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**REPORT FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE
COUNCIL AND THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE**

Ex-post evaluation of the Euratom Research and Training Programme 2014-2020

{SWD(2024) 271 final} - {SWD(2024) 272 final}

1 Introduction

1.1 Purpose of the evaluation

This report presents the results of the *ex post* evaluation of the Euratom research and training programmes for 2014-2018¹ and 2019-2020² ('the Programme')³. The purpose of this report is to analyse the rationale, implementation and achievements of the Programme, as well as the longer-term impacts and sustainability of measures taken as part of the programme, to inform the preparation and design of future Euratom programmes.

The evaluation is based on the legal requirement in the regulations laying down the programmes⁴. The evaluation was carried out by the Commission with the assistance of independent experts selected on the basis of a transparent process. The report is structured according to the main evaluation questions, ending with conclusions. Annexes to this report set out the findings and recommendations from the experts and the Commission's own observations. The evaluation is underpinned by an extensive body of evidence, including: (i) four thematic studies prepared by experts on indirect actions taken as part of the programme (these thematic reports are based on project reports, deliverables and interviews with coordinators); (ii) the report from the Commission expert group on direct actions; and (iii) a stakeholder consultation. The report is accompanied by two staff working documents, one for direct actions and another for indirect actions. These two staff working documents present a detailed assessment of the activities of the Programme, the methodology used, and the results of the stakeholder consultation. The main limitation of this evaluation is that any picture of the Programme's results and impacts can only be partial at present. The evaluation is taking place 3 years after the end of the Programme, while almost a third of projects (29) will be completed in 2024 or 2025. The key challenge for the evaluators is the long timespan required for projects to demonstrate their impacts, and this complicates monitoring and the evaluation processes. Although the Programme helped to produce important research results, significant impacts from these research results (such as the introduction of new solutions and techniques by nuclear power-plant (NPP) operators and new designs or influences on the regulatory framework) will require more time to become apparent. These long-term effects are also more difficult to capture through the usual indicator systems, and often need complex investigative work to match outputs from past projects with eventual impacts many years later, sometimes in different technical areas. Data limitations include issues related to data availability and the

¹ Council Regulation (Euratom) No 1314/2013 of 16 December 2013 on the Research and Training Programme of the European Atomic Energy Community (2014-2018) complementing the Horizon 2020 Framework Programme for Research and Innovation (OJ L 347, 20.12.2013, p. 948).

² Council Regulation (Euratom) 2018/1563 of 15 October 2018 on the Research and Training Programme of the European Atomic Energy Community (2019-2020) complementing the Horizon 2020 Framework Programme for Research and Innovation, and repealing Regulation (Euratom) No 1314/2013 (OJ L 262, 19.10.2018, p. 1).

³ Article 7 of the Euratom Treaty, which is the legal basis for research and training programmes, places a 5-year limit on the length of these programmes. For this reason, in order to follow the 7-year cycle of the EU's multiannual financial framework, Euratom programmes are proposed first as a 5-year programme followed by a 2-year programme.

⁴ Art. 22(1) of Council Regulation (Euratom) No 1314/2013 and Art. 22(1) of Council Regulation (Euratom) No 2018/1563.

measurability of outcomes. To mitigate these limitations, the staff working documents are transparent in indicating their data sources.

1.2 The Euratom research and training programme (2014-2020)

The Programme was the EU's main funding programme for nuclear research for this period, with a budget as set out in the table below.

	2014-2018 programme (EUR)	2019-2020 programme (EUR)	Total (EUR)
Direct actions (fission only)	559 562 000	268 807 000	828 369 000
Indirect actions (fission)	315 535 000	151 579 000	467 114 000
Indirect actions (fusion)	728 232 000	349 834 000	1 078 066 000
<i>Total</i>	<i>1 603 329 000</i>	<i>770 220 000</i>	<i>2 373 549 000</i>

The Programme focused on maintaining the highest nuclear-safety standards and EU's skilled workers in the nuclear domain. To this end, the Programme aimed to: (i) support research and training; (ii) improve the safety of existing and future NPPs; and (iii) improve protection from ionising radiation, including through safe radioactive-waste management and decommissioning activities. In addition, the Programme funded the development of fusion energy, a long-term option for large-scale, low-carbon electricity production, which could help address energy demand in the future. The details on the specific objectives of the Programme are provided in Box 1.

<u>Box 1. Specific objectives for 2014-2020 Euratom programmes</u>	
Indirect actions (research grants)	Direct actions (by the Joint Research Centre)
1. Safety of nuclear systems	1. Nuclear reactor and fuel safety, radioactive waste management, decommissioning, and emergency preparedness
2. Solutions for the management of radioactive waste	2. Nuclear security (safeguards, non-proliferation, combating illicit trafficking, and nuclear forensics)
3. Nuclear expertise and excellence in the EU	3. Nuclear science base for standardisation
4. Radiation protection and medical applications of radiation	4. Knowledge management, education and training
5. Demonstration of feasibility of fusion as a power source	5. Supporting EU policy on nuclear safety and security
6. Preparations for future fusion-power plants	
7. Innovation and industrial competitiveness	
8. Research infrastructures of pan-European relevance.	

The Programme was implemented through: (i) direct actions in fission in the form of research carried out by the Commission's Joint Research Centre (JRC); (ii) indirect actions in fission and fusion through research via competitive calls for proposals (in fission safety, waste management and radiation protection); and (iii) a comprehensive named-beneficiary co-fund action on fusion energy managed by the Commission's Directorate-General for Research &

Innovation (RTD). Euratom fission research falls under both direct and indirect actions, while all Euratom fusion research falls under indirect actions managed by DG RTD.

Euratom research and training programmes have been implemented by the Commission since 1959. Council Regulations laying down these programmes set out the broad lines of action and set out the indicative financial amount to fund them. Euratom work programmes for direct and indirect actions are adopted by the Commission, which set out the detailed priorities, budget and instruments to be used, usually on 2-year basis.

2 Summary of main findings

2.1 Programme relevance

The general objective of the Programme in 2014-2020 was to pursue nuclear research and training activities with an emphasis on continuously improving nuclear safety, security and radiation protection. Secondly, the Programme also aimed to contribute to the long-term decarbonisation of the energy system in a safe, efficient and secure way. The Programme's objectives and scope were based on the compromise reached by the Council following the Fukushima nuclear accident in March 2011. In line with this compromise, the Programme aimed to ensure the safe use of nuclear technologies, striking the right balance between the need to support the safety of existing nuclear technologies in Europe and the need to underpin safety in the future.

The results of the evaluation show that the Programme supported highly relevant research and training actions in nuclear safety, security, and radiation protection, helping to ensure that Europe meets the highest standards in these fields. At the same time, the Programme contributed to the long-term decarbonisation of the EU energy system by providing a knowledge base and solutions for: (i) the long-term operation of existing NPPs; (ii) the development of fusion energy; and (iii) the safety case for advanced nuclear systems. Consultation revealed that the Programme was also pertinent for research stakeholders and end-users of nuclear research, i.e. the nuclear industry, operators of power plants, and safety authorities. The relevance of actions proposed in the work programmes was also shown by the sustained interest in the competitive calls. In line with the work programmes, the Programme funded a portfolio of 96 research and training projects, 3 European joint programmes (EJPs) and JRC actions supporting research relevant for specific objectives (see table below).

Specific objective	Euratom indirect actions launched during 2014-2020
Nuclear safety	<ul style="list-style-type: none"> – Safety of existing NPPs and other nuclear installations including long-term operation: 32 projects – Safety of advanced nuclear systems: 13 projects – Decommissioning & dismantling: 7 projects – Other projects for safety: 6 projects
Radioactive-waste management	<ul style="list-style-type: none"> – Geological disposal of spent fuel and long-lived radioactive waste, predisposal research: EURAD joint programme and PREDIS project – Specific scientific and technological issues in waste characterisation, treatment, disposal and monitoring: 13 projects
Nuclear expertise and excellence	Support for training and mobility activities maintaining multidisciplinary nuclear skills: 15 projects (in addition, all Euratom-funded research and innovation actions dedicated about 4-5% of their budget for training (at PhD level and below))
Radiation protection and medical	<ul style="list-style-type: none"> – Research on the risks from low doses due to industrial, medical or environmental exposure: CONCERT Euratom joint programme, RadoNorm project – Optimisation of radiation protection in medical applications of ionising radiation

applications of radiation	(imaging, radiotherapy): 4 projects – Research on securing EU production of medical radioisotopes in research reactors: 1 projects
Fusion energy (feasibility, preparations for future fusion-power plants, innovation)	– Introduction of a new organisation of fusion research (EUROfusion consortium) – Development and implementation of the roadmap focused on: (1) experiments on fusion devices to provide a basis for extrapolations to ITER and fusion-power plants; (2) development of power-plant design and technologies for future fusion-power plants (materials, breeding blankets, etc.) – Fusion technology transfer to industry (EUROfusion action)
Research infrastructures	Support for the qualification of innovative fuel for research reactors (2 projects), securing access rights to future research reactors (1 project), support for the coordinated use of research reactors in Europe (1 project), preparations of IFMIF-DONES (1 project)

Indirect actions (research grants and training actions)

a) Safety of nuclear systems

The Programme funded projects in fission research focused on crucial safety-related issues, (including issues such as the operational safety of NPPs and safety features for new designs), in line with the work programmes and based on feedback from ongoing research. The increasing average age of the fleet of NPPs in Europe required – and still requires – particular attention to their ageing and long-term operation strategies. Research is needed to understand the degradation mechanisms of safety-relevant components and the impact of this degradation on overall safety. The knowledge produced by this research can support a science-based assessment of the safety margins and make possible the timely implementation of safety improvements. The predictive tools and assessment methods produced by research of this type will benefit periodic safety reviews of existing nuclear installations. They will also help regulators to assess new designs. Research funded by the Programme, in particular research on enabling the long-term operation of NPPs, also demonstrated significant cross-cutting benefits of nuclear research for energy and climate policies, as well as for security of energy supply.

b) Development of safe, longer-term solutions for the management of radioactive waste

Research actions launched through subsequent Euratom work programmes aimed to help Member States address key issues for the safe and effective management of radioactive waste in the EU, as required by Directive 2011/70/Euratom establishing a Community framework for the responsible and safe management of spent fuel and radioactive waste. The issues addressed by these research actions included: (i) the safety of future geological disposal facilities; (ii) the conditioning of radioactive waste; (iii) the long-term behaviour of spent fuel in a repository; and (iv) the clean-up of decommissioned sites. The Programme's actions also aimed to deploy joint programming in this field to help Member States to develop and implement their national waste programmes.

c) Development and sustainability of nuclear expertise and excellence in the EU

The Programme funded specific actions to maintain critical skills and capacities in the nuclear sector. And in line with work programmes, the Programme dedicated part of the budget of all research and innovation actions to this end. The use of nuclear technologies in all areas of application as well as nuclear safety and security require a highly specialised workforce and preservation of the knowledge base. The overall workforce situation in the EU was – and

continues to be – at risk due to retirements and a decline in the number of students studying relevant subjects.

d) Radiation protection and the development of medical applications of radiation

Through calls for proposals, the Programme funded actions which: (i) enabled a better understanding of the harmful effects of radiation from natural and artificial sources; and (ii) helped expand the beneficial applications of radiation technologies, in particular in the medical field (imaging and radiotherapies). Actions selected for funding in 2014-2020, included in particular the CONCERT European joint programme (EJP)⁵. This EJP followed a new approach promoted by European platforms for research in radiation protection in the five key areas of: low-dose risks; dosimetry; emergency and preparedness; radioecology; and medical applications. Further multidisciplinary research that integrates different scientific communities is needed to determine the mechanisms involved in these risks and to quantify the risks of latent cancers and vascular diseases at these low doses.

e) Fusion energy research (demonstration of feasibility, power-plant preparations)

The evaluation highlights the relevance of Euratom-funded actions for making progress towards two of the Programme's specific objectives: demonstrating the feasibility of fusion as a power source and preparing for future fusion-power plants. To achieve this progress (97% of milestones achieved in 2020), the organisation of Euratom-funded fusion research required a new approach, as mandated by the Council Regulation. In 2014, European fusion laboratories set up a new research organisation, the EUROfusion consortium, which implemented an EJP centred around the fusion roadmap and based on eight thematic 'missions'. The fusion roadmap represented a comprehensive, detailed and goal-oriented approach to developing magnetic-confinement fusion as an energy source. Its implementation enabled considerable progress towards establishing the scientific basis for constructing and exploiting ITER⁶, the international nuclear fusion research project, and advancing the technical basis for a future fusion-power plant. The new organisation allowed national laboratories with substantial national co-funding (45% of the consortium's budget) to join forces in the exploitation of common research facilities by 5 815 researchers, engineers and support staff (734 active doctoral students in 2020), leading to a wide variety of discoveries and knowledge creation (through 5 350 peer-reviewed publications). The relevance of EUROfusion actions was confirmed by ITER and the Euratom Scientific and Technical Committee.

Direct actions by the JRC

The *ex post* evaluation has demonstrated the relevance of the direct actions against the specific objectives by the Programme, namely: (i) improving nuclear safety and nuclear security; (ii) increasing excellence in the nuclear science base for standardisation; (iii) fostering knowledge management, education and training; and (iv) supporting nuclear-related policies. By meeting these objectives, the JRC's nuclear research has helped to address

⁵ Since Horizon Europe and the Euratom Programme 2021-2025, EJPs have been renamed European Partnerships. The terminology used in the Euratom Programmes 2014-2020 is retained here.

⁶ See <https://www.iter.org/>

existing needs and challenges in the nuclear field, therefore displaying continued relevance. The relevance was continuously: (i) ensured through necessary changes to the JRC's bi-annual work programme, (ii) examined against the Programme's specific objectives; and (iii) adjusted to changes in the nuclear landscape.

Over the evaluated period, the relevance of the JRC's activities was also verified through its research on nuclear materials. This research both: (i) strengthened the safety analysis for the possible long-term operation of the EU's current nuclear fleet; and (ii) laid the ground for the safety assessment of new nuclear designs such as small modular reactors (SMRs). Direct research on reference materials has helped to harmonise the measurement of radioactivity in the environment inside and outside the EU, meeting the overall objective of increased standardisation. The JRC's expertise also assisted in the implementation of the Euratom nuclear safeguards system. In 2014-2020, the development by the JRC of the EUSECTRA training centre was instrumental in meeting the objective of strengthening nuclear-security capacities in the EU Member States by training more than 1 600 front-line and law-enforcement officers in nuclear detection and forensics. Long-standing expertise and breakthrough research by the JRC, enabled by the direct actions in the field of medical applications of nuclear science, also had a significant impact for cancer treatment.

Through its activities, the JRC supported the objectives of: (i) building and maintaining essential skills; and (ii) supporting knowledge management in the fields of nuclear safety, security and safeguards in the EU. This was also made possible, in large part, through the open-access programme to its research facilities, which benefited 84 institutions from 23 Member States and associated countries over the evaluated period, producing 140 scientific papers and enabling the achievement of 64 PhD theses as direct outputs.

The independent technical and scientific expertise acquired by the JRC through the Programme supported other European Commission DGs in three areas of implementation. This supported the implementation of Council Directives on nuclear safety⁶, spent fuel and radioactive-waste management⁷, shipments of radioactive waste and spent fuel⁷, and basic safety standards⁸. JRC's technical and scientific expertise also contributed to the implementation of the Instrument for Nuclear Safety Cooperation⁸ and addressed nuclear and radiological aspects of the Instrument contributing to Stability and Peace⁹.

To fulfil the objectives laid out in the Programme, the JRC participates in the appropriate fora, networks and technological platforms such as: (i) SNE-TP (Sustainable Nuclear Energy Technology Platform); (ii) IGD-TP (Implementing Geological Disposal for radioactive waste Technology Platform); (iii) the EERA (European Energy Research Alliance) joint programme on nuclear materials; and (iv) the European Nuclear Education Network Association. The JRC has also concluded collaboration instruments with a variety of partners, including: (i) key stakeholders from EU research institutions; (ii) international partners (such as the International

⁷ Council Directive 2006/117/Euratom of 20 November 2006 on the supervision and control of shipments of radioactive waste and spent fuel.

⁸ Council Regulation (Euratom) No 237/2014 of 13 December 2013 establishing an Instrument for Nuclear Safety Cooperation.

⁹ Regulation (EU) No 230/2014 of the European Parliament and of the Council of 11 March 2014 establishing an instrument contributing to stability and peace.

Atomic Energy Agency and the OECD-Nuclear Energy Agency); and (iii) institutions from non-EU countries like the US Department of Energy or Japan's Atomic Energy Agency. The goal of the collaboration instruments with these partners is to identify the critical areas of nuclear research where the JRC's nuclear activities are most relevant and present a critical interest for the Euratom Community.

2.2 Programme effectiveness

Evidence from completed and ongoing actions indicates that direct and indirect actions have made a tangible contribution to achieving all of the Programme's objectives across the board¹⁰.

Indirect actions – Fission

By the end of 2020, the Commission had published five calls for proposals in fission research. There were 98 projects selected, engaging an estimated workforce of around 8 000 people including 200 scientific managers (2.5% of the 8 000 engaged), 5 000 experienced researchers (62.5%), 500 researchers (6.25%), 800 PhD students partially or full-time on a project (10%) and 1 500 in other sectors (engineers, technicians, administrative support) (18.75%).

The projects on nuclear safety produced many relevant results. In some cases, these results made significant progress on the original state-of-the-art in the main areas of safety and long-term operation of existing NPPs, future concepts and decommissioning. The main achievements include:

- the setting up of advanced computer models and simulations for safety analysis – including in the event of severe accidents – of different reactor systems (Generation II and III of NPPs);
- the preparation of strategies to manage severe accidents to ensure in-vessel retention of the melted reactor's core;
- contribution to the safety demonstration and assessment of generic design Generation IV reactors as well as testing and qualification of safety-relevant components;
- the production of databases on accident scenarios for all existing and new types of NPPs in Europe;
- the production of databases on irradiated materials and models for assessing the long-term integrity of primary systems and components;
- the preparation of protocols for fatigue-testing NPP components;
- the design and testing of innovative backup cooling systems that can be retrofitted into existing NPPs and included in future NPPs;
- the development of advanced materials for nuclear systems, including computer models to evaluate radiation effects, and the development of new structural materials and their stress testing;

¹⁰ For more details see accompanying Staff Working Documents.

- tools and methods for safe decommissioning and dismantling, which should reduce risks.

In some cases, outputs and deliverables are already being used by project stakeholders (industries, utilities, transmission-system operators, safety authorities, etc.) and end-users.

The Programme has been successful in the area of radiation protection by: (i) bringing together several research platforms, organisations and institutions for the very first time in the EU; and (ii) developing the very first joint roadmap for radiation protection. Lessons learned from the drafting of this first roadmap are already reflected in the development of a more specific strategic research agenda (SRA) in the medical field as part of the EURAMED rocc-n-roll project. In addition, the CONCERT platform conducted the very first calls making use of the lessons learned from other calls under EJPs. In parallel with the preparation of the SRA, 13 fundamental research projects were successfully conducted with promising results. The Programme made a clear contribution to risk assessment, the optimisation of radiation protection and the management of both radon and naturally occurring radioactive materials (NORM).

There were major achievements in 2014-2020 in the geological disposal of radioactive waste and spent fuel, such as: (i) the granting of licences for repositories in crystalline rock in Finland and Sweden; (ii) the construction and operating-licence application for a repository in clay in France; and (iii) siting progress (e.g. in Switzerland). This indicates that different concepts of geological repositories in various host rocks have reached the necessary scientific and technological maturity to support safety assessment and industrial deployment. In those advanced Member States, strong national R&D programmes and Euratom projects co-funded over the decades, including the projects under review, were essential to reach the current status in implementing repositories of spent fuel and high-level waste. Throughout the successive programmes, the uncertainties (e.g. in relation to disposal performances and safety margins), were progressively identified and addressed at the right level. Consequently, the knowledge base made it possible to build a solid case when it comes to safety. First steps have now been taken to identify areas for optimisation and potential technological innovations.

Indirect actions – Fusion

Although fusion energy remains a long-term endeavour, the evaluation shows that in 2014-2020 the EUROfusion consortium made incremental progress following the roadmap, achieving 97% of the milestones set for 2014-2020.

The EUROfusion consortium has also substantially reduced risks and improved the projected ITER performance, increasing confidence that ITER, once completed, will reach its baseline goals. The record-breaking 59MJ of fusion energy achieved at the Joint European Torus (JET) on 21 December 2021 is a clear success and the crowning achievement of the Programme. While the JET result provides the headline goals and integrated scenarios for ITER, it is backed by substantial progress in the understanding of the plasma physics of confinement. Predictive simulation tools have been validated against experimental results across different labs in Europe.

Progress has also been made in specific technologies for future fusion-power plants (materials, breeding blankets, etc.) and the DEMO¹¹ design effort. Candidate materials have been selected for all components of future fusion reactors, requiring a test facility for fusion materials. The engineering work behind the DEMO pre-conceptual design has brought much greater clarity to both a number of critical design issues and the overall integration challenge.

Nevertheless, DEMO research has not yet led to a conceptual design of sufficiently low risk to proceed to engineering design, particularly with regard to scenarios concerning plasma and power handling.

In the area of education and training, data from EUROfusion shows a positive trend in the number of doctorates working on relevant subjects (increasing by 9% year-on-year to 734 PhD students in 2020) and post-doctoral fellows (increase of 100% to 34 per year in 2020). This should maintain the number of fusion researchers at a level required for implementation of the roadmap.

Taken as a whole, fusion research supported by the Programme is a step towards ensuring that the EU has the know-how and skills to operate ITER once completed, while advancing in parallel on the scientific and technical basis of a future fusion-power plant. These dual objectives were – and remain – fundamental to the development of fusion as an energy source. The relevance of these actions becomes even more apparent when seen in a more recent context, characterised by: (i) intensifying international competition in the area of fusion research, including for talent; (ii) the emergence of a private sector active in the field, including start-ups; and (iii) strong investor interest.

Direct actions – Fission

The evaluation of the effectiveness of the JRC activities confirmed the JRC's impact on science and policymaking in the areas identified by the specific objectives of the Programme. In fact, the JRC's contribution was instrumental in shaping and supporting the implementation of EU policies in those areas, as illustrated by the following specific case studies, which were selected and evaluated by independent experts. These activities contribute to effectively meeting each of the specific objectives set for the direct actions as demonstrated by the following case studies:

- the EU's Clearinghouse on Operating Experience for NPPs;
- the JRC's participation in the European Safeguards Research and Development Association;
- the open access given to the JRC's nuclear research facilities;
- research on targeted alpha therapy;
- the CBRN (chemical, biological, radiological and nuclear) threats centres of excellence;

¹¹ The DEMOnstration power plant, for more information see <https://euro-fusion.org/programme/demo/>

- research on spent fuel characterisation to help improve the safety assessment of extended interim storage;
- support for the implementation of the Instrument for Nuclear Safety Cooperation (INSC);
- the implementation of the Instrument contributing to Stability and Peace.

The activities evaluated were deemed to achieve long-term societal impacts in over 90% of cases, addressing environmental, social or health issues. The evaluation also noted an improvement in the JRC's interactions with stakeholders and its policy relevance. The JRC made a noticeable contribution to scientific knowledge by producing well-cited and peer-reviewed work published in top scientific journals. Overall, based on the assessment of its research activities, the JRC is a competent and effective science and knowledge service.

Objective 1: Improving nuclear safety (including in nuclear reactors and fuels, waste management and emergency preparedness):

JRC research helped to improve the safety of nuclear reactors and fuels, and supported the safety assessment of ageing NPPs for long-term operation through the development of software for accident modelling; tools and reference data; and codes. This research also supported the safety and performance analysis of conventional nuclear fuels. Through the EU Clearinghouse for Operating Experience Exchange, operated by the JRC, nuclear safety has been improved by: (i) sharing best practices; (ii) producing topical studies; and (iii) maintaining data and analysis on incident occurrences in nuclear installations. The JRC also provided technical expertise to maintain and operate the EURDEP system to exchange radiological data and the ECURIE system to carry out the early notification of a radiological accident or emergency, thus supporting the fulfilment of the Council Decision 87/600 (ECURIE Arrangements) and the [Recommendation 2000/473/ Euratom](#).

On innovative technologies and Generation IV systems, the JRC carried out underpinning and applied research, focusing on radioactive waste management, nuclear safety and the proliferation resistance of advanced nuclear systems. This research contributes to the safety assessment of innovative nuclear technologies. The development and potential future contribution to a sustainable energy system of these technologies (in those Member States that decide to use them) have an impact on EU policies. In this context, the JRC is also Euratom's implementing agent on the Generation IV International Forum.

Direct actions in the area of radioactive-waste management covered scientific and technical aspects relevant to a sound strategy for radioactive -waste management. The direct actions also supported the development of regulatory and licensing procedures for the geological disposal of spent fuel and high-level radioactive waste. Research outputs stemmed from investigating the characteristics of spent fuel, as well as the properties and behaviour of spent fuel rods during storage.

Objective 2: Improving nuclear security (including safeguards, non-proliferation, forensics and illicit trafficking)

For nuclear safeguards and non-proliferation, the JRC helped to develop and support safeguard technologies through R&D, equipment development, and trainings for Euratom inspectors to ensure the effective implementation of the Euratom safeguards regime. Such technical support was also provided to both the International Atomic Energy Agency (IAEA) through the European Commission's Support Programme and to other stakeholders in order to strengthen the international safeguards regime. Other research activities (such as information collection, analysis, and studies on dual-use goods) aimed to strengthen the EU's nuclear non-proliferation regime. Nuclear security is a field in high demand amongst EU Member States, and the JRC's expertise in this area has focused on: (i) the detection of – and response to – illicit trafficking of nuclear and other radioactive materials; and (ii) capacity-building activities.

Objective 3: Increasing excellence in the nuclear science base for standardisation

In the field of environmental monitoring and radiation protection, research has aimed at harmonising the radioactivity measurements performed by national laboratories through various activities, including comparison exercises across laboratories to train staff across EU Member States. The JRC's state-of-the-art experimental nuclear facilities enabled the production of: (i) nuclear data; (ii) reference materials measurements; and (iii) conformity tools. These helped to keep nuclear data up-to-date and available, directly contributing to international reference-data libraries.

Objective 4: Fostering knowledge management, education and training

The research infrastructure was made accessible to external users from EU Member States via the open-access programme, as a way to complement national research and optimise the use of highly specialised infrastructure within Euratom. This enabled the JRC to continue playing a key role in knowledge management, education and training. The JRC also promoted knowledge and training through various courses and trainings.

Objective 5: Supporting EU policy on nuclear safety and security

The JRC's technical expertise helped support a variety of activities in nuclear safety and security. For example, the JRC supported the implementation of the Directive on the safe management of radioactive waste and spent fuel, by reviewing national programmes and periodic national reports. The JRC also supported the implementation of safeguards in the EU as part of the legal obligation derived from Chapter 7 of the Euratom Treaty. The JRC carried out dedicated activities to develop concepts, tools and methodologies directly supporting EU policy in this area. Improving nuclear safety outside of the EU has also been achieved through the Instrument for Nuclear Safety Cooperation, the effective implementation of which is supported by the JRC.

In the area of nuclear security and CBRN risks, the JRC has supported Commission programmes in non-EU countries through the Instrument contributing to Stability and Peace.

2.3 Programme efficiency

Indirect actions

Overall, the *ex post* evaluation shows a high level of efficiency in both the Commission's own management (e.g. grant management and proposal evaluation for indirect actions) and implementation by research consortia. The Commission kept its own administrative expenditure for indirect actions well below the average of 6.5% of the operational budget for 2014-2020. Simplification measures introduced from the start of Horizon 2020 and the Programme have greatly improved efficiency, in particular for the time-to-grant metric.

By 2020, five calls had been published under the Programme and, by the time these calls were closed, 254 eligible proposals had been submitted, requesting a total financial contribution of EUR 726 million. Of these eligible proposals, 98 were selected for funding, with a Euratom contribution of EUR 415 million.

The average time-to-grant for the Programme was 238 days (from 313 days for the Euratom programme 2007-2013).

Analysis of the efficiency of the EJPs in fusion research, radiation protection and radioactive waste, in particular in the areas of management and governance, is especially important as these instruments account for 75% of the budget for indirect actions.

The organisational architecture for fusion research underwent a major restructuring with the launch of the Programme. Fusion research had long been a field apart due to: (i) the nature and scale of the undertaking; (ii) the unique mix of instruments used; and (iii) the Commission's unique coordination role which, despite gradually diminishing since the 1990s, was still unlike what happens in other fields. To effectively implement the 2012 fusion roadmap, the organisation of fusion research supported through the Programme needed a new approach¹².

Following an independent evaluation, in 2014 the Commission awarded a 5-year grant to the EUROfusion consortium of national fusion laboratories and institutes to implement an EJP based on the fusion roadmap. In 2019, following the adoption of the Regulation establishing the Euratom Programme 2019-2020¹³, the EUROfusion grant was prolonged until the end of 2022. The total budget contribution from Euratom to the EJP was EUR 679 million, representing 51% of the consortium's total budget. The extension beyond 2020 provided for a smooth transition to a co-funded European partnership in fusion research – EUROfusion – still active today.

The effective integration of all national efforts across Europe represents a first for EU-supported research and includes comprehensive research activities in some 33 separate work packages (projects and taskforces). These separate work packages cover education and training actions, international cooperation aspects, industrial involvement, centralised programme management, and the efficient use of key resources through a truly transnational access approach to key facilities. Programme and project management – and their related

¹² This new approach was first presented in the Commission Staff Working Document *Towards a Modern Euratom Fusion Research Programme* (SWD(2013)213).

¹³ Council Regulation (Euratom) 2018/1563 of 15 October 2018 on the Research and Training Programme of the European Atomic Energy Community (2019-2020) complementing the Horizon 2020 Framework Programme for Research and Innovation, and repealing Regulation (Euratom) No 1314/2013 (OJ L 262, 19.10.2018, p. 1).

governance structures – have become more transparent, with information now readily available to the Commission, which retains overall monitoring and assessment responsibilities. Evaluation also showed that EUROfusion's 2014-2020 organisational structure was fit for purpose to continue to implement the fusion roadmap into the 2021-2025 programming period, assuming that the scope and breadth of the roadmap remains similar to 2014-2020.

JRC direct actions

Evaluation experts acknowledged: (i) efforts made to introduce a common project-management methodology across the JRC; and (ii) the increase in efficiency created by gathering all nuclear activities under one directorate. The total budget allocated for direct actions during the evaluated period of 2014-2020 was EUR 828 369 000.

During the same period, the JRC received an additional EUR 30 million per year as a specific credit to fund the decommissioning programme of some of its obsolete nuclear research facilities. While this financial contribution was separate from the budget for direct actions, the expenses for JRC staff involved in decommissioning activities were borne by the research budget.

In the budget execution for JRC direct actions, overall staff costs represented 55% of the budget, accounting for 710 people at the beginning of the reporting period in 2014, gradually reduced to 660 by 2020. This included staff carrying out activities under direct actions (around 47%) staff assigned to infrastructure, maintenance and radiation protection (around 12%), staff engaged in decommissioning activities (11%) and staff working in other support functions (29%).

In order to ensure the efficient monitoring of the JRC's performance as part of the research programmes, an organisation-wide yearly review is carried out. This exercise aims to measure both productivity and impact, assessing policy-support outputs and scientific publication in peer-review journals on the one hand and the policy-support impact of the output on the other.

Over the period 2014-2020, a variety of policy-support outputs (1 114 scientific and technical reports, 147 technical systems, 154 training courses) were delivered to specific users and in support to EU policies. Through the JRC's direct actions, a large number of scientific outputs were also produced, with 1 076 articles and conference-proceedings contributions published in peer-reviewed periodicals; 444 articles contributed to monographs or published in other periodicals; and 51 books or chapters of books. 28 PhD dissertations were also successfully completed by students who benefitted from the access to JRC facilities. Based on bibliometric indicators and impact metrics, the JRC's performance in terms of research publication ranked well above average with a respectable productivity, featuring amongst the most cited publications or in the most cited journals.

All these outputs have resulted in the provision of scientific support to EU policies, with 373 tangible impacts identified during the evaluation period. The COVID-19 pandemic had a significant negative impact on research activities in 2020 and resulted in some delays in the delivery of outputs. Nevertheless, a number of mitigating measures were put in place, ensuring continuity of the highest priority work in areas such as the nuclear safeguards

laboratories. The issue of open access to JRC nuclear facilities (made difficult because of lockdown restrictions) was also partially circumvented via remote monitoring of experiments, and a number of training courses were made available virtually.

The interim evaluation report of the Euratom Programme for 2014-2018 had recommended that the JRC provide proof of its cost-effectiveness. In response to this recommendation, a comparative study was carried out on three projects under indirect actions where the JRC's role was particularly relevant. This study showed that the cost-effectiveness of the JRC's participation was in line with that of other partners. Although experts also recommended in their evaluation that the JRC should develop key performance indicators for measuring the efficiency of its science for policy support, it is worth mentioning that a complete set of indicators has now been proposed for the 2021-2025 Euratom programme. This complete set of indicators will help to measure the impact pathway in the short, medium and long-term.

2.4 Programme coherence and EU-added value

The Programme was coherent internally and with other EU programmes and policies. Within the Programme itself, the Commission ensured links between fission and fusion research by supporting projects addressing topics relevant to both fields, such as materials research and tritium management. Synergies and complementarities between direct and indirect actions were also ensured through the JRC's participation in 38 projects out of the 86 granted under the indirect actions (as a member of research consortia) and by giving access to its research infrastructures to a variety of researchers.

This guaranteed the overall sharing of expertise and know-how. The JRC ensured coherence across the five specific objectives of direct actions described in the Programme and between the different research areas (safety and radioactive waste management; security and safeguards; education and training; and knowledge management). Moreover, in order to promote good cooperation between the different areas of activity, a new structure was adopted in 2016 inside the JRC to group all responsibility for the implementation of the Euratom direct actions under a single directorate. This led to improved communication and transparency, and had a positive impact on the effectiveness, efficiency and coherence of the activities carried out.

Coherence with other EU programmes and policies was assured through the JRC services and indirect actions' grant requirements to support implementation of Euratom Directives and Instruments¹⁴. Possible areas of improvement include the need to exploit synergies with other thematic areas of Horizon Europe in order to address cross-cutting aspects such as health, space energy systems and civil security research.

The Programme's external coherence with research programmes carried out by both EU Member States and international organisations was ensured through careful alignment of the scope of activity of the JRC. It was also ensured through the JRC's own participation in and exchanges with: (i) technology platforms or networks (such as SNE-TP (Sustainable nuclear energy TP), IGD-TP (Implementing Geological Disposal TP) or the EERA joint programme on Nuclear Materials); and (ii) associations like the European Nuclear Education Network.

¹⁴ See Section 1.3.

Bilateral cooperation agreements with external stakeholders also served to support the coherence of the JRC's work under the Programme at EU and global level. These external stakeholders also included the IAEA, the Organisation for Economic Co-operation and Development's Nuclear Energy Agency (OECD-NEA), and non-EU countries.

The Programme's EU-added value stemmed from the ability to mobilise a wider pool of excellence, expertise and multidisciplinary in fission and fusion research than would have been possible by individual Member States acting on their own.

This is demonstrated in the area of fission by the diverse portfolio of projects launched under the Programme. Another example is the joint exploitation of fusion-research infrastructures, which relies on the collective endeavours of researchers and engineers supported by Euratom funding from all across Europe (about 8 300 people during the period covered by the Programme). This broad-based coordination is of particular benefit to smaller Member States which can take advantage of the economies of scale afforded by the pooling effect. In fusion research, this is exemplified by smaller laboratories that can specialise in scientific topics or subsystems for fusion-research facilities in Europe to make significant contributions while maintaining visibility in the European consortium.

The EU-added value of the direct actions was grounded in the JRC's unique position as an independent and long-standing technical and scientific service, which supports the preparation, implementation and monitoring of EU policies, in particular the Nuclear Directives¹⁵ (i.e. the Nuclear Safety, Basic Safety Standards, Safety of Radioactive Waste and Spent Fuel, and Shipments of Radioactive Waste and Spent Fuel Directives). Another example was in the area of safeguards, where JRC expertise was essential in providing the necessary support to the Euratom safeguards system.

Overall, through the Programme, the JRC was able to develop further knowledge and maintain skills and expertise, therefore bringing added value to Euratom. This is exemplified, for example, in:

- the pooling of operational experiences in the EU through the Clearinghouse, which contributes to improved nuclear safety;
- the access to JRC nuclear infrastructures as part of EU projects, allowing external users to perform experiments not possible in their home organisation;
- the manning of an EU security-training centre providing training in nuclear safeguards and security to front-line officers, or the coordination of Euratom's research efforts in Generation IV systems as Euratom implementing agent in the Generation IV International Forum.

¹⁵ See Section 1.3

3 Conclusions and lessons learned to feed into the decision-making process

3.1 Conclusions

The evaluation concludes that the Programme significantly supported nuclear safety, security and radiation protection in the EU, helping to ensure that Europe meets the highest standards in these fields. At the same time, the Programme contributed to the long-term decarbonisation of the EU energy system by providing a knowledge base and solutions for the long-term operation of existing NPPs. The Programme also helped to advance both: (i) the knowledge and technologies necessary for the development of fusion energy; and (ii) the safety case for advanced nuclear systems.

The evaluation provides a number of important conclusions, six of which are set out in the paragraphs below.

1. Through cooperative research, the Programme enabled a Europe-wide approach to both: (i) the improvement of nuclear safety and radiation protection in all areas of application; and (ii) the challenge of developing fusion as an energy source. The Programme significantly increased the EU's ability to mobilise a wider pool of excellence, expertise and multidisciplinary in nuclear research, achieving impacts that extend far beyond what would have been achieved at national or regional level. This is of particular benefit to smaller Member States, which were able to take advantage of economies of scale afforded by the Europe-wide pooling effect and open access to JRC facilities.

- 402 organisations participated in EJPs for research in radiation protection, radioactive-waste management and fusion
- A doubling in the number of researchers travelling outside their home institution (from 872 in 2014 to 1734 in 2020) to work on the joint exploitation of fusion experimental facilities
- 84 institutions from 23 Member States benefited from open access to JRC facilities

The evaluation showed important involvement of Member States which joined the EU after 2004 as 89% of projects involved at least one entity from these Member States. Member States not using nuclear power participated mainly in projects on radiation protection, medical applications and radioactive-waste management. Some Member States, like Austria, Denmark, Greece, Ireland and Portugal, also participated in research on nuclear safety and nuclear data to maintain skills in these areas.

2. The Programme played a significant role in maintaining critical skills and capacities in the nuclear sector. Euratom projects involved around 13 815 researchers, engineers and support staff (8 000 in fission and 5 815 in fusion), providing a supporting environment for the exchange of ideas and for training a new generation of researchers.

- Increased support for PhDs in fusion – from 675 per year in 2014 to 734 in 2020

- About 800 PhDs involved in fission projects
- JRC training of 1 600 law-enforcement officers in nuclear detection and forensics for nuclear security

The Programme's results will be assessed against a profoundly changed policy context today. This changed policy context is marked by: (i) the new geopolitical and economic reality (EU's decarbonisation targets, the drive for energy security, and a focus on the safety and security of existing installations); and (ii) increased interest in nuclear energy and research needs (emerging technologies such as SMRs). This changed policy context has boosted interest in the nuclear field and highlighted a variety of new needs for research.

3. There was a substantial over-subscription rate for research grants in Euratom calls for proposals (2.6 proposals submitted for each project selected). This indicates: (i) a high level of interest in both the research community and in industry; and (ii) a high level of capacity in both the research community and in industry for excellent research projects. The competitive nature of the Euratom funding process further increased the quality of proposals, ensuring that research was conducted in areas of significant relevance for nuclear safety and radiation protection. Data also show that there was a significant mobilisation of public and private funding from stakeholders participating in Euratom research projects and EJPs.

- EUR 161 million mobilised from stakeholders in fission research
- EUR 555 million mobilised from the EUROfusion consortium

This indicates that although there is a clear demand for more public funding, mobilising funds from private and public stakeholders is still possible and will be even more necessary in the future to advance Euratom objectives. Mobilising public and private funding will be especially necessary to both: (i) retain and foster industrial value chains and overall competitiveness in the EU nuclear sector; and (ii) use the innovation potential of the EU private sector to accelerate the development of fusion technology.

4. Research funded by the Programme demonstrated the significant cross-cutting benefits of nuclear research for: (i) energy and climate policies; (ii) the security of energy supply; and (iii) non-power applications, in particular in healthcare.

Impacts on the security of energy supply – maintaining the safety of existing and future NPPs and ensuring their long-term operation

- Advanced modelling and simulation for NPP safety analysis (projects CAMIVVER, McSafe, McSafer, IVMR and MUSA)
- Tools and data for ensuring the long-term integrity of key components of existing NPPs (STRUMAT-LTO, NOMAD, SOTERIA, ENTENTE, FRACTESUS, ATLAS+, APAL)
- Development of an innovative backup cooling system that can be retrofitted into existing NPPs and included in future NPPs (projects sCO₂-HeRo, sCO₂-4-NPP)

- Development of advanced materials for nuclear systems, including computer models to evaluate radiation effects, development of new structural materials and their stress testing (projects M4F, GEMMA and ORIENT-NM)

Impacts on EU healthcare (medical imaging and cancer treatment)

- Solutions for securing the EU production of medical radioisotopes – research for qualification of the nuclear fuel for European research reactors (Projects LEU-FOREver, EU-QUALIFY, HERACLES-CP)
- Solutions to optimise radiation protection for oncology patients (projects SINFONIA, HARMONIC, MEDIRAD)
- Vision for future research – roadmap on medical applications of ionising radiation to improve patients' lives (project EURAMED)

5. Results from the Programme indicate there has been some improvement in gender balance. While similar figures are shared by many other engineering and scientific sectors, it is clear that gender inequality in nuclear research must be addressed much more vigorously under the current and future Euratom programmes.

- In fission-research projects, women accounted for 29% of researchers
- In fusion-research projects the percentage of woman increased from 18% to 23% of researchers

6. The evaluation of the Programme highlighted the need for better communication and visibility for nuclear research, which will also help to improve both the quality of scientific assessment and the uptake of research results. The Commission will encourage further outreach towards policymakers and other key stakeholders. In its new nuclear strategy for 2021-2025, the JRC has already drawn up a plan for systematic and targeted communication on nuclear activities.

3.2 Lessons learned

The *ex post* evaluation has yielded significant evidence-based findings, highlighting key areas for improvement.

For indirect actions in fission research (nuclear safety), the evaluation suggests that efficiency could be improved by supporting larger, more integrated projects encompassing all the different issues and aspects of a particular topic, for example, the effects of ageing in reactor pressure vessels. To guarantee an appropriate engineering approach and system integration, the evaluation said that European industry should coordinate safety projects related to developing new power reactors. Work should also continue on integrating the research done with the support of the Euratom grants (indirect actions) with both: (i) the relevant work carried out at the national level; and (ii) relevant work carried out through Euratom direct actions (carried out by the JRC). Finally, the evaluation recommended that international cooperation should be increased to include relevant research under the auspices of the IAEA and the OECD-NEA.

The evaluation has identified a need for improved reporting by consortia implementing Euratom-funded fission projects. Clear, concise, and factual reporting is crucial to provide a comprehensive understanding of the projects' progress, achievements and expected outcomes.

The evaluation shows that further progress in research on advanced nuclear systems will require concentrating efforts and resources on the few advanced nuclear systems and applications that are really of interest to European industry.

Experts recommended to get involved and engage with relevant non-nuclear and non-traditional partners in advancing nuclear research. Examples of areas in which nuclear research could develop include: artificial intelligence; advanced manufacturing; 3D printing applied to nuclear technologies; integrated and hybrid energy systems; and nuclear energy applications other than those generating electricity (like nuclear heat, hydrogen production, decarbonisation of energy-intensive industries and nuclear desalination). Synergies between fusion and fission should be further developed, not only in the traditional area of advanced materials but also in: artificial intelligence; non-power applications; advanced modelling and simulation; and experimental tests.

In research on radiation protection, the evaluation indicates that a multidisciplinary approach could be further encouraged to increase coverage of a broader spectrum of scientific questions, including low-dose risks and several other questions related to planned, existing and emergency exposure situations. The radiation-protection roadmap prepared by the CONCERT EJP and SRA in the medical applications of ionising radiation provide a sound basis for future state-of-the-art calls and should be systematically developed.

The evaluation shows that, given the progress achieved in radioactive-waste management, research should progressively depart from the acquisition of pure scientific knowledge to instead focus on the operation, closure and oversight of deep geological facilities. The governance of a joint programme should integrate this evolution by strengthening the role of waste-management organisations and technical safety organisations. The ethical basis for the strategic choices made in radioactive-waste management and disposal also deserve more attention.

While the Programme made substantial progress in fusion energy, this research field has changed rapidly in recent years as international competition increases and a vibrant private sector working on fusion emerges globally. The evaluation shows that, to proceed with the engineering design of a future fusion-power plant, the Euratom programme should focus now and in the coming few years on identifying the critical issues and risks and determining how much risk is acceptable. Innovation will then be needed to address critical enabling technologies for fusion energy and to mitigate related risks. While the Programme helped to make substantial progress in our understanding of plasma physics for ITER and beyond, there is also a need to develop computational tools to further predict, analyse, and interpret experimental results. A future fusion-power plant also requires efficient project engineering. Although efficient project engineering is expected to be delivered by industry, Euratom-funded actions could include a project-engineering and management-training scheme combined with specialised fusion knowledge.

Next steps: The insights and conclusions drawn from this final evaluation of the Programme are set to play a significant role not only in shaping the ongoing implementation of the 2021-2025 programme but also in influencing policy development for future nuclear research initiatives. Most of the observations made by independent experts have already been addressed in the ongoing 2021-2025 Euratom programme (see Annex for details). The evaluation also identified a number of challenges for Euratom-funded research such as: (i) the quality of reporting and data availability; (ii) the need for the evolution of fusion research; and (iii) fission partnerships taking into account the changing research landscape. These issues will be taken into account alongside the upcoming interim evaluation of the current 2021-2025 programme, when presenting the Commission proposal for the extension of the Euratom programme for 2026-2027 and for the next multiannual financial framework.

Annex 1 - Recommendations by the experts on indirect actions and the Commission's response

Recommendations on fusion research

1. To proceed with the engineering design of a future fusion-power plant, Euratom programmes should focus now and in the coming few years on: (i) identifying the critical issues and risks; and (ii) determining how much risk is acceptable. Innovation will be therefore needed to mitigate these risks. The real challenge will be to put in place a process to identify and prioritise these innovations and to incorporate them in the Euratom programme.
2. While the Programme helped make substantial progress in understanding the plasma physics for ITER and beyond, there is a need to further develop computational tools under the Euratom programme for 2021-2025 to predict, analyse and interpret experimental results. These tools can be then used to produce comprehensive between-shot analysis for ITER.
3. A future fusion-power plant requires efficient project engineering. Although this element is expected to be delivered by industry, EUROfusion should consider developing a training scheme for project engineering and management adapted to specialised fusion knowledge.

Commission's response

The Commission shares the experts' views and aims to improve fusion research funded by the Euratom programme. The fusion-research landscape is changing rapidly as international competition is increasing and a vibrant private sector in the area of fusion is emerging globally. European fusion know-how and industrial capacity may be lost if the way we organise our research is not adapted and if the innovation potential of the private sector in the EU is not put to use to accelerate technology development. An important step would be to support innovation in the EU on critical enabling technologies for fusion energy.

The interim evaluation of the ongoing Euratom programme for 2021-2025 will address a wide range of issues essential to accelerating the delivery of fusion electricity. Following the conclusion of the interim evaluation, the Commission intends to put forward a proposal to extend the Euratom programme for 2026-2027, in which the most pressing issues will be addressed.

Recommendations on fission research and the Commission's response

1. To increase the efficiency and effectiveness of indirect actions in nuclear safety, the Commission should favour the submission of larger, more integrated projects encompassing all the different issues and aspects of a particular topic, for example the effects of ageing in reactor pressure vessels. Funding should be increased to support education and training, knowledge management, the development of skills, and staff capacity. It is of paramount importance to integrate the work done with the support of the Euratom grants (indirect actions) and through Euratom direct actions (carried out by the JRC) with the relevant work carried out at national level. To guarantee an appropriate engineering approach and system integration, all safety projects related to the

development of new power reactors should be coordinated by European industry. Finally, international cooperation should be increased to include the IAEA and the OECD-NEA.

Commission's response: in the 2021-2025 programme, the Commission introduced provisions that already address some of these recommendations. Less prescriptive call topics than in previous programme give the consortia more freedom in self-organisation, thus increasing efficiency. Our plan for larger projects that systematically support access to education, training and infrastructures should improve the situation in the long-term. Integration of the Programme's direct and indirect actions should be further strengthened by introducing the access to JRC's facilities and know-how to consortia in Euratom calls for proposals. The Programme's interim evaluation will assess these actions and provide further guidance for future Euratom support.

2. It is time for Euratom to streamline support for research activities and concentrate its efforts and resources on the few advanced nuclear systems and applications in which European industry has a real interest. Other systems which are of no interest to EU industry should not be funded or, if they are funded, it should only be to maintain general skills.

Commission's response: the 2021-2025 programme focuses on advanced nuclear systems, for which research projects can provide a scientific basis for regulators to assess safety and demonstrate compliance with nuclear-safety Directives. Following the evaluation of the call, the Programme launched projects based on the highest quality proposals and backed by solid consortia, including from the research community and industry. The Programme's interim evaluation will evaluate these actions and provide further guidance on future Euratom support for advanced systems. The Commission will also consider the evolving industrial and research landscape, including the results of the SMR industrial alliance and work under the Net Zero Industrial Act.

3. The quality of reporting from consortia implementing Euratom-funded fission projects could be improved. Reports should describe in a clear, concise and factual way: (i) the progress made with respect to the initial state-of-the-art; (ii) the gaps covered; (iii) the main achievements; and (iv) the expected outcomes. The reports should also include reference to interactions with existing and potential end-users of research results.

Commission's response: the Commission will work with consortia to ensure that the quality of reporting is improved and focused on the elements highlighted by the evaluation to facilitate project monitoring and future evaluation of the Programme. To this end, the Commission will use its powers as granting authority to request periodic report changes before making subsequent grant payments.

4. For the most innovative topics and technologies which already have a wide application outside the nuclear community, it is highly recommended that to engage with and involve relevant non-nuclear and non-traditional partners. Examples of areas in which nuclear research could develop include: artificial intelligence; advanced manufacturing; 3D printing applied to nuclear technologies; integrated and hybrid energy systems; and the application of nuclear energy other than for generating electricity (such as nuclear heat, hydrogen production, decarbonisation of energy-intensive industries and nuclear desalination).

Commission's response: support for cross-sectoral synergies that leverage progress in

various sectors to increase nuclear safety is essential for the Commission in the ongoing Euratom programme for 2021-2025. The Commission also puts a strong emphasis on addressing the safety aspects of alternative applications of nuclear energy. Finally, the Programme provides funding for developing non-power applications of ionising radiation in the medical field and in other innovative areas such as: (i) nuclear techniques for EU strategic autonomy (production and recovery of raw materials); (ii) the circular economy (reduction of non-radioactive waste); and (iii) monitoring climate change and pollution. The Commission addressed these topics in the 2021-2025 Euratom calls for proposals, which will be discussed in detail in the interim evaluation.

5. Synergies between fusion and fission research should be further developed, not only in the traditional area of advanced materials, but also in the use of artificial intelligence, non-power applications, advanced modelling and simulation; and experimental tests.

Commission's response: under the ongoing 2021-2025 programme, the Commission is pursuing the development of fission-fusion synergies in fields such as the harmonisation of safety assessment, tritium management, and nuclear data. The Commission also emphasises the further use of fusion technologies in non-power applications through the EUROfusion technology-transfer programme. The Commission addressed these topics both in Euratom calls for proposals and via the EUROfusion partnership, which will be discussed in detail in the interim evaluation.

6. A multidisciplinary approach should be further encouraged in radiation protection. Euratom should increase its coverage of a broader spectrum of scientific questions, not only on low-dose risks but also on several other questions related to planned, existing and emergency exposure situations.

Commission's response: the Commission has tasked PIANOFORTE, a new co-funded European partnership in radiation protection, with adopting a comprehensive, multidisciplinary approach to research and innovation in this field under the 2021-2025 programme. PIANOFORTE's calls for proposals confirm this approach, by including calls on issues such as threats arising from war, armed conflict, natural disasters, and emergency preparedness and response for novel nuclear technologies. The Programme's interim evaluation will assess these actions and provide further guidance for future Euratom support for the partnership.

7. The SRA in the field of medical applications of ionising radiation and related radiation protection, prepared together with a corresponding roadmap by the EURAMED rocc-n-roll project, provides an excellent basis for future state-of-the-art calls. SRAs should be systematically developed in all areas of planned, existing and emergency exposure situations. The joint roadmap for radiation protection prepared by CONCERT EJP might be a good starting point.

Commission's response: with the Euratom grant award and establishment of the PIANOFORTE partnership in 2022, a dedicated stakeholders' forum exists today to discuss and further develop SRAs and research roadmaps in radiation protection and related fields. These documents will both shape PIANOFORTE actions and inform the implementation of other actions under the Euratom programme. The Programme's interim evaluation will assess these actions and provide further guidance on future Euratom

support for radiation protection.

8. EURAD's research in radioactive-waste management is the result of a joint decision process between waste-management organisations (WMOs), technical safety organisations (TSOs) and research entities, enabling a balanced approach to research needs. However, the chosen research directions are still strongly in line with previous Euratom actions. Considering that disposal facilities are currently already licensed (Finland, Sweden) or under licensing review (France), research should progressively depart from the acquisition of pure scientific knowledge and instead focus on operation, closure and oversight. The governance of EURAD should integrate this evolution by strengthening the role of the WMOs and TSOs and allowing an earlier and more effective role for the External Advice Committee in deciding on research. Research will have to evolve to a strategic level to tackle emerging issues of common interest. The ethical foundation of the fundamental strategic choices made for radioactive-waste management and disposal also deserves more attention.

Commission's response: in 2024 the Commission aims to launch a co-funded European partnership on radioactive-waste management (EURAD-2). The Commission has already put in place several requirements to improve the organisation of research in this field, in particular to: (i) consolidate knowledge on the safe start-up and operation of geological disposal facilities; and (ii) support Member States with less advanced national programmes. EURAD-2 must also engage in regular interactions with regulatory bodies and industrial stakeholders to make the future partnership comprehensive. Additionally, EURAD-2 will need to be more inclusive and reach out to the Member States that did not participate in EURAD, as the scope of the partnership covers all Member States with radioactive-waste inventories and is not limited to countries with nuclear power. The Programme's interim evaluation will assess progress and guide future Euratom support.

Annex 2 - Recommendations by the Commission Expert Group on direct actions and Commission's response

Recommendations on prioritisation of work

1. The JRC should be involved at an early stage in priority-setting among policy DGs, and set up a centralised process for ensuring that the work programme reflects both these priorities and the breadth of knowledge needed to support the priorities. This process should also incentivise policy DGs and the JRC to break silos and integrate suitable workstreams.
2. The panel encourages the JRC to systematically develop and apply criteria in relation to its unique strengths and policy relevance for deciding whether to engage/disengage in a particular activity.

Commission's response

The panel of experts highlighted that, considering the breadth of activities covered by the JRC direct actions: (i) there was some room for the JRC to better focus resources on activities with the highest impact; and (ii) there were some areas in which the JRC is uniquely positioned to provide the necessary scientific evidence. The JRC's new nuclear strategy comprises a whole set of actions aimed at prioritising its work and clearly setting priorities for current and prospective activities.

The panel pointed out a certain lack of integration of the various activities carried out in the JRC, saying that this sometimes led to a fragmented approach. In order to counter this trend, the JRC has reorganised its work programme by introducing portfolios. These portfolios aim to provide an integrated view and better coordination of the relevant activities under clearly defined priorities.

The anticipation of research and policy needs from other DGs in the European Commission is ensured through planned cluster meetings with several DGs in order to set priorities based on a coordinated assessment. In these meetings, several DGs of the European Commission are invited to express and discuss their priorities with the JRC. Within the nuclear area, the JRC holds additional coordination meetings with partner DGs in charge of research and innovation, energy, international partnerships, internal affairs, etc. for exchanges on future needs.

Overall, the experts found a good awareness within the JRC of its unique strengths, including its independence, solid scientific foundation, long-standing expertise, sharing of research facilities with other researchers, and ability to provide continuity of research where other actors are tied by different imperatives. These JRC strengths complement its new nuclear strategy, and reinforcing these identified strengths is largely compatible with the implementation of the JRC's strategy plan, including prioritising and optimising research infrastructures and the open-access programmes.

Recommendations on a holistic approach to nuclear and non-nuclear activities

1. The JRC should use more holistic approaches in designing both its work programme and its response to policy needs. It should develop, as part of its business model, a strategic plan for integrating social sciences into its research.

2. The JRC should integrate social-science research into Euratom activities, in particular in the area of risk assessment, crisis preparedness, and response, and make use of the approaches that are developed for the JRC as a whole.
3. The JRC should further embed the concept of resilience and the green and digital transition in the Euratom part of its work programme.

Commission's response

The need for a more holistic, multidisciplinary integration of policy priorities was underlined by the experts, who pointed out the added value of addressing social-science aspects in nuclear research. Under the reorganisation of the work programme, the portfolios were set up with the idea of improving collaboration and interaction between the nuclear and non-nuclear domains. Integration across disciplines will therefore unfold by design over time. For instance, efforts to integrate social-science research have been made within the portfolio on risk and crisis management, where nuclear risk is now being assessed using a holistic approach alongside other CBRN risks developed by another non-nuclear directorate of the JRC. Similar cooperation with social scientists also takes place on the topic of SMRs as part of research into the non-electricity applications of nuclear technology such as hydrogen production, district heating, and medical applications of nuclear science. This approach aims to increase the JRC's impact on policy and share expertise/resources, all while covering different aspects of the same challenge.

This integrated approach between nuclear and non-nuclear activities is also targeted in the implementation of the JRC's nuclear strategy. The experts also noted that opportunities for integrating cross-cutting issues such as digitalisation, artificial intelligence or machine learning should be assessed in the areas of nuclear security, safeguards and radioactive waste management. Efforts to integrate these cross-cutting issues in the JRC's work have been reflected in reshaped governance and the new portfolio-based structure. The advanced use of digital technologies is now the specific focus of a new directorate in the JRC and, more specifically, of a unit in the nuclear directorate, targeting nuclear safeguards and non-proliferation research, but with the potential to be expanded further to other areas.

Recommendation on communication

1. The JRC should develop a communication strategy to improve its communication at different levels, customising this communication to different target groups and using the most suitable channels (digital or traditional) to reach these groups.

Commission's response

The experts highlighted an opportunity to improve communication at different levels: (i) within the JRC; (ii) between the JRC and the European Commission; and (iii) between the JRC and its external stakeholders. This would provide more clarity on the research conducted by the JRC and the tangible impacts it achieved. A strand of actions within the JRC's nuclear strategy aims to address this issue by emphasising more strategic communication and the identification of target audiences, as well as better cooperation with relevant stakeholders.

Recommendation on resources

1. The JRC should implement a proactive talent-acquisition approach at all levels of seniority, with the aim of putting in place a more diverse workforce, in particular with

regard to gender balance. This applies to external recruitment but also to suitable internal development programmes to incentivise and motivate potential candidates.

Commission's response

Due to the reduction of the Euratom budget under the 2021-2027 multiannual financial framework, the JRC is facing a challenging situation in developing and maintaining the skilled workforce it needs. Notwithstanding this issue, the JRC has included a strand of actions in its nuclear strategy targeting skills and staff aspects to try to mitigate the impact of this reduction over time. This exercise aims to ensure that knowledge is efficiently managed keeping in mind the necessary critical skills that must be retained or replaced. It also aims to recruit diverse new talent (within the current stringent constraints) to integrate highly skilled future staff likely to trigger innovation in line with the evolving priorities of the JRC.

To more effectively pool nuclear expertise and knowledge inside and outside of the JRC, the strategy intends to optimise the management of staff and reduce fragmentation by integrating similar research activities in single locations in the JRC sites. Experimental activities involving the use of nuclear and radioactive materials will be integrated in only two JRC sites: Geel, in Belgium, and Karlsruhe, in Germany.

Recommendations on monitoring impact and efficiency

1. The JRC should review the indicators for measuring impact, taking into consideration current Commission initiatives on reforming research-assessment methodologies.
2. The JRC should develop key performance indicators for measuring the efficiency of its science for policy support.

Commission's response

The panel of experts acknowledged both: (i) the difficulty of measuring efficiency in a research context; and (ii) the efforts made by the JRC, in response to the interim evaluation recommendation, to provide evidence of its cost-effectiveness. The JRC assessed the engagement of resources and outputs derived from its participation in several projects under indirect actions against that of other consortium partners. While the interpretation of these comparisons is not always clear cut, the JRC determined that its cost-effectiveness was similar to that of other partners. The experts also noted the recent introduction of a common project-management methodology across the JRC and the pooling of nuclear research activities under one directorate to improve efficiency.

Additionally, in the course of drafting the Euratom programme for 2021-2025, a complete set of impact indicators was reviewed and incorporated into the programme as part of the Council Decision. These include indicators for short-, medium- and long-term impacts, considering scientific, societal, innovation and policy dimensions.

Recommendations on nuclear safety, security and skills

1. On SMRs, in addition to studying regulatory aspects, the JRC should also focus on safety, security, and safeguards approaches for these new technologies.
2. The JRC should strengthen its skills to support activities related to spent nuclear fuel disposal and develop strategies to capture and share best practices from EU and national projects with all EU Member States.

Commission's response

The panel of experts recognised that by building and maintaining skills in nuclear safety, security and safeguards, the JRC had served both EU and Member State policymaking. The panel also encouraged the JRC to continue responding to and focusing on a number of challenges and drivers, in particular new technologies like SMRs but also: (i) the decommissioning of NPPs; (ii) long-term operation issues; (iii) cyber security; (iv) safeguards; and (v) open access to nuclear infrastructures.

Acknowledging that regulation of nuclear safety is a national responsibility, the JRC, as part of the reorganisation of its work programme, has grouped activities under a dedicated portfolio on SMRs. Its goal is for this portfolio to focus on desktop, simulation and experimental R&D in part to support the licensing process by helping to harmonise practice and guidelines at EU level. Other portfolios, such as NUCTEC, address the other relevant topics mentioned such as the long-term operation of NPPs and the management of spent fuel and radioactive waste. The open access to nuclear infrastructures is included as much as possible in relevant research projects. Overall, the drivers for new research indicated above feature among the priorities identified in the JRC nuclear strategy, with the partial exception of decommissioning, which is now the subject of a separate instrument¹⁶ addressing: (i) operational decommissioning activities of the JRC; (ii)_, as well as management and dissemination of knowledge on decommissioning.

In particular, the experts highlighted an opportunity to improve the selection of objectives and activities supporting nuclear-safety policies in order to follow any changes in the demands for the energy systems. The experts also stressed that ensuring the continuity of European resources in nuclear safety and security is paramount to be able to respond to unexpected events and crises. The JRC's attention and response to shifting priorities/needs related to both nuclear-safety standards and nuclear security is reflected in the evolution of its own work programme. This is particularly evident in the response given to specific events, like the nuclear-safety assessment of the situation following the Russian aggression and invasion in Ukraine. The JRC also helped to draw up sanctions on Russia, based on strategic trade analysis and export-control expertise developed for non-proliferation purposes.

Recommendations on anticipation and foresight

1. The JRC should develop foresight activities for nuclear energy to support the green transition and promote the resilience of the energy system.
2. The JRC should: (i) give anticipation capacities a high priority, as set out in the JRC 2030 strategy; (ii) allocate sufficient resources; and (iii) set up a governance structure to optimise efforts.
3. The JRC should build capacities and tools to prepare for and respond to future shocks. To this effect, it should invest in collecting and maintaining data on past and future shocks.

Commission's response

The JRC implements anticipation as a priority within its nuclear activities by both: (i) maintaining permanent contact with its main partners and stakeholders; and (ii) exploring

arising needs and trends in the nuclear fields at both EU and international level. The JRC also participates in European technological platforms and associations that gather the main stakeholders and provide guidance on research priorities in related nuclear areas.

Anticipation and foresight are embedded in the portfolio approach and integrate aspects related to crisis anticipation. This is the case for the portfolio on situational awareness for crisis management, which integrates all capacities within the JRC for risk analysis, risk assessment, and early warning. This includes specific nuclear activities like the operation of two alert systems, EURDEP and ECURIE.

The emphasis on foresight is one of the priorities identified in the JRC nuclear strategy. The Directorate for Nuclear Safety and Security at the JRC also operates its own foresight network and activities as part of a regular ‘horizon scanning’ effort, which also includes other non-nuclear directorates. Plans are also ongoing to deploy a ‘futures scenario’ exercise in line with a similar endeavour undertaken by the IAEA in 2022 on safeguards. A foresight workshop with external stakeholders was organised before the end of 2023.

JRC management has put in place flexible working mechanisms that will make it possible to pool resources usually allocated to research, coordination or support activities for responding to unanticipated shocks.

Recommendation on safeguards

1. The JRC should maintain a strong research programme for nuclear safeguards and non-proliferation.

Commission’s response

The experts acknowledged the essential role of the JRC in supporting and developing nuclear safeguards and non-proliferation in the EU and globally. Sufficient staff and infrastructures should therefore be ensured for the experimental work and modelling activities. The relevance of maintaining a strong research programme in safeguards is included in the JRC’s nuclear strategy. An important element in this capacity is the JRC’s direct contribution to the Euratom safeguards, necessitating sufficient numbers of skilled staff and experimental infrastructure availability. Due to the budget reduction and pressure put on staff availability, the nuclear strategy intends to concentrate all experimental activities and laboratories used with nuclear and radioactive materials on two research sites (Karlsruhe and Geel) and will evaluate opportunities for joint implementation of activities with Euratom safeguards.

The JRC maintains a strong research programme for safeguards and non-proliferation by interacting with relevant key players in the EU through networking and collaboration within the European Safeguards Research and Development Association. The JRC also provides significant scientific and technical support to the IAEA through the European Commission’s dedicated support programme on safeguards. In the area of non-proliferation, the JRC provides expertise on strategic trade-control issues and further integrates work between the nuclear and non-nuclear parts of its work programme.