EPJ Nuclear Sci. Technol. **9**, 10 (2023)

https://doi.org/10.1051/epjn/2022053

EPJ Nuclear Sciences & Technologies

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

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

REVIEW ARTICLE

OPEN ACCESS

SHARE: Stakeholder based analysis of research for decommissioning

Robert Winkler[1,*], Laura Aldave de las Heras[2], Federica Pancotti[3,4], Anthony W. Banford[5], Kurt Van den Dungen[6], Réka Szőke[7], Gintautas Poškas[8], Angelika Bohnstedt[9], and Muhammad Junaid Ejaz Chaudhry[9]

[1] CEA Marcoule, Chusclan, France
[2] European Commission, JRC, Karlsruhe, Germany
[3] SOGIN, Rome, Italy
[4] JRC, Karlsruhe, Germany
[5] NNL, Warrington, UK
[6] SCK CEN, Mol, Belgium
[7] IFT, Halden, Norway
[8] LEI, Kaunas, Lithuania
[9] KIT, Karlsruhe, Germany

Received: 29 April 2022 / Received in final form: 21 October 2022 / Accepted: 12 December 2022

Abstract. The H2020 EU-funded SHARE project (Stakeholders- based Analysis of REsearch for Decommissioning) is a forerunner to the establishment of a framework for collaboration on research activities related to the decommissioning of nuclear facilities. SHARE aimed to provide an inclusive roadmap for decommissioning research, in both technical and non-technical areas, in the EU and abroad, to enable stakeholders to improve jointly safety, reduce costs and minimise environmental impact. SHARE has been built on a consultation process considering the needs and perspectives of different stakeholders all across the decommissioning value chain. The project also considered existing and emerging innovative technologies solutions as well as the international best practices in the field of decommissioning. After a three-year process, the project provides a Strategic Research Agenda and a Roadmap built on the participation of the international Stakeholder community in a multi-step process including a questionnaire survey, a state-of-the-art review, a gap analysis and multiple workshops. As the final output, the SHARE roadmap effectively set the framework for organizing the priorities identified in the SHARE SRA.

1 Introduction

In Europe, the boom of nuclear power generation in the second half of the 20th century, incarnated by the Euratom treaty, gave rise to a strong nuclear industrial environment. As of March 2022, 119 nuclear power plants are operating in the European Union (EU), Switzerland and the UK contributing around 24% of the total electricity production [1,2] with a greenhouse gas intensity comparable to renewables around the whole lifecycle [3]. Additionally, many research facilities and fuel cycle facilities are operating, contributing to a total of 1.1 million jobs in the nuclear industry. Despite these significant strengths, nuclear power production has declined by over 25% since its peak at 930 TWh in 2004. Current plans foresee 50 European nuclear power plants in shutdown by 2025, which will then be decommissioned. The European Nuclear Illustrative Programme estimates a total budget of 263 Mrd€$_{2014}$ up to 2050 for decommissioning operations (123 Mrd€$_{2014}$) and radioactive waste management (140 Mrd€$_{2014}$) [4]. For perspective, this corresponds to 2% of the total GDP of the former 28 Member States in 2014 and 24% of the EU budget in the period 2014–2020. These numbers underline the importance of future decommissioning activities.

Decommissioning nuclear facilities is a significant task with technical and non-technical challenges including many Stakeholders: facility operators, supply chain industry, research organizations, regulators, technical support organizations, waste management organizations, universities, international organizations and consultants. Technical challenges exist because, while a certain level of maturity has been reached for many technologies used for operations in rather "standard" nuclear facilities, there remains room for optimization/cost reduction in characterization methods, dismantling techniques and waste management. Furthermore, there is a need for the

* e-mail: robert.winkler@cea.fr

development of innovative technologies for less common facilities such as graphite reactors or legacy waste facilities. Non-technical challenges exist because the organization of work and regulation during decommissioning are significantly different from the operational phase and will last for 20–30 years. Thus, decommissioning activities require the retention of historical site knowledge and the recruitment and development of new competencies as well as good supply chain management and a solid education and training network. Many of these challenges require an investment that might exceed the capacities of individual entities. Therefore, multilateral and international development and research projects that are underpinned by confidence and the understanding of the common interest are key for effective decommissioning.

The European Commission, convinced by this importance, decided to fund the Coordination and Support Action called SHARE (Stakeholder-based Analysis of REsearch for decommissioning) in the framework of the EURATOM nuclear fission research programme. The ambition of SHARE is to organise international efforts towards collaborative research and co-financing in decommissioning research, development and demonstration. To this end, the main objective is to provide a roadmap for collaborative research over the next 10–15 years so Stakeholders can jointly work to improve safety, reduce costs and minimise the environmental impact during the decommissioning of nuclear facilities. The data for SHARE is acquired by the iterative consultation of the international Stakeholder community. This point of view is complementary to the classical approaches that identify key issues in a top-down manner [5,6].

2 Project structure and methodologies

The foundation for the bottom-up approach is the global stakeholder community of nuclear decommissioning. Indeed, the understanding of the consortium formed by the CEA, Enresa, IFE, In Extenso, JRC, KIT, LEI, NNL, SCK-CEN, SOGIN, and VTT [7] is to make explicit the needs originating from the stakeholders. The consortium aimed to create a thorough frame for stakeholders to be able to express their needs. The work structure of the project that was created to this end is displayed in Figure 1.

The work packages WP5 and WP6 are overarching the whole project and concern project management and dissemination and communication. The main results were obtained in the four work packages WP1 to WP4. The task of WP1 was to work on the methodology of the project data generation and data processing. WP2 consisted of, (i) conducting a questionnaire survey among the Stakeholders to determine the importance and urgency of their needs and, (ii) weighing and analyzing the results. Almost simultaneously, WP3 reviewed the state-of-the-art of available solutions. In the frame of WP3, several interactive workshops with the Stakeholders lead to the combination of the results from WP2 and the state-of-the-art review. The outcome, in the form of collectively consolidated activities, is the content of the WP3 "Gap analysis" deliverable. Based on these results, WP4 worked on the presentation of the obtained data by providing a strategic research agenda and a roadmap for future development. The international stakeholder community showed active support and commitment throughout the project duration. As shown in Figure 2, almost 1000 Stakeholders engaged in or followed the project.

The main outcome of the first work package was the collection of a representative list of Stakeholders and the initial structuring of the decommissioning activities in eight thematic areas comprising 71 sub-thematic areas. Among them were three *non-technical areas*: safety and radiological protection (Q1), project management and costing (Q2), and human resources management (Q3); and five *technical areas*: characterization (Q4), site preparatory activities (Q5), dismantling technologies (Q6), environmental remediation and site release (Q7), and radioactive waste management (Q8). A complete list of the associated sub-thematic areas is presented in appendix Table A.1. In anticipation of later chapters, it is important to note that this structure evolved as the project progressed.

2.1 Questionnaire survey

The questionnaire survey was conducted online between March and July 2020 based on the methodology defined in WP1. First, the Stakeholders from the representative list were invited to complete the questionnaire which consisted of rating, on a scale from 0 to 5, the importance and the urgency of the eight thematic areas and the 71 sub-thematic areas. Stakeholders were additionally provided with the possibility to add free format comments. For completeness, the Stakeholders provided some profile-relevant data such as their country, their type of organization (Industry, Operator, University, Consultant, International organization, Research Org., Regulator, Standardization Org., Technical Service Org., Waste Management Org., Other), the number of employees of their organization, the type of facilities treated in their organization (Power Reactor, Research Reactor, Fuel Cycle Facility, Other) and the status of their current decommissioning activities (None, Planning, On-Going, completed/nearly-completed). Then, the collected responses were analysed, first, by weighting the Stakeholder opinion by their profile data and, second, by defining rating categories for the prioritisation of the (sub-)thematic areas.

For the weighting, first, the Stakeholders were categorised by their type of organization to, then, make the respondent population match the invited target population. I.e., overrepresented organizations were weighted lower and underrepresented organizations were weighted higher. As Figure 3 shows, a minor adjustment was needed since the populations matched well.

Second, the relevance of the Stakeholder opinion for the EU project SHARE as collectively determined by the consortiums allowed the weighting of the results further. To this end three different methods of collective evaluation were used [8]:

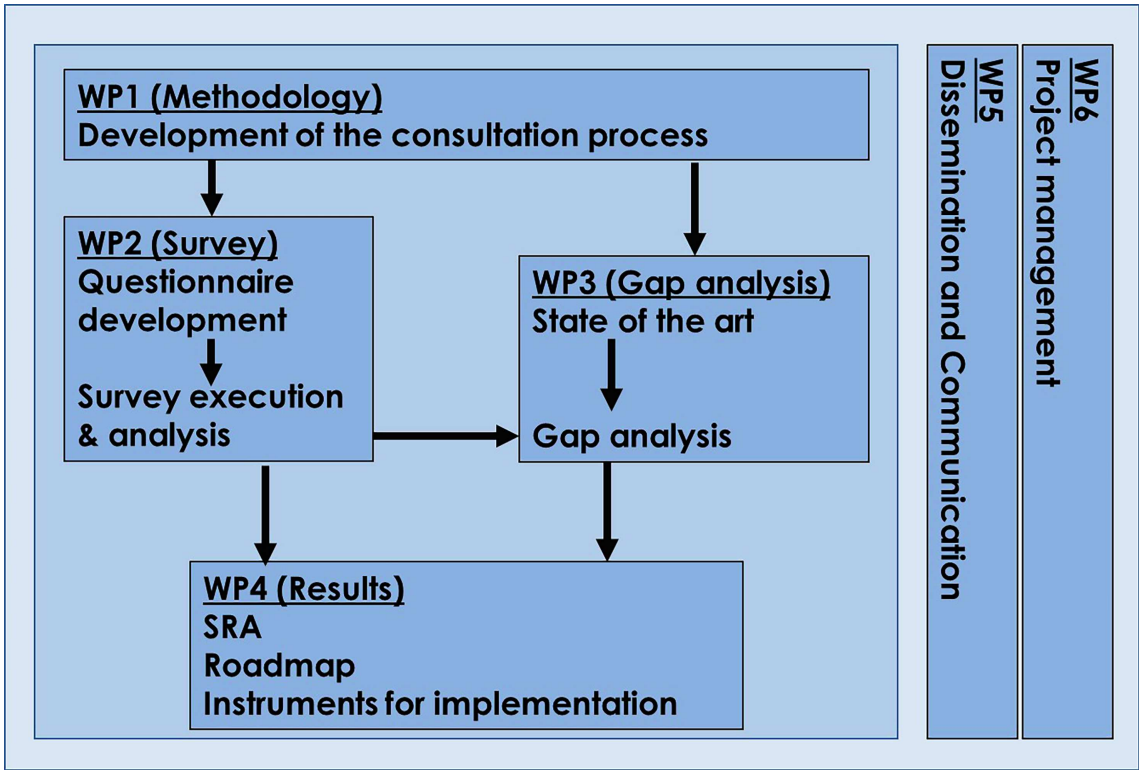

Fig. 1. Work structure of the SHARE project.

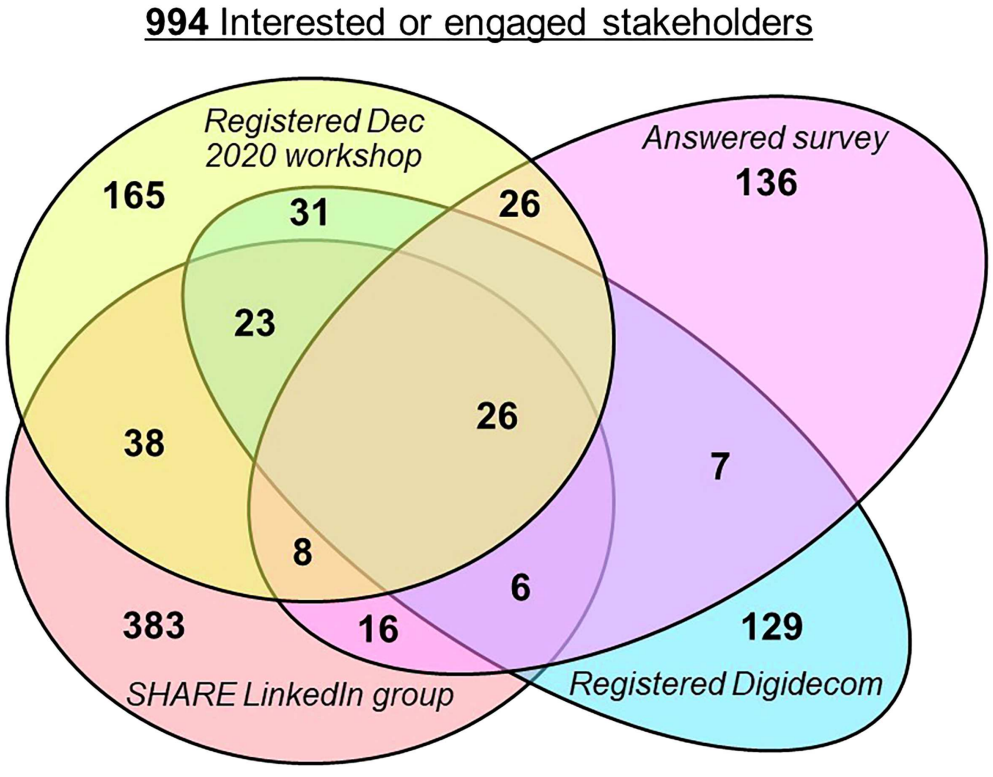

Fig. 2. Overview of the number of Stakeholder that engaged in or followed the project.

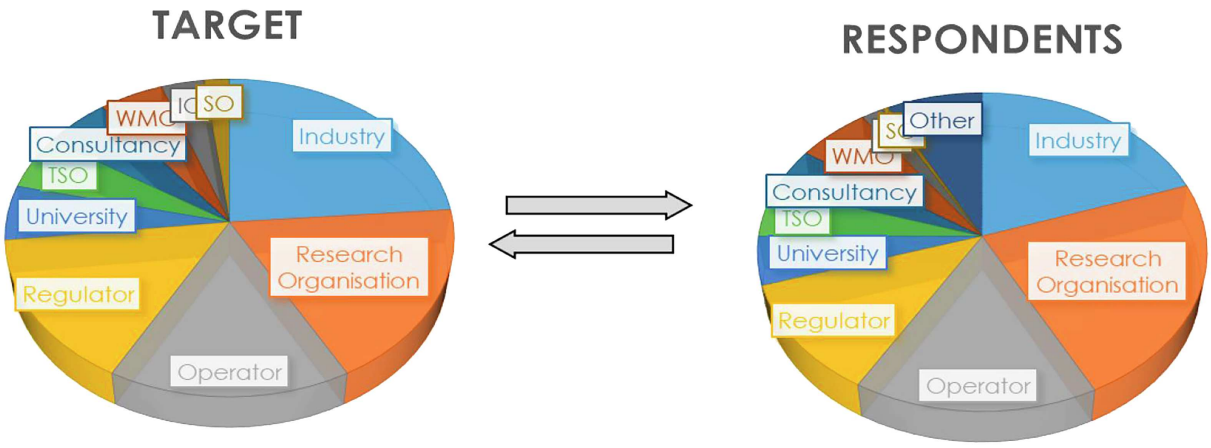

Fig. 3. The population of responding and targeted Stakeholders in the questionnaire survey by their type of organization.

- a pairwise comparison for the type of Stakeholder organization.
- The DELPHI method for the status of the decommissioning project.
- General Consensus for the regional factor.

Whatever the method, the maximum weighting factor was unity (1).

Then, the prioritisation of the (sub-)thematic areas required a pertinent method for categorizing the different ratings. To this end, three levels (low, medium, and high) were introduced for importance and urgency ratings. The (sub-)thematic areas are assigned to them depending on the share of "top 2 responses". This term refers to the sum of the shares of respondents rating a (sub-)thematic area either very important/urgent (rating "5") or important/urgent (rating ("4"). The threshold for medium importance and medium urgency was at 40% and 30% respectively and for high importance and high urgency at 50% and 40% respectively. For example, 46% of the respondents rated the thematic area "Q4 Characterization" "very important" and 33% ranked it "important" leading to a top 2 share of 79% and, thus, a high importance rating.

2.2 State-of-the-art

The state-of-the-art review was conducted to identify the existing and emerging techniques and solutions or best practices to meet the needs of decommissioning community. The method of analysis was to use the structure of the thematic areas established before and to look at each thematic area on four different scales as illustrated in Figure 4.

By reviewing journal articles, industry reports, conference proceedings and expert input, the consortium identified strategies and initiatives on the international, regional and national scale. A dive into available technologies was performed on the national and local levels. A dedicated two-day workshop in October 2020 allowed Stakeholders to engage with the content produced so far by reviewing and consolidating it.

2.3 Gap analysis

The previously obtained results served as the foundation for the gap analysis. In the December 2020 workshop facilitated by the consortium, the Stakeholders brainstormed to produce possible activities in 71 sub-thematic breakout sessions. For the Stakeholder's feedback, Mural was chosen as the online interactive brainstorming tool. The ideas were collected on digital post-its and were shared in real-time with the participants. Each session was dedicated to a sub-thematic area and involved a four-step process. First, Stakeholders identified needs, challenges and opportunities for the corresponding sub-thematic area. Second, a consortium member acted as a facilitator to group the identified needs. Third, the Stakeholders provided some insight into the available solutions and opportunities, which helped to identify the gaps. Finally, Stakeholders proposed activities to close those gaps. Afterwards, the consortium synthesised the outcomes of this workshop on the scale of the sub-thematic areas and, then, presented these at the DigiDecom 2021 conference. Here, the SLIDO live polls tool was used during the event and the Stakeholders provided further input in the form of feedback on the results of the gap analysis. The results of the gap analysis were categorised into four different "action types" for the gap analysis deliverable to provide a better overview [9].

In the same work package, relevant international collaborative research initiatives were also identified.

2.4 Strategic research agenda/roadmap

In the final work package, the consortium pushed the analysis of the project outcomes further by, first, modifying the previously assigned action type to facilitate the categorization of the activities.

The second step consisted of associating importance ratings from the survey with the activities from the same sub-thematic area. In this step, several rearrangements of the activities among the sub-thematic areas were made to ensure clear categorization. For the Strategic

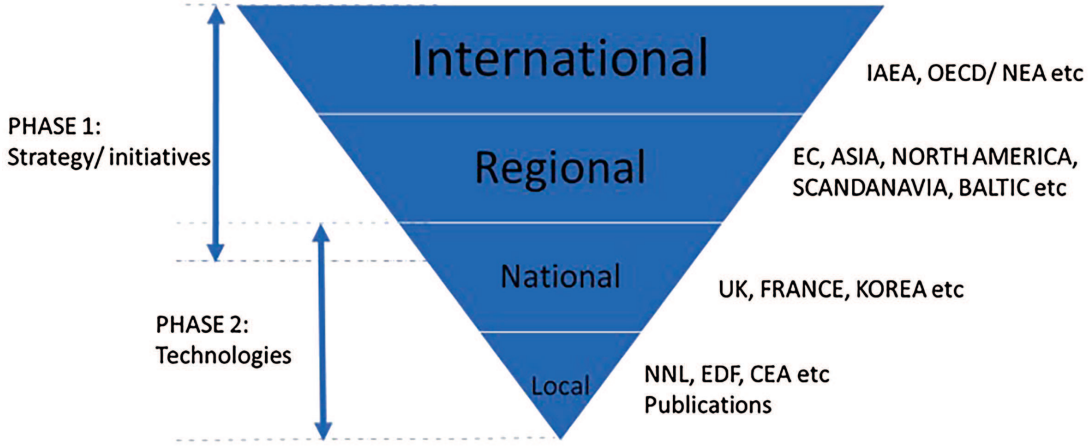

Fig. 4. Scales of the state of the art review.

Research Agenda (SRA), the sub-thematic areas were prioritised by the importance rating for each of the action types.

Finally, for the roadmap, the urgency rating was attributed to the activities of the corresponding sub-thematic area. This allowed the establishment of a time horizon for the activities going from <5 years (high urgency), over 5–10 years (medium urgency) to >10 years (low urgency). If possible, activities with the same time horizon were merged according to their content and action type. Lastly, some related thematic areas were merged.

Figure 5 emphasizes how the SHARE SRA and roadmap have been built through an iterative consultation process considering the needs and points of view of different stakeholders.

3 Results of the inquiry and discussion

3.1 Representativity of the collected data

The first data point to be noted is the participation of the Stakeholder community in the questionnaire survey. Out of the 650 invited Stakeholders, 224 fully completed the questionnaire which corresponds to a participation of 34%. This strong engagement confirms the interest of the community in this project and its premise. As mentioned above, the profiles of the respondents matched the profile of the invited Stakeholders. Care was taken to invite a representative average of Stakeholders to the survey, the latter fact supports the project's ambition to provide broad outcomes. This point is underlined when looking at the other profile factors of the responding Stakeholders. Figure 6 shows the four profile criteria "type of facility", "type of organization", "region" and "status of the decommissioning project".

Indeed, the respondents come from organizations that are in various stages of their decommissioning process and operate different types of facilities. Furthermore, many different global regions are represented.

3.2 Data evaluation and results

Coming to the results of the survey, a thorough discussion of all results would be out of the scope of this article. This article intents to give an overview and then focus on the most salient results. First, Figure 7 shows the weighted results on the scale of the thematic areas, in terms of importance and urgency.

Red circles indicated the sum of the share of the top 2 rankings. Radioactive waste management or characterization is rated highest. Following are safety and radiological protection or project management and cost. The last group is formed of environmental remediation, dismantling, human resources management and site preparatory activities.

Figure 8 shows the weighted importance and urgency ratings of the sub-thematic areas.

Each circle corresponds to a sub-thematic area that is noted by a number (QXX) which relates to the survey question number. The question numbers can be found in appendix Table A.1. The different colours represent the different thematic areas. The size of the circle indicates the urgency category from low to high. The place on the x axis shows the importance category. Importance and urgency ratings for the same sub-thematic areas are correlated. Despite the appearance in this figure where some sub-thematic areas (e.g., Q35, Q45, Q33, Q19, Q25) with medium importance have high urgency, numerically, all sub-thematic areas have higher importance ratings than urgency ratings. The average difference between the importance and the urgency rating for the same sub-thematic is 11 points. This supports the categorization limits set by the consortium which differ by 10 points between importance and urgency. I.e., "High importance" is above 50 points and "high urgency" is above 40 points. The difference varies between the thematic areas. For example, Q2 and Q3 show the smallest average difference (7 points) whereas Q6 and Q7 show the highest average difference (15 and 16 points). For most thematic areas except Q5 and Q7, the thematic area rating is higher than the average of the sub-thematic area ratings. On average,

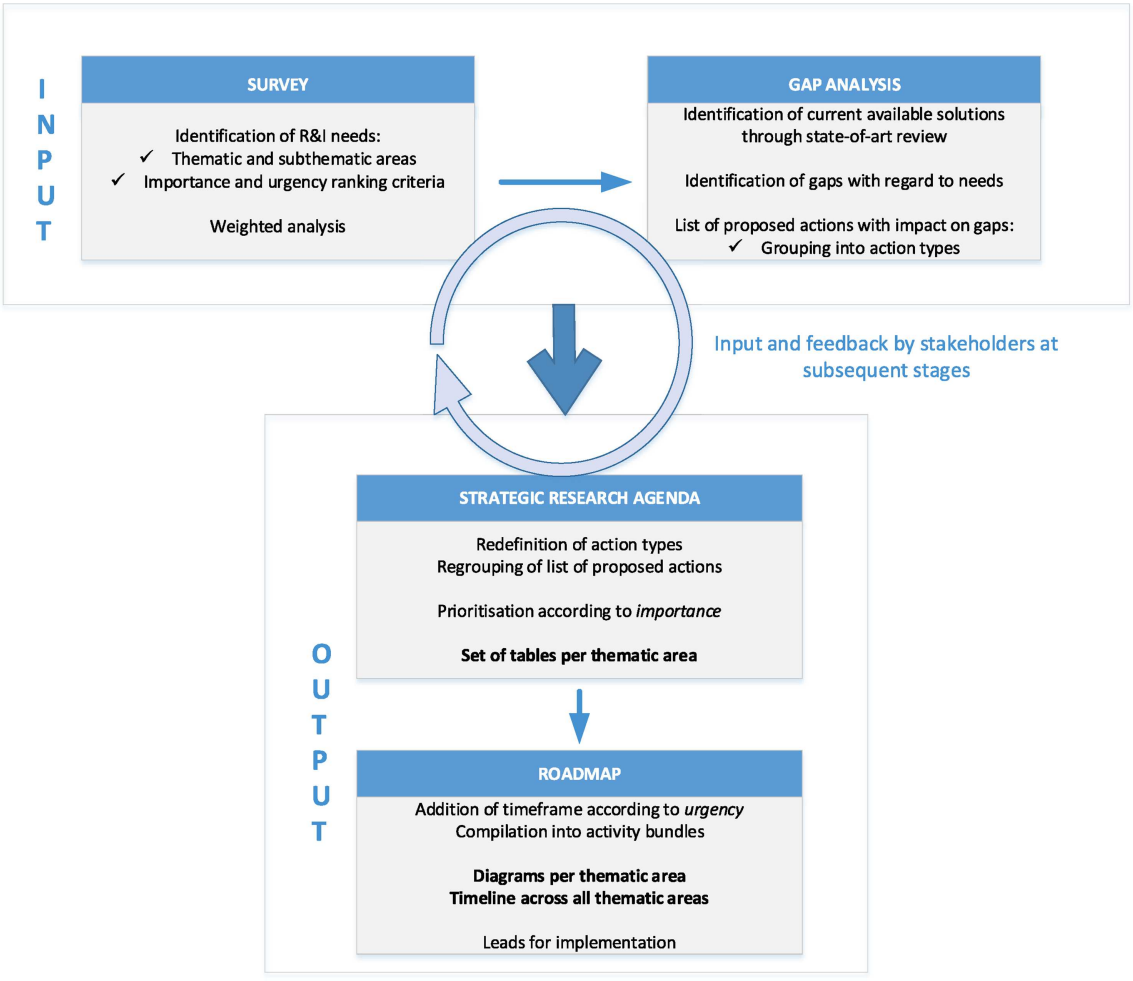

Fig. 5. SHARE methodology.

the difference is 19 points for importance ratings and 13 points for urgency ratings. The biggest gaps are found for Q4 with 30 points for importance and 22 points for urgency, and for Q8 with 30 points for importance and 28 points for urgency. The differences are smallest for Q3 and Q6 below 10 points. As mentioned earlier, for Q5 and the urgency rating Q7 the difference is reversed. However, a more profound analysis must be done carefully, since it involves many hypotheses and assumptions concerning the questionnaire formulation, interpretation and respondent population. Additional analysis can be found in the corresponding project deliverables [8,10,11]. In view of this heterogeneity, looking at the top 10 sub-thematic areas shown in Table 1 provides further insight.

Of the top 10, eight sub-thematic areas are common in terms of importance and urgency. Three (Q32, Q84, Q63) of the other four can be found in the top 20. Only Q62 is at place 31 in terms of urgency. A large number of sub-thematic areas in the top 10 concern characterization in some form (Q36, Q53, Q38, Q37, Q63). Other focus points are robotics (Q60, Q40), material clearance (Q13, Q62, Q84) and radioactive waste management (Q53, Q70). This confirms that the knowledge of the inventory and the existence of adapted solutions for waste management or clearance is key to the success of decommissioning projects. General education for decommissioning is also attributed to a very urgent position.

It is also noted that some of the needs in the sub-thematic areas are already addressed to some degree by available solutions and best practices already provided for in the community. To establish a vision of the current state of the art before moving to the identification of possible actions, the consortium reviewed the available literature and consulted experts [12]. This work laid the foundation for the gap analysis.

The combination of the questionnaire survey in its structure and results and the review of current best practices and technical solutions allowed the team to work out propositions for future activities together with the Stakeholders. The exchange platform for this collaboration was provided by two online workshops in December 2020 and dedicated sessions during the DigiDecom 2021 conference. Stakeholders showed significant interest and engagement in these workshops with participants from diverse groups in the community. Indeed, as Figure 9 shows, the 459 registered participants in these workshops represent the

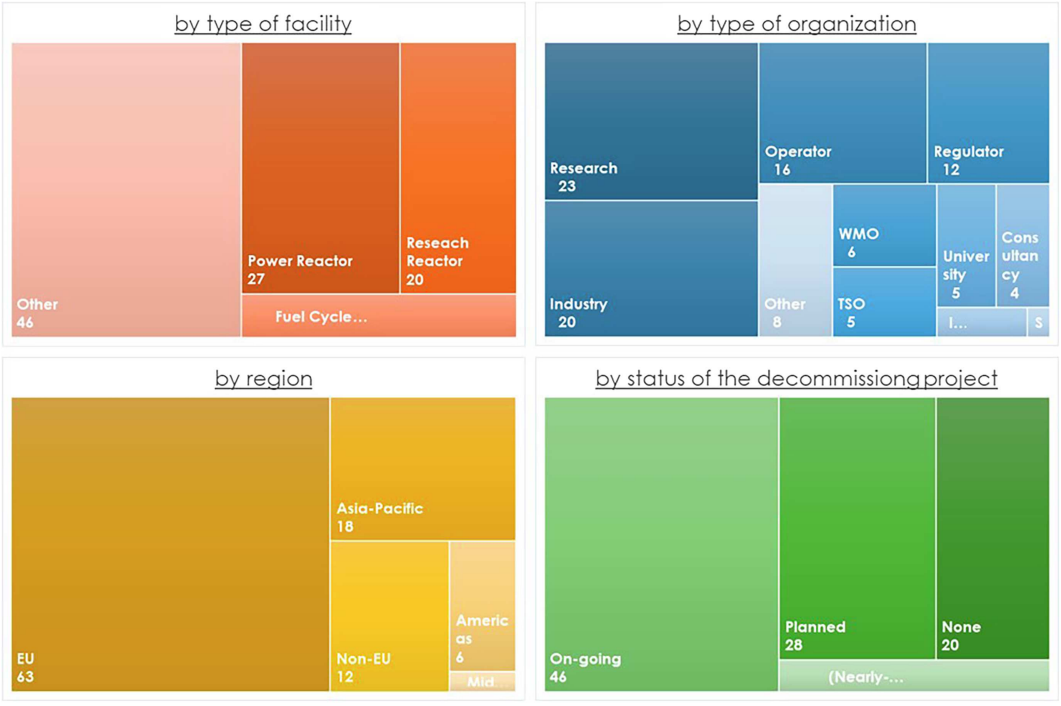

Fig. 6. Profiles of the Stakeholders responding to the questionnaire survey.

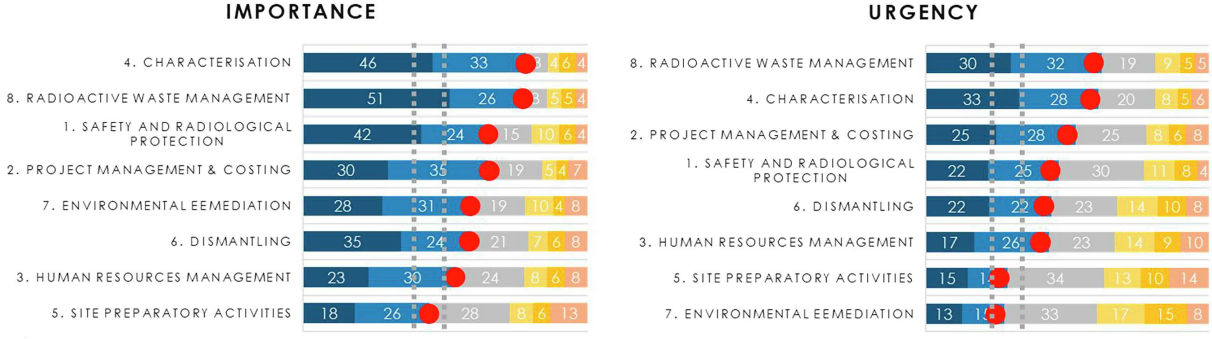

Fig. 7. Results of the questionnaire survey for the thematic areas.

decommissioning Stakeholder community from all over the world well.

The output of this process was published in the Gap Analysis Report [9]. The collective consultation structured by the facilitator action of the consortium gave rise to the proposition of around 220 activities to address the needs. For each thematic area, different key aspects were identified (Tab. 2).

3.3 The SRA and the Roadmap

The research needs highlighted by the SHARE survey were prioritised according to the survey-weighted analysis [8]. The following gap analysis highlighted the gaps in technology, best practices and crosscutting activities [9].

The proposed actions to fill the identified gaps were categorised into four types of activities:

- *implementation of RD&D:* the category includes research, development, demonstration and deployment activities. This also includes underpinning activities such as benchmarking. These research activities aim to create knowledge across all TRL (Technological Readiness Level) levels and to advance the maturation and adoption of new and innovative technologies.
- *Knowledge sharing:* this category of actions focuses on knowledge exchange, ranging from knowledge management to dissemination activities, such as sharing best practices and networking.
- *Education and training:* these activities aim to develop capabilities, skills and competencies for the "nuclear" workforce.
- *Harmonization of practices:* the activities in this category consider the opportunities and benefits of harmonization in the areas of regulatory frameworks and technology development. They are typically achieved by

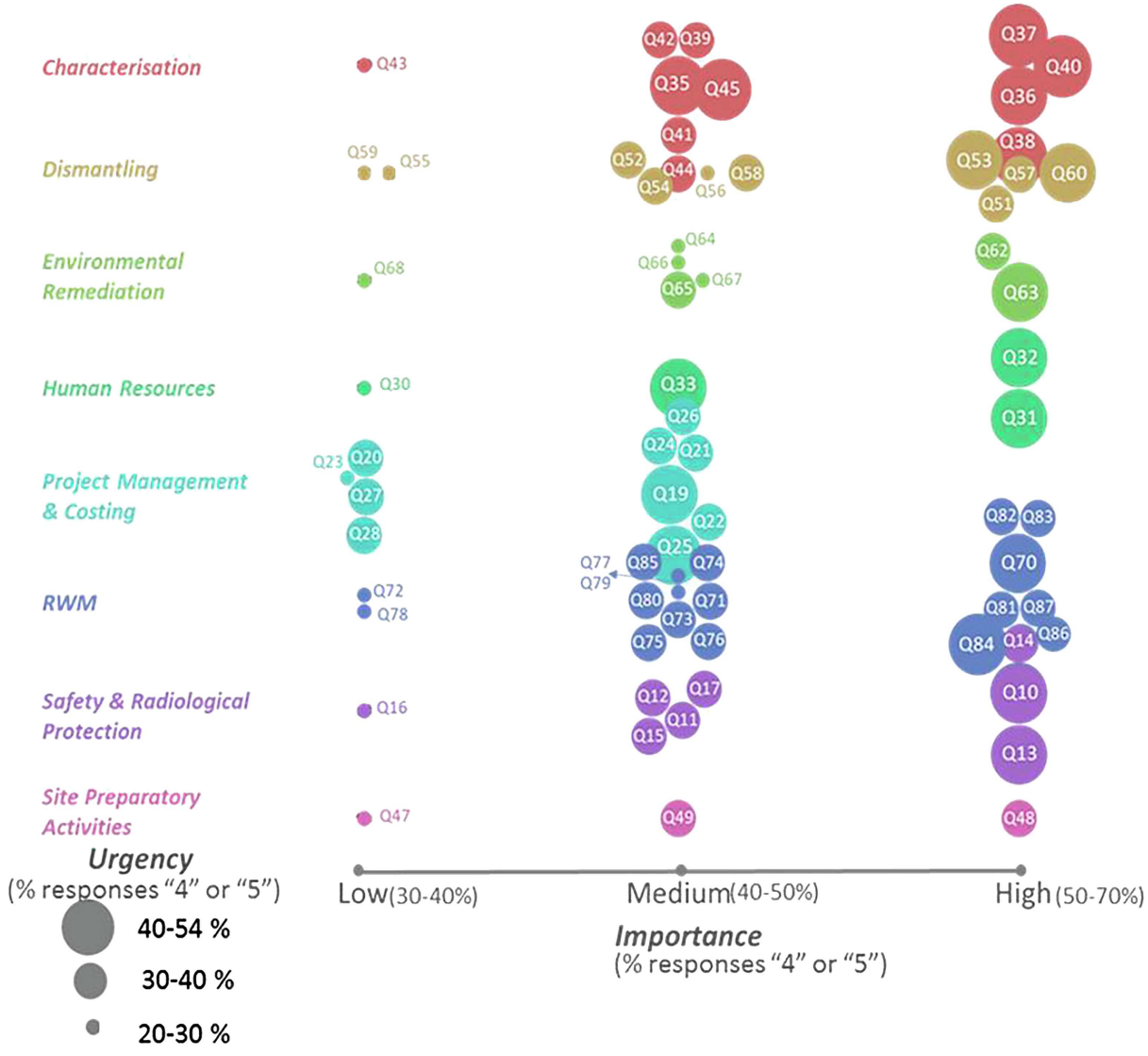

Fig. 8. Importance and urgency rating of the subthematic areas.

mutual agreement and are consolidated in recommendations, directives and guidelines.

This categorization was pre-defined for the Gap Analysis. However, the categories defined in the associated deliverable were ultimately revised. The new categories, being either RD&D or cross-cutting (knowledge sharing, harmonization, education and training) were deliberately chosen to reflect the nature of the desired outcome of the activity. For example, benchmarking requires pre-emptive knowledge sharing of harmonised knowledge. Categorization, at first, seems ambiguous. It was resolved by considering that benchmarking, ultimately, aims at creating knowledge and is, therefore, RD&D. Because progress was made in the field of the activities the consortium provided the updated status for the ongoing project per thematic area. The compiled and categorised actions, where further developments could lead to cheaper, faster and safer future decommissioning activities while improving safety, reducing costs and minimise environmental impact, are presented as main activities of common interest for the six thematic areas of the SHARE Strategic Research Agenda (SRA) [13].

Recent reports [14,15], on innovation in decommissioning identified the future, suggested R&D areas and focus [16] on new aspects, trends and innovative technologies. SHARE continues the work of identifying research and innovation needs and crosscutting activities based on stakeholder involvement, with an emphasis to strengthen international networking and complementarity between national research programmes for decommissioning. The SHARE SRA identifies and prioritises the activities needed to advance the decommissioning field in various thematic areas.

For the non-technological topics (safety and radiological protection, project management, costing and human resources management) in the first thematic area of the SRA, mainly crosscutting activities in the field of

Table 1. Top 10 subthematic areas in terms of importance and urgency.

Place	Importance		Urgency	
	Number	Title	Number	Title
1	Q36	Inventory assessment (Radiological and non-radiological)	Q36	*
2	Q53	In situ Radioactive Waste characterization and segregation	Q53	*
3	Q60	Robots and remote-controlled tools for dismantling	Q32	General education for decommissioning
4	Q38	Characterization of activated components and areas (Concrete)	Q13	*
5	Q40	Technologies for hard-to-access areas (high walls, embedded components, harsh environment...)	Q38	*
6	Q37	Characterization of activated components and areas (Metal)	Q70	*
7	Q70	Management routes for materials including radioactive waste streams	Q37	*
8	Q13	Development of National regulatory guidance for Decommissioning (Clearance of structures and materials)	Q40	*
9	Q62	Clearance of surfaces and structures (interiors and exteriors)	Q60	*
10	Q63	Characterization methods and technologies to identify subsurface contamination	Q84	Material clearance (methodology and procedures)

* indicate that the title of a sub-thematic area was already mentioned in the table.

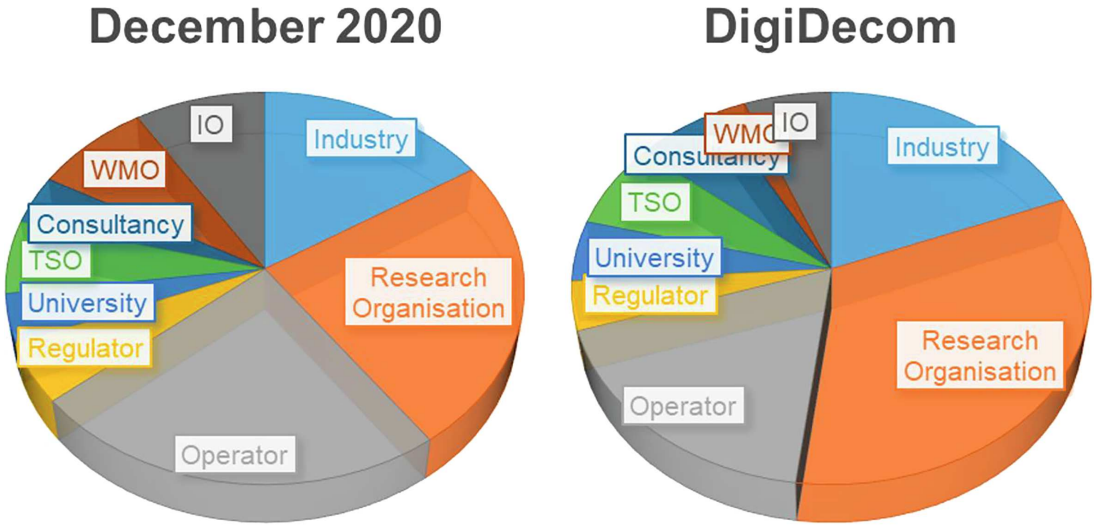

Fig. 9. Pie charts of the profiles of the participants to the two workshops organised for the gap analysis.

Table 2. Key aspects of the gap analysis by thematic area.

Thematic areas	Key aspects
Q1 Safety and radiological protection	Enhancement in international/national harmonization
	Homogenization of regulations
	Future coordination and collaborations
	Regulatory guidance
Q2 Project management and costing	Guidance on tools for cost management and digitization
	Development of IT tools for project management
	Enhance use of BIM (Building Information Modelling) and virtual software
Q3 Human resources management	Coordination among EU, IAEA, and NEA to update existing documents
	Harmonization of knowledge bases
	Enhance use of IT tools, training methods and education of employees
	Benchmarking on methods and tools for knowledge management
Q4 Characterization	Fast and cheap methods of radionuclide measurements
	Technology for digital methods and automation
	Developments towards knowledge management, training and standardisation
Q5 Site preparatory activities	Moved to Q8 "Radioactive Waste Management"
Q6 Dismantling technologies	Development of technologies for detection of contamination, decontamination and cutting of metals and concrete
	R&D towards automation and digitization
	Enhance the use of mobile systems and robotics for worker safety
	Experience sharing in dismantling technologies and benchmarking
	Standardization of autonomous systems
Q7 Environmental remediation and site release	Models, digital tools, multi-criteria analysis, and international guidance for remediation and site release
	Benchmarking of technologies and IT tools
	Experience sharing for harmonization
Q8 Radioactive waste management	Harmonization of best practices, waste minimization
	Enhance optimization opportunities
	Encourage the use of new technologies
	Simpler and cheaper processes for secondary waste handling
	Experience sharing for IT tools and specific waste forms (asbestos)
	Harmonization and standards for waste acceptance criteria

knowledge sharing, harmonisation of practices and education and training have been identified when compared to the technological RD&D topics. The needs that stand out most are the education and recruiting of the next-generation workforce, the development and dissemination of adequate digital tools to plan and follow-up decommissioning activities and the harmonisation of safety standards and waste criteria as enablers for collaboration.

The thematic areas of characterisation and material and waste management have been identified by the stakeholders as most important and urgent overall, with activities for technology advances formulated in the field of measurement optimisation and waste treatment and conditioning techniques, together with crosscutting activities.

Innovative processes, technologies and methodologies for dismantling, decontamination and environmental remediation with a focus on waste minimisation and a need for further development to enhance efficiency, mobility and/or automation are highlighted in the relevant thematic areas. The stakeholders also emphasised the need for sharing best practices and the development of guidance for certain topics.

Ongoing initiatives and recent activities in all thematic areas demonstrate continuous development and innovation, to Figure 10 ether with existing possibilities for the

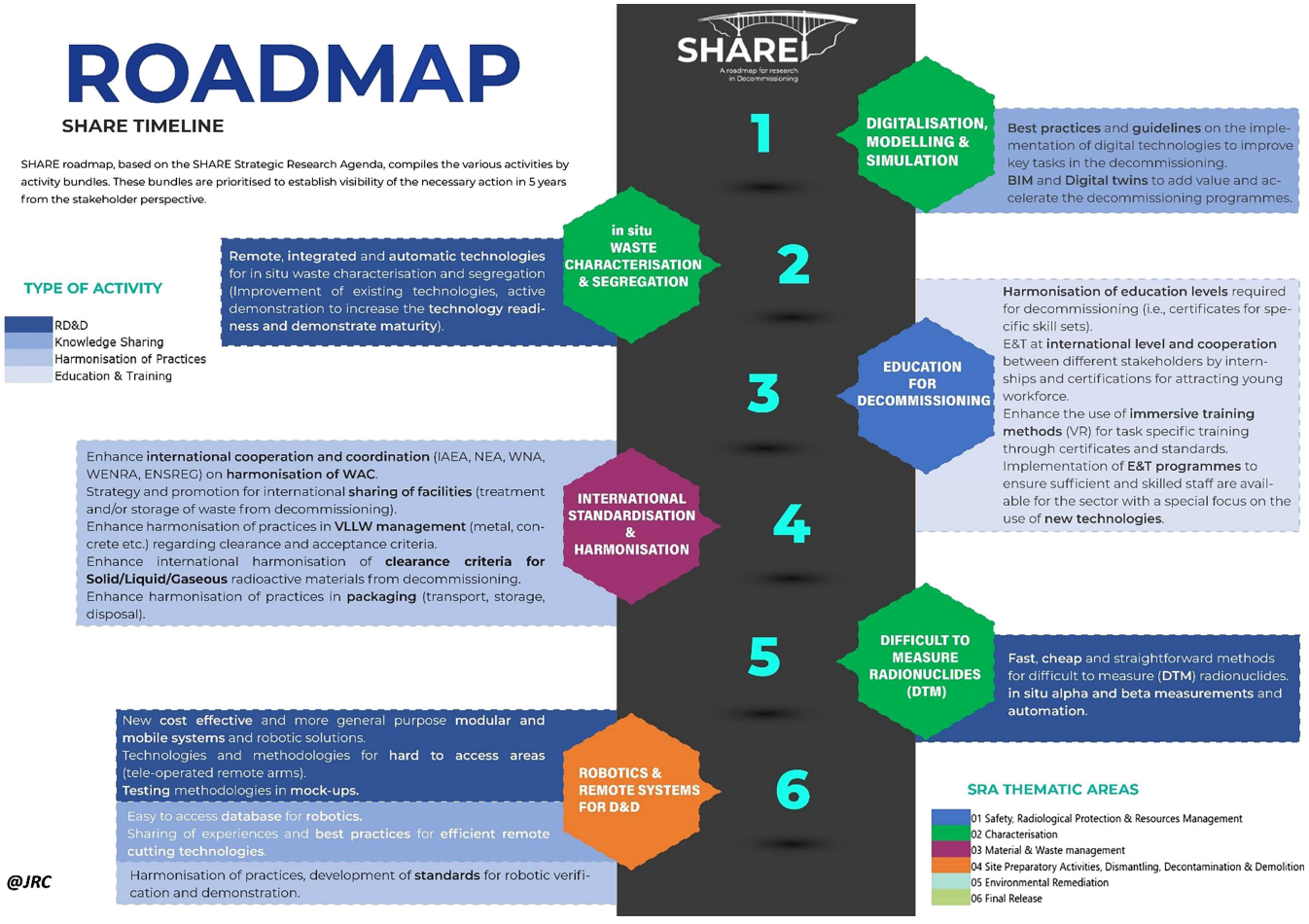

Fig. 10. SHARE Roadmap part I.

exchange of information and lessons learnt. There are opportunities for multinational projects co-financed by stakeholders with common challenges. To go further (and faster) to deliver cost-effective research and innovation, however novel "instruments for collaboration" need to be established to achieve this goal. Open science has a potential role to play, in supporting future coordination of R&I efforts.

Finally, the SHARE Roadmap [17] applies the urgency rating to the same activities. By allowing the moving and merging of similar activities inside an urgency rating, complexity was reduced and readability enhanced. Figures 10 and 11 show the SHARE roadmap compiling the most urgent activities by activity bundles.

4 Conclusion

The SHARE project has through extensive international stakeholder engagement and dialogue, produced a consolidated view of the opportunities to enhance the landscape of decommissioning and this is encoded in the Strategic Research Agenda (SRA) and the present Roadmap document. The activities range from RD&D for activities that create knowledge including benchmarking and technology development, Knowledge Sharing for activities that demand dissemination, Harmonisation of Practices for activities that require at least the adoption of best practices but can include regulatory measures, and Education and Training for activities that aim at creating and developing workforce competencies. The process was performed as a "bottom-up" approach by co-constructing the outcome with the international Stakeholder community. This approach is complementary to the usual top-down scheme found in roadmaps and strategic documents. To maximise objectivity, in all Stakeholder consultations, the consortium acted as facilitator and structured the frame of reference. Indeed, the consortium configured the discussions by establishing the thematic areas and reviewing the state of the art in the field of nuclear decommissioning. The structure of eight thematic areas was inspired by the phases of existing decommissioning programmes: there were three non-technical areas (safety and radiological protection, project management and costing and human resources) that span the whole project duration and five technical areas (characterization, site preparatory activities, dismantling technologies, environmental remediation and site release, and radioactive waste management) that intervene more or less at specific moments.

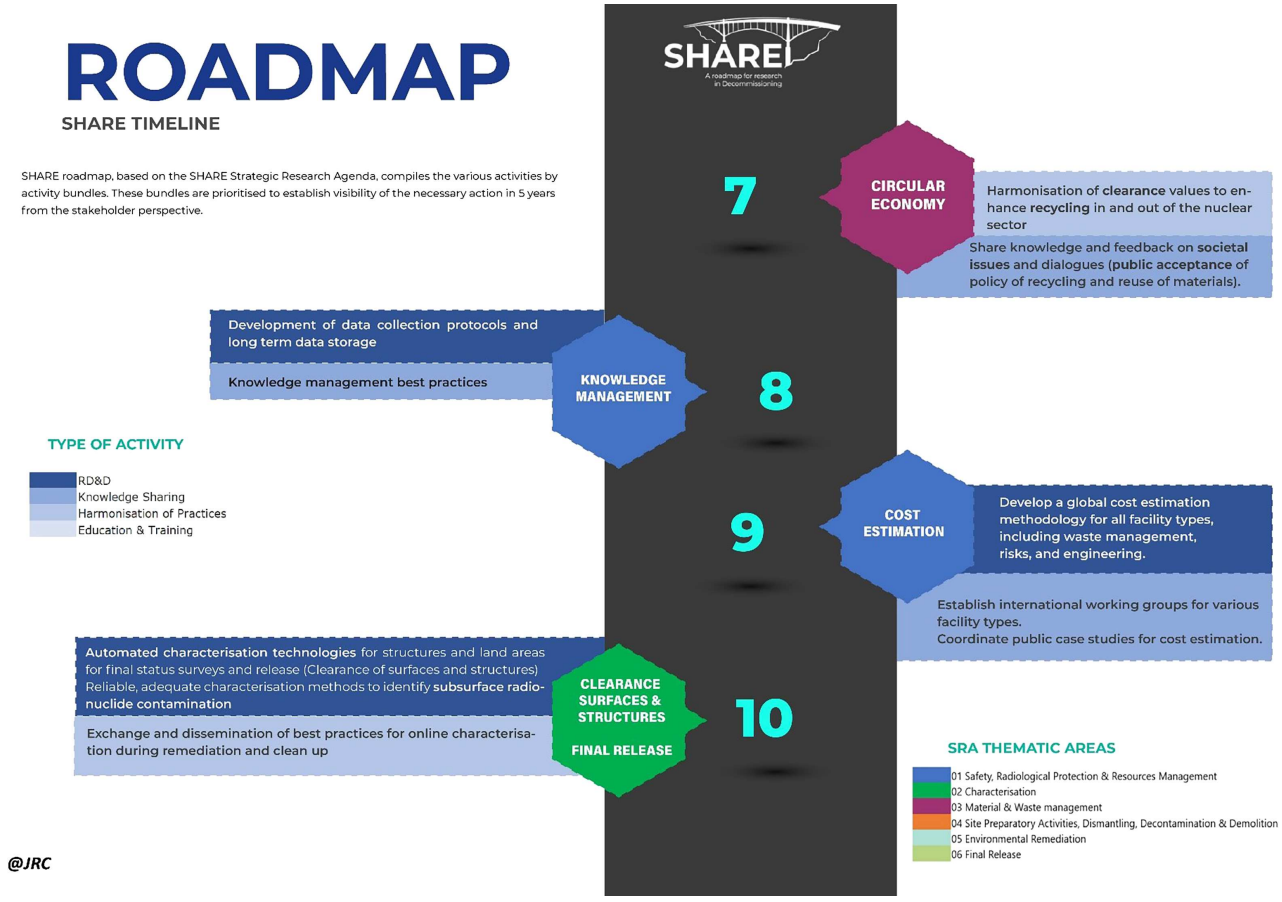

Fig. 11. SHARE Roadmap part II.

The SHARE consortium successfully fulfilled the project purpose by providing the SRA and the Roadmap for future collaborative activities in the decommissioning sector.

There are many advantages in collaboration to deliver these activities, notably, cost sharing of RD&D but also in the intellectual gearing of bringing the experience of different actors together to solve a problem. Collaboration and cooperation offer benefits for knowledge sharing, harmonisation and education and training. Within the SHARE project report, D3.3 [18] many instruments for collaboration were identified as relevant to the decommissioning context.

European instruments led by the European Commission such as Horizon Europe are likely to continue to be the key facilitating instruments for open collaborative Research, Development & Demonstration (RD&D) across Europe. Experience of EURATOM projects such as Theramin, PREDIS and CHANCE have illustrated how powerful these collaborations can be, benefitting from sharing of both expertise and national facilities to address technological challenges. On-going projects such as the European Joint Programming EURAD or Euratom H2020 HARPERS can, thus, now pick up on the knowledge created by SHARE

These collaborations can be aided and indeed initiated by strong European networks, notably SNETP, Nugenia and ETSON. A strong European network perhaps facilitated through SNETP-Nugenia has the potential to continue the stakeholder dialogue and networking achieved in SHARE, to inform policy, strategy, and the research agenda in decommissioning at a European level.

For regulatory issues that occur frequently in the roadmap, close interaction with regulator networks such as ENSREG or WENRA could be fruitful. The same is true for educational issues where several expert networks exist. Indeed, an expert insight provided by such groups is crucial for pertinent project development.

However, other international organisations including OECD-NEA and IAEA are also facilitating cooperation beyond Europe and remain important instruments for collaboration and networking in the nuclear sector, notably on knowledge sharing, harmonisation and education and training globally.

The effective implementation relies on strong collaboration based on shared drivers and goals, as embodied in the initiatives outlined above. However, bilateral or smaller regional (local) collaborations will also play an important role in driving innovation where incentives and drivers align, to make progress against common goals.

Appendix A

Table A.1. List of thematic and sub-thematic areas in the questionnaire survey.

Thematic area	Sub thematic area
Safety and Radiological Protection aspects	Q10 International harmonization of safety standards
	Q11 Development/National regulatory guidance for Decommissioning: Preparatory activities
	Q12 Development/National regulatory guidance for Decommissioning: Dismantling
	Q13 Development/National regulatory guidance for Decommissioning: Clearance of structures and materials
	Q14 Development/National regulatory guidance for Decommissioning: Final site release
	Q15 Methods and tools for nuclear safety
	Q16 Methods and tools for conventional industrial safety
	Q17 Development of radiological protection approaches and guidance for Decommissioning
Project management and costing	Q19 Methodologies and software tools for comparison of alternative decommissioning strategies
	Q20 Methodologies and software tools for project management and performance monitoring
	Q21 Tools for data collection in the field (e.g., for work monitoring)
	Q22 Digital transformation in decommissioning (big data, business intelligence)
	Q23 Supply chain management for decommissioning
	Q24 Methods and tools for communication (public)
	Q25 Methodologies and guidance for cost estimation
	Q26 Software for cost estimation (partly discussed in other sessions)
	Q27 Development of mechanisms for cost benchmarking
	Q28 Methods and tools for sensitivity and uncertainty analysis in cost estimation (partly discussed in other sessions)
Human resources management	Q30 Organization models (staff & resources)
	Q31 Methods and software tools for knowledge management (e.g., competence preservation)
	Q32 General education for Decommissioning
	Q33 Methodologies and tools for task-specific training
Characterization	Q35 Methodology for historical site assessment
Site preparatory activities	Q47 Adaption of auxiliary systems for decommissioning (ventilation, electrical, monitoring, etc.)
	Q48 Preparation of infrastructures and buildings for decommissioning (storages, capabilities for material sorting and treatment...)
	Q49 Systems decontamination (internal)
Dismantling	Q51 Segmentation of large irradiated metallic components (reactor vessel internals, etc.)
	Q52 Handling, segregation and loading of segmented elements and secondary waste
	Q53 In situ Radioactive Waste characterization and segregation
	Q54 Segmentation of large surface-contaminated components
	Q55 Dismantling of surface-contaminated piping and small components
	Q56 Segmentation of interior concrete structures (e.g., bioshield)
	Q57 In situ decontamination of building surface (concrete)
	Q58 Management (characterization, decontamination, removal) of radiological embedded elements
	Q59 Demolition of large, reinforced concrete structures
	Q60 Robots and remote-controlled tools for dismantling
Environmental remediation	Q62 Clearance of surfaces and structures (interiors and exteriors)
	Q63 Characterisation methods and technologies to identify subsurface contamination
	Q64 Modelling and statistical tools to analyse contaminant transport in subsurface soil and groundwater
	Q65 Soil remediation technologies (washing, bioremediation, contamination fixing)
	Q66 Remediation of contaminated groundwater (radiological)
	Q67 Methodologies and techniques for final release survey of the Site
	Q68 Tools for statistical analysis and management of survey data for site release
Radioactive waste management	Q70 Management routes for materials including radioactive waste streams
	Q71 Radioactive material decontamination (mechanical)
	Q72 Radioactive material decontamination (electrochemical)

Table A.1. continued.

Thematic area	Sub thematic area	Thematic area	Sub thematic area
	Q36 Inventory assessment (Radiological and non-radiological)		Q73 Radioactive material treatment processes (metals)
	Q37 Characterization of activated components and areas (Metal)		Q74 Radioactive material treatment processes (concrete)
	Q38 Characterization of activated components and areas (Concrete)		Q75 Radioactive material treatment processes (aqueous liquids)
	Q39 Characterization of activated components and areas (Graphite)		Q76 Radioactive material treatment processes (non-aqueous liquids)
	Q40 Technologies for hard-to-access areas (high walls, embedded components, harsh environment...)		Q77 Radioactive material treatment processes (organic materials)
	Q41 Development of modelling and simulation software for characterization of irradiated components		Q78 Radioactive material treatment processes (VLLW)
	Q42 Standards for statistical sampling		Q79 Radioactive material treatment processes (LLW)
	Q43 Geostatistical software applications		Q80 Radioactive material treatment processes (ILW)
	Q44 Sample analysis technologies		Q81 Radioactive waste conditioning
	Q45 Alpha and beta non-destructive measurements		Q82 Radioactive waste packaging and logistics
			Q83 Characterization and survey of containerised radioactive waste
			Q84 Material clearance (methodology and procedures)
			Q85 Material clearance (instrumentation and logistics)
			Q86 Management of hazardous and toxic materials (asbestos, lead in paint, etc.)
			Q87 Conventional and cleared materials recycling (circular economy)

Conflict of interests

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

Funding

The project SHARE (847626) was funded by the European Commission in the H202 EURATOM programme.

Data availability statement

GDPR was respected. All published data from the project is publicly available in the deliverables on the project homepage.

Author contribution statement

Robert Winkler was project coordinator of SHARE and drafted the manuscript. Laura Aldave de las Heras was work package leader (WP1 "Methodology"). Development of the methodology used in the project, including the survey analysis, the gap analysis and SRA and roadmap setup. Federica Pancotti contributed to all work packages and was the author of the state of the art (3.1) and the questionnaire explanatory deliverable (2.5). Anthony Banford was the leader of work package 3 and contributed to the state-of-the-art analysis, the gap analysis, leading stakeholder engagement workshops and the subsequent needs analysis. He participated to the Work Package 4 Strategic Research Agenda and Roadmap Team doing preparation of, co-authoring and dissemination. Reka Szoke reviewed the paper. Kurt van den Dungen was leader of WP4 and coordinated and authored the SRA and the Roadmap. Gintautas Poškas is the author of the deliverables D2.3 and D2.4 and contributed to the article by reviewing and coauthoring chapter 2. KIT participants (Angelika Bohnstedt and Muhammad Chaudhry) have been involved in all WPs, with strong input in WP 1 as task leader being responsible for "Inventory of relevant actors within stakeholder's profile by country" and in WP 2 "Questionnaire on innovation needs for decommissioning". They put in a lot of effort was done in the gap analysis on identified needs and available solutions, which included literature research as well as stakeholder workshops with the final outcome in the Strategic Research Agenda.

References

1. Eurostat, Nuclear energy statistics, 2022
2. WNA, Nuclear Power in the European Union, https://world-nuclear.org/information-library/country-profiles/others/european-union.aspx (The 103 nuclear power reactors, in only one country – France) (2022)
3. N. Scarlat, M. Prussi, M. Padella, Quantification of the carbon intensity of electricity produced and used in Europe, Appl. Energy **305**, 117901 (2022)
4. European Commission, *Nuclear Illustrative Programme* (European Commision, 2017)
5. JRC, ENS, FORATOM, Roundtable supporting european expertise in nuclear decommissioning, 2018
6. JRC, IAEA, *Advancing Implementation of Nuclear Decommissioning and Environmental Remediation Programmes* (Publications Office of the European Union, Luxembourg, 2017)
7. CEA: Commissariat à l'énergie atomique et aux énergies alternatives, Enresa: Empresa Nacional de Residuos Radiactivos, S.A., IFE: Institute for Energy Technology, JRC: Joint Research Center, KIT: Karlsruhe Institute of Technology, LEI: Lietuvos ener
8. F. Pancotti et al., D2.5: Matrix and explanatory report from Task 2.3, 2021
9. M. Chaudry et al., D3.2: Technology assessment/gap analysis report, 2021
10. G. Poskas, L. Aldave de las Heras, C. Georges, D2.3: Report on analysis of preliminary results from the questionnaire, 2020
11. G. Poskas et al., D2.4: Report on analysis of preliminary results from the questionnaire, 2021
12. F. Pancotti et al., D3.1: Report detailing applicable technologies/methodologies, 2021
13. K. Van den Dungen et al., D4.1: Strategic research agenda, 2022
14. OECD/NEA. R&D and innovation need for decommissioning nuclear facilities, 2014
15. SNETP, SNETP strategic research and innovation agenda, 2021
16. M. Laraia, *Advances and Innovations in Nuclear Decommissioning* (Elsevier, UK, 2017)
17. K. Van den Dungen et al., D4.2: Roadmap & D4.3: View on implementation, 2022
18. S. Ree et al., D3.3: Report identifying and comparing international collaborative research initiatives

Cite this article as: Robert Winkler, Laura Aldave de las Heras, Federica Pancotti, Antony W. Banford, Kurt Van den Dungen, Réka Szőke, Gintautas Poškas, Angelika Bohnstedt, and Muhammad Junaid Ejaz Chaudhry. SHARE: Stakeholder based analysis of research for decommissioning, EPJ Nuclear Sci. Technol. **9**, 10 (2023)