, presented in this work, can be considered as a first step to assessing health impacts for Life Cycle Impact Assessment (LCIA) associated with the ionising radiation impact category.

Some preliminary steps of LCA were conducted by focusing on ionising radiation related to NORM as a new defined impact category in mineral processing industries. The first example is phosphoric acid production (*Dvorzhak et al., 2025b, in prep.,* Appendix A). Information about doses for workers was collected from existing sources in different European countries during various industrial manufacturing processes and at different stages of the entire life cycle (such as raw material extraction, transportation, etc.) for phosphoric acid production.

A specific life cycle inventory diagram is presented in *Figure 10*. Information on NOR activity concentrations (inventory) are indicated in the life cycle stages, where dose loads may occur, highlighting when they should be taken into account in the impact assessment for human health.

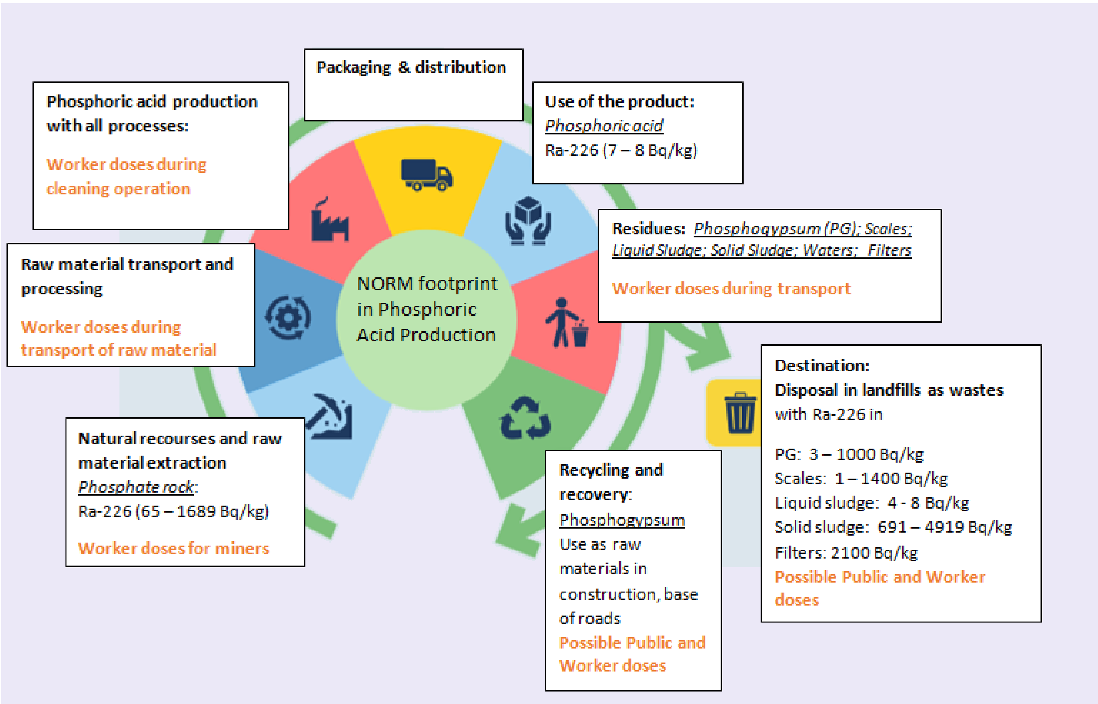

Figure 10 - Life Cycle Inventory of phosphoric acid production in ionising radiation category with ranges of ^{226}Ra activity concentration at different life cycle stages.

Future developments of the impact category in LCA defined as NORM ionising radiation are necessary, with more details on other NORs, other industries, and materials flows (environmental discharges, etc.) On the other hand, the review and necessary adaptations of existing LCA functionalities in terms of emerging needs in NORM management and treatment is essential to enhance the comprehensiveness of LCA assessments.

In the light of zero waste economy, the interest in analysing the possible recovery of residues and by-products from NORM involving industries is increasing, what significantly expand the scope of LCA applied towards NORM. Information on wastes management routes can warn, in advance, about the risk of using secondary raw materials or, on contrary, increase the confidence in their use.

Applied methodology makes LCA a relevant platform to combine NOR and other stressors into one evaluation process. Analysis of mechanisms responsible for possible interaction of simultaneously occurring contaminants let one predict and evaluate other than a priori assumed human toxicity effects caused by radioactivity including synergistic or antagonistic effects, or a possibility of masking the effects caused by each other. Moreover, LCA platform creates an opportunity to consider possible mutual interactions between radioactivity and other impact categories, in general. In the context of NOR these interactions can be considered in different terms, starting with incompatibility of existing regulations ending with interaction of mechanisms directly responsible for any emerging effect. And finally, developing the LCA methodology and improving of applied evaluation criteria or combining protected objectives an opportunity would emerge to investigate impact related to NORM involving industries operation from the perspective of One Health approach. Addressing these gaps will allow for a more precise and holistic evaluation of NORM, ensuring that innovation in such material use aligns with long-term environmental safety and regulatory compliance.

7. Hazards other than NOR

Industrial activities involving NORM and the presence of NORM affected legacy sites are commonly complex exposure situations that include multiple hazards for which the radiological hazard is not necessarily the dominant one. Consequently, there are research, management, and regulatory aspects of importance at these multiple-hazards exposure sites for further consideration. While presence of multiple hazards at NORM exposure sites is well-known (ICRP, 2019), studies on exposure characterisations and integrated risk assessment that include NOR and other hazards have still been limited and mainly in laboratory conditions (Beaumelle et al., 2016; Brechignac and Desmet, 2005; Salbu et al., 2019).

On the regulatory side, international organisations strongly suggest applying an inclusive, graded operative and regulatory approach for radiation protection, in which the radioactive hazards coming from NORM are considered, assessed and integrated alongside the non-radioactive hazards that may include chemical pollutants, biological and physical hazards or even other things that may present constraint in certain ways in site specific situations (ICRP, 2019; IAEA, 2003). It should be emphasized, especially with respect to operational and regulatory control aspects in industries that the dynamic risk assessment, which comprises of the identification, assessment, and management of risks for safety and health at work, is an already existing concept, largely employed regarding health and safety. However, still in practice, exposure to radiation in a NORM context, in this overall risk assessment in industries, is often neglected. This neglection may be a result of lack of knowledge and information about NORM of the different involved parties, but also due to missing a properly adapted assessment methodology that would be available and user friendly.

To improve knowledge about existing non-radioactive hazards at different exposure situation that involve NORM, data were collected on this topic both by e-NORM survey and tools. Having updated knowledge would allow optimization of management approaches while complying with radiation protection, health, safety and environmental standards.

Examples of non-radioactive hazardous substances, identified for some of NORM involving mineral industries and legacies present in Norway, are given in the *Table 6* (extracted from the Norwegian Pollution Release and Transfer Register, Norwegian PRTR, 2022).

Table 6 - Examples of hazards other than radioactive ones, identified in some of NORM involving exposure situations (Mrdakovic Popic et al., 2023a)

NORM involving industry	Non-radioactive hazardous substances
Oil and gas production	Arsenic, anthracene, benzene, benzopyrene, benzofluorene, alkyl-phenols, cadmium, carbon-dioxide, chromium, copper, anthracene, drill-cuttings, dioxins and furans, gas, lead, mercury, nickel, methane, nitrogen oxide, polyaromatic hydrocarbons, pyrene, sulphur oxide, volatile organic compounds, xylene, zinc (over 60 elements and compounds identified)
Phosphate fertilisers production	Ammonia, carbon dioxide, fluorides, methane, methanol, nickel, nitrogen oxide, particulate matter, total phosphorus, sulphur dioxide, total nitrogen, volatile organic compounds, zinc
TiO_2 and iron production	Arsenic, cadmium, lead, particulate matter, mercury, zinc, polyaromatic hydrocarbons, sulphur dioxide, dust, chromium, carbon dioxide, copper, iron, manganese, methane, nitrogen oxide, volatile organic compounds
NORM affected legacy site	Arsenic, iron, lead, cadmium, copper, chromium, nickel, manganese, dust, particulate matter, asbestos, physical threats

8. Overview of regulatory and research challenges

The main identified challenges and directions for further work across the herein investigated NORM exposure situations include:

- Need for a more efficient collaboration between regulators, industry operators and researchers to identify knowledge gaps and provide research, information and data for scientifically based regulatory control and management of NORM
- Optimization of processes with regards to efficiency and RP measures
- Conditions for recovery of NORM residues to support Circular Economy and European Green Deal initiatives
- Waste management – improvement of mitigation methods and disposal options; sharing the best practices, integration of NORM residues management into common framework developed for ordinary waste
- Development and application of a holistic approach to NORM management and control (e.g., improved and harmonized monitoring programs, improved dose modelling in different NORM exposure scenarios, including legacies)
- Development and/or adaptation of Life Cycle Assessment (LCA) to NORM
- Development of a standardised procedure for NORM characterisation, including reference measurements techniques, scope of measurement and measurement results interpretation.

9. Identified uncertainties

During the extensive work of the task 2.5. certain uncertainties were observed and evaluated as follows:

- Even though higher number of various NORM involving industries were reported from the European countries (RadoNorm participants and wider from e-survey participants) than those provided in the EU BSS *Annex VI* list, not all NORM involving industries/practices are considered in the present work with respect to the radiation protection issues. After discussions and considerations, the reason for this was found to be a somewhat limited access of RadoNorm researchers/participants in this work to certain data (e.g., data regarding bauxite mining and alumina refining to produce aluminium, iron production, mining, processing and refining of rare earth elements). Due to confidentiality issues, perspectives that different countries have on data sharing were different, especially if regulators from the country were not included or well-informed and with proactive attitude towards the RadoNorm project and this task.
- Quantitative data provided in the tools were in different formats, i.e., ranges, min, max, mean, median value. On one side, it allowed gathering as many datasets available as possible, but on another side, it produced difficulties for statistical consideration and evaluation of collected data sets. Therefore, in the Deliverable and published peer-review papers, activity concentrations of NOR are given either in ranges or as maximal reported values and as pooled values from all European countries, contributors. However, it didn't always allow direct comparisons of the data sets from the different countries or comparisons of the various NORM exposure situations.
- Issues related to radiation exposure dose modelling – there is still a knowledge lack about models and parameters used in modelling of the exposure doses for worker, public and non-human biota in different NORM exposure situations.
- Reported data on exposure doses for certain industries were scarce, and not including the number of workers exposed to elevated doses that would allow proper evaluation of the radiation risk.
- Scarce data and information on environmental and non-human biota were provided – confirming that anthropocentric approach is still present in most of European countries, what is not in accordance with ICRP, EC, IAEA initiative on environmental protection and development of integrated approach that will include humans as a part of the environment fully equal to other environments 'parts and participants'
- Understanding of Exemption and Clearance concepts – it was observed, during data collection and later analyses, that application of these concepts is not completely clear or at least not the same understanding of them is observed in various countries. This affects countries' considerations of NORM residues reuse and may present the constraint for circular economy development with respect to NORM.
- When NORM are characterised, there is general tendency to report the activity concentration of decay series parent radionuclides (as EL or CL are expressed in regulation) regardless which radionuclide was actually measured, based on secular equilibrium assumption. It makes the proper interpretation of such data difficult and can cause significant over (under) estimation of related hazard as in NORM resulted from a technological process the radioactive equilibrium state may especially be disturbed. Considering that all NOR (besides K-40) are subject successive decay, it is necessary to assume factual NOR activity concentration is changing according to the passage of time. Moreover, the isotopic as well as chemical composition of NORM may change, depending on the time horizon assumed, as a new decay product, which could be a new element, will appear, which was not present at the moment of the creation of the material in question. It implies that the proper evaluation of materials measurement results must be carefully interpreted considering supporting information about overall history of tested materials. Moreover, a forecast is necessary, especially for processed materials where a high probability exists that secular equilibrium in the decay series has been disturbed. As processes of residues recovery and, especially disposal, must be considered in specific time horizons, such forecast can significantly influence the final choice of management options.

10. Conclusions

Naturally occurring radionuclides (NOR) are ubiquitous in the natural environment, from the Earth origin. In most of the rocks, minerals and soil NOR are not of radiation protection concern since they are present at low activity concentrations. However, there are certain rocks and minerals as well as processes (e.g. mining, chemical mass reduction, high temperature processes) that may lead to accumulation of naturally occurring radioactive materials (NORM) in the facilities of certain industries or in the environment. In such cases, the radiation exposure of workers, public and the environment cannot be excluded without careful consideration of radiation protection aspects and principles of justification, optimisation and dose constraints or reference levels use.

In task 2.5 "The overview of NORM sites and exposure scenarios in Europe and their characteristics", of the RadoNorm WP 2 Exposure, a detailed investigation of existing and planned NORM exposure situations was conducted according to designed work plan that included: development of NORM identification methodology, development of tools for information and data collection in a systematic and harmonised way, conducting electronic NORM survey (with 3 developed parts for regulators, industry operators and waste managers) across European countries, collecting detailed information about NORM exposure situations using developed tools from RadoNorm task 2.5 participant countries and finally conducting a literature review for missing information. The main outcome presented in the report included:

- Compiled information for an overview of the different NORM sites across Europe,
- Description of the main identified planned exposure situations – NORM involving industries and existing exposure situations – NORM affected legacy sites,
- Consideration of regulatory practices in different countries with respect to NORM,
- Improved data on NORM matrices per different exposure categories, updated quantitative data on NOR in different materials – raw materials, main and by-products, residues, discharges and wastes,
- Overview of exposure scenarios and pathways considered in different countries for estimation of radiation dose magnitude for workers, public and environment, including non-human biota,
- Overview of other simultaneously present hazards that are not radioactive and application of radiation protection but also occupational, health and safety measures,
- Consideration of approaches to NORM residues and waste
- Identified challenges and directions for future work

Although different exposure situations were investigated, analysis of big amount of data (from survey and tools) showed a quite harmonised legislation (this was expected since EU Directive 2013/59/Euratom came as mandatory for EU Member states in 2014), but also somewhat different regulatory approaches, a reflection of flexibility of EU BSS requirement and national circumstances (e.g., presence of different industries, infrastructure solutions, available waste disposal sites and/or reuse options). It has been also observed that European countries in general are aware of good practices related to NORM and EU BSS requirements are transposed in their national legislation, but still advancement in realisation of the first task considered as NORM inventory, significantly differ from country to country.

When comparing NORM involving mineral industries, but also NORM energy production sectors – raw materials contained NOR in wide ranges of activity concentrations, mainly low, but with some of the used minerals, rocks or ores containing ^{238}U, ^{232}Th and decay products above the exemption and clearance level of 1 kBq kg^{-1}, given by EU BSS. This and variety of technological processes and conditions that could lead to NOR accumulation in NORM involving industries requires a careful consideration/characterisation or first screening to make a decision about proper regulatory approach. When evaluating further processes in NORM involving industries and quantitative data in NORM matrices – commonly, main products contain no elevated NOR and are not of radiation protection concern, while the most important in that aspect are residues and waste. Some of the industries ‘produce’ large quantities of NORM residues and waste, such as phosphogypsum, mining rocks and excessive soil, production/formation water, alum shales waste rocks that commonly do not contain high activity concentrations of NOR. On another side, there are also materials such as scale, sludge, filter materials that are present comparably in smaller quantities but on many occasions contain high activity concentrations of NOR. The main radionuclides of radiation protection concern are ^{226}Ra, ^{210}Pb, ^{210}Po, ^{228}Ra, ^{228}Th and Rn-isotopes, depending on particular situation. This makes some problem with formal data interpretation as CL or EL are expressed in terms of activity concentration of decay series parent radionuclides. The problems are additionally amplified as once in the environment (via air discharge or liquid effluent) NOR can have a complex fate due to numerous environmental conditions and parameters that can influence their behaviour and final fate.

Analyses of the exposure doses to workers, public and non-human biota, however, showed low exposure doses. Considering occupational exposure, this is most probably due to, applied in frame of regular OH&S systems, personal protective measures focused on other hazards present in workplaces (as e.g. dust), which also are efficient towards some pathways of exposure to radiation. Application of radiation exposure oriented protective measures are rarely reported, based mainly on work time control. Environmental impact assessment and risk assessment for non-human biota is not considered as priority in most of the investigated countries as they still apply ‘anthropocentric view’ saying that ‘*if man is protected the environment and biota is protected too’*. However, some positive movements in terms of required environment considerations, proper monitoring programmes and non-human biota risk assessment are observed in some of the countries. This situation is resulting from the lack of precise regulation in this matter. However, to justify the legislator, it must be underlined that, due to the specificity of each situation, it is not possible to establish such criteria that are universal in nature. Illustration of the existing problem is provided in the following article from EU BSS:

- *Article 25*, point 3 "*Notwithstanding the exclusion criteria set out in Article 26, in situations identified by Member States where there is a concern that a practice identified in accordance with Article 23 may lead to the presence of naturally occurring radionuclides in water <u>that is likely to affect the quality of drinking water supplies</u> or <u>affect any other exposure pathways</u> so as <u>to raise concerns from a radiation protection perspective</u>, the competent authority may require the practice to be covered by a notification*".
- *Article 65* , point 2 ‘*’The competent authority shall where appropriate establish authorised limits as part of the discharge authorisation and conditions for discharging radioactive effluents which shall take into account, where appropriate, the results of a <u>generic screening assessment based on internationally recognised scientific guidance</u>, where such an assessment has been required by the Member State, <u>to demonstrate that environmental criteria for long-term human health protection are met</u>.*”

As there are no common procedures applicable in such situations, the requirements formulated in this manner created a wide variety of options and needs for further research in this matter.

NORM waste vs radioactive waste is type of consideration that is most difficult across countries. For most investigated countries, the positive attitude towards NORM recovery has been seen, however, a practice to classify NORM (that could be recovered) as radioactive waste is a crucial obstacle in making any kind of recovery process and causing needs for final disposal in many situations. That additionally generates technical problems to be solved (to find a radioactive waste repository big enough) and additional costs. Finally, this situation results in some legal/technical inconclusiveness across countries where NORM waste, even when considered as radioactive (in about 50% of countries when exceeding the levels of 1 kBq kg^{-1}), are commonly disposed in conventional, hazardous and non-hazardous waste disposal sites, although with some regulatory requirements from the national authority to prevent radiation exposure at present and future time.

The main identified challenges and directions for further work for investigated NORM exposure situations included:

- Need for a more efficient collaboration between regulators, industry operators and researchers to identify knowledge gaps and provide research for scientifically based regulatory control and management of NORM,
- Conditions for use of NORM residues to support Circular Economy and European Green Deal initiatives,
- Waste management – improvement of mitigation methods and disposal options; sharing the best practices,
- Development and application of an integrated approach to NORM management and control (e.g., improved and harmonized monitoring programs, improved dose modelling in different NORM exposure scenarios, including legacies),
- Development and/or adaptation of Life Cycle Assessment (LCA) to NORM,
- Development of a standardised procedure for NORM characterisation, including reference measurements techniques, scope of measurement and measurement results interpretation.
- Updated identification and characterisation of NORM affected legacy sites together with development of proper tools/models for the holistic assessment of commonly present multiple contaminants, including naturally occurring radionuclides.

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APPENDIX A: Overview of Naturally Occurring Radioactive Materials (NORM) in mineral processing Industries and first steps to consider Ionising Radiation in Life Cycle Assessment (two papers)

Manuscript 1: Overview of Naturally Occurring Radioactive Materials (NORM) in mineral processing Industries and first steps to consider Ionising Radiation in Life Cycle Assessment – Part I. NORM inventory

Abstract:

A systematic overview of NORM related issues in mineral processing industries as production of phosphoric acid, titanium dioxide (TiO_2) pigment, phosphate fertilizers, zircon and zirconium industry, and cement industry in different European countries is provided in this work. The current study tracks composition, content of Naturally Occurring Radionuclides (NOR) and their changes throughout the entire production cycle in these common and important industries: from raw materials, different production processes, end product, residues and wastes, and releases, with analysis of possible subsequent use of some by-products and residues in the concept of the circular economy.

Such work improves the radiation protection knowledge in mineral processing industries, assists in the management of generated residues and wastes, and supports the regulatory decision-making process. A significant novelty is ensured through comprehensive comparison of the given mineral industries and respective NORM issues in various aspects – from legislative frameworks applied, NORM matrices with different NOR activity concentrations and possible challenges with respect to recovery or disposal when they are above exemption and clearance levels of 1 kBq kg^{-1}. This type of a systematic and comprehensive overview is especially important for European countries regarding the framework of Life Cycle Assessment (LCA) and the circular economy, where resources are maximally used, the involvement of new ones is reduced, waste is avoided, and the life cycle of products is extended. Additionally, here presented inventory work is expected to be useful for many countries worldwide that are at the beginning of their NORM involving practices mapping.

Status: ***Dvorzhak et al., 2025a***, ongoing submission for publication in peer-reviewed journal.

Manuscript 2: Overview of Naturally Occurring Radioactive Materials (NORM) in mineral processing industries and first steps to consider Ionising Radiation in Life Cycle Assessment – Part II. NORM Impact Assessment

Abstract:

A systematic overview of NORM related issues in mineral processing industries as production of phosphoric acid, titanium dioxide (TiO_2) pigment, phosphate fertilizers, zircon and zirconium industry, and cement industry in different European countries is provided in this work. The current study tracks impact assessment of these industries with exposure of workers, public and environment to NORM for possible exposure scenarios are analysed.

The amount, destination and possible management of wastes generated by such industries are analysed in line with their possible valorisation and reusing.

Such work improves the radiation protection knowledge in mineral processing industries, assist in the management of generated residues and wastes, and supports the regulatory decision-making process. The last one is especially important within the framework of Life Cycle Assessment (LCA) and the circular economy, where resources are maximally used, the involvement of new ones is reduced, waste is avoided, and the life cycle of products is extended. In short, today's residues become the raw material of tomorrow. In such economic strategy, the risk associated with NOR in these new raw materials can be missed or not taken into account in some of the stages of the product life cycle. An illustrative example of this approach, currently under development regarding NORM, is also presented in the case of phosphoric acid production.

Status: ***Dvorzhak et al., 2025b*** in preparation for submission to peer-reviewed journal.

APPENDIX B: A Systematic Review of Naturally Occurring Radioactive Materials (NORM) in Energy Production Sectors: Exposure, Effective Doses and Regulatory Challenges

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Abstract

The oil and gas industry, coal mining and coal-fired power plants as well as geothermal energy plants have been investigated in the past with respect to the different aspects of naturally occurring radioactive materials (NORM). However, existing assessments are usually too specific and inconclusive, due to different perspectives, and a systematic overview of NORM issues for these energy sectors is still missing.

The European data, collected in the international RadoNorm project and presented in this paper, made it possible to find a common denominator for the primordial source of radiation risk in these industrial sectors. Depending on the technological processes, radionuclides of natural origin (e.g., $^{226,228}Ra$, ^{222}Rn, ^{210}Pb, ^{210}Po) were found in a range of materials, such as scales, sludge, production water, liquid and gaseous discharges. Both radionuclides and materials may further have different fates, leading to radiation exposure doses in various exposure scenarios for workers, the public, and the environment.

The important novelty of this paper is related to the comparative qualitative and quantitative assessment of radiation protection aspects for a whole sequence of given energy-generating processes, which includes the sourcing of raw material, NORM-generating processes, their fate and potential risks towards humans and the environment, as well a comparison of management, regulatory control, and existing challenges. The provided overview will help in the future international harmonization of decision-making processes during industrial activities, decommissioning activities or at legacy sites, which are often reported in the context of such energy-generation sectors. Moreover, this information will especially help countries worldwide that may still be in the initial phase of NORM inventory characterization and/or legislation development.

Status: ***Mrdakovic Popic et al., 2025*** *– under review in the journal Environment International*

Pre-print available at SSRN Elsevier owned pre-print network: 5270528.pdf