SHARE

H2020 NFRP-2018 CSA: Coordination and Support Action

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D4.2: Roadmap

D4.3: View on Implementation

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Executive Summary

Technology advances and innovative solutions in all phases of the decommissioning process can enhance efficiency, reduce cost and schedule, improve worker safety, and reduce waste generation. Complementary efforts on planning and project management, training material and operational experience transfer, organisational aspects and change management will contribute towards an optimised execution - cheaper, faster, safer and more sustainably - of challenging decommissioning projects.

The SHARE roadmap has identified more than 140 activities in all fields of decommissioning based on the strategic research agenda for which research and/or development will bring improvement into future decommissioning, once promising technologies and capabilities are deployed. The roadmap diagrams in this document summarise these activities with an indication of importance, urgency and action type (RD&D, Knowledge Sharing, Harmonisation of Practices, Education and Training).

The SHARE timeline has been made based on the assessment of all stakeholders' inputs, where the most urgent bundled activities are presented according to their thematic area and action type. This timeline partially reflects the trends towards digitalisation, sustainability and circular economy, but also acknowledges reoccurring demands for training and education and harmonisation.

Views on implementation and perspectives for deployment are briefly stated for stimulating the organisation and coordination of R&I multinational projects, the use of innovative technologies and the continuous involvement of known international organisations on technical and crosscutting activities.

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Introduction

The goal of the project SHARE is to identify the ***technical and non-technical needs*** in the international stakeholder community and to provide a roadmap for the developments that will help reduce costs, minimise waste and environmental impact, and improve the worker safety in decommissioning projects. The needs were determined and consolidated with the stakeholder community in an iterative and inclusive process based around the key thematic areas in the decommissioning process: safety and radiological protection, project management and costing, human resources, characterisation, site preparatory activities, dismantling and decontamination, material and radioactive waste management, and environmental remediation.

SHARE provides the present roadmap within the scope of the H2020 Euratom Work Programme 2018 (NFRP-2018-5)[1] as the final outcome based on the valuable data generated in three steps. First, a survey was conducted among the decommissioning stakeholders providing over 220 responses that evaluated the key thematic areas and their listed topics in terms of urgency and importance. Second, on the same thematic areas, the consortium established a state-of-the-art review highlighting existing methodologies and current international initiatives. Third, identified needs, existing and on-going solutions were further investigated and consolidated with stakeholders during various public workshops. A gap analysis was carried out and a list of actions proposed to fill the identified gaps.

The identification of specific activities where further developments could lead to cheaper, faster and safer future decommissioning while improving safety, reducing costs and minimising environmental impact, provided the basis for establishing the SHARE Strategic Research Agenda (SRA). The activities were assigned to different categories: ***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 SHARE SRA prioritised the categorised activities of common interest according to the importance of the SHARE weighted survey, reflecting the stakeholders' point of view.

The activities as determined in the course of this project provide solid empirical data that are coherent with the most prominent implementation issues in decommissioning projects as identified in the policy support document from the project "CIDER" in 2016. The latter sketched the outline of the implementation barriers for decommissioning projects by defining (i) legal and regulatory issues, (ii) technology and infrastructural issues, (iii) limited resources, knowledge management and organisational issues, and (iv) societal issues. In the past years, reports published by international organisations that address these issues on an international level have increased.

[1] h2020-wp1820-euratom_en.pdf (europa.eu)

Examples that can be cited are: for (i) guides on regulations[2], the IAEA safety standards series with currently over 130 reports[3], for (ii) R&D needs reviews[4], for iii) the ISDC[5], guides for costing processes[6], case studies, organisational guides and multiple training programmes, for (iv) communicational guides. Despite the considerable effort behind these reports, the persistence of these issues in the over 180 activities proposed in the SRA shows that the organisation of the decommissioning industry on the international level is still evolving. However, this is not contradicting the efforts of international organisations but proves their pertinence via the bottom-up quality of the results. It can be seen as fostering the confidence in the routes proposed by the international organisations for regulatory decisions and evaluation of strategic topics for (future) focus.

The roadmap tries to go a step further by compiling the various activities by activity bundles. These bundles are prioritised to establish a visibility of the necessary actions in 5, 10, and 15 years from the stakeholder perspective. It should support future coordination of R&I efforts. Before presenting the results by means of diagrams and timelines, the project methodology is further detailed for better interpretation and understanding.

[2] IAEA. Model Regulations for Decommissioning of Facilities. (2017).
[3] IAEA. LONG TERM STRUCTURE OF THE IAEA SAFETY STANDARDS AND CURRENT STATUS - April 2022. (2022).
[4] OECD/NEA. R&D and Innovation Need for Decommissioning Nuclear Facilities. (2014).
[5] OECD/NEA. International Structure for Decommissioning Costing (ISDC) of Nuclear Installations. (2012).
[6] OECD/NEA. Guide for International Peer Reviews of Decommissioning Cost Studies for Nuclear Facilities. (2014).

Methodology

The vision of SHARE is to initiate and carry out collaborative actions in Europe and beyond, to provide an inclusive roadmap for joint near future decommissioning research in a broad sense for stakeholders to improve safety, reduce costs and minimise environmental impact in the decommissioning of nuclear facilities, with commitment to:

- Build confidence in the steps needed for the generation of knowledge on decommissioning and its safety, economic and environmental aspects;
- Encourage the future coordination of Research & Innovation (R&I) activities strategically recommendable for financing in the next decade(s);
- Facilitate access to expertise and technology and maintain competences in the field of decommissioning and environmental remediation for the benefit of Member States.

The SHARE main outputs - Strategic Research Agenda (SRA) and roadmap – have been built through an iterative consultation process considering the needs and points of view of different stakeholders. The subsequent steps towards these deliverables are presented in Figure 1.

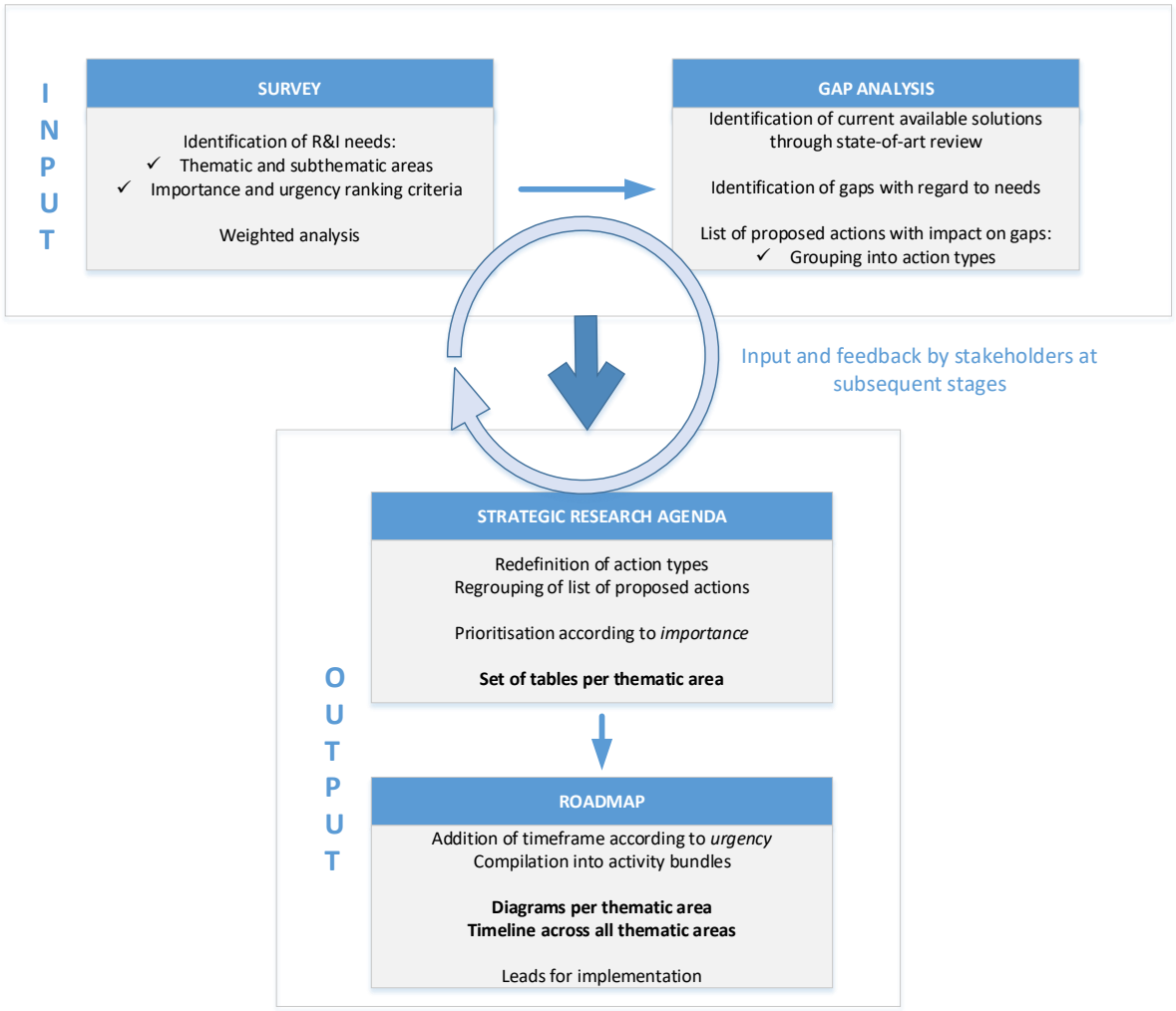

Figure 1 : SHARE Methodology

The survey consisted of a list of predefined and open questions (in so-called subthematic areas) where needs could be expressed and evaluated/ranked according to importance and urgency. The whole of stakeholders' inputs have been processed and analysed extensively to produce an impartial, balanced and reliable assessment of the opinions collected.

In the course of SHARE, activities in different fields of RD&D and crosscutting issues have been considered, refined and reviewed. These activities have been agreed on to be valuable for future research – in a broad sense – with an impact on the gaps identified. This eventually has led to a list of activities prioritised and grouped thematically by means of the SRA. Further condensation by identifying similarities and common trends in the roadmap has reduced complexity and improved readability.

The SRA consists of a set of tables per thematic area, where for the four different action types, activities are listed according to their importance. Ongoing activities and recent initiatives give an update on the state-of-art. The roadmap and its diagrams add (per thematic area) a timeframe context in terms of urgency, while the timeline gives an overview of the most urgent activities over all thematic areas related to decommissioning.

Roadmap Timeline

The SHARE roadmap timeline (see figures), based on the SHARE SRA, compiles the various activities by activities bundles. These bundles are prioritised to establish visibility of the necessary action in 5 years from the stakeholder preparative. This corresponds to the activities of high urgency.

An overview of all activities over all urgency types can be found in the roadmap diagrams later in this document.

ROADMAP

SHARE TIMELINE

SHARE roadmap, based on the SHARE Strategic Research Agenda, compiles the various activities by activity bundles. These bundles are prioritised to establish visibility of the necessary action in 5 years from the stakeholder perspective.

DIGITALISATION, MODELLING & SIMULATION

Best practices and **guidelines** on the implementation of digital technologies to improve key tasks in the decommissioning.
BIM and **Digital twins** to add value and accelerate the decommissioning programmes.

in situ WASTE CHARACTERISATION & SEGREGATION

Remote, **integrated** and **automatic technologies** for in situ waste characterisation and segregation (Improvement of existing technologies, active demonstration to increase the **technology readiness and demonstrate maturity**).

EDUCATION FOR DECOMMISSIONING

Harmonisation of education levels required for decommissioning (i.e., certificates for specific skill sets).
E&T at **international level and cooperation** between different stakeholders by internships and certifications for attracting young workforce.
Enhance the use of **immersive training methods** (VR) for task specific training through certificates and standards.
Implementation of **E&T programmes** to ensure sufficient and skilled staff are available for the sector with a special focus on the use of **new technologies**.

INTERNATIONAL STANDARDISATION & HARMONISATION

Enhance **international cooperation and coordination** (IAEA, NEA, WNA, WENRA, ENSREG) on **harmonisation of WAC**.
Strategy and promotion for international **sharing of facilities** (treatment and/or storage of waste from decommissioning).
Enhance harmonisation of practices in **VLLW management** (metal, concrete etc.) regarding clearance and acceptance criteria.
Enhance international harmonisation of **clearance criteria for Solid/Liquid/Gaseous** radioactive materials from decommissioning.
Enhance harmonisation of practices in **packaging** (transport, storage, disposal).

DIFFICULT TO MEASURE RADIONUCLIDES (DTM)

Fast, **cheap** and straightforward methods for difficult to measure (**DTM**) radionuclides. **in situ alpha and beta measurements** and **automation**.

ROBOTICS & REMOTE SYSTEMS FOR D&D

New **cost effective** and more general purpose **modular and mobile systems** and robotic solutions.
Technologies and methodologies for **hard to access areas** (tele-operated remote arms).
Testing methodologies in **mock-ups.**

Easy to access **database** for **robotics.**
Sharing of experiences and **best practices** for **efficient remote cutting technologies**.

Harmonisation of practices, development of **standards** for robotic verification and demonstration.

TYPE OF ACTIVITY

- RD&D
- Knowledge Sharing
- Harmonisation of Practices
- Education & Training

SRA THEMATIC AREAS

- 01 Safety, Radiological Protection & Resources Management
- 02 Characterisation
- 03 Material & Waste management
- 04 Site Preparatory Activities, Dismantling, Decontamination & Demolition
- 05 Environmental Remediation
- 06 Final Release

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ROADMAP

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Roadmap Diagrams

For each of the six main thematic areas, so-called diagrams have been produced which represent the assembled results in terms of identified activities for future research in relation to action types, importance and urgency. These diagrams each follow the same structure, as explained in Figure 2.

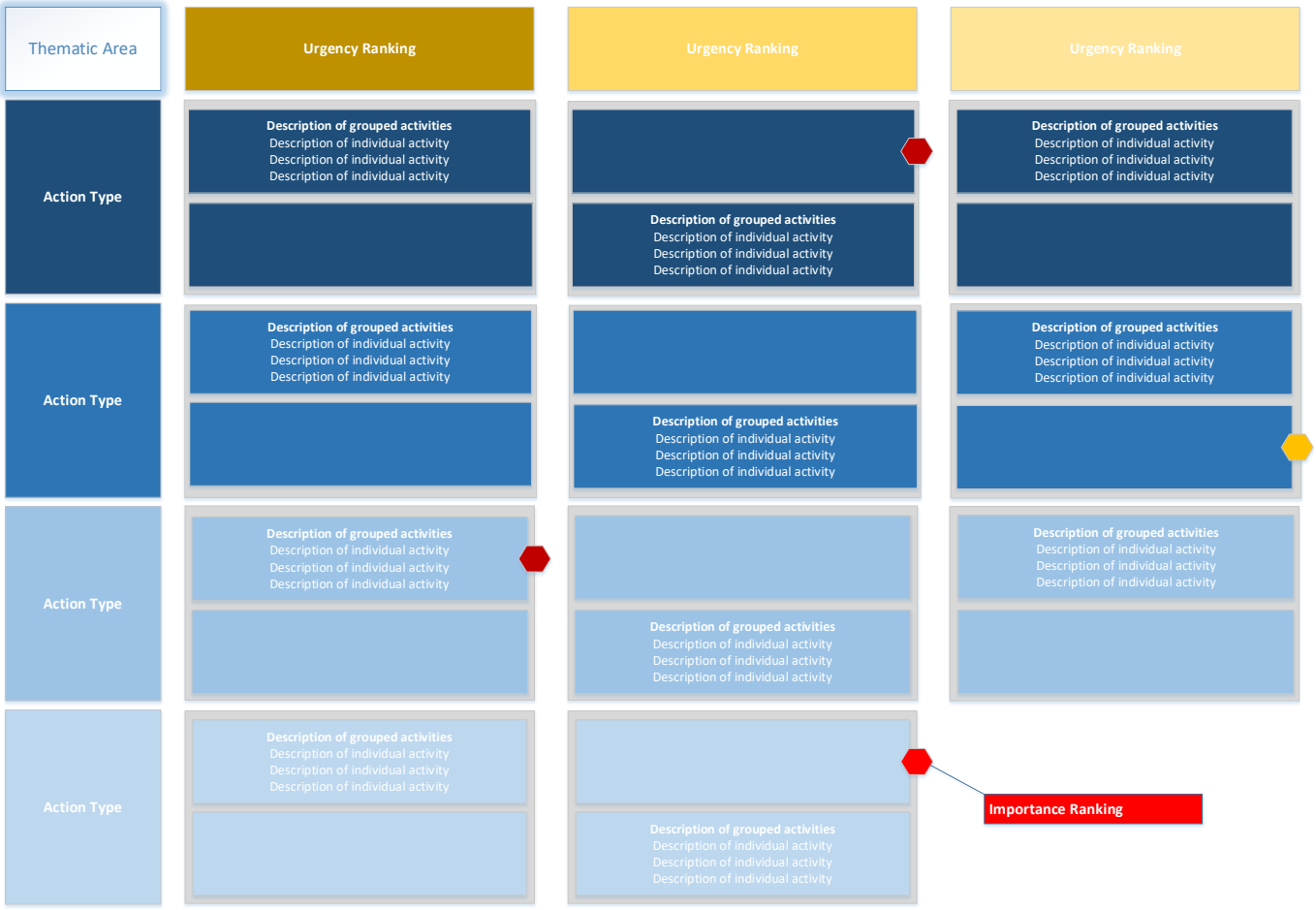


Figure 2 : Key to Roadmap Diagrams

The roadmap tables explained:

- Top left corner: Thematic Area
- Top horizontal row: High, Medium and/or Low urgency ranking (when applicable)
- Left vertical column: Four Action Types (when applicable)
- Table cells: Grouped activities description + Listing of individual activities
- Hexagonal shapes after each cell: High, Medium and/or Low importance ranking

1.1 Safety & Radiological Protection

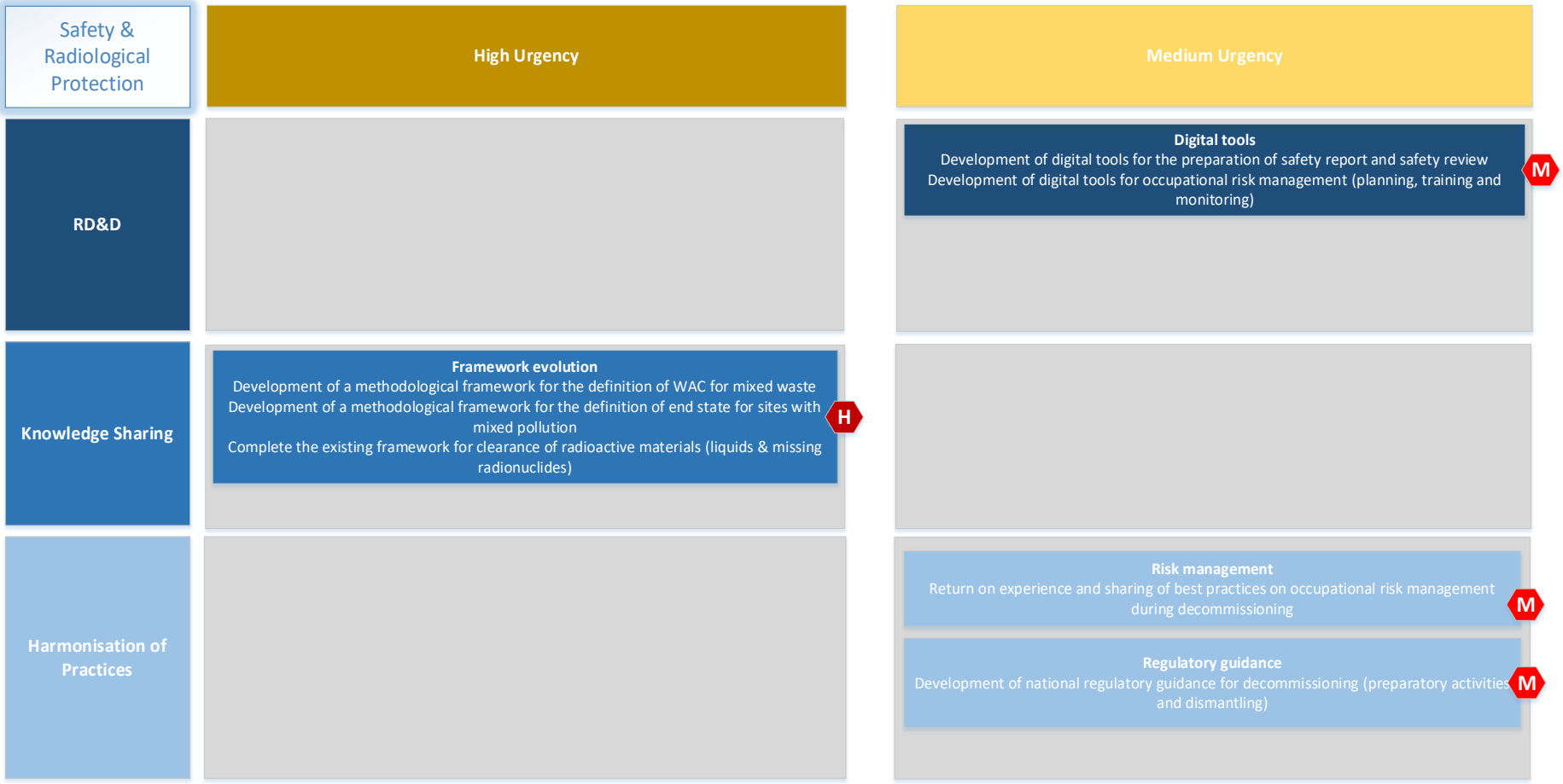
Radiological protection of the public, workers and the environment is an important aspect of a successful decommissioning project. It must be taken into account from the beginning (transition phase and decommissioning project conception) up to the end, e.g. final status survey and comparison of the results with the desirable end state based on dose criteria. Adequate regulation is in place in most countries with a nuclear industry. It is based on international basic safety standards, which have proven to be effective. Nevertheless, decommissioning differs in various aspects from operation and there is room for improvement. Stakeholders have identified within the framework of SHARE a number of actions related to the important area of safety and radiological protection for which the implementation should help in improving decommissioning practices.

Management of occupational exposures occurring during the decommissioning of a nuclear facility could benefit from an increase in development and use of digital tools: real time dose rate measurements, 3D mapping, job briefing on risks and safety etc. Solutions already exist and could benefit from exchange and dissemination of operational experience dedicated to end-users. Radionuclides are not the only pollutants workers may have to deal with. Lead, asbestos, PCBs etc. are present in most facilities and should be also managed together with ionising radiation, requiring adequate methods, guidance and experience sharing.

Guidance should also be developed in order to deal efficiently with mixed pollutants in waste, structures, building or soils. Methods for the definition of WAC for mixed waste, based on the actual hazardous properties of the waste, should be made available. In addition, when it comes to site remediation, methods and tools to deal with multiple pollutants including radionuclides are required to ensure remediation actions commensurate with the level of risk (graded approach). Stakeholder engagement in the remediation process is recognised as an important aspect, but here guidance as well as sharing of experience are required.

International basic safety standards provide a framework for clearance of solid radioactive materials, based on the 10 µSv.y-1 concept. Still, some radionuclides are not considered in these frameworks and values for liquid materials are not available. The framework for clearance of all types of radioactive materials should be completed in the years to come.

Further research in the non-technical area of safety and radiological protection has to be seen in a broad sense, with a focus on further development and demonstration of tools and technologies for improved management of industrial and radiological safety, sharing of knowledge and best practices, and harmonisation of practices taking into account the individual responsibility of nations, regulators and operators.


Safety & Radiological Protection
High Urgency
Medium Urgency
RD&D
Digital tools
Development of digital tools for the preparation of safety report and safety review
Development of digital tools for occupational risk management (planning, training and monitoring)
M
Knowledge Sharing
Framework evolution
Development of a methodological framework for the definition of WAC for mixed waste
Development of a methodological framework for the definition of end state for sites with mixed pollution
Complete the existing framework for clearance of radioactive materials (liquids & missing radionuclides)
H
Harmonisation of Practices
Risk management
Return on experience and sharing of best practices on occupational risk management during decommissioning
M
Regulatory guidance
Development of national regulatory guidance for decommissioning (preparatory activities and dismantling)
M

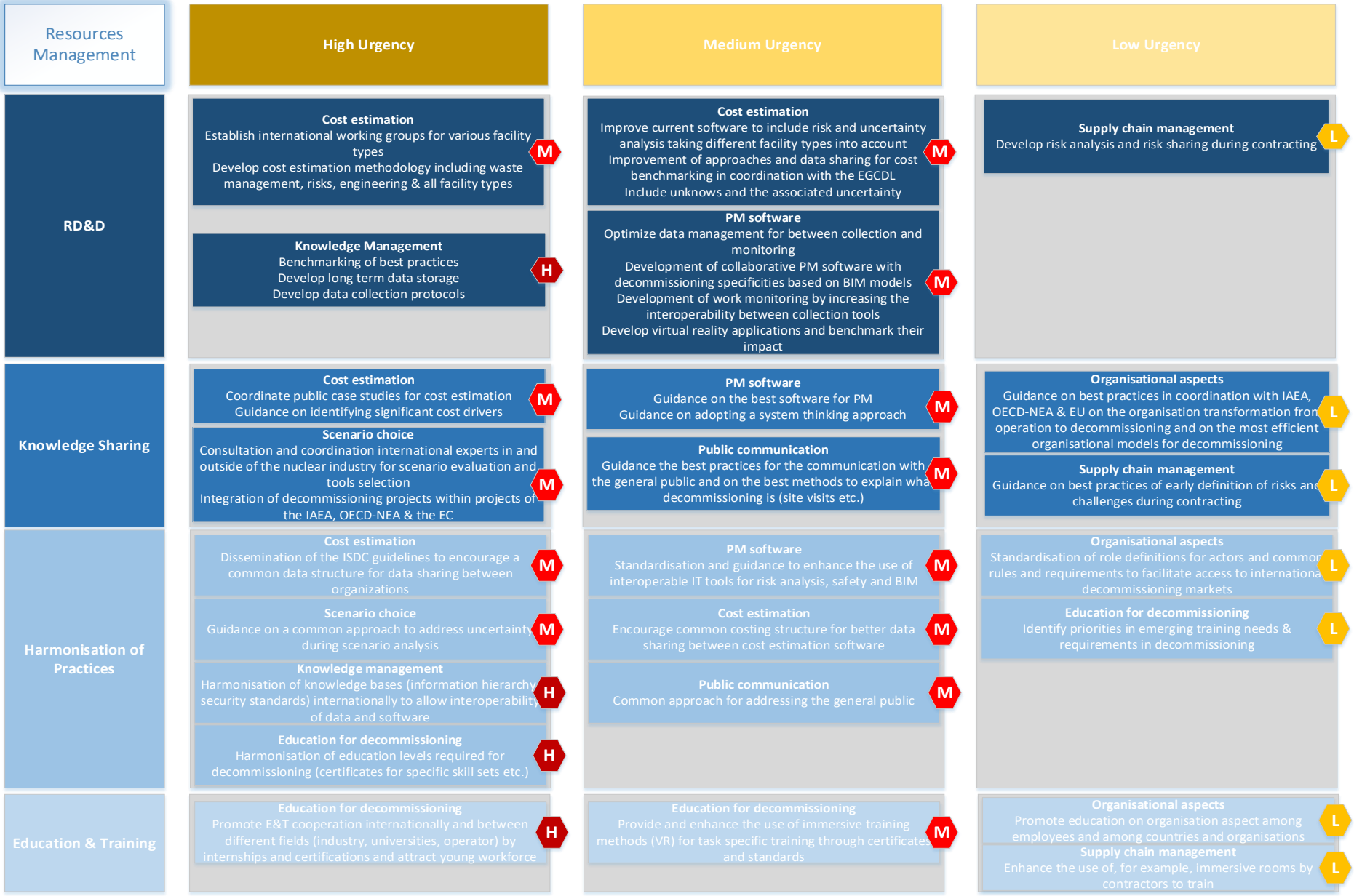
1.2 Resources Management

The organisation of resources through competent project management and good human resource choices is a key element for successful decommissioning projects by minimising costs and delays. It is critical all along the decommissioning project especially during the transition from the operation phase. A successful transition assures the availability of knowledge about the facility while guaranteeing the recruiting of new competences that are specific to decommissioning. After a successful transition, activities are incessant because of the generally long duration of decommissioning projects in the nuclear sector that require continuous education, recruiting and organisation adaptation efforts.

The stakeholders participating in SHARE specified the activities that address these challenges. The foundation is constituted by the availability of a competent workforce. Most urgent are the development of standardised education levels (e.g. certificates) and the exchanges by internships between different actors. These more general topics are supported by providing training for task specific skills and new training methods e.g. VR. Any training program should identify emerging needs for training early on and try to encourage the next generation of workforce to join the industry.

Among the most urgent is the further development of cost estimation. While progress has been made, notably with the establishment of the ISDC (International Structure of Decommissioning Costing), costs of decommissioning activities continue to exceed early estimations. Today, anticipating 20% contingency costs is reasonable even in final budget calculations. Considering the size of decommissioning projects this leads to significant cost increases. Therefore, stakeholders express the need for the development of cost estimation methodologies in coordination with the international organisations. These developments should address the specificity of different facility types and the whole value chain of decommissioning including radioactive waste management, risks, and engineering. Underpinning these developments, the stakeholders propose to coordinate public studies for cost estimation, to institutionalise the ISDC and to provide guidance for cost drivers. Other factors that increase the unanticipated rise of costs is the insufficient knowledge of the facility and the inventory of contaminated objects. Therefore, stakeholders propose to work on knowledge management by developing knowledge management methodologies. Activities such as benchmarking best practices, developing long term data storage and data collection protocols should be underpinned by the harmonisation of knowledge bases internationally. Both cost estimation and knowledge management are entwined in the smart scenario choice that addresses all sources of uncertainty. To this end stakeholders think that decommissioning projects should seek inspiration from experts outside of the nuclear industry.

Medium urgency is attributed to the development of project management software. Here, data collection linked to work monitoring, the development of collaborative BIM-based tools and virtual reality are underpinned by the sharing of best tools and harmonisation of best practices. Equally urgent is the need of guidance for public communication. Less urgent are activities that concern contract management with the supply chain and organisational aspects. Nonetheless stakeholders specify the need for guidance on the best practices of organisational transition and the standardisation of certain roles in project management to facilitate interactions among actors.


Resources Management
High Urgency
Medium Urgency
Low Urgency
RD&D
Cost estimation
Establish international working groups for various facility types
Develop cost estimation methodology including waste management, risks, engineering & all facility types
M
Knowledge Management
Benchmarking of best practices
Develop long term data storage
Develop data collection protocols
H
Cost estimation
Improve current software to include risk and uncertainty analysis taking different facility types into account
Improvement of approaches and data sharing for cost benchmarking in coordination with the EGCDL
Include unknows and the associated uncertainty
M
PM software
Optimize data management for between collection and monitoring
Development of collaborative PM software with decommissioning specificities based on BIM models
Development of work monitoring by increasing the interoperability between collection tools
Develop virtual reality applications and benchmark their impact
M
Supply chain management
Develop risk analysis and risk sharing during contracting
L
Knowledge Sharing
Cost estimation
Coordinate public case studies for cost estimation
Guidance on identifying significant cost drivers
M
Scenario choice
Consultation and coordination international experts in and outside of the nuclear industry for scenario evaluation and tools selection
Integration of decommissioning projects within projects of the IAEA, OECD-NEA & the EC
M
PM software
Guidance on the best software for PM
Guidance on adopting a system thinking approach
M
Public communication
Guidance the best practices for the communication with the general public and on the best methods to explain what decommissioning is (site visits etc.)
M
Organisational aspects
Guidance on best practices in coordination with IAEA, OECD-NEA & EU on the organisation transformation from operation to decommissioning and on the most efficient organisational models for decommissioning
L
Supply chain management
Guidance on best practices of early definition of risks and challenges during contracting
L
Harmonisation of Practices
Cost estimation
Dissemination of the ISDC guidelines to encourage a common data structure for data sharing between organizations
M
Scenario choice
Guidance on a common approach to address uncertainty during scenario analysis
M
Knowledge management
Harmonisation of knowledge bases (information hierarchy, security standards) internationally to allow interoperability of data and software
H
Education for decommissioning
Harmonisation of education levels required for decommissioning (certificates for specific skill sets etc.)
H
PM software
Standardisation and guidance to enhance the use of interoperable IT tools for risk analysis, safety and BIM
M
Cost estimation
Encourage common costing structure for better data sharing between cost estimation software
M
Public communication
Common approach for addressing the general public
M
Organisational aspects
Standardisation of role definitions for actors and common rules and requirements to facilitate access to international decommissioning markets
L
Education for decommissioning
Identify priorities in emerging training needs & requirements in decommissioning
L
Education & Training
Education for decommissioning
Promote E&T cooperation internationally and between different fields (industry, universities, operator) by internships and certifications and attract young workforce
H
Education for decommissioning
Provide and enhance the use of immersive training methods (VR) for task specific training through certificates and standards
M
Organisational aspects
Promote education on organisation aspect among employees and among countries and organisations
L
Supply chain management
Enhance the use of, for example, immersive rooms by contractors to train
L

1.3 Characterisation

Characterisation is the basis for radiation protection, identification of contamination, assessment of potential risks, cost estimation, planning and implementation of decommissioning of nuclear facilities. Characterisation is relevant in all phases of the life cycle of a nuclear installation with different levels of detail and with differing objectives. In the framework of SHARE only characterisation during the transition phase, main decommissioning phase, including decontamination, characterisation for environmental remediation and to support the end-state study for site release have been considered.

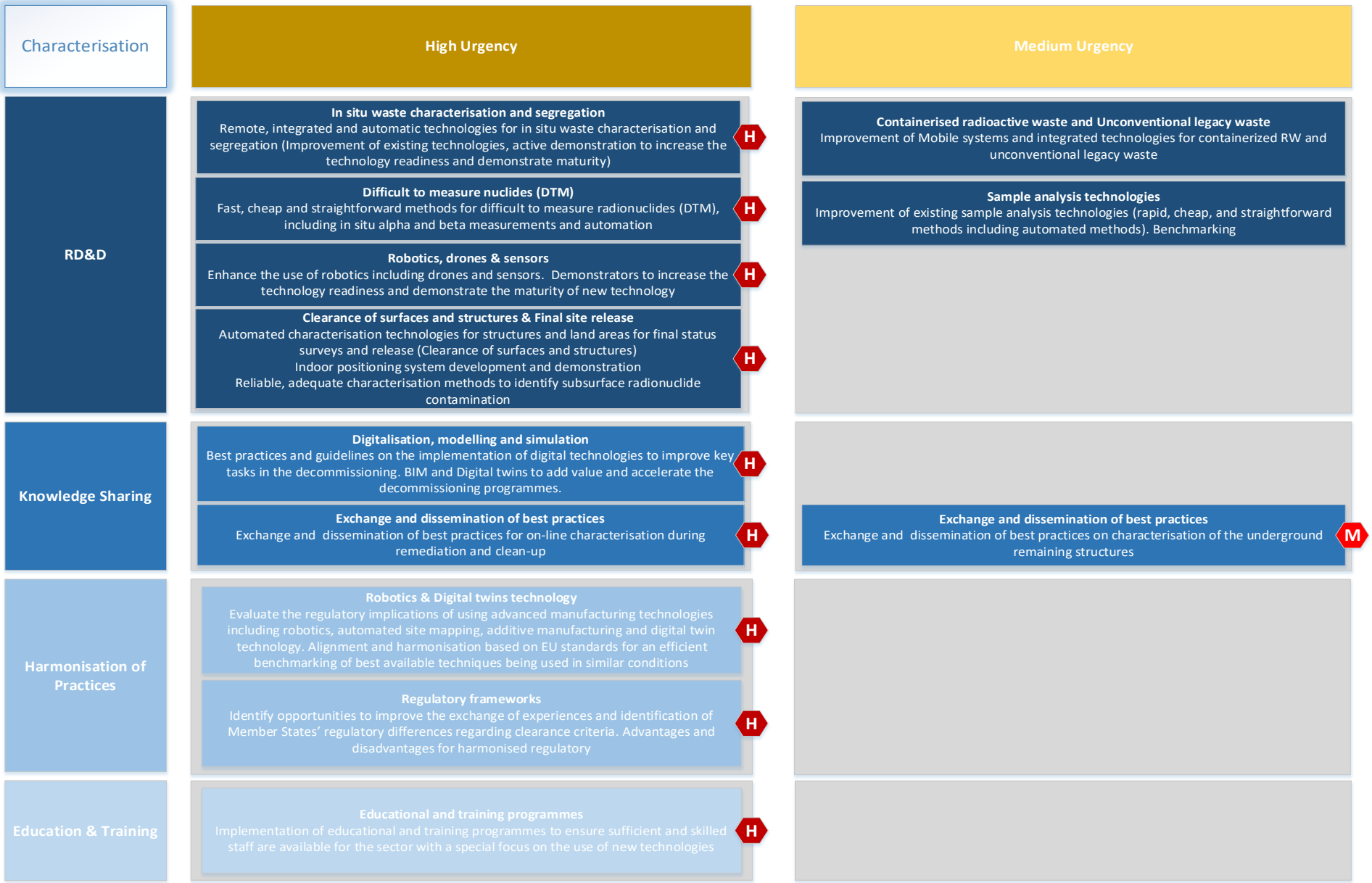
Stakeholders rated 94% of the thematic sub-areas related to characterisation as of medium and high importance, while half of them are considered to be of high urgency. Furthermore, half of the priorities identified by the stakeholders in this area are related to the implementation of research, development and demonstration (RD&D) while 38 % of the priorities are associated to sharing knowledge.

With regard to the implementation of RD&D, the main technologies and methodologies are already available but there is still the opportunity for further developments in terms of automation, remote control, integrated systems. Active demonstration of new technology is vital to increase the technology readiness and demonstrate the maturity of new approaches. Fast, cheap and straightforward methods for difficult to measure (DTM) radionuclides is an issue *per se* as the available technology has not reached the required level. The main impact of the implementation of these activities would be the reduction of characterisation time and cost, as well as the optimisation of waste segregation and the recycling and reuse of material. Main technology is available with the exception of very specific issues but with the expectation of improving the existing technology taking benefits of new technological developments (fast computing, AI, IoT, new materials, etc…).

Building, collecting, transferring, sharing, preserving, maintaining and using knowledge is essential to developing and keeping the necessary technical expertise and competences required for nuclear decommissioning programmes. Despite notable commitment by the international organisations in sharing knowledge, good practices and technical information through their international networks and working groups, best practices and guidelines in different phases of a decommissioning programme with special focus in digitalisation, modelling and simulation is highlighted by the stakeholders.

Harmonisation of regulations between countries seems to be a challenge that should be overcome. Several reports concerning international cooperation in decommissioning and radioactive waste management claim that the lack of regulatory harmonisation is making multinational approaches more difficult. Regulatory discrepancies prevent stakeholders from benchmarking the efficiency of decommissioning and waste management strategies between countries, making it difficult for them to identify the best available techniques. This could also have an impact in public risk perception and public acceptance. The enhanced use of robotics including drones and sensors is highlighted from both standardisation and regulatory implications points of view, in addition to the regulatory differences regarding clearance criteria.

Finally, in terms of education and training activities as well as the development of competences, the implementation of educational and training programmes to ensure sufficient and skilled staff are available for the sector with a special focus on the use of new technologies is identified.


Characterisation
High Urgency
Medium Urgency
RD&D
In situ waste characterisation and segregation
Remote, integrated and automatic technologies for in situ waste characterisation and segregation (Improvement of existing technologies, active demonstration to increase the technology readiness and demonstrate maturity)
H
Difficult to measure nuclides (DTM)
Fast, cheap and straightforward methods for difficult to measure radionuclides (DTM), including in situ alpha and beta measurements and automation
H
Robotics, drones & sensors
Enhance the use of robotics including drones and sensors. Demonstrators to increase the technology readiness and demonstrate the maturity of new technology
H
Clearance of surfaces and structures & Final site release
Automated characterisation technologies for structures and land areas for final status surveys and release (Clearance of surfaces and structures)
Indoor positioning system development and demonstration
Reliable, adequate characterisation methods to identify subsurface radionuclide contamination
H
Containerised radioactive waste and Unconventional legacy waste
Improvement of Mobile systems and integrated technologies for containerized RW and unconventional legacy waste
Sample analysis technologies
Improvement of existing sample analysis technologies (rapid, cheap, and straightforward methods including automated methods). Benchmarking
Knowledge Sharing
Digitalisation, modelling and simulation
Best practices and guidelines on the implementation of digital technologies to improve key tasks in the decommissioning. BIM and Digital twins to add value and accelerate the decommissioning programmes.
H
Exchange and dissemination of best practices
Exchange and dissemination of best practices for on-line characterisation during remediation and clean-up
H
Exchange and dissemination of best practices
Exchange and dissemination of best practices on characterisation of the underground remaining structures
M
Harmonisation of Practices
Robotics & Digital twins technology
Evaluate the regulatory implications of using advanced manufacturing technologies including robotics, automated site mapping, additive manufacturing and digital twin technology. Alignment and harmonisation based on EU standards for an efficient benchmarking of best available techniques being used in similar conditions
H
Regulatory frameworks
Identify opportunities to improve the exchange of experiences and identification of Member States' regulatory differences regarding clearance criteria. Advantages and disadvantages for harmonised regulatory
H
Education & Training
Educational and training programmes
Implementation of educational and training programmes to ensure sufficient and skilled staff are available for the sector with a special focus on the use of new technologies
H

1.4 Material & Waste Management

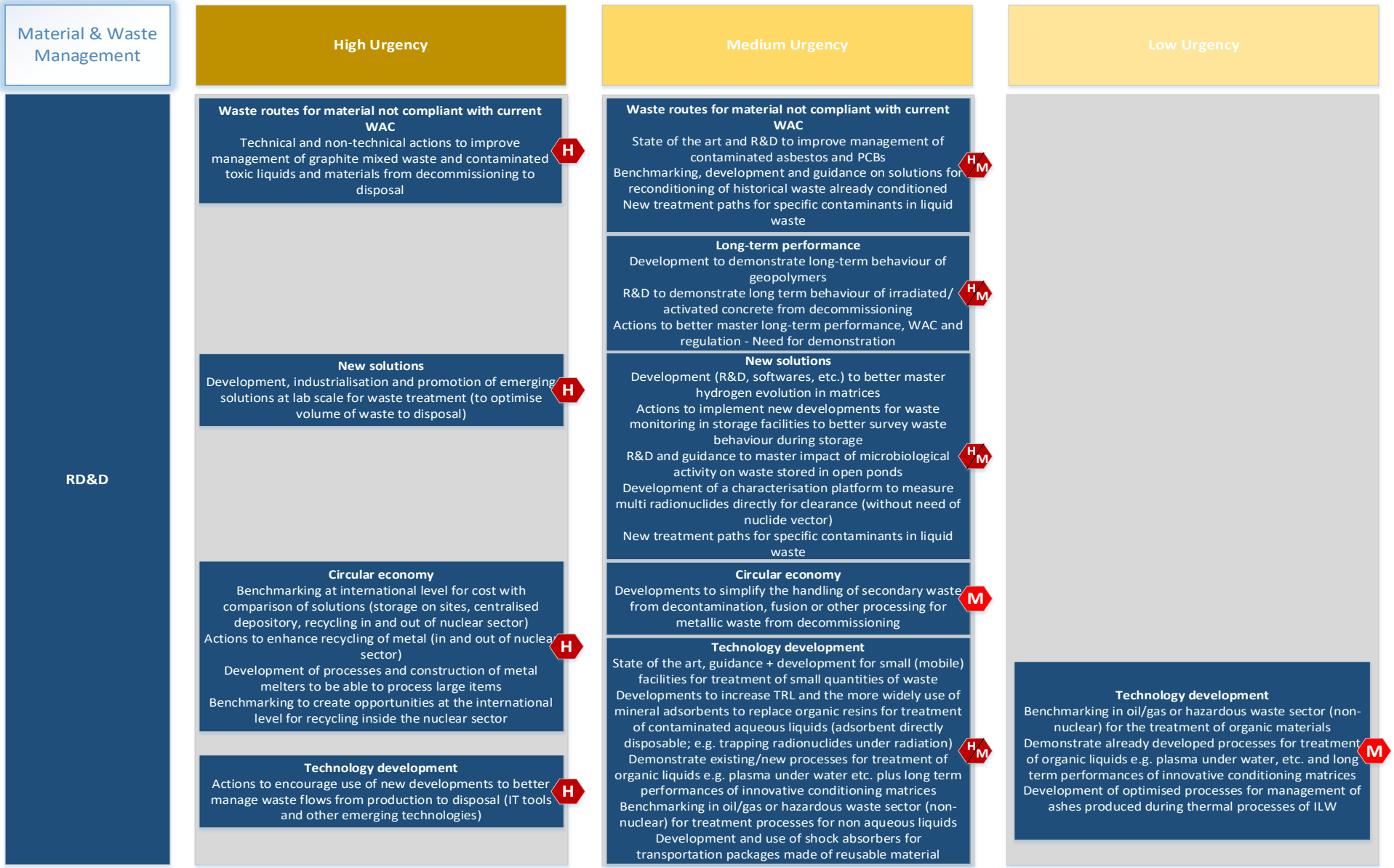
Nuclear facilities are generally large civil structures with radioactive inventory, that also have significant volumes of infrastructure materials, including pipes, vessels and significant quantities of structural materials such as concrete and steel which may be contaminated or activated. A key challenge of any decommissioning project is ensuring that suitable waste management routes are available for these materials. Without appropriate waste management routes, decommissioning cannot proceed. Waste management is therefore a critical part of the decommissioning process. Whilst many decommissioning projects are progressing globally, the extensive stakeholder engagement in the SHARE project identified several themes to focus future research, development, and demonstration, knowledge sharing and harmonisation. Activities identified in other sections of this roadmap, including decontamination and characterisation technologies are both important facilitating technologies in waste treatment.

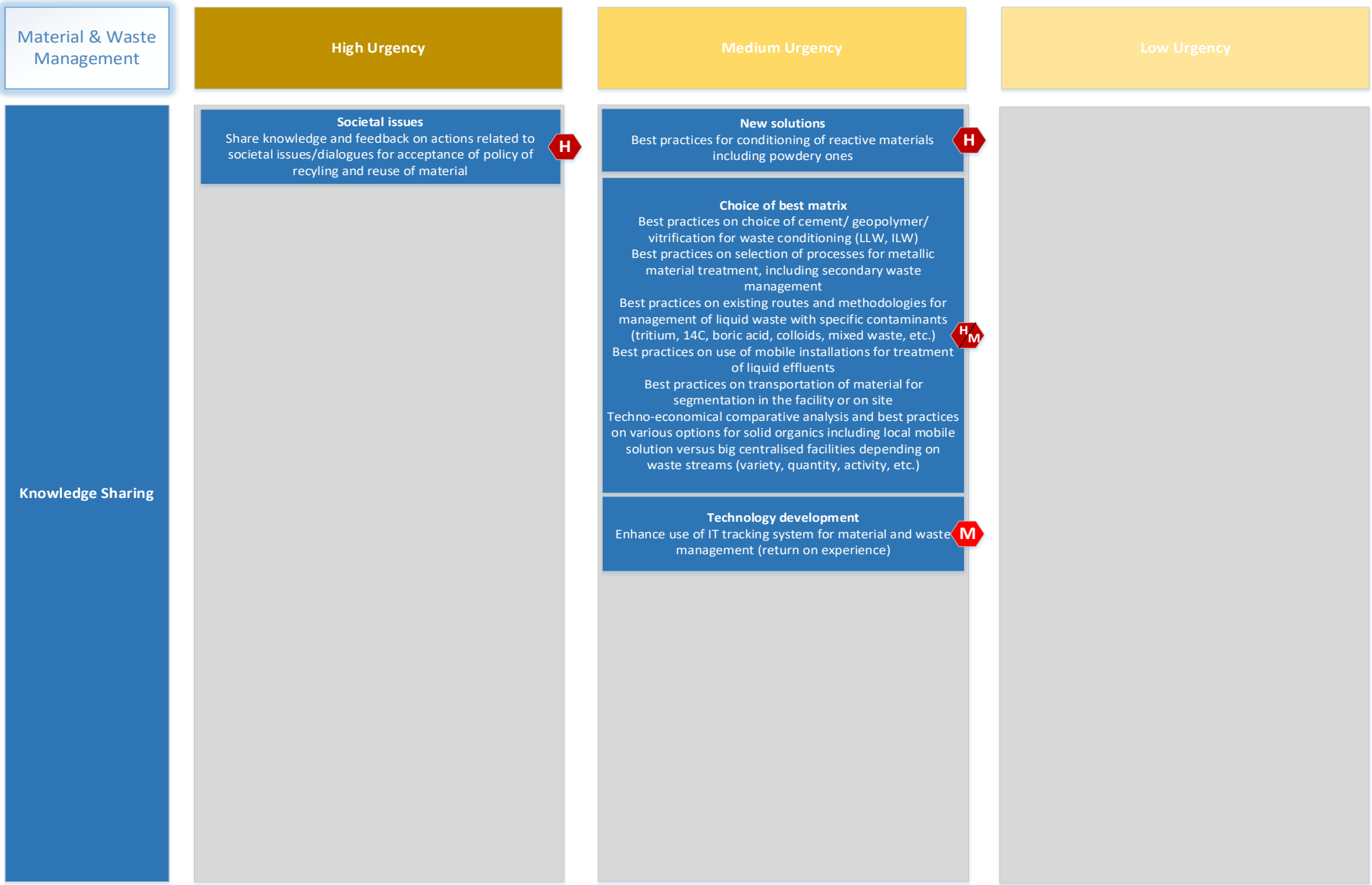
The stakeholders emphasised the need to minimise the amount of waste destined for disposal, thus reducing the burden on repositories, but also striving to increase the amount of material reused and recycled, in line with the application of the waste hierarchy, thus promoting a circular economy. Specific areas identified were development and benchmarking of technologies for recycle and reuse of materials (such as metals). Developments in this area would need to address both the technological (process) issues, the regulatory requirements for release and potentially societal engagement to enable recycling. The work highlighted the need to develop and demonstrate new innovative waste treatment technologies and decontamination processes to enable the circular economy. A further opportunity highlighted the potential for IT solutions to manage waste flows to enable optimisation.

The stakeholders also recognised the high urgency of developing waste routes for materials without established waste treatment routes or waste acceptance criteria (WAC). Mixed graphite waste, reactive materials and contaminated toxic liquids were specifically highlighted as high urgency and high/medium importance. Further to this the research highlighted the need to understand the long-term behaviour of waste forms, including alternative matrices and encapsulants such as geopolymers.

From a knowledge sharing perspective, the stakeholders recognised the high importance and urgency for collaboration on societal issues around the recycling of materials, if this approach is to be successfully implemented. The SHARE project dialogue also identified differences of knowledge ‘awareness’ between stakeholders, where for example a solution existed in one member state but this was not widely known elsewhere. Increasing the knowledge sharing around the best practices in waste management, selection of disposal matrices and in particular the development of treatments for problematic wastes was therefore identified.

The roadmap below also highlights how the harmonisation of practices/regulations, or international standardisation could facilitate the implementation of the recycle of materials from decommissioning and reduce the degree of duplication of work in different countries. Specific areas highlighted by stakeholders included standardisation of clearance levels for recycle and Waste Acceptance Criteria (WAC) /waste routes for problematic wastes. The ongoing EURAD Routes Project and PREDIS project are recognised as key vehicles for knowledge sharing in the waste management arena going forward.


Material & Waste Management
High Urgency
Medium Urgency
Low Urgency
RD&D
Waste routes for material not compliant with current WAC
Technical and non-technical actions to improve management of graphite mixed waste and contaminated toxic liquids and materials from decommissioning to disposal
H
Waste routes for material not compliant with current WAC
State of the art and R&D to improve management of contaminated asbestos and PCBs
Benchmarking, development and guidance on solutions for reconditioning of historical waste already conditioned
New treatment paths for specific contaminants in liquid waste
H M
Long-term performance
Development to demonstrate long-term behaviour of geopolymers
R&D to demonstrate long term behaviour of irradiated/ activated concrete from decommissioning
Actions to better master long-term performance, WAC and regulation - Need for demonstration
H M
New solutions
Development, industrialisation and promotion of emerging solutions at lab scale for waste treatment (to optimise volume of waste to disposal)
H
New solutions
Development (R&D, softwares, etc.) to better master hydrogen evolution in matrices
Actions to implement new developments for waste monitoring in storage facilities to better survey waste behaviour during storage
R&D and guidance to master impact of microbiological activity on waste stored in open ponds
Development of a characterisation platform to measure multi radionuclides directly for clearance (without need of nuclide vector)
New treatment paths for specific contaminants in liquid waste
H M
Circular economy
Benchmarking at international level for cost with comparison of solutions (storage on sites, centralised depository, recycling in and out of nuclear sector)
Actions to enhance recycling of metal (in and out of nuclear sector)
Development of processes and construction of metal melters to be able to process large items
Benchmarking to create opportunities at the international level for recycling inside the nuclear sector
H
Circular economy
Developments to simplify the handling of secondary waste from decontamination, fusion or other processing for metallic waste from decommissioning
M
Technology development
Actions to encourage use of new developments to better manage waste flows from production to disposal (IT tools and other emerging technologies)
H
Technology development
State of the art, guidance + development for small (mobile) facilities for treatment of small quantities of waste
Developments to increase TRL and the more widely use of mineral adsorbents to replace organic resins for treatment of contaminated aqueous liquids (adsorbent directly disposable; e.g. trapping radionuclides under radiation)
Demonstrate existing/new processes for treatment of organic liquids e.g. plasma under water etc. plus long term performances of innovative conditioning matrices
Benchmarking in oil/gas or hazardous waste sector (non-nuclear) for treatment processes for non aqueous liquids
Development and use of shock absorbers for transportation packages made of reusable material
H M
Technology development
Benchmarking in oil/gas or hazardous waste sector (non-nuclear) for the treatment of organic materials
Demonstrate already developed processes for treatment of organic liquids e.g. plasma under water, etc. and long term performances of innovative conditioning matrices
Development of optimised processes for management of ashes produced during thermal processes of ILW
M


Material & Waste Management
High Urgency
Medium Urgency
Low Urgency
Knowledge Sharing
Societal issues
Share knowledge and feedback on actions related to societal issues/dialogues for acceptance of policy of recyling and reuse of material
H
New solutions
Best practices for conditioning of reactive materials including powdery ones
H
Choice of best matrix
Best practices on choice of cement/ geopolymer/ vitrification for waste conditioning (LLW, ILW)
Best practices on selection of processes for metallic material treatment, including secondary waste management
Best practices on existing routes and methodologies for management of liquid waste with specific contaminants (tritium, 14C, boric acid, colloids, mixed waste, etc.)
H
M
Best practices on use of mobile installations for treatment of liquid effluents
Best practices on transportation of material for segmentation in the facility or on site
Techno-economical comparative analysis and best practices on various options for solid organics including local mobile solution versus big centralised facilities depending on waste streams (variety, quantity, activity, etc.)
Technology development
Enhance use of IT tracking system for material and waste management (return on experience)
M

Material & Waste Management	High Urgency	Medium Urgency	Low Urgency
Harmonisation of Practices	**International standardisation** Actions to enhance international harmonisation of WAC in terms of policy and regulation, in coordination with IAEA, NEA, WNA, WENRA, ENSREG, etc. Actions to enhance international harmonisation of clearance criteria for Solid/Liquid/Gaseous radioactive materials from decommissioning Actions to enhance harmonisation of practices in packaging (transport, storage, disposal) H/M Actions to enhance harmonisation of practices in VLLW management (metal, concrete etc.) regarding clearance and acceptance criteria Actions to define strategy and promote international sharing of facilities for treatment or storage of waste from decommissioning Guidance to improve the existing Clearance Criteria (values are missing for some isotopes in DIRECTIVE 2013/59/EURATOM and defined scenario for liquids)	**International standardisation** Guidance and enhance harmonisation of practices through coordination between waste producers and WMO's to provide best strategy for packaging: where? type? use of same containers for storage, transport and disposal, whatever storage extension? Actions to enhance harmonisation of practices for treatment of VLLW metallic and concrete waste, including recycling Actions to enhance harmonisation of practices in the regulation for authorised release levels in operation and in decommissioning phases (for boron, tritium, etc.) H/M Coordination for guidance on strategies for organic liquid waste management (with all actors along the value chain (and ideally with international experts) to brainstorm and propose solutions and future action plan Guidance to enhance co-ordination between waste producers and operators of melting systems (on requirements, on location)	**International standardisation** Actions to enhance harmonisation of practices in VLLW management Enhance the use of standardised practices in the field of waste management M/L
	Choice of best matrix Guidance on the best decontamination products/tools in terms of (chemical) aggressiveness linked to their evacuation as waste M	**Choice of best matrix** Guidance on methodologies and strategies in the choice of treatment process for LLW waste (efficiency, de-categorization, volume reduction, compliance with WAC, etc. H	**Choice of best matrix** State of the art, comparative analysis and guidance on various options for liquid organics including local mobile solutions versus big centralised facilities M
	Waste routes for material not compliant with current WAC Identify other needs and coordinate with ROUTES and PREDIS H		**Waste routes for material not compliant with current WAC** Guidance to improve management of broken packages M
	Circular economy Actions to homogenise good practices in recycling of released materials H		

1.5 Dismantling & Decontamination

Dismantling of nuclear facilities involves decontamination of structures and components, segmentation/cutting of components and demolition of buildings as well as management, handling, and segregation of segmented elements.

During the actual dismantling of a nuclear facility's components and structures, various techniques are involved, and they are chosen based on radiological criteria, availability of suitable equipment, complete knowledge of the problem, structured timings and cost-effectiveness of the proposed solutions. Most of the dismantling and decontamination techniques are already available and in use, nevertheless there is room for improvement.

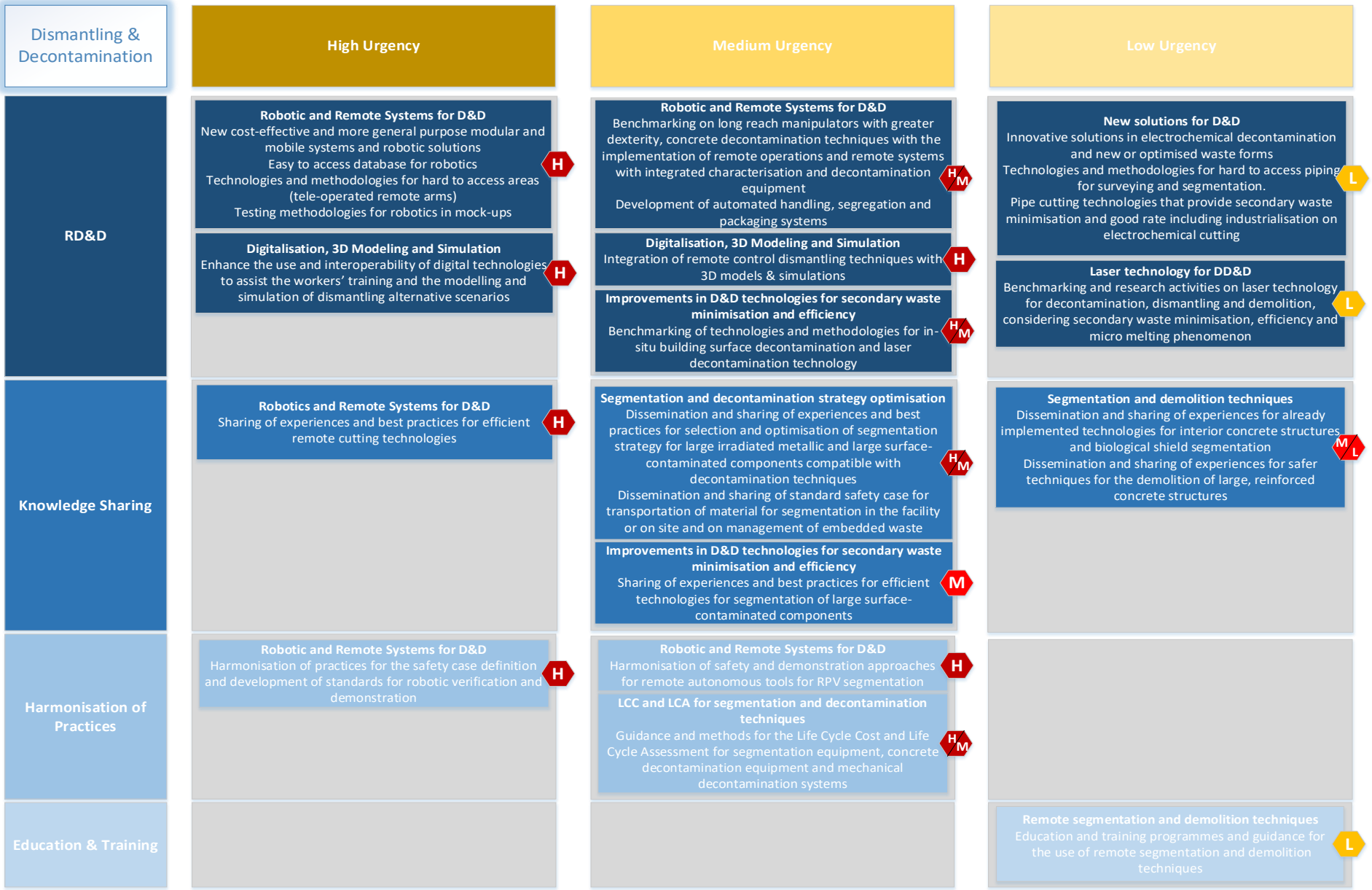
Stakeholders have identified, within the framework of SHARE, a number of actions related to the Dismantling and Decontamination area for which the implementation should help in improving safety, strategy optimisation, technology effectiveness and efficiency, life-cycle performances and secondary waste minimisation.

Today, in most of the cases, dismantling operations rely heavily on manual labour which is time consuming (i.e. costly) and not without risks for personnel. The key use of robotics and remote systems in dismantling applications is highlighted as a high urgent priority mainly to reduce the radioactive dose levels to which workers are exposed. In addition, more general purpose, modular and mobile systems and the enhancement in the use and in the interoperability of digital technologies to assist the workers' training and the modelling and simulation of dismantling alternative scenarios, will lead to an overall reduction of the project duration and cost.

The development and updating of an easy to access database that provides information on evaluated robotics for different tasks in decommissioning and the harmonisation of practices and demonstration approaches, can further enhance the use of such technologies and provide advantages in safety and standardisation.

Benchmarking of technologies and methodologies for dismantling and decontamination as well as guidance for the Life Cycle Cost (LCC) and Life Cycle Assessment (LCA) of the techniques are needed, with a medium urgency priority, to evaluate the impact on the dismantling task, to develop more efficient techniques and to minimise the volume of the secondary waste produced.

Moreover, the exchange and dissemination of operational experience in the field of dismantling and decontamination are needed to bring significant advantages for the selection and optimisation of a segmentation strategy and further enhance the efficiency and effectiveness of these complex tasks.


Dismantling & Decontamination
High Urgency
Medium Urgency
Low Urgency
RD&D
Robotic and Remote Systems for D&D
New cost-effective and more general purpose modular and mobile systems and robotic solutions
Easy to access database for robotics
Technologies and methodologies for hard to access areas (tele-operated remote arms)
Testing methodologies for robotics in mock-ups
H
Digitalisation, 3D Modeling and Simulation
Enhance the use and interoperability of digital technologies to assist the workers' training and the modelling and simulation of dismantling alternative scenarios
H
Robotic and Remote Systems for D&D
Benchmarking on long reach manipulators with greater dexterity, concrete decontamination techniques with the implementation of remote operations and remote systems with integrated characterisation and decontamination equipment
Development of automated handling, segregation and packaging systems
H M
Digitalisation, 3D Modeling and Simulation
Integration of remote control dismantling techniques with 3D models & simulations
H
Improvements in D&D technologies for secondary waste minimisation and efficiency
Benchmarking of technologies and methodologies for in-situ building surface decontamination and laser decontamination technology
H M
New solutions for D&D
Innovative solutions in electrochemical decontamination and new or optimised waste forms
Technologies and methodologies for hard to access piping for surveying and segmentation.
Pipe cutting technologies that provide secondary waste minimisation and good rate including industrialisation on electrochemical cutting
L
Laser technology for DD&D
Benchmarking and research activities on laser technology for decontamination, dismantling and demolition, considering secondary waste minimisation, efficiency and micro melting phenomenon
L
Knowledge Sharing
Robotics and Remote Systems for D&D
Sharing of experiences and best practices for efficient remote cutting technologies
H
Segmentation and decontamination strategy optimisation
Dissemination and sharing of experiences and best practices for selection and optimisation of segmentation strategy for large irradiated metallic and large surface-contaminated components compatible with decontamination techniques
Dissemination and sharing of standard safety case for transportation of material for segmentation in the facility or on site and on management of embedded waste
H M
Improvements in D&D technologies for secondary waste minimisation and efficiency
Sharing of experiences and best practices for efficient technologies for segmentation of large surface-contaminated components
M
Segmentation and demolition techniques
Dissemination and sharing of experiences for already implemented technologies for interior concrete structures and biological shield segmentation
Dissemination and sharing of experiences for safer techniques for the demolition of large, reinforced concrete structures
M L
Harmonisation of Practices
Robotic and Remote Systems for D&D
Harmonisation of practices for the safety case definition and development of standards for robotic verification and demonstration
H
Robotic and Remote Systems for D&D
Harmonisation of safety and demonstration approaches for remote autonomous tools for RPV segmentation
H
LCC and LCA for segmentation and decontamination techniques
Guidance and methods for the Life Cycle Cost and Life Cycle Assessment for segmentation equipment, concrete decontamination equipment and mechanical decontamination systems
H M
Education & Training
Remote segmentation and demolition techniques
Education and training programmes and guidance for the use of remote segmentation and demolition techniques
L

1.6 Environmental Remediation & Site Release

Environmental remediation involves different technologies and methodologies with the final goal of returning a site to the conditions that prevailed before the contamination and in compliance with the national legal and regulatory requirements. It is generally considered the last step in a nuclear decommissioning project because it prepares the site for its next use, eliminating ongoing contamination processes.

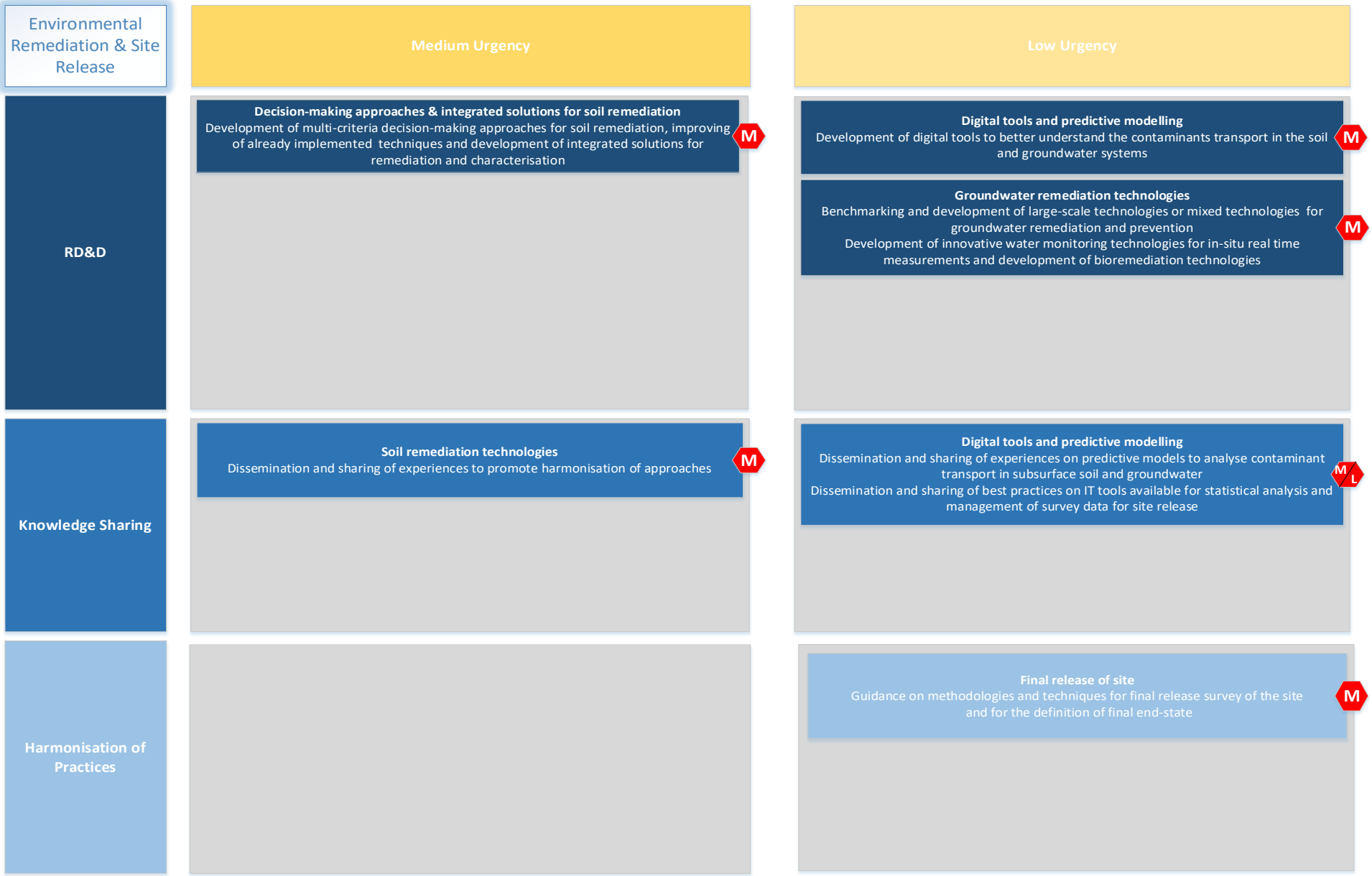
Environmental remediation involves different challenges mainly related to the characterisation methods and technologies used during the different phases of the process, from the first problem definition phase to the final release phase, and to the technologies and methodologies applied during the implementation phase to remove/reduce to acceptable level the contamination.

Multi-criteria decision-making approaches are used to choose the best alternative among a set of many solutions. Stakeholders have identified the development of a multi-criteria optimisation and decision-making technique, as a medium urgency priority that can facilitate the assessment of cost, end state and environmental protection, giving rise to a fairer, more consistent, and adequate final compromised solution or remediation process.

Moreover, collecting and sharing of knowledge and best practices on soil remediation techniques can lead to the harmonisation of the approaches and technologies to apply.

Contaminant transport models are often the only available means to reconstruct the origin of a contaminant release into the soil and groundwater. Stakeholders have identified, as low urgency, the need for improvements in the accuracy of predictive modelling to assess the migration of contaminants (in the soil and groundwater systems) and the need for dissemination and exchange of experience to improve the model building and long-time follow-up.

The Final Release of the Site is the last step of a series of surveys designed to demonstrate compliance with a dose- or risk-based regulation for sites with radioactive contamination. Many reference documents and standards are available to provide guidance on the release of sites or parts of sites from regulatory control after a practice has been terminated, however Stakeholders highlighted the need for further alignment and harmonisation on the release of sites or parts of sites from regulatory control and development of guidance on the definition of final end-state or the future of the site.


Environmental Remediation & Site Release
Medium Urgency
Low Urgency
RD&D
Decision-making approaches & integrated solutions for soil remediation
Development of multi-criteria decision-making approaches for soil remediation, improving of already implemented techniques and development of integrated solutions for remediation and characterisation
M
Digital tools and predictive modelling
Development of digital tools to better understand the contaminants transport in the soil and groundwater systems
M
Groundwater remediation technologies
Benchmarking and development of large-scale technologies or mixed technologies for groundwater remediation and prevention
Development of innovative water monitoring technologies for in-situ real time measurements and development of bioremediation technologies
M
Knowledge Sharing
Soil remediation technologies
Dissemination and sharing of experiences to promote harmonisation of approaches
M
Digital tools and predictive modelling
Dissemination and sharing of experiences on predictive models to analyse contaminant transport in subsurface soil and groundwater
Dissemination and sharing of best practices on IT tools available for statistical analysis and management of survey data for site release
M/L
Harmonisation of Practices
Final release of site
Guidance on methodologies and techniques for final release survey of the site and for the definition of final end-state
M

Implementation

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 codified in the Strategic Research Agenda (SRA) and this 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.

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[7] many instruments for collaboration were identified as relevant to the decommissioning context. Whilst it is not appropriate for the SHARE project to match specific instruments to specific scopes and tasks, it is possible to make the following observations:

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 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.

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, expert insight as provided by such groups is crucial for pertinent project development.

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

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.

[7] SHARE D3.3 Report identifying and comparing international collaborative research initiatives – Public deliverable

Acknowledgements

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Table 1 : List of SHARE Project Participants

Project participant	Country
CEA	France
EI (Efficient Innovation)	France
JRC	Europe
ENRESA	Spain
NNL	United Kingdom
SCK CEN	Belgium
SOGIN	Italy
IFE	Norway
KIT	Germany
VTT	Finland
LEI	Lithuania
EPRI	USA