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REGULAR ARTICLE

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Advancing sustainability and innovation in waste management and decommissioning within the Euratom HARPERS project

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Abstract. The HARPERS (HARmonised PracticEs, Regulations and Standards in waste management and decommissioning Harpers [1]) project aims to clarify and demonstrate the benefits of aligned methodologies and approaches in the fields of decommissioning and radioactive waste management. The duration is from June 2022 to June 2025, spanning a period of 3 years, and it builds on the outcomes of previous Euratom initiatives such as SHARE (NFRP-2018-5 Stakeholder-based Analysis of Research for Decommissioning (SHARE) [2]), EURAD (NFRP-2018-6 European Joint Programme on Radioactive Waste Management [3]), and PREDIS (NFRP-2019-2020-10 Pre-disposal Treatment of European Radioactive Waste Streams (PREDIS) [4]). By leveraging these foundations, HARPERS enhances collaboration across the European nuclear research community, engaging with key platforms including SNETP (Home – SNETP), DigiDECOM (DigiDECOM – IFE), OECD NEA (Nuclear Energy Agency (NEA) – Home), IG-DTP (IGD-TP | Safe Solutions for Radioactive Waste), IAEA (International Atomic Energy Agency | Atoms for Peace and Development), ENSREG (ENSREG |), and ERDO (Home – ERDO Association for Multinational Radioactive Waste Solutions). By fostering harmonization and stakeholder-driven approaches, HARPERS directly supports the objectives of the Euratom Research and Training Programme. The Euratom Research and Training Programme is a multi-annual framework programme, implemented by the European Commission, under the provisions of the Euratom Treaty, in which all EU Member States participate. The Programme promotes nuclear research and training, while fostering collaboration and innovation in key areas such as decommissioning and radioactive waste management. Through coordinated research actions and strategic partnerships involving Member States and international organizations, Euratom aims to keep Europe at the forefront of nuclear science and technology. HARPERS contributes to this vision by promoting more consistent and efficient practices across Europe's nuclear landscape. This paper presents the objectives and key achievements of the HARPERS project to date. It includes a brief overview of two related projects, PARCOVAL (PAlladium Recovery for CO2 VALorisation https://cordis.europa.eu/project/id/101166280 [5]) and MaLaR (MaLaR Novel 2D-3D Materials for Lanthanide Recovery from Nuclear Waste [6]), and highlights the outcomes of the online stakeholder engagement workshops conducted during HARPERS' first year. It also outlines the methodology used to prioritize topics based on stakeholder input during Phase 1, and describes the main deliverables planned for Phase 2.

1 Introduction

The management of radioactive waste and the decommissioning of nuclear facilities are critical challenges facing the European nuclear research community. Addressing these complex issues requires a coordinated, multi-disciplinary approach involving diverse stakeholders and research initiatives. Euratom Council Directives [7,8] and IAEA Safety Standards [9] provide the basis for the underlying legal and regulatory framework in radioactive waste management and decommissioning. However, the implementation of international safety standards and European Union (EU) directives can vary from one country to another as they are adapted to local considerations and national policies. These national differences

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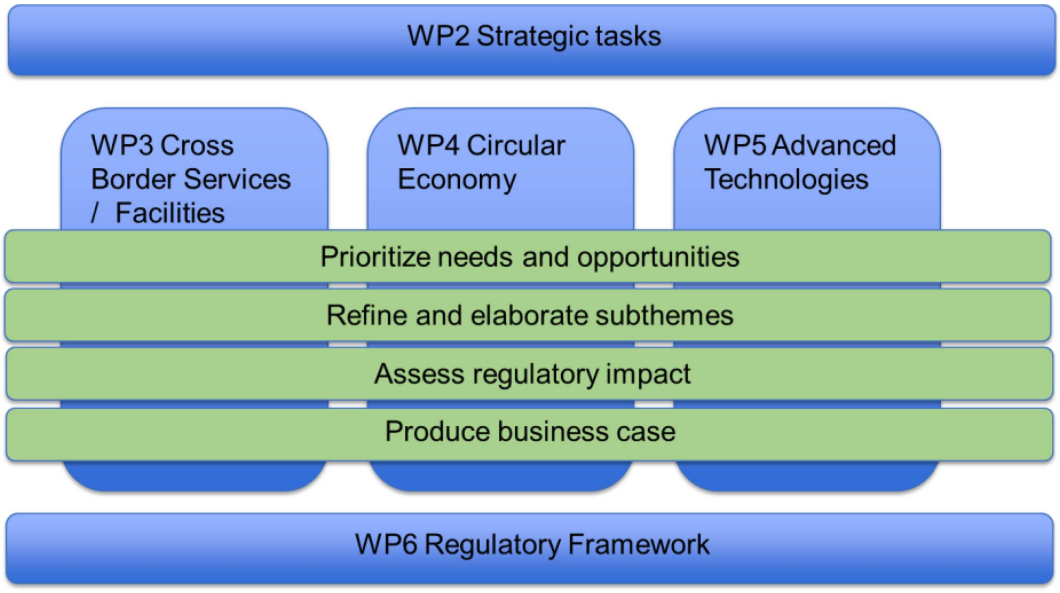

Fig. 1. Schematic overview of project scope and work package arrangement.

can create difficulties in interpreting and comparing waste management practices between Member States (MS) and establishing consistent and coherent waste management policies and implementation strategies at the European scale. Moreover, this lack of commonality may contribute to sub-optimal waste management outcomes in terms of safety, economics, sustainability and innovation, as well as public acceptance. However, a greater alignment of methodologies and approaches could support international cooperation among all relevant actors in nuclear decommissioning and radioactive waste management and could lead to expanded international market opportunities and more rapid adoption of advanced and/or emerging technologies. Alignment based on EU standards would also be advantageous towards enabling more robust comparisons of the efficiency, suitability and limits of available techniques being used in similar conditions. The HARPERS project's high-level objectives are to:

- improve scientific and technology-based solutions and foster the sharing of best practices to improve operational excellence in decommissioning, as well as minimizing operational, decommissioning, dismantling and secondary wastes production;
- engage interested players in sharing experiences on how to fulfil requirements, mainly from the industry and innovator perspective;
- support initiatives for the various actors involved, while providing competent evaluation by technical support organisations (TSOs) and regulators;
- identify the benefits of more aligned approaches and methodologies in line with European and International directives, recommendations, and best practices
- identify the needs and challenges in implementation the more aligned approaches and methodologies.

The schematic overview of the project is shown in Figure 1. Work package 3 (WP3) aimed to identify the most important needs and challenges for Cross Border Services/Facilities for radioactive waste management activities across Europe. Work package 4 aimed to identify the most important conditions and opportunities for promoting circular economy when managing materials and waste coming from nuclear decommissioning across Europe [10–12]. Work package 5 (WP5) aim was to identify and prioritize the needs and opportunities for advanced technologies.

The project consortium itself was well balanced across both geographic regions and types of organisations, comprising 30 partners from 14 members states.

2 Methodology in HARPERS

A good alignment of practices, methodologies and approaches will decrease the fragmentation of the European market, and therefore will contribute to cross-European mobility of industry and services, shared facilities, acceptance of advanced technologies and encourage implementation of circular economy principles [9]. For the project's success, it was essential to have a clear knowledge of previous and on-going initiatives so as not to duplicate actions in national or international programmes. HARPERS was deployed in a two-phase format (Phase 1 and 2), to ensure that the main focus/attention was given to the highest priority topics identified by stakeholders. The successful implementation of the HARPERS project was guided by a stepwise approach, depicted in Figure 2.

Phase 1a (between M0 to M12) started with building a Stakeholder Community which was established based on existing networks and the networks of the HARPERS partners. Having Stakeholders (SH) representing the complete waste management and decommissioning value chain is important because stakeholders are expected to provide important input to HARPERS at different stages of the project. Next, a thorough gap analysis of 400+

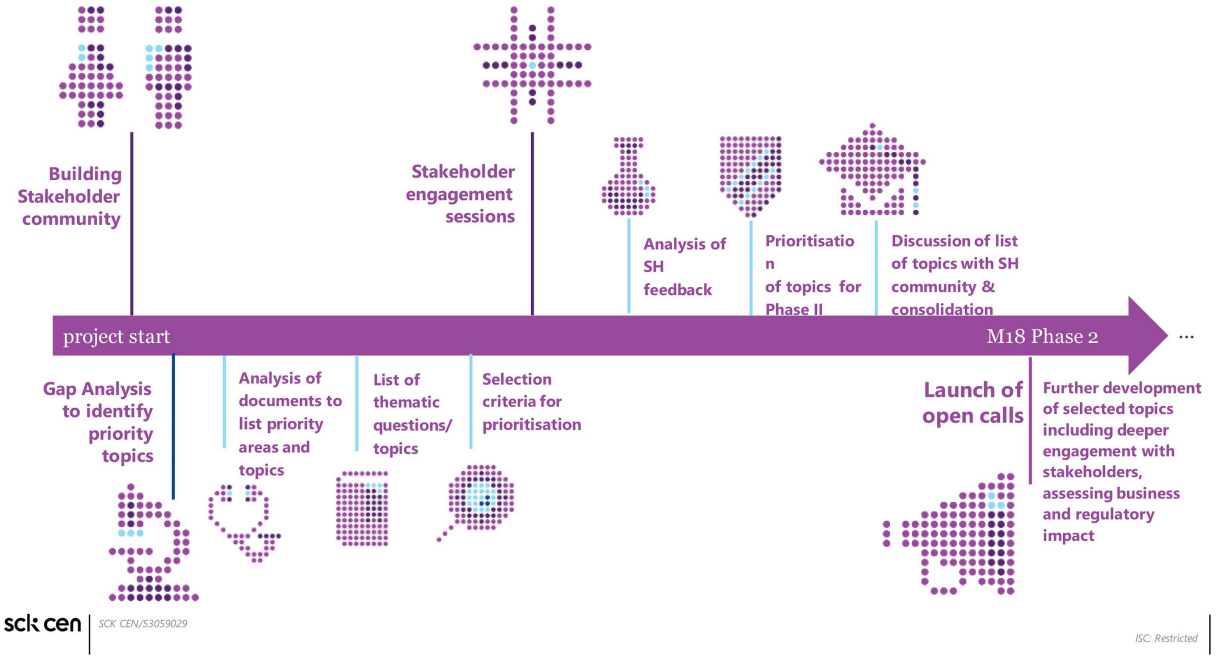

Fig. 2. Stepwise approach of Phase 1 of HARPERS.

documents were performed to identify topics for harmonisation and cooperation across the HARPERS interest areas. After setting the selection criteria for the topic prioritisation process, several stakeholder engagement sessions were held, followed by analysis of the received feedback and leading to the final prioritisation of topics. The prioritised topics were consolidated with the stakeholders in a closing workshop.

This last step was the starting point for Phase 1b (initiated at month 12), which included the Open Calls action, that ensured onboarding new consortium partners to further increase the project's expertise. The selection of these new partners was guided by a set of criteria established under the project, such as proven experience in the relevant topics, geographic diversity, and the perspective or approach they could bring to the project (e.g., regulatory, technology/service provision, customer). These criteria ensured that the new partners contributed meaningful value and expertise to strengthen the overall consortium, rather than duplicating. The priority topics were brought forward for deeper analysis in Phase 2.

The final selection of topics to be investigated in Phase 2 was based on a transparent approach considering prioritisation by stakeholders, relevance for the European community (economic potential, volume of waste, number of countries involved) and achievability (quick wins versus those requiring steep efforts). The prioritization process identified nine key topics (three for each of WP3, WP4, and WP5), and for each priority topic, a group of 3 to 5 partners was selected to further advance the topic. The project partners continued to review existing national and international practices, capture lessons learned and evaluate new opportunities for improvement and innovation. The work focused on identifying the enablers and blockers, while clarifying the gaps. Phase 2 (M18 to M36) also focused on deepening stakeholder engagement to discuss the findings and incorporate their perspectives on the selected priority areas.

To achieve its goal, Work package 6 (Regulatory Framework) established a regulatory advisory group consisting of parties involved in oversight of radioactive waste management (RWM) and decommissioning activities to ensure that regulator opinions and comments are captured.

3 Results

The successful implementation of the HARPERS project required (i) effective engagement with a wide Stakeholder Community covering EU MS and countries outside, including regulators, waste generators, waste management organisations, service providers and civil society representatives, (ii) clear and transparent criteria for setting the prioritization of topics that are evaluated in Phase 1, (iii) willingness of MS regulatory and governmental bodies to engage with the HARPERS consortium, (iv) a consortium with a broad range of expertise to provide scientifically and technically sound recommendations and conclusions during Phase 2, based on the prioritization results of Phase 1. All these aspects were achieved by following the two-phase approach which is described in the methodology section.

3.1 Setting up the stakeholder community

The project maintained a continuous focus on stakeholder engagement across all Member States. At the outset, a list of potential stakeholders was compiled, including

both organizational stakeholders (e.g., SNETP, IGD-TP, DigiDECOM) and individual stakeholders. Using expert judgment from the HARPERS consortium partners, the relevance of each identified stakeholder was assessed. In October 2022, HARPERS was introduced to the stakeholder groups via email, inviting them to join the HARPERS stakeholder community. Individual stakeholders were also contacted by the relevant consortium partner. National radiation safety regulatory bodies and associations of regulatory authorities were also approached during the proposal preparation phase, though some chose not to join the consortium to maintain their independence from the project's deliverables. Since radioactive waste management is a global issue, HARPERS considered it valuable to gather input from countries outside the EU/Europe as well. Currently, the HARPERS stakeholder community consists of 60 organisations, covering 23 countries of Europe, Japan and the USA and a wide variety of actors is represented.

3.2 Gap analysis

The project delivery was guided by a balance between technological interests (WP3-5), stakeholder interests (WP2), and regulatory interests (WP6). The challenges and needs identified during the proposal phase were discussed with Consortium members, and a gap analysis was carried out within the framework of WP2. This analysis resulted in over 400 records deemed relevant for the project, including strategic research agendas, position papers, final project reports, public deliverables, techdocs and websites. The gap analysis highlighted the key topics where HARPERS should focus to maximize its impact across various dimensions, such as scientific/technical, economic, societal, environmental, and regulatory aspects. Prioritization of these topics was done by using a structured process and an appropriate scoring method, leading to the grouping of relevant items into thematic topics.

3.3 Stakeholder engagement

A key requirement for the project is to ensure alignment of the priority topics with the needs of stakeholders. Therefore, the second step in the topic prioritization exercise was the interaction with internal and external stakeholders. Targeted stakeholder engagement efforts for Phase 1a began in 2022 and concluded in fall 2024. The stakeholders primarily represent organizations such as regulators, NPP operators, waste management organizations, and industry. Several other interactions took place, e.g. at DigiDECOM, meetings of EGRRS, IGD-TP, WENRA.

Between January and February of 2023, the project organized two online Stakeholder Workshops for WP's 3 to 5 to present and discuss the pre-defined list of topics already developed within HARPERS, based on the input of the different partners and on the review conducted on the existing literatures (including SRA, position papers, as well as past and on-going projects). Using Slido's live Q&A feature, the work package (WP) teams engaged all attendees, with 30 to 40 participants responding to questions during each workshop. All questions and poll results were captured in Slido Analytics, which could be downloaded for analysis. Participants actively engaged with Slido polls and contributed to open discussions. The participants represented a wide range of organizations, including waste management organizations, operators, technical support organizations, research entities, universities, industries, and consultants.

Discussions between the work package leads for WP2, WP3, WP4, and WP5 concluded that prioritization would be carried out by each individual work package, taking into account the findings from stakeholder engagement sessions. In each work package, topics were prioritized using a common set of selection criteria based on drivers for implementation. These drivers, societal, actor-specific, scientific, and financial impacts, were derived from the Strategic Research Agenda of the PREDIS project [4] and the SHARE project [2].

3.4 Final prioritisation of topics

While a common set of selection criteria was used across Work Packages 3−5, each work package identified the most relevant drivers for its specific scope. A semi-quantitative process was developed to derive prioritized topics from the workshop responses. The prioritization process and the top prioritized topics were presented and discussed during a joint stakeholder webinar for WP3, WP4, and WP5 in May 2023, to share the outcome of the stakeholder engagement process. The final selection of the top three priority topics to be further analysed in Phase 2 of the HARPERS project was made using an "Importance-Urgency" and "Impact-Effort" matrix.

3.4.1 Example of combined outputs from the HARPERS Stakeholder Workshops: WP5 advanced technologies

This work package aimed to evaluate the regulatory implications of using advanced technologies in waste management and decommissioning, identify opportunities for harmonisation of standards across MS and investigate and conclude on the need and benefits of the adoption and standardisation of advanced technologies to enhance waste management and decommissioning operations in Europe.

Based on the input from partners and interested externals and a literature review various topics of interest were identified that could be grouped into three categories: (i) waste treatment, (ii) automation/robotics and (iii) digitalization. Following the initial analysis, these topics were discussed with external stakeholders, leading to the identification of three tasks, which were subsequently processed and selected for Phase 2 of the HARPERS project. These tasks were designed to address the challenges and opportunities identified during the discussions, ensuring that the project's next steps were aligned with stakeholder needs and project objectives.

– Standardising Approaches to Technology Assessment and Qualification for Decontamination, Environmental Restoration, Waste Treatment and Immobilization

("Innovative waste management and decommissioning technologies Decontamination in the nuclear back end").
- Standardising Protocols and Systems to Support Adoption of Robotics and Automation in Decommissioning, Dismantling and Waste Management ("Adoption of robotics and automation in decommissioning, dismantling and waste management Robotics in the nuclear back end").
- Standardising Digital Twin and Advanced Building Information Management (BIM) Technology and Their Application ("DT and BIM for nuclear decommissioning DT and BIM in the nuclear back end").

The main purpose of these tasks was to provide a transparent picture of the challenges that innovative technologies are currently facing and to indicate the potential of standardization and harmonisation to mitigate these challenges without compromising safety and security. The technical results of these tasks will be documented in a position paper.

3.5 Development of prioritized topics, business cases and position papers in Phase 2

In Phase 2, the nine key topics identified in Phase 1 were further refined by collecting existing data and engaging with relevant international working groups to assess prior efforts and advancements. Further, each technical work package, collaborated closely with stakeholders to review the findings, identifying key enablers and blockers that could influence the development of the topics. Case studies, lessons learned, and good practices were also gathered, offering valuable insights into successful strategies and identifying challenges encountered. These case studies focused on understanding the factors that contributed to positive outcomes, such as effective methods or approaches, while also highlighting obstacles or barriers that hindered progress, adaptation, or deployment. This process helped to pinpoint critical enablers and blockers while also providing valuable lessons for future initiatives.

Comprehensive questionnaires were developed across all three work packages to gather targeted feedback from nuclear professionals and organizations both within and outside the HARPERS consortium. The survey ensured a holistic perspective. Once the responses were collected, a detailed analysis was conducted to extract key insights, identify trends, assess potential challenges or opportunities. Identifying the key enablers and blockers was essential to driving progress. The dimensions T-E-C-O-P (Technical, Environmental, Commercial, Operational, (Socio)Political) was adopted early by HARPERS, to categorize and understand the key enablers and blockers, to structure the collection and evaluation of relevant factors. This framework supported the creation of targeted questions, streamlined data collection, and helped engage relevant stakeholders and information sources. By utilizing T-E-C-O-P attributes, HARPERS was able to effectively assess the potential benefits and barriers and few risks associated with the topics. This approach ensured that both positive and negative factors were recognised and addressed, helping informed decision-making and strategic planning that guided the project towards successful outcomes. The analysis conducted and provided crucial insights for both the regulatory impact assessment and the development of the HARPERS business cases.

The HARPERS project developed business cases (BCs) for each three wp, in which cases for change (high level, strategic) are described to describe the potential benefits (related to T-E-C-O-P) of the proposed changes against a base line (current situations). The BCs were designed to communicate key messages to decision-makers, ensuring clarity and focus. Each BC included an executive summary, a problem statement outlining the need or gap, proposed solutions or recommendations, real-world examples, an assessment of benefits, and actionable recommendations.

3.5.1 Example of combined outputs from the HARPERS WP5 advanced technologies business case

Developing a business case in WP5 for emerging technologies involves more than just demonstrating cost efficiency. It requires a comprehensive evaluation of their strategic, economic, operational and sustainability impacts. The WP5 BC focused on the Strategic and Economic Cases, the initial stages of the Five Case Model, to establish a compelling rationale and evaluate project options for adopting innovative technologies in the nuclear back end, delves into specific challenges, opportunities, and frameworks supporting this transformation, setting the stage for informed decision-making and meaningful improvements in nuclear decommissioning and waste management. The Economic Cases presented in the WP5 BC report provides a generic framework for evaluating the adoption of innovative technologies in the nuclear back end. These analyses are intended to offer high-level insights and guidance. However, more quantitative and detailed evaluations would require application to specific use-cases, with tailored assessments of site conditions, regulatory frameworks, and technological specifications. Despite the generic nature of these cases, the analyses clearly prove a strong Economic Case for harmonization and alignment in the three areas (WP5 priority topics) addressed:

1. innovative decontamination, environmental restoration, waste treatment, and immobilization technologies),
2. robotics and automation, and
3. Digital Twin (DT) and advanced BIM technologies.

Harmonization or better alignment in these areas is critical to overcome key barriers such as fragmented regulations, inconsistent qualification standards, and interoperability challenges.

At DigiDECOM 2024, a breakout session dedicated to the EURATOM HARPERS project further explored the business case for the WP5 Advanced Technologies. Experts, policymakers, and industry leaders gathered to discuss the strategic and economic implications of the emerging technologies. The session underscored the value of long-term innovation and efficiency improvements

within the nuclear and safety-critical sectors. A key takeaway from this session was the critical role of standardization in facilitating the widespread adoption of these technologies. While the potential for increased efficiency and value creation is clear, participants identified several challenges that could hinder progress, particularly the diversity of regulatory frameworks across regions. These challenges can create barriers to the integration of new technologies, preventing their full potential from being realized. The session provided actionable insights on how stakeholders can address these challenges, with a focus on developing practical strategies for overcoming regulatory hurdles. In addition, participants discussed methods for assessing the return on investment (ROI) of these transformative technologies. The need for collaboration across sectors was emphasized as a critical factor for the successful integration of these technologies. By aligning efforts among experts, policymakers, and industry leaders, the nuclear sector can maximize the benefits of these innovations, ensuring that they contribute to be more efficient, safe, and sustainable practices in nuclear decommissioning and waste management.

In conclusion, the development of a business case for WP5 emerging technologies requires a comprehensive approach that evaluates not only the economic but also the strategic, operational, and sustainability impacts. The discussions at DigiDECOM 2024 reinforced the importance of standardization and harmonization across key technological areas, offering valuable guidance on how to address the challenges and capitalize on the opportunities these technologies present.

By the end of the Project, work package 2 will summarise the industry and business impacts resulting from all three BC (wp 3−5) project findings.

4 Recent projects in line with the HARPERS' orientations

Over the last years, sustainability has gained more and more importance, also in the nuclear sector. If nuclear energy wants to be considered as a green and sustainable solution, nuclear industry should embed this aspect in all its facets, and from cradle to grave. Within HARPERS, sustainability is addressed in WP4 (circular economy) and by the end of the project, recommendations towards circular economy and sustainability assessment in waste management and decommissioning will be provided.

On the international stage, the Euratom programme is growing emphasis on sustainability and circularity in nuclear energy. Recently, two new Euratom projects were launched that focus on the recovery of Critical Raw Materials from nuclear waste, contributing to enhanced sustainability within the nuclear sector. These initiatives complement the objectives of the HARPERS project by promoting resource efficiency and reducing the environmental footprint of waste management practices. Together, they reflect a broader sectoral shift toward harmonized, innovative approaches that align with global sustainability goals and support the role of nuclear energy in a low-carbon, circular economy.

PARCOVAL started in September 2024 aims to leverage the recognised catalytic capabilities of radioactive Platinum-Group Metals (PGMs) to demonstrate their potential for use and market. PARCOVAL will create two circular loops from two wastes: (1) recover Pd from spent nuclear fuel (today vitrified and considered a nuclear waste) and (2) reuse the CO_2 produced by an existing industry to perform CO_2 electroreduction into CO, a platform chemical for the chemical industry. PARCOVAL will also issue best-practice framework to ensure the safety and security of PGMs use in the industry, including radioprotection, traceability and collection after use [10]. The project consortium consists of 7 beneficiaries and 1 third party.

– The objectives of PARCOVAL are aligned with HARPERS WP4 (circular economy) and can be also linked to WP5 (Emerging technologies).

MaLAR started in January 2025 aims to develop an innovative approach leading to technology for the selective recovery of rare-earth metals from nuclear waste. It involves exploiting materials assembled from 2D sheets into 3D structures to improve the efficiency and selectivity of the recovery process of lanthanides from spent nuclear fuel. The project consortium consists of 4 beneficiaries and 1 third party.

– MaLAR's objectives align closely with HARPERS WP4, which focuses on circular economy principles, by demonstrating how nuclear waste can be transformed into valuable resources. Through its efforts, MaLAR highlights the potential for circular solutions to reduce environmental impacts, improve material efficiency, and support the sustainable management of resources within the nuclear sector.

These two new projects will contribute to a broader vision of sustainable resource utilization, driving improved environmental and economic outcomes within the nuclear sector and outside. HARPERS offers the potential to ensure that both PARCOVAL and MaLAR align their outcomes with established European and international standards. By collaborating with WP6 (Regulatory Framework) of HARPERS, both projects can gain valuable insights into the regulatory frameworks that govern decommissioning activities and radioactive waste management, enabling them to navigate regulatory complexities and support the effective deployment of new technologies and strategies within the nuclear sector.

HARPERS emphasizes the importance of stakeholder engagement and fostering collaboration through national and international platforms to enhance decommissioning processes and radioactive waste management. PARCOVAL and MaLAR stand to benefit from HARPERS' extensive experience in stakeholder engagement, helping to strengthen partnerships, address challenges, and uncover opportunities to improve the implementation of innovative solutions.

These collaborative initiatives, alongside EURAD-2, and the partnerships between HARPERS and its predecessors such as SHARE, PREDIS, and EURAD-1

highlight EURATOM's strategic approach to integrating shared knowledge platforms, joint research efforts, and collaborations with international organizations.

5 Conclusion

HARPERS focuses on delivering actionable outcomes, including a series of position papers that provide guidance on the technological, business, economic, and societal impacts identified across its core work packages (WP3 on cross-border cooperation, WP4 on circular economy, and WP5 on emerging technologies), as well as insights into the regulatory framework analysed in WP6. These position papers will serve as critical inputs to future strategic research agenda updates.

The HARPERS project's relevance is particularly high now, with the potential for significant impacts in the next 5−10 years. As the decommissioning markets expand and the demand for more efficient predisposal waste management services grows, the project's results can drive accelerated business offerings, boost confidence in market solutions, and reduce potential conflicts or litigation. By addressing key issues in decommissioning and waste management, the project lays a foundation for more effective and streamlined approaches in the sector, contributing to long-term sustainability and operational excellence, while reducing conflict and litigation. By integrating stakeholder input, the project was able to evaluate potential challenges across all selected topics, propose business models, and ensure that proposed solutions are both feasible and in compliance with current and anticipated regulations. Collaboration across work packages (WPs) and input from stakeholders was crucial in shaping HARPERS' business cases.

Projects like PARCOVAL and MaLaR align closely with HARPERS, creating valuable collaborative synergies, both projects aim at advancing key circular economy objectives explored in HARPERS's WP4. By collaborating, these projects can share knowledge, integrate solutions, and build on each other's findings to accelerate progress in waste management and sustainability within the nuclear sector. This collaborative approach enhances the impact of each project, fostering innovation and ensuring that the outcomes are more comprehensive and aligned with the broader goals of the Euratom programme.

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Conflicts of interest

There is no financial or professional conflicts of interest that could have influenced the research presented in this manuscript.

Data availability statement

Requests for data may be submitted to the corresponding author at `reka.szoke@ife.no`. In cases where ethical or confidentiality constraints apply, anonymized datasets may be shared upon reasonable request, pending the required approvals.

Author contribution statement

Each author has made substantial contributions to the development of this research over the past three years of the project, ensuring the quality and reliability of the work. The data presented in the manuscript have been approved by co-authors, validating its accuracy, transparency, and integrity.

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