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Study on the European nuclear energy ecosystem: is it fit for the EU's climate objectives?

Acknowledgments

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STUDY ON THE EUROPEAN NUCLEAR ENERGY ECOSYSTEM: IS IT FIT FOR THE EU'S CLIMATE OBJECTIVES?

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Abstract

This study conducted by Deloitte provides an assessment of the fitness of the European nuclear ecosystem to support EU decarbonisation objectives. To do so, this study provides a comprehensive assessment of the EU nuclear ecosystem covering different aspects: financing, regulatory environment, supply chain, human capacities, fuel cycle, radioactive waste management and, decommissioning. Findings illustrate that the nuclear ecosystem prepares to achieve 100 GW of installed capacity by 2050, but additional changes and investments are required to improve its readiness. The main challenges to address have been identified in the supply chain, human capacities, regulatory environment, and the financing environment. The assessment illustrates among others a need for substantial investments in new nuclear power plants to address the ageing of the current fleet. In addition, collaboration, standardisation and alignment could be enhanced to facilitate addressing challenges in human capacities and to provide a stable regulatory environment that encourages additional investments in the ecosystem. Clear political support and commitment to nuclear power in the EU could facilitate swift actions to achieve the construction and decommissioning of several nuclear power plants simultaneously, facilitate the development and deployment of Small Modular Reactors (SMRs) and encourage Long-Term Operation (LTO) beyond 60 years. These actions could enhance the capacity of the the ecosystem to contribute to the EU's decarbonisation objectives.

Executive Summary

This study provides an assessment of the fitness of the European nuclear ecosystem to support EU climate objectives[1]. To do so, it provides a comprehensive assessment of the EU nuclear ecosystem covering different aspects: **financing, regulatory environment, supply chain, human capacities, fuel cycle, radioactive waste management, and decommissioning.**

The assessment is based on thorough desk research and stakeholder engagement. A stakeholder group with representatives from the industry, research institutions, nuclear safety regulatory bodies and finance sector was established to provide insights and regular feedback via questionnaires, interviews, and workshops. In addition, insights were collected via questionnaires to the EU Member States and industry representatives in early 2023[2].

Current potential and challenges have been identified for each aspect of the ecosystem to assess its fitness. Potential challenges are assessed against a baseline scenario describing a development of the ecosystem based on today's state of the art on human capacities, technologies, and assumed development of nuclear power plants. Also, the study presents an **economic analysis,** depicting the ecosystem's main contribution to the EU economy now and the possible contribution in 2050.

Baseline scenario of the European nuclear ecosystem until 2050

Nuclear energy plays an important role in the EU's energy mix. With increasing energy generated by renewable sources, nuclear energy provides a low-carbon and reliable source of electricity, as acknowledged in EU strategic policy documents including the Commission Communication "A Clean Planet for All".

The current capacity of nuclear power in the EU is about 100 GW electric, corresponding to an approximate 25% share of the electricity production[3]. The European Commission Communication "A Clean Planet for All" estimates 15% of electricity to originate from nuclear power in the EU **in 2050** which could represent **100 GW installed nuclear capacity**. This value has been considered as a reference value for the **study's baseline scenario**. This reference value facilitated the definition of the following assumptions that further guided the discussions with the study's stakeholders to assess potentials and challenges for the ecosystem to achieve 100 GW installed capacity in 2050[4]. The following assumption are defined:

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1 Reduce greenhouse gas emissions by 55% by 2030 compared to 1990 levels and achieve climate neutrality by 2050.

2 This implies that inputs from the Nuclear Alliance could be captured partially by the study. The Alliance is an informal collation of like-minded Member-States launched to coordinate common views towards defending the technology neutrality principle, particularly the role of nuclear power, in the EU decision-making process and any other non-legislative initiatives.

3 This is an average capacity in the EU, which may change from year to year. For example, in 2022 13 EU countries generated 97 GW of nuclear electricity, a decrease compared to 2021. The decrease was mainly due to maintenance activities in France, the EU's largest nuclear power producer.

4 Main challenges and potentials presented in this report refer to the baseline scenario's assumptions. Different scenarios are possible as well, including considering enhanced long-term operation

- The share of nuclear in the EU's electricity mix is 15% in 2050,
- This share of 15% would correspond to approximately 100 GW of installed capacity representing about 80 large reactors,
- The LTO of currently operated reactors is considered to be 60 years,
- The additional nuclear capacities coming from SMRs/AMRs are 5 GW,
- The baseline scenario builds upon data about future installed capacity received from Member States representatives, through desk research and the study's questionnaire.
- Achieving 150 GW instead of 100 GW would multiply the potentials and challenges presented in this report.

Considering these assumptions **only 17 GW of currently operating reactors could be in operation in 2050**. This implies a need to construct new nuclear power plants with an output of 83 GW (including mainly large reactors) in 26 years (100 GW goal). This objective is ambitious considering the estimated construction efforts in EU Member States. Assuming an average construction time of seven to ten years for a new nuclear power plant and the necessity to construct 83 GW by 2050, it would require constructing **approximately 25 GW simultaneously**, if the construction starts today. With every year of delayed action, the number of simultaneously built nuclear power plants would increase. Nevertheless constructing 25 GW of nuclear capacity could be possible, based on past experience. In the 1970s and 1980s, there was on average 30 GW of parallel construction in Europe. To achieve this, all aspects of the nuclear ecosystem must be aligned. Therefore, this study provided a comprehensive overview of challenges and potential for each aspect of the nuclear ecosystem while keeping this objective in mind.

Financing

Nuclear financing refers to the **process of securing funding for the development, construction, and operation** of a nuclear power plant. These processes are considered complex due to various factors, including **high upfront costs, long project lifecycles, and regulatory together with the electricity market uncertainties.** Other financing challenges relate to an **unpredictable political environment** and the **complexity of the notification period**, in particular the time required to approve state aid.

The availability of funds does not hinder investments in the sector and may support the construction of about 80 new reactors simultaneously in the next years, according to the members of the study's stakeholder group. Banks are willing to finance the construction of nuclear units, e.g. under the condition of state guarantees. At the same time, stakeholders highlight the selection of the most adequate financing model as a challenge. The market applies different financing options, each with specific associated risks depending on the characteristics of the

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programmes, enhanced development and deployment of Small Modular Reactors and achieving 150 GW installed capacity as projected by the Nuclear Alliance.

nuclear project and its context. In general, the study's stakeholders assume a **mix of state support and private** financing as the most adequate option to finance nuclear investments.

Standardisation of financing options could be a way forward to address the above-described challenges, according to the study's stakeholders. In this regard the inclusion of nuclear power in the taxonomy is a step in the right direction, as it allows classifying financing of nuclear projects as a sustainable activity under strict conditions. Other initiatives, such as the adopted regulation to establish a framework of measures strengthening Europe's net-zero technology products manufacturing ecosystem (Net Zero Industry Act) may further attract investments across EU Member States. To provide a predictable environment for nuclear investments, the nuclear ecosystem could be considered from a holistic perspective in other legislative measures as well.

Overall, there are options how to finance the construction of nuclear power plants, but these are limited due to associated risks. These **risks could be lowered by a predictable political environment that recognises the role of nuclear energy to support the EU's climate objectives.**

Regulatory environment

A crucial part in the development of nuclear power in the EU is the regulatory environment, which directly affects the financing of nuclear projects. Overall, **the existing regulatory framework is well set up** and plays a crucial role in **ensuring the safe and efficient operation of nuclear power plants** and in raising public awareness and engagement in the decision-making process. At the same time, major changes of the nuclear fleet until 2050 and the deployment of **advanced reactors as well as SMRs pose new regulatory challenges and issues**.

The study's stakeholders highlight the **capacity of national regulatory authorities** as another challenge to meet the decarbonisation target. Building around 80 GW of nuclear power requires providing licenses of an equal amount in a very short timeframe. Licensing large nuclear power plants is a time consuming and costly process. Speeding up these processes to meet the decarbonisation targets cannot however jeopardize necessary safety evaluations.

For SMRs based on Light Water Reactors (LWRs) technology, the regulatory framework - while not being fully established - could rely to a large extent on the existing regulatory framework for large LWRs. To deploy SMRs swiftly and adequately at a large scale coordinated efforts may be required. Stakeholder group members suggest **harmonisation of the licensing processes** as a possible solution to speed up the processes of licensing large nuclear power plants and SMRs. **The graded approach**[5] could be a solution to SMR licensing but requires enhanced discussion and cooperation among Member States. The

[5] The IAEA Safety Glossary defines 'graded approach' as follows: "For a system of control, such as a regulatory system or a safety system, a process or method in which the stringency of the control measures and conditions to be applied is commensurate, to the extent practicable, with the likelihood and possible consequences of, and the level of risk associated with, a loss of control."

situation is **similar but even more complicated with the advanced Generation IV reactors** where the specific regulatory framework is almost non-existing.

Supply chain

The nuclear supply chain is a complex field that includes suppliers, contractors, manufacturers, and service providers all interacting in providing services, delivering materials and equipment necessary for the safe and reliable design, construction, operation, and maintenance of nuclear power plants. The nuclear supply chain in the EU has undergone several changes in the past years.

In the recent past, the EU nuclear supply chain contracted: companies left the field, ended business, or merged due to fewer new constructions. **Since the year 2000, the supply chain in Europe has been relying mainly on the operation, maintenance of the operating plants** and the construction, in particular, of European Pressurized Reactors - EPRs (in France, the UK, Finland and China). Today, the status of the supply chain differs across the EU. In France, the UK and Finland, capabilities are present due to ongoing construction projects. At the same time, **in most other EU Member States, the nuclear supply chain suffers from a lack of development of new nuclear power plants in the last 20 years.** Nevertheless, players in the supply chain are ready to ramp up and support the delivery of around 80 GW of new nuclear power plants by 2050 required for the study's baseline scenario. A healthy supply chain at the EU scale already allows for adequate services to older plants, which has become apparent over the past 10 years by the successful implementation of post-Fukushima safety improvements at all nuclear power plants in the EU.

To ramp up the production, the supply chain stakeholders require clear commitment from the state to invest in nuclear power. Clear commitment provides the stable environment required by companies to launch activities allowing constructing several power plants at once, in a reasonable timeframe, without large gaps between the first-of-the kind and a standardised design.

Long-term planning of a standardised design fleet - to the extent possible - is key to shorten construction times and maximize productivity gains. **Long-term public engagement is vital** for enabling the investments and the efficient construction of new nuclear power plants. From a technical and regulatory perspective, LTO is deemed enabled by the owners and operators' involvement in international cooperation under the coordination of the IAEA, periodic World Association of Nuclear Operators (WANO) safety inspection and exchange of good practices within the operators' groups, all supervised by national nuclear safety authorities.

In addition, **it is important to attract new companies to the sector**, which is often perceived as too complex and complicated. To this end, the challenges and difficulties of the industry must be clearly communicated. In France the supply chain identified gaps between existing and needed capacities, launched main investments to modernise the facilities to increase quality, efficiency and capacity. On the EU scale, partnerships are constituted to reestablish a strong industrial capacity.

Another identified challenge is **the need to shorten the time of construction of a new nuclear power plant and of manufacturing some components**. A lever

to speed up the construction and help to attract new companies **is the standardisation** of the products (limitation of differences for a considered design, **use of industrial-grade components** where safety standards allow this).

Overall, the supply chain could continue its preparation **for the extensive task of constructing several new nuclear power plants simultaneously. Standardisation and clear commitments to the sector could facilitate the implementation of these plans.** From a contractors' point of view, manufacturing capacities could be extended as a function of needs, provided that funding are provided in due time to meet the demand.

Human capacities

Human capacities are a key part of the nuclear ecosystem. However, the **workforce is ageing in the nuclear energy sector,** and the ecosystem faces challenges to **attract new talent** resulting in **diminishing expertise and knowledge**. Seen from the industry, the development and maintenance of human resources with the expected skills, competencies, and experience, is a **matter of anticipation**, early contracting and long-term deployment planning. Early contracting illustrates clear commitment to nuclear power and long-term planning facilitates the development and deployment of a standardised design fleet, to the extent possible. Together these elements may facilitate upscaling of the existing workforce, while ensuring skills and competencies are maintained over time. The successful delivery of a nuclear new built would require strong project and programme management capabilities, and this could be achieved through a combination of the owners' own resources, those from main contractors and support from external specialised companies (managing contractors) with experience from infrastructure projects of similar scale and complexity.

Also, **digital transformation** of the nuclear industry **could support the ramping up of human capacities**. Large investment programmes at national scale need to be supported to deal with interoperability, data management in a secure digital environment and skills development.

The long and demanding process of educating nuclear professionals is one of the root causes for the above-mentioned challenges. In addition, the **nuclear industry is sometimes not perceived as competitive and attractive compared to other industries due to uncertain long-term perspectives**.

To address these human capital challenges, stakeholder group members suggest enhancing **collaboration between industry, academia and government**. **Public policies encouraging nuclear energy could be key to foster the industry's attractiveness in the context of competing demand from other sectors**. The industry should cooperate with academia to illustrate the volume of new capacities needed. In addition, the stakeholders could showcase the work in the nuclear ecosystem by offering mentorship schemes and industry lectures to name a few examples. Governments could facilitate such enhanced collaboration between academia and industry. Such initiatives have the potential to increase the attractiveness of the sector and thus attract and retain human capacity. **Without additional human capacities in the nuclear sector it is unlikely that the EU decarbonisation goals will be achieved.**

Fuel cycle

The main potential and challenges of the fuel cycle are linked to the global character of its supply chain. The challenges and potential are different for each step of the fuel cycle, and fuel cycle actors have already shown interest in increasing their capacity in light of customer needs:

- Uranium supplies originate from few countries across the globe. The fuel supply chain could **diversify their portfolio of suppliers to enhance EU security of supply**.
- Based on the assessment of the EU industrial capabilities, the **conversion and enrichment capacity in the EU could be made sufficient** to meet the target of 100 GW of nuclear power in 2050. Seeing the EU supply together with supply to global West, both conversion and enrichment capacities need to increase to meet the current demand. Increasing demand from outside the EU may affect the supply in the EU. This both with the increasing demand in the EU are expected to incentivise additional investments in these capacities.
- Diversification of nuclear fuel supply is a challenge for Russian designed reactors. **Individual Member States and utilities are addressing this issue and are working on diversifying their supplies.**
- Assuming a similar installed capacity in 2050 as today, reprocessing capacities could be sufficient to meet future demand. This depends, however, largely on the type of reactors being deployed. Generation-IV and AMRs might require more mixed-oxide (MOX) fuel and require more reprocessing capacities. In addition, closing the fuel cycle may require additional reprocessing capacities. Therefore, capacities should be monitored to facilitate the renewal of current facilities, as well as the increase in their capacity, if needed.
- A critical issue highlighted by the study's stakeholders is **the lack of a reprocessed uranium (RepU) conversion facility in the EU.** Considering the global situation and the security of supplies, it would be beneficial to build such a facility in the EU.

Another factor that must be monitored is **the development of SMRs.** Some SMRs plan to use high-assay low-enriched uranium (HALEU, greater than 5% and less than 20% of U-235), which is currently not produced in the EU. Thus, facilitating the development of a HALEU facility would favour EU self-sufficiency. Else, non-European countries might take leadership creating a dependence and a potential risk on security of supplies. In terms of **AMRs**, **the fuel cycle is even more challenging** than the SMRs fuel cycle. AMRs are using different and sometimes new types of fuel, which demand extensive Research and Development (R&D) according to the study's stakeholders. The **deployment of these reactors is, therefore, generally expected around the year 2040/2050**, which also gives time for inventing new technologies, ways to produce these fuels, and qualify them.

Radioactive waste management

Radioactive waste management is a topic that resonates across the entire ecosystem with each Member State responsible for its own radioactive waste. The management of radioactive waste is a complex issue that presents several challenges, among others around long-term management and safe containment.

Assuming the baseline scenario, the amount of radioactive waste produced in 2050 may be similar to today. In addition, the baseline scenario assumes a focus on building large nuclear power plants. Additional radioactive waste of SMRs may be negligible while the large-scale deployment of AMRs based on fast reactor technology is assumed to be possible beyond 2050 in this scenario. Different possibilities such as burning minor actinides in fast reactors are still in the R&D phase and the commercial deployment is considered as uncertain. The baseline scenario assumes different challenges to materialise innovations. Therefore, reprocessing may increase in some Member States, yet it may not be implemented at a large scale. At the same time, the amount of radioactive waste produced per year may change depending on reactors in operation.

There are two possibilities on how to deal with radioactive waste, disposal, or reprocessing (for spent fuel management only). Waste disposal can be done in two ways that are dependent on the classification of the waste and the legislation of each Member State. Very low-level and low-level waste could be disposed in near-surface facilities. The same applies for short-lived intermediate level waste in some Member States. **Deep geological repositories (DGR)** are required for long-lived intermediate level waste and high-level waste including spent fuel. **Deep geological repositories are developed in several Member States**. The most advanced project is in Finland where the beginning of operation is planned by 2025. Reprocessed waste may increase when more Member States use reprocessed fuel in their reactors.

Depending on the development of SMRs/AMRs, the type of waste may change, posing additional challenges to radioactive waste management in the future. For example, some SMRs/AMRs plan to use HALEU. Another uncertain area is the waste management of advanced reactors where not much information is available, but uncertainties can be reduced given the time frame for development of advanced reactors.

Deepened international cooperation, sharing of best practices, and learning from existing DGR projects can help overcome some of the challenges and ensure the safe long-term storage of radioactive waste.

A **shared deep geological repository (DGR)** was proposed by the study's stakeholders and is also discussed among several Member States. A shared repository could be a solution for Member States that operate a small number of reactors and do not have a significant amount of waste. However, such a solution comes with a plethora of challenges such as public acceptance, regulatory harmonisation, cross border transportation, funding, and international cooperation.

Decommissioning

Decommissioning, the final phase of a nuclear power plant's lifespan, is a complex process that **requires careful planning, sufficient resources, expertise, and adherence to strict safety and regulatory requirements.** The need for decommissioning could increase in the EU as the majority of nuclear power plants reach the end of their lifetime, assuming a long-term operation of 60 years.

Current systems and practices in decommissioning of nuclear power plants aim at preserving safety and future generations. However, policies, legislation and best practices differ on detailed objectives to be achieved and vary significantly across Member States. Thus, **a better sharing of information, experience, and knowledge would contribute to future assessments and improvements**.

The decommissioning process is **lengthy, costly, and currently often exceeding initial cost estimates**. **With the increasing number of decommissioning projects experience is build up and cost estimates may improve. Future decommissioning is expected to be faster and cheaper due to the experience gained, including better cost estimation.** Insufficient decommissioning funds available at the time of decommissioning may represent a key challenge for nuclear power plant shut down well in advance of their estimated date to end operation. In addition, **decommissioning needs professionals in large numbers**, a number which is likely to increase in the future when several nuclear power plants might need to be decommissioned at once. Thus, the readiness for decommissioning several NPPs at once depends on a range of factors, including the availability of qualified personnel and resources, financial considerations, regulatory oversight, waste management capabilities, and stakeholder involvement. Each project must be assessed individually to determine its feasibility and ensure that safety, environmental protection, and public acceptance are prioritised.

The ecosystem's contribution to the EU economy

The potential dynamics of the nuclear ecosystem to contribute to the EU energy and climate objectives as discussed above, provide economic output in the EU in terms of gross value added and jobs. Following the baseline assumptions, the **nuclear ecosystem is estimated to provide a gross value added of, on average EUR 113 billion per year between 2023 and 2050.** The current gross value added of the nuclear energy sector encompasses an estimated average contribution to GDP of EUR 51 billion through direct means, EUR 28 billion through indirect means, and EUR 7 billion through induced means. The GDP of EU Member States in total is around 15 trillion EUR in 2023, accordingly the nuclear ecosystem contributes to around 0.6% in terms of Gross Value Added.

Breaking down the gross value added, a significant impact on private households (wages and salaries) may be expected. Currently, the sector generates EUR 28 billion in gross wages and salaries, including the disposable income of employees directly and indirectly employed in the industry and also the disposable income of employees of suppliers to the industry (indirect impact) as well as induced employment impacts. This in turn corresponds to an estimated 653 thousand jobs created and maintained by the nuclear sector in 2023. This may increase up to approximately EUR 1,158 billion gross wages and salaries in the

period between 2023 and 2050, representing an average total employment effect of around **800 thousand jobs per year**.

Furthermore, the positive economic output resulting from the construction and operation of nuclear power plants as well as decommissioning and nuclear fuel activities, including increased output, job creation, and higher wages, could lead to higher tax collection and subsequently contribute to public revenues. Presently, the industry is estimated to have an impact of EUR 66 billion on fiscal revenues, including contributions to social security systems. **Between 2023 and 2050, the total impact of the industry on fiscal revenues is estimated to be EUR 2,500 billion in Europe.**

Is the EU nuclear ecosystem fit for the EU's climate objectives?

In short, the **nuclear ecosystem has been preparing** to achieve the EU's climate objectives for several years, but **numerous key challenges should be addressed** to enhance the ecosystem's capacity and reach the desired contribution to the EU's decarbonisation targets. The assessment illustrates among others a **need for substantial investments in new nuclear power plants** to address the **ageing of the current fleet**. In addition, collaboration, standardisation and alignment could be enhanced to facilitate addressing changes in **human capacities** and to provide a stable regulatory environment that encourages additional investments in the ecosystem. **Clear political support and commitment to nuclear power in the EU** as well as enhanced collaboration between stakeholders in the ecosystem and across Member States could facilitate swift actions to achieve the construction and decommissioning of several nuclear power plants simultaneously, facilitate the development and deployment of SMRs/AMRs and encourage long-term operation. The study lists concrete actions points at European, Member State and industry level to address these challenges and enhance the potentials. These actions should make the ecosystem swiftly fit to contribute to the EU's climate objectives.

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List of abbreviations

ACPA	A Clean Planet for All
AI	Artificial intelligence
ALFRED	Advanced Lead Fast Reactor European Demonstrator
AMR	Advanced Modular Reactor
ATF	Accident Tolerant Fuel
BOP	Balance of Plant
BWR	Boiling-Water Reactor
CANDU	Canada Deuterium Uranium
CEA	Atomic Energy Commission
CFD	Contract for difference
DD	Deferred dismantling
DG	Distributed generation
DGR	Deep geological repository
EC	European Commission
ECA	European Court of Auditors
EC-JRC	EC Joint Research Centre
EDF	Electricité de France
EIB	European Investment Bank
ENEA	European Environment Agency
ENEF	European Nuclear Energy Forum
ENEN	European Nuclear Education Network
ENSA	European Neutron Scattering Association
ENRESA	Nuclear Waste Management Authority
ENSREG	European Nuclear Safety Regulators Group
ENSREG	European High-Level Group on Nuclear Safety and Waste Management
ENUSA	Empresa Nacional del Uranio, S. A.
EU	European Union
EURAD	European Joint Programme on Radioactive Waste Management
ENTSO-E	European association for the cooperation of transmission system operators
EPR	European Pressurized Reactor
ET	Safe enclosure and entombment
FIT	Feed-in tariff
FOAK	First of a kind
Nucleareurope (former FORATOM)	The European Atomic Forum
GDP	Gross Domestic Product
GHG	Greenhouse gas

HALEU	High-Assay Low-Enriched Uranium
HLW	High-level waste
IAEA	International Atomic Energy Agency
ID	Immediate Dismantling
IEA	International Energy Agency
ILW	Intermediate-level waste
IPCC	Intergovernmental Panel on Climate Change
IPCEI	Important Projects of Common European Interest
ISDC	International Structure for Decommissioning Costing
ITER	International Thermonuclear Experimental Reactor
KHNP	Korea Hydro & Nuclear Power
LCOE	Levelized cost of electricity
LLW	Low-level waste
LTO	Long-Term Operation
max.	Maximum
MOX	Mixed oxide fuel
MS	Member States
NDC	National Decommissioning Centre
NEA	Nuclear Energy Agency
NPP	Nuclear Power Plant
NZE	Net-Zero Emission
OECD	Organization for Economic Cooperation and Development
PF	Project financing
PINC	Nuclear Illustrative Programme
PGE	Pacific Gas and Electric Company
PPA	Power Purchase Agreements
PWR	Pressurized Water Reactor
Q&A	Question and Answer
RAB	Regulated Asset Base model
R&D	Research and Development
RES	Renewable Energy Sources
RRF	Recovery and Resilience Facility
SMR	Small Modular Reactor
SNETP	Sustainable Nuclear Energy Technology Platform
SNF	Spent Nuclear Fuel
STEM	The fields of Science, Technology, Engineering and Math
TFEU	Treaty on the Functioning of the European Union
TOURR	Towards Optimized Use of Research Reactors in Europe
ToR	Terms of References
TSO	Transmission System Operators
TVO	Teollisuuden Voima Oyj
UK	United Kingdom

UN	United Nations
U.S.NRC	U.S. NUCLEAR REGULATORY COMMISSION
USA	United States of America
VLLW	Very low-level waste
WENRA	Western European nuclear Regulators Association
WNA	World Nuclear Association

1 Introduction of the study

The European Commission (EC), via the Directorate General for Energy (DG ENER) called for a study to analyse **whether the current ecosystem of the EU nuclear energy sector is fit for the longer-term prospects of climate neutrality of the EU's energy system**. The research process encompassed several key stages, including desk research and in-depth stakeholder engagement via questionnaires, interviews, workshops and analysis[6]. A stakeholder group was established consisting of 15 representatives from the industry, research institutions, and financing organisations. Extensive stakeholder engagement allowed the study team to collect insights directly from the market and verify findings, conclusions, and recommendations. Together the insights depict the different perspectives on the fitness of the EU nuclear ecosystem in this report. Furthermore, these stakeholders provided key information to the study by answering questionnaires, interviews, and by active participation in workshops. In addition, Member State representatives and industry representatives have been surveyed. Findings from all data collection methods have been further supplemented with rigorous desk research. A detailed overview of the methodology is presented in Annex A.

In 2018 the European Commission in its Communication "A Clean Planet for All"[7] as part of its Long-term Strategy presented scenarios for reaching climate neutrality in the EU by 2050. In all scenarios, the EU **energy supply system is expected to rely on safe nuclear energy as a complement to the leading role of renewables**. Different scenarios forecast an installed capacity of nuclear energy in 2050 which is similar to the current capacity, i.e., around 100 GW. To meet the EU's climate and energy targets for 2050 and reach the objectives of the European Green Deal, the European Commission has set several initiatives and instruments to support the required investments, such as the EU taxonomy[8] and The Fit for 55[9] package which identify nuclear energy as one of the energy sources for the future.

Nuclear energy provides a stable emission fossil free source of energy and serves as a baseload necessary for a safe and reliable energy mix in the EU. Nuclear energy acts as a bridge between fossil fuel-based power generation and intermittent renewables energy generation. Despite a structural decline in recent years, nuclear energy still accounts for a bit less than a quarter of the EU electricity production, and it could remain an important source of energy. Therefore, the use of nuclear energy is expected to contribute to achieving the EU's energy and climate objectives.

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6 Data collection was performed until 16 June 2023 to prepare draft conclusions and recommendation to be discussed with the stakeholders group on 5-6 September 2023. Findings and conclusions presented in this report reflect thus the state of play until that date. See for more information the methodological annex.

7 A Clean Planet for all: A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy. EU, 2018.

8 Complementary Climate Delegated Act. EU, 2022.

9 Fit for 55 EU, 2022.

Maintaining the contribution of nuclear energy to achieve the EU's energy and climate objectives comes with different challenges. The existing nuclear fleet is ageing and is facing a stable decline. At the same time, the construction of new nuclear power plants is a long and demanding process. Maintenance, retiring, and development of new nuclear power plants face challenges related to the availability of adequate financial resources, regulatory frameworks, industry capabilities, staffing with the relevant expertise, access to fuel and dealing with complex waste management. This study provides a comprehensive overview of these perspectives from different types of actors of the industry, Member States and NGOs. The perspectives have been verified during the study's stakeholder engagement activities such as interviews and workshops. These perspectives are as complete as possible[10]. Findings suggest that the combination of challenges across these aspects limit the assumed capacity for nuclear energy by 2050. Therefore, there is a risk of nuclear energy contributing less to the EU's energy and climate objectives than anticipated.

At the same time, the nuclear energy sector continues to have a significant impact on the EU economy. On average, the sector's contribution to GDP (Gross Value Added) is estimated at EUR 113 billion per year between 2023 and 2050. In total, around EUR 1,158 billion gross wages and salaries over the entire reference period will be generated, representing an average total employment effect of around 800 thousand jobs per year in this field. Therefore, the study also discusses different opportunities for policymaking. The study provides recommendations for the EU, Member States, and industry to address the challenges and to seize opportunities for the EU's nuclear energy ecosystem.

The remainder of this report is structured as follows:

Chapter 2 sets the scene by describing the current EU decarbonization plans and define a baseline scenario for the remainder of the report.
Chapter 3 looks at the financial landscape.
Chapter 4 discusses the regulatory framework.
Chapter 5 analysis nuclear supply chain considerations.
Chapter 6 looks at human capacities.
Chapter 7 covers the fuel cycle.
Chapter 8 discusses waste management.
Chapter 9 presents and discusses decommissioning challenges.
Chapter 10 provides an economic evaluation of the proposed new required infrastructure.
Chapter 11 summarises conclusions and provides recommendations for the EU, Member States, and Industry.

The Annexes include all information concerning the data gathering methods (questionnaires, interviews and additional information).

[10] Not all Member States responded to the request for information or took part in the discussion of the study's conclusions.

2 EU decarbonisation plan – are the nuclear development plans sufficient to achieve decarbonisation targets?

This chapter presents the main assumptions to set a baseline scenario for the remainder of the report. The assumptions illustrate a possible development of nuclear energy production until 2050, based on current capacities. The assumptions follow EU climate and energy objectives and the perceived role of nuclear energy therein, as well as plans for nuclear energy by EU Member States. Therefore, the next sections discuss the EU's decarbonisation plan from the angle of the **share of nuclear power in the electricity mix in 2050**, individual nuclear development plans of EU Member States, and the differences between the EU's and Member State's plans. The information discussed within this chapter was obtained from questionnaires to Member State representatives and National Energy and Climate Plans (NECPs)[11]. The consolidated data was used to develop a **Baseline scenario** which is used as a starting point to assess the ecosystem's fitness in the remainder of this report.

2.1 The EU's decarbonisation scenario

The EU's energy mix is on the brink of an important transformation. The EU aims to achieve climate neutrality by 2050, in line with the EU's long-term climate strategy as well as the EU's commitment to the Paris Agreement[12] and UN Sustainable Development Goals. The EU's commitment to achieve climate neutrality is set forth in several strategic documents, including the Long-term vision , "A Clean Planet for All (ACPA)"[7], European Green Deal, EU Climate law, Fit for 55 package, and REPowerEU. Together, these documents set a clear strategy on how to achieve this overarching goal.

11 **Data collection was performed until 16 June 2023.** NECPs available until that date have been included. Next, conclusions and recommendations have been discussed with the stakeholder group and Member State representatives during a workshop in September 2023 to verify findings. Any revised objectives and developments since the closure of the data collection to this study have been considered for the discussion but have not been included in the baseline scenario. See Annex A for more details on the methodology and its limitations.

12 It is a legally binding international treaty on climate change, which was signed by 196 parties (195 countries + European Union) during the UN Climate Change Conference (COP 21) in 2015. The goal of the agreement according to Article 2, §1a) is to hold "the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change".

Figure 2.1 European decarbonisation landscape



Source: Study team

The EU Climate Law[13] provides milestones in the path to decarbonisation, in general, it presents the 2030 climate goal set out in the European Green Deal and it makes it legally binding for the Member States.

The Climate Law presents an intermediate and final target of zero emissions. By 2030, Greenhouse gas emissions shall be reduced by at least 55% compared to levels of 1990. By 2050, the EU shall meet the climate-neutrality target through: emission cuts, green technology, and protection of the natural environment. In more detail, the Climate Law aims to:

- Set the long-term direction of travel for meeting the 2050 climate neutrality objective through all policies, in a socially fair and cost-efficient manner,
- Set a more ambitious EU 2030 target, to set Europe on a responsible path to becoming climate-neutral by 2050,
- Create a system for monitoring progress and take further action if needed,
- Provide predictability for investors and other economic actors,
- Ensure that the transition to climate neutrality is irreversible.

The Communication "A Clean Planet for All" presents seven main areas of actions that were created to act as building blocks of the transition[14]:

1. Maximize the benefits from Energy Efficiency including zero building emission,
2. Maximize the deployment of renewables and the use of electricity to fully decarbonize Europe's energy supply,
3. Embrace clean, safe, and connected mobility,
4. A competitive EU industry and the circular economy as a key enabler to reduce greenhouse gas emissions,
5. Develop an adequate smart network infrastructure and inter-connections,
6. Reap the full benefits of bioeconomy and create essential carbon sinks,
7. Tackle remaining CO2 emissions with carbon capture and storage.

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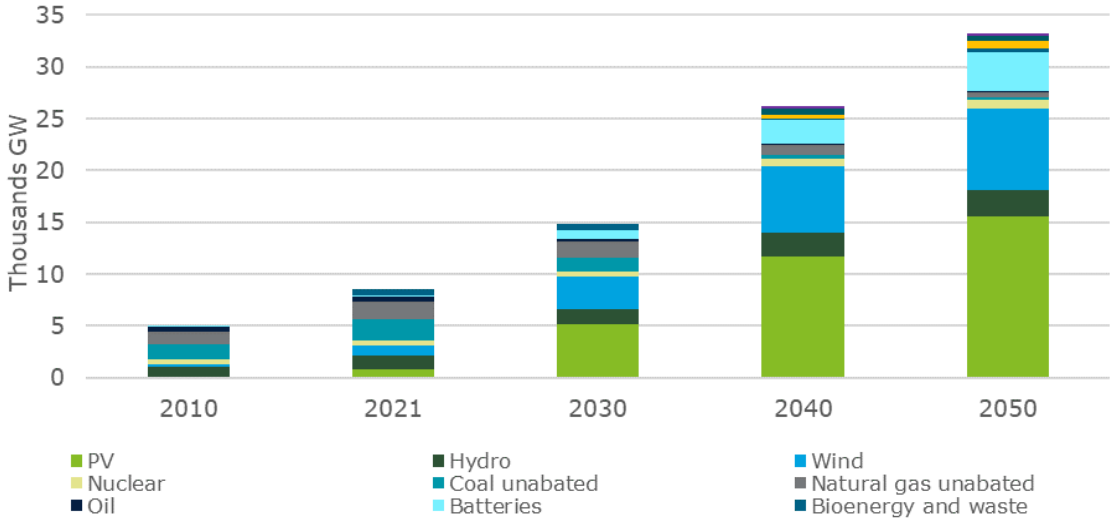
13 European Climate Law - European Commission (europa.eu)
14 COM (2018) 773 final : EUR-Lex - 52018DC0773 - EN - EUR-Lex (europa.eu)

The transition to clean energy is crucial from the point of climate mitigation and relies to a large extent on electrification of the economy. According to the net-zero emission (NZE) scenario presented in the World Energy Outlook 2022 by the International Energy Agency (IEA), the global electricity generation will more than double between 2021 and 2050[15]. Also, the consumption of electricity is expected to increase, for example due to the increased use of electricity in end-uses (industry electrification, heating, electrical vehicles etc.). The share of electricity in the consumption is projected to increase from 20% in 2021 to almost 30% in 2030 and reach more than 50% in 2050[15].

The International Energy Agency's (IEA) net-zero emissions (NZE) scenario assumes an important role for nuclear energy. The scenario assumes that **10% of generated electricity could originate from nuclear energy.** This is a similar share of nuclear power as the current global nuclear capacity which represents 400 GW produced by 440 reactors and which generated 2 653 TWh of the world's electricity in 2021[16].

To meet increasing demand for electricity, the IEA expects a doubling power generation from nuclear energy by 2050. The projection by IEA further predicts a major comeback of nuclear energy in the coming years, with annual average capacity to be commissioned reaching 30 GW in the 2030s.[15] This provides a stable backbone for electricity provision generated by intermitted renewable sources such as wind or solar energy. Their share in electricity generation is expected to increase to more than 60% in 2030 and reaching nearly 90% in 2050[15]. The annual renewables capacity should rise from 290 GW in 2021 to 1 200 GW in 2030[15].

Figure 2.2 Total installed capacity by source in the NZE scenario, 2010-2050

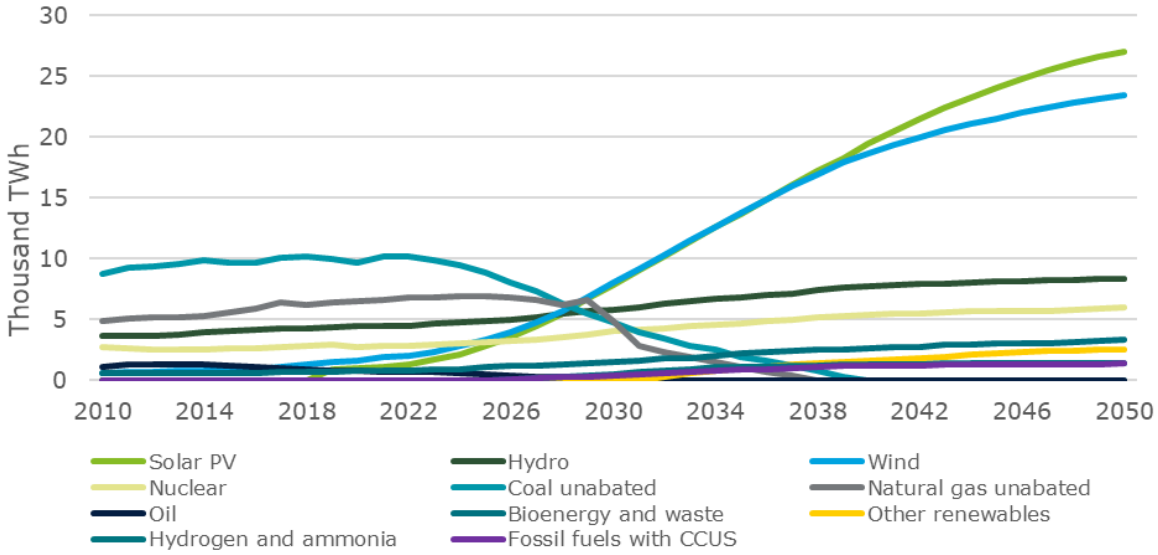


Source: World Energy Outlook 2022, IEA

15 World Energy Outlook 2022, IEA. These global trends are assumed to be applicable to the EU as well as discussed with the study's stakeholders.

16 World Nuclear Association

Figure 2.3 Electricity generation by source in the NZE scenario, 2010-2050



Source: World Energy Outlook 2022, IEA

Building upon the IEA's net-zero emissions scenario, nuclear energy may be required to support a stable energy provision, complementing the intermittent renewable energy sources, as confirmed by the study's stakeholders and as presented in the European Commission's Communication on "A Clean Planet for All" (ACPA)The ACPA states: "*By 2050, more than 80% of electricity will be coming from renewable energy sources (increasingly located offshore). Together with a nuclear power share of circa 15%, this will be the backbone of a carbon-free European power system.*" A similar number is presented in the last Nuclear Illustrative Programme (PINC) released in 2017, where the predicted nuclear capacity is expected to be between 95 – 105 GW[17] in the electricity mix[18].

Even though, the current capacity of nuclear power in the EU is similar to the expected capacity in 2050, namely 100 GW[19], the capacity is not sufficient to meet the climate objectives.[20] This is mainly due to the likely shutdown of a number of nuclear power plants until 2050, considering a lifetime extension between 50 or 60 years. **The average age of nuclear power plants in the EU is 35 years and 83% of nuclear power plants in the EU is more than 30 years old.**[21]

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17 Figures for the EU28. Discussing the adequateness of this objective is not in the scope of this study, although the study's stakeholders expressed via the questionnaires, interviews, and workshop that the share of electricity from nuclear power in the EU in 2050 is likely to be different from the 15% target, depending on the overall production. Answers ranged between 15 % and 38 % as this also depends on various external factors such as changing demand in electricity and other uncertainties. This study acknowledges such external factors but focuses on assessing the sectoral ecosystem's own capabilities to contribute to the EU's overall objectives and illustrate factors that hinder or support meeting these objectives.

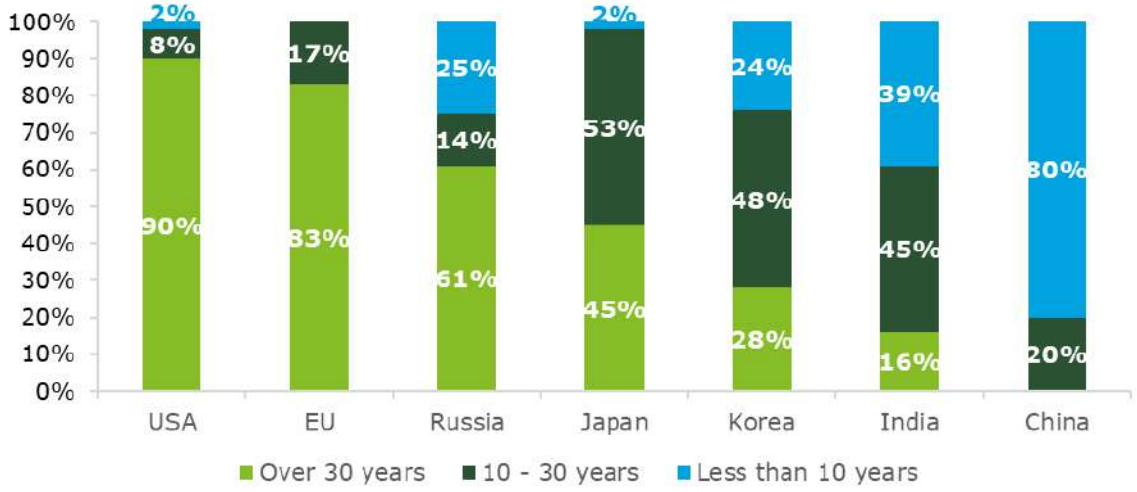
18 Nuclear Illustrative Programme, European Commission, 2017.

19 This corresponds to an approximate share of 23% of the EU's electricity mix

20 Eurostat, EU, 2023.

21 Nuclear Power in a Clean Energy System, IEA, 2019.

Figure 2.4 Age profile of nuclear power capacity in selected regions



Source: Nuclear Power in a Clean Energy System, IEA, 2019

2.2 Nuclear development and phase-out plans of EU Member States

EU Member States have the sovereignty right to decide on their own energy mix. Some Member States include nuclear power in their energy system, specifically Belgium, Bulgaria, Czech Republic, Finland, France, Hungary, Netherlands, Poland, Romania, Slovakia, Slovenia, and Sweden. Other Member States are discussing to include nuclear power in their energy mix such as Estonia, Poland, Lithuania, and Latvia. At the same time, Austria, Germany, Luxembourg, and Ireland are strongly opposing the use of nuclear power.

The installed capacity for nuclear energy production is likely to decline until 2050, **based on the data collected until June 2023**[11]. National Energy and Climate Plans as well as insights collected from EU Member States depict more shutdowns than increasing capacities. 11 EU Member States have plans or discussions about the construction of nuclear power plants, large reactors and SMR but these are not finalised yet.

Based on the collected data until June 2023, the combined expectations of EU Member States depict an installed capacity of almost 59 GW in 2050, much less than the assumed required capacity to meet climate objectives. At the same time, currently operating nuclear power plants undergo Long-Term Operation (LTO) programmes, extending their operating lifetime. The situation today is very dynamic as EU Member States updated their NECPs lately and commit to develop additional nuclear power plant, i.e. through Small Modular Reactors (SMRs). In addition, the duration of LTO is discussed. The estimation above is based on an assumed LTO of 60 years. **Many of the utilities are currently also considering LTO of up to 70, 80 or even 100 years of operation**.

2.2.1 Constructing new, large reactors

The construction of new, large reactors is one way to increase capacities. Yet, construction times shall be considered when assessing their contribution to meet decarbonisation targets. The World Nuclear Association (WNA) assessed the median construction time for reactors and nuclear power plants to be seven years,

based on data between 1981 and 2019[22]. Between 2011 and 2019 the average construction time increased to ten years suggesting increasing complexity and possibly delays which is confirmed by recent projects. The Olkiluoto plant began its commercial operation in 2023 after a long 18-year construction period. The Flamanville project is still in construction (it began in 2007), with the fuel loading expected to happen in 2024.[23] in the US, the AP1000 plant at Vogtle site has been constructed in approximately 10 years (it reached full power in May 2023).[24]

In addition, to the actual construction, the planning phase should be considered as well. This includes several activities such as concluding environmental impact assessments (EIA), obtaining construction permits, sitting permits, etc. examples show that this phase may take several years and prolong the construction project extensively. For example, **the EIA process takes on average 11.6 months, but the duration in different Member States varies from 5 to 27 months.[25]**

Figure 2.5 Median construction phase length for reactors since 1981 (in months)



Source: World Nuclear Association, IAEA PRIS database

2.2.2 Long term operation

LTO can be defined according to the Nuclear Energy Agency (NEA) "*as operation, justified by a comprehensive safety assessment, that goes beyond a previously established time frame corresponding to initial design assumptions (typically referred to as "original design lifetime" and usually 30-40 years depending on the design)*."[26] In 2020 nuclear operators worldwide were operating more than 100 nuclear reactors beyond their initially licensed lifespan, which on average is 40 years. Also, more than 30% of the NPPs were considered to be operated under the LTO condition, as indicated by the current national regulations.[21] This means that a significant proportion of nuclear power plants have been already granted an extension of their operational period.

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22 World Nuclear Association (WNA)

23 Further delay to Flamanville EPR start up : New Nuclear - World Nuclear News (world-nuclear-news.org)

24 Vogtle 3 reaches full power : New Nuclear - World Nuclear News (world-nuclear-news.org)

25 Impact assessment on Directive 2011/92/EU on the assessment of the effects of certain public and private projects on the environment. EC, 2012.

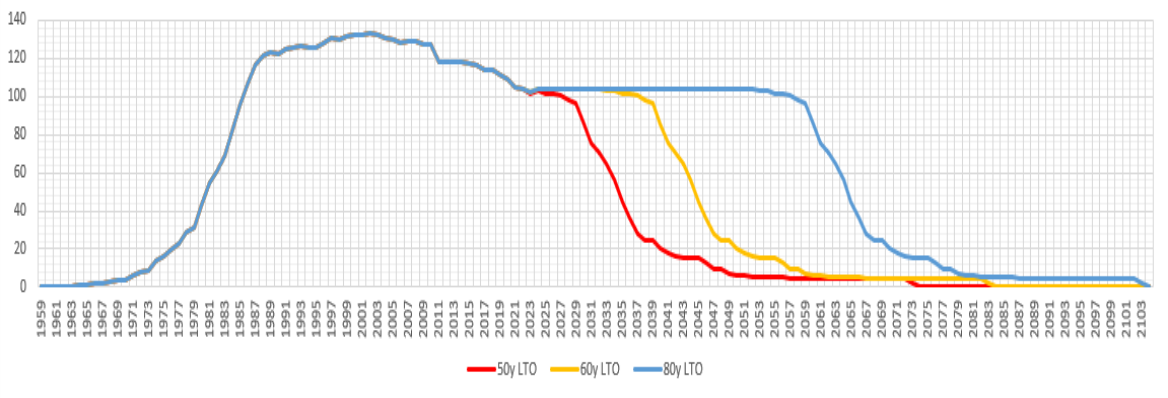
26 Long-Term Operation of Nuclear Power Plants and Decarbonization Strategies

The extended lifetime to 60 years is a standard today. But discussions are ongoing to further prolong the lifetime of reactors, e.g. to 80 or 100 years.[27] There are several ongoing activities to enable such extensions, including research done in the USA by the DOE and EPRI. Several nuclear power plants in the USA already applied for the 80-year lifetime extension. Three NPPs already received initial approval to run for 80 years, this approval was, however, revoked and the nuclear power plants must go through a full environmental review before they may be given the permission to operate for 80 years.[28] In Europe the Finnish power plant Loviisa was granted an operational licence till 2050.[29] This implies that in 2050 the first unit of Loviisa NPP would be operational for 73 years and the second unit for 70 years. This illustrates the will to operate nuclear power plants for 80 years, an endeavour that could be supported to meet climate and energy targets.

The below figure illustrates scenarios for nuclear power plants in the EU for different LTOs. Discussions with the study's stakeholder group illustrate the following assumed effects of LTO:

- 6 GW with 50 years of operation
- 22 GW with 60 years of operation
- 104 GW with 80 years of operation

Figure 2.6 Nuclear installed capacity by year (GW)



Source: Stakeholder discussion

The LTO scheme could help meeting the capacity target of 100 GW in 2050. Extending the lifetime of currently operating reactors would decrease the number of power plants phasing out and thus limited the assumed capacity gap. At the same time, the LTO would not be sufficient to close this gap and construction of new capacities remains needed to meet the decarbonization targets and the increasing electricity demand.

27 Nuclear plants could safely operate for 100 years, suggests Grossi director of the International Atomic Energy Agency (IAEA): Energy & Environment - World Nuclear News (world-nuclear-news.org)

28 Feds walk back plans for nuclear reactors to run 80 years - E&E News by POLITICO (eenews.net)

29 Fortum granted licence to operate Loviisa power plant units until end of 2050 (valtioneuvosto.fi)

2.2.3 SMRs and AMRs

Currently the development of Small Modular Reactors (SMRs) and Advanced Modular Reactors (AMR), and their deployment is widely discussed. Both types of reactors are still in the research and development phase, with the first ones expected to be deployed in the 2030s. Therefore, their effects to contribute to meeting EU climate targets is uncertain.

SMRs may be used for electricity production and heat, e.g. for the production of hydrogen and synthetic fuels, as well as for a combination of heat and power or district heating, as illustrated in the scenarios of the European SMRs Pre-Partnership Workstream 1 report[30]. SMRs have the potential to reduce costs, ensure faster and modular construction, with smaller power that is suitable for some purposes, such as the direct replacement of fossil fuels-based power plants. The main part (about 75%) is assumed to be based on light water technology due to the maturity of that technology. The rest is projected to be based on the AMR technology to address the issues of waste management or special industrial purposes (high temperature applications etc.).[31]

The assumed global energy supply by the SMRs in 2050 ranges between 17 GW to 50 GW.[31] This may require between 2 to 8 SMRs of 300 MW per year to be connected to the grid between the years of 2030 to 2050. As such SMR could provide part of the required capacity. Yet, the number of required reactors is too high to consider SMR as the only solution.

Small Modular Reactors could provide a complementary source to the commercial large-size reactors. Therefore, establishing relationships between stakeholders involved in SMR and large-size reactors could be further promoted and supported.

2.2.4 Different scenarios

By combining these different situations regarding new build, LTO and SMRs different scenarios emerged:

- **June 2023 scenario** depicting a continuation of current developments to construct new reactors and power plants, LTO and SMRs (based on data collected until June 2023 from EU Member States)
- **Intermediate scenario** which considers additional capacities of planned new reactors based on data collected after the June 2023 cutoff for this study[32], a LTO of 70-80 years as confirmed in Finland and Hungary and a minimum contribution of SMRs/AMRs coming from the European SMRs pre-Partnership report published in July 2023[33],

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30 The workstream considers 2 scenarios for the development and deployment of SMR based on market analysis and "*Boosted Deployment*" and "*Net Zero 2050*"

31 European SMR pre-Partnership. Executive summary and way forward, 2023.

32 This includes additional capacity foreseen following the cut-off data for data collection of the study. Additional data received until the stakeholder workshop in September 2023 was considered in this scenario, this includes the decision in Sweden to maintain nuclear energy (representing about 7 GWe) and reinforced planned capacity in Poland representing about 13 GWe compared to the estimate until June 2023).

33 17 GW from SMR in EU as presented in the scenarios of the European SMR Pre-Partnership Workstream 1 report

- **Advanced scenario** which considers the intermediate scenario and 80 years LTO applied to 50% of the currently operating nuclear power plants. It also considers the ambitious scenario for SMRs/AMRs of the European SMR Pre-Partnership report[34]. This allows to meet and exceed the nuclear capacity target as formulated by the nuclear alliance[35].

The different scenarios illustrate the possibilities for the nuclear ecosystem to contribute to EU decarbonisation targets. Constructing additional large nuclear power plants, increasing the LTO and advancing the development and deployment of SMR and AMR positively contribute to achieving targets. At the same time, it may also increase challenges that are detailed in the remainder of the report.

Figure 2.7 Different scenarios for the development and contribution of the nuclear ecosystem to EU climate objectives

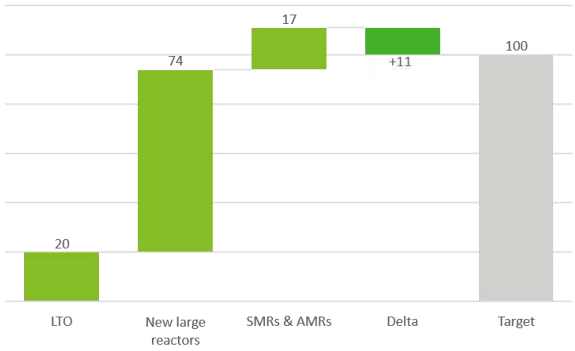
The graphs illustrate a breakdown of nuclear capacity in GW against the required capacity to meet EU climate objectives. The breakdown illustrates the main development trends discussed in this chapter, namely increasing capacity through LTO, new, large reactors and SMR & AMR. The increased capacity is illustrated by the first 3 bars in dark green. The last bar illustrates the target. The fourth bar illustrates the difference between the assumed capacity and the target:

- a gap of 24 GW in the June 2023 scenario,
- a surplus of 11 GW in the intermediate scenario,
- a surplus of 74 GW in the advanced scenario.

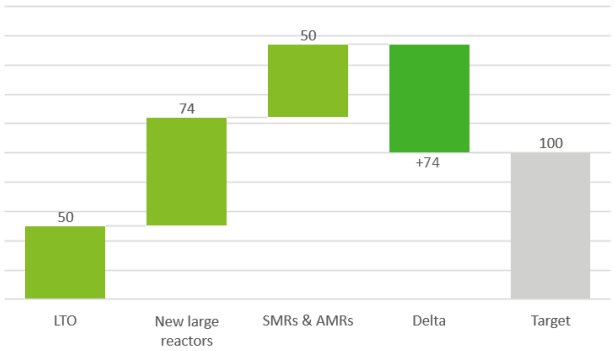
June 2023 scenario



Intermediate scenario



Advanced scenario



34 50 GW from SMR in EU as presented in the scenarios of the European SMR Pre-Partnership Workstream 1 report

35 The EU Nuclear Alliance aims to achieve 150 GW of nuclear power. The ambition is seen as possibility but has not been further used for the analysis in the remainder of this study.

2.3 Baseline scenario of this study: assumptions and projections

Based on data collected until June 2023, the EU nuclear ecosystem may fall 24 GW short against the 100 GW target for installed capacity in 2050, assuming a continuous development of large reactors, decommissioning, LTO and development of SMR & AMR. As presented in this chapter (depending on the assumption on LTO and SMRs development) this gap of 24 GW could be compensated and most optimistic scenarios would foresee even more than 150 GW by 2050.

This **baseline scenario** assumes the current situation of the EU nuclear ecosystem and its likely development path in view of the objective of achieving 15% of nuclear electricity production **by 2050 which corresponds to approximately 100 GW of installed capacity. The objective of this baseline scenario is to serve as a reference to analyse the fitness of the European nuclear ecosystem to deliver the required contribution.** The main parameters of the baseline scenario are the planned construction, planned shutdowns, decommissioning, and SMRs deployment in each EU Member State. These parameters facilitate examining the capacity and capabilities of the nuclear sector and discussing possible challenges and opportunities in the ecosystem to meet the objective. Therefore, **the baseline does not allow to predict a possible situation of the nuclear mix (new build, LTO, SMRs) in Europe by 2030, 2040 or 2050.**

Based on the main parameters discussed in this chapter, assumptions for the baseline scenario have been defined. These assumptions function as a benchmark to assess possible supporting and hindering factors for the nuclear ecosystem in the remainder of the report. **The assumptions and projections were discussed and agreed with the study's stakeholders during the first workshop and during the interviews**[36].

[36] The assessment focuses exclusively on the nuclear energy ecosystem. External factors and changes in the electricity market have been excluded from the assessment to focus on the challenges and potentials in the ecosystem. Changes such as increasing share of renewables and increasing electrification of the economy (e.g. including heating) have their impact on the ecosystem as well, however, this would deserve a specific study to explore the consequences of these trends in more detail.

The assumptions are presented below:

- The share of nuclear in the electricity mix is 15% in 2050[37],
- The share of 15% corresponds to approximately 100 GW[38] of installed capacity representing about 80 large reactors[18],
- The LTO of currently operated reactors is considered 60 years,
- The additional nuclear capacities coming from SMRs/AMRs are 5 GW[39],
- The baseline scenario builds upon data about future installed capacity received from Member States representatives, through desk research and the study's questionnaire[40],
- Achieving 150 GW instead of 100 GW would multiply the potentials and challenges presented in this report.

37 The target of 15% of nuclear energy in the EU´s electricity mix follows the objective presented in the Communication of the European Commission "A Clean Plant for All" as presented in chapter 2.1. Assumptions and projections in this study are formed on the basis of this target.

38 Calculated with the average reactor power of 1 200 MW.

39 Based on planned activities by Member States until June 2023. Since then projected capacities of SMR have increased. The SMR Industrial Alliance aims to deploy first SMR in the early 2030 which could contribute to meeting the advanced scenario of 50GW electricity produced by SMR. https://single-market-economy.ec.europa.eu/industry/strategy/industrial-alliances/european-industrial-alliance-small-modular-reactors_en

40 See Annex A for more details on the data collection and limitations.

3 Financing nuclear investments – Do we use the best financing tool?

Nuclear financing refers to the **process of securing funding for the development, construction, and operation** of a nuclear power plant. Financing investments in the nuclear sector is a complex and challenging task, among others due to **high upfront costs, long project lifecycles, and regulatory uncertainties.** The combination of challenges is different by EU Member State. Therefore 10 out of the 15 study's stakeholders request additional support from the European Commission[41]. 11 out of the 15 study stakeholders see possibilities to speed up the development of nuclear power in Europe by focusing on improving financing options. In the interviews a few of the study's stakeholders proposed a standardised approach to financing nuclear investments across EU Member States. In this regard the inclusion of nuclear power in the taxonomy is a step in the right direction. At the same time, stakeholders continue to perceive the landscape as complex as further explained in this chapter.

Key findings

- Building nuclear power plants requires substantial upfront investment. The related **high capital cost** of building nuclear power plants is a significant challenge for nuclear investments.
- Financing of nuclear projects requires a period to recoup investments or repay loans. This long period implies increased uncertainties on the electricity market providing the revenues to recoup investment or repay loans. This may increase risk levels and the capital costs for these investments.
- The market applies different financing options, each with specific risks. In general, the study's stakeholders assume a mix of state support and private funding as the most adequate option to facilitate investments.
- **Unpredictable political environments** and the **length and complexity of the notification period,** e.g. the time required to approve state aid are the two main obstacles.

[41] Via an online questionnaire the study's stakeholders were asked, "*On which topics should the communication with the European Commission be focused more?*" 10 out of 15 stakeholders suggested to focus on financing possibilities.

3.1 Current possibilities of financing nuclear power plant construction

At the end of 2016, the European Commission appointed a High-Level Expert Group[42] on sustainable finance to share a comprehensive vision on how to build a sustainable finance strategy for the EU. In January 2018, the expert group published its final report Action Plan: Financing Sustainable Growth[43] which includes a proposal for an EU Taxonomy Regulation (TR)[44], a proposal for a regulation on sustainability disclosures and on developing low-carbon benchmarks. It acts as the European Commission's action plan on financing sustainable growth[45]. The TR[46] establishes the basis for the EU Taxonomy by setting out 4 overarching conditions that an economic activity must meet to qualify as environmentally sustainable. Under the regulation, the Commission came up with the actual list of environmentally sustainable activities through delegated acts in which technical screening criteria for each environmental objective are defined. The taxonomy looks at a number of major sectors including agriculture, manufacturing, transportation, energy, construction, and communication. For each sector, it provides a list of industry-relevant activities that could be considered sustainable.

On 9 March 2022, the European Commission adopted a Complementary Climate Delegated Act[47] including specific nuclear and gas energy activities in the list of sustainable economic activities covered by the EU Taxonomy. It was published in the Official Journal in July 2022 and applies from January 2023. The criteria for the specific gas and nuclear activities are in line with EU climate and environmental objectives and could help to accelerate the shift from fossil fuels to a climate-neutral future. The inclusion of nuclear activities is time-limited and dependent on specific conditions and transparency requirements, but it now indicates that all financing mechanisms and instruments of the EU have to treat nuclear equally with other low carbon sources. The specific conditions are listed below:

- Pre-commercial stages of advanced technologies to produce energy from nuclear processes with minimal waste from the fuel cycle,
- Construction and safe operation of new nuclear power plants, for the generation of electricity or heat, including for hydrogen production, using best-available technologies,

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42 The group comprised of 20 senior experts from civil society, the finance sector, academia, and observers from European and international institutions.

43 Action Plan: Financing Sustainable Growth, European Commission, 2018.

44 In order to meet the EU's climate and energy targets for 2030 and reach the objectives of the European Green Deal the EU acknowledged that a common language and a clear definition of what is sustainable is needed.

45 The Report argues that sustainable finance is about two urgent imperatives: (1) improving the contribution of finance to sustainable and inclusive growth by funding society's long-term needs; (2) strengthening financial stability by incorporating environmental, social and governance (ESG) factors into investment decision-making.

46 It was published in the Official Journal of the European Union on 22 June 2020 and entered into force on 12 July 2020.

47 A first delegated act on sustainable activities for climate change adaptation and mitigation objectives was published in the Official Journal on 9 December 2021 and is power since January 2022.

- Electricity generation from nuclear energy in existing installations should also be considered. **The Complementary Delegated Act[48] provides a proposal to ensure investments needed for energy transition**.

Nuclear power plant construction projects are characterised by **substantial initial upfront investment,** with long lead times on items, **high cost through a long construction period, and lengthy return on investment** making them very capital-intensive, similar to other large infrastructure projects[49]. Unlike, some other large infrastructure projects, **the role of the state and public financing** is pivotal. In recent years a significant number of models have been used to facilitate investment but broadly speaking, there are two main ways in which a nuclear power plant projects, and its ownership can be structured: government (public) or corporate (private) owned/financed.

On top of the already complex ecosystem, electricity price uncertainty introduces a significant risk for a new investment in nuclear power plants. In response, investors and decision makers are employing a range of ownership structures and financing mechanisms across different market environments to support construction of large new scale baseload nuclear generation projects. This chapter provides an overview of how NPPs are financed via available public-private schemes.

3.1.1 Public investments

Historically states, i.e. directly or indirectly financed nuclear power plant projects from the governmental budget or through guaranteed loans, in places where a regulated utility regime and regulatory arrangements are present. Under these conditions many of the risks associated with nuclear power plant construction, operating performance, fuel price changes, and other factors are thus borne by the state rather than by investors. This was the situation during the 1970s where electricity customers paid a standard price for the power. For utilities investing in large power plants, regulated markets provided a high degree of assurance on return on investment.

Today this situation is different due to liberalised electricity markets and increased competition. This transferred most of the risk to electricity generating companies. In a competitive market, there is no guarantee for an investor or an operator that it will find a ready market with prices high enough to provide an acceptable return on investment. While deregulated markets have generally reduced the wholesale price of electricity, they also introduced greater uncertainty and price volatility. Therefore, the state still plays an important role in regulated and deregulated markets.

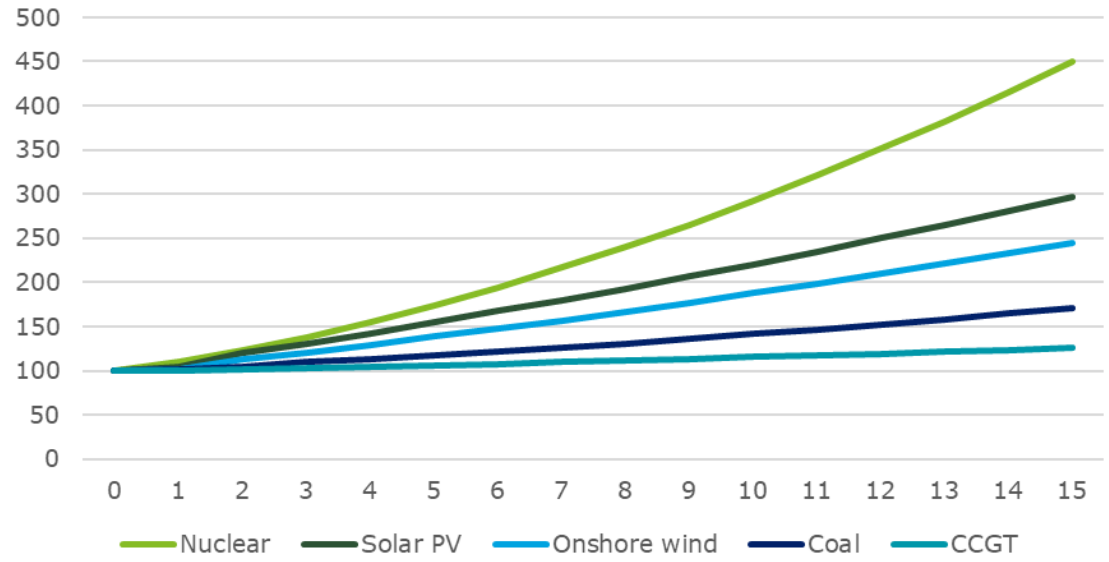
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48 Commission Delegated Regulation (EU) 2022/1214 amending Delegated regulation (EU) 2021/2139 as regards economic activities in certain energy sectors and Delegated Regulation (EU) 2021/2178 as regards specific public disclosures for those economic activities.

49 Financial exposure and risk grow in proportion to the size of a project and its subsequent technical and managerial complexity.

In general, the **cost of capital is typically a key component** of the overall cost of nuclear power plants. A project's cost of capital reflects the risks associated with the project. The duration of the construction period, potential revenue streams from the project, and interest on funds (debt financing) are important components to determine the costs for nuclear power plant projects[50]. If the cost of capital is high, then the capital expenditure rises disproportionately and may undermine the viability of the project. The chart below shows a comparison of the effect that different discounts rates have on the levelized cost of electricity.

Figure 3.1 Effect of discount rate on LCOE for different technologies



Source: OECD, 2015[51]

Governments could introduce different levers to lower the cost of capital and thus significantly reduce the cost of nuclear projects and ultimately the price of electricity for consumers. One possible lever to reduce the average cost of capital is to co-finance a nuclear project by investing public capital in the company that is in charge of the project. There are a few examples of such public financing:

- The French nuclear fleet in the 1970–1990s by the state-owned utility EDF,
- The Qinshan 1 and 2 project in China,
- The Barakah project in the United Arab Emirates[52].

In the past, the World Bank, the European Investment Bank (EIB), and a wide range of commercial lenders financed nuclear projects. Today, the World Bank and EIB are financing support for nuclear power plants. The Development Bank of Latin America is the only international development bank to have made a loan in recent times: to support the refurbishment and license extension of Argentina's Embalse nuclear power plant in 2013[53].

50 https://world-nuclear.org/information-library/economic-aspects/financing-nuclear-energy.aspx
51 2015 NEA Annual Report. OECD-NEA, 2015.
52 Financing Nuclear Power in Evolving Electricity Markets. IAEA, 2018.
53 https://www.world-nuclear-news.org/c_embalse_wins_loan_for_longer_life_2203131.html

3.1.2 State guarantee

Another form of government support are **credit enhancement mechanisms**. These are used in nuclear projects to reduce the risk exposure of investors, and particularly lenders. The concept aims to support a financially weaker party e.g., the developer by transferring liabilities to a financially stronger party, e.g., a government. By reducing the risk exposure, credit enhancement allows to reduce the cost of debt and therefore increase the desirability of the project[54]. It also opens for a wider pool of potential investors. The main upside - the lower cost of capital which improves not just the project's economics but also the attractiveness of the project. There are a variety of credit enhancement mechanisms used: governmental guarantees and Export Credit Agencies financing (ECA).

Government guarantees

The host government is the ultimate guarantor for the liabilities of the developer. As such it shows commitment of the government to the project[55]. Government financing options include for example:

- governmental financial guarantees on loans,
- bond issues,
- funding from local government budget and-or local suppliers.

This credit enhancement mechanism is only as valuable as the perceived financial solidity of the government providing the guarantee. Thus, the sovereign credit rating of the host country is an important metric to be taken into account. Examples of governments financing the construction of NPPs are:

- the projects Qinshan 1 and 2 in China,
- the Barakah project in the United Arab Emirates[56],
- the Vogtle project in the USA[57].

Export Credit Agencies (ECA)

ECA are financial institutions, private entities, or (quasi-) governmental agencies that provide financial services to a domestic company to support their activity overseas and to promote exports. In other words, it is non-recourse/limited recourse financing[58], where the lenders have no or limited recourse to the borrower and the only collateral for the loan is the project itself.

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54 Managing the Financial Risk Associated with the Financing of New Nuclear Power Plant Projects. IAEA, 2017.

55 Government guarantees might also give creditors additional comfort in the stability of the regulatory regime during the payback period of the loans. If the government guarantees the loans, it may be less inclined to introduce regulatory changes in the future (e.g. forced premature decommissioning) that could endanger the payback of the loans, even after a potential change in government.

56 The financing comprises direct loans of $19.6 billion, with $16.2 billion from the Abu Dhabi government and another $2.5 billion from Kexim. https://www.txfnews.com/articles/5845/UAE-secures-24-4bn-for-its-first-nuclear-power-plant

57 The U.S. Energy Department approved $3.7 billion in loan guarantees to finance the construction of two reactors at the delayed Vogtle nuclear power plant in Georgia in March 2019. https://www.reuters.com/article/us-usa-nuclearpower-vogtle-idUSKCN1R31X9

58 Nonrecourse financing is debt where the loan is completely secured by collateral, which is often real estate. In case of default, the borrower is not liable because the lender is limited to collateral pledged for that loan—the lender has "no recourse" to the borrower's other assets.

There are various types of ECA services: direct loans (with generally a medium to long-term maturity), loan guarantees and cover insurances. ECAs also play an important role in removing some of the uncertainties and risks of political or commercial nature faced by the seller when exporting, in exchange for a premium. Examples include the Coface (French ECA) loan for the Olkiluoto project in Finland, the loan provided by the Korean ECA for the Barakah project in the United Arab Emirates and the export credit given by the Russian government to build a VVER in Belarus[59].

3.1.3 Private financing

Nowadays, governments are seeking to attract private investors for nuclear power plant projects. Investors are mainly large companies with strong balance sheets due to the high cost and risks associated with nuclear investments. Nevertheless private investors support nuclear projects, for in the USA, France, Korea, Finland, and China.

Private companies use their capital structure, a combination of debt and equity, to finance projects. In other words, they attract debt for a new project. Therefore, as with state-aid, the cost of capital is particularly important to assess whether investments can be repaid.

Project Financing (PF) is one way to deal with high cost of capital for private companies. PF refers to a special form of financing for large-scale investment projects[60], where the debt is repaid from the future income of a facility under construction. As such PF provides companies with access to large loans when the classic corporate finance approach is not possible, for example, due to economic constraints, financial difficulties of project stakeholders, the balance sheet situation of the project sponsor. To implement PF for large energy projects, a legally and economically independent project company (Special Purpose Vehicle) is usually established[61]. In the table below features used in PF are outlined.

59 Russia financed the plant with a state loan of up to $10 billion to be paid over the span of 25 years. The loan is to cover 90 percent of the total cost of about $11 billion. Caspian News, 2021.

60 Projects such as chemical plants, refineries, solar power plants, LNG terminals, pipelines, in which different project participants jointly implement a project.

61 https://esfccompany.com/en/articles/project-finance/project-finance-in-energy-sector/

Figure 3.2 Examples of PF features used in the energy sector

Lending based on cash flows	• All obligations of the project company (operational costs, interest, and repayment) are covered by the future free cash flow of the energy project, which means the difference between incoming and outgoing flows, considering replacement investments. • PF lending is based on proof of the technical and economic viability of the project. • In the absence of collateral, creditors are provided with special rights, such as the right to enter into contracts, the right to participate in the management and control of Special Purpose Vehicles (SPV).
Off-balance sheet financing	• Project sponsors are not required to consolidate their balance sheets, project finance does not expose these participants to risk. • Received loans are considered only SPV and thus do not worsen their financial performance. • Sponsors' obligations are limited to their contribution to the project and assets owned by SPV (the so-called non-recourse financing). • In most cases, additional obligations are assumed, for example, in the form of guarantees or obligations to make additional payments (limited recourse financing).
Rational distribution of risks	• Energy project risks are shared among various project participants (sponsors, suppliers, operators, buyers, lenders, project company, insurance companies). • For export shipments of equipment and cross-border services, insurance policies are often issued to hedge risks. • Depending on the situation, there are also guarantees from the government, public banks or supranational institutions, including European Investment Bank (EIB).

Source: ESFC Investment Group, 2022

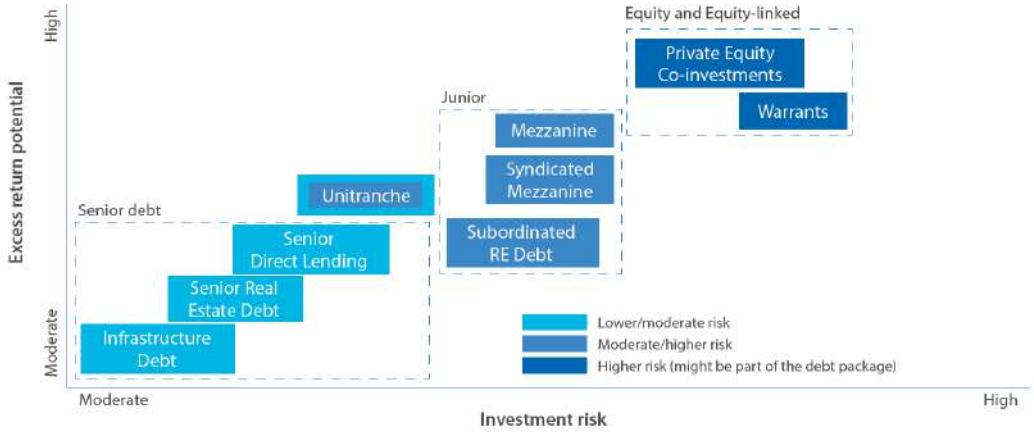
One of the advantages of PF is that energy companies can limit the risk and project debt repayment obligations. The funds received are initially used to support the project, then the interests are paid to the creditors, and finally the remaining funds are distributed to the capital providers. PF is being widely used but it is not commonly used in the nuclear sector, among other due to imbalanced risk levels for partners involved in the project and imbalanced collaterals to ensure dept financing for the project partners. Another factors is the lack of standardised designs for nuclear reactors which requires specific project financing schemes each time[62].

There is no minimum cost for each project, but PF makes sense for large energy projects and would therefore be fit for purpose when financing nuclear power plants[63] As illustrated in the figure below the higher the investment risk the higher the expectation on return.

62 The OECD lists several reasons for the limited use of project financing for nuclear project. This is mainly linked to risks levels bared by project partners, possible assets to be used as collateral for dept financing (equity or loans), the duration of repaying debts, and the objective to keep ownership of the newly constructed power plant in the hand of the utility company. See for more details The Financing of Nuclear Power Plants | READ online (oecd-ilibrary.org).

63 The Financing of Nuclear Power Plants. OECD, 2009.

Figure 3.3 Relationship between return and investment risk



Source: © nucleareurope (former FORATOM), 2021[64]

3.1.4 Mankala model

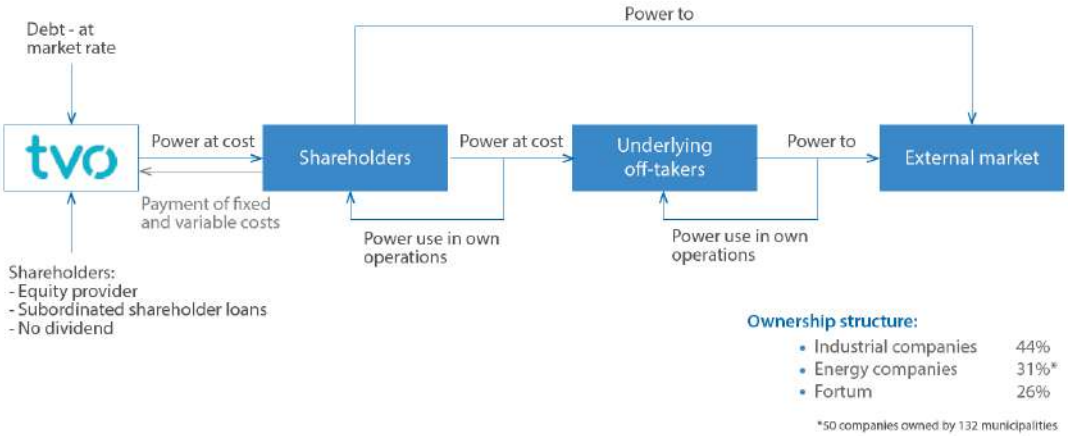
The Mankala model is a specific type of financing used to build nuclear power plants. The Mankala model is an ownership model for energy producers which is **unique to the Finnish energy markets**. It originated in the 1960s and it is a special scheme that combines both public and private financing. Mankalas are limited liability companies run like zero-profit cooperatives in which power plants are owned by multiple partners through equity[65]. Mankala syndicates organise consortia of Finnish industrial companies, wholesalers, distributors, retailers, and municipal energy providers to cooperatively purchase, finance, and share the output of jointly owned nuclear energy generation facilities. For example, an entity owning about X% of a Mankala company would pay about X% of the total costs to build, maintain, and manage the Mankala's cooperatively owned nuclear reactor. It would, in turn, receive the same X% of its energy output in return. Furthermore, the owners of the Mankala are allowed and obliged to purchase electricity from the power plant equal to their shareholding at a cost price. This electricity can then be used by the investors or can be sold to the market. If one owner were to seek more energy at some point in the future, it could negotiate with other owners to buy more shares of a Mankala and hence pay more of its operating and maintenance costs. If it were to want less energy, it could sell its shares, assuming there would be someone willing to buy them, and pay commensurately less of the costs.

This diversity of ownership was intended to pool capital from many different sources and thus to disperse risk and liability across several partners. Mankala cooperation was not dictated by government legislation, but through private contracts called Articles of Association[66]. Unlike standard limited liability companies, a Mankala does not generate profit, but instead, aims to ensure the

64 Investment Framework Task Force Report. nucleareurope (former FORATOM), 2021.
65 Mankala Chronicles: Nuclear Energy Financing and Cooperative Corporate Form in Finland. American Nuclear Society, 2021.
66 Mankala principle: A concept to finance large clean energy investments in Finland. Juho Korteniemi, 2018.

stability and accessibility of energy supply. The Mankala owners are obligated to buy their share of energy from the private, jointly owned reactor even if its costs exceeded the current market price, which they often did. Since its origin, the concept has been used to help develop various forms of infrastructure. For example, Finland's nuclear energy companies Teollisuuden Voima Oyj (TVO) and Fennovoima are backed by a corporate ownership model called Mankala.[67] The figure below provides a detailed overview.

Figure 3.4 Financing model - example of Mankala in Finland



Source: © nucleareurope (former FORATOM), 2021

3.1.5 Vendor equity

Reactor technology vendors may be able to support new build projects financially as well as technologically. In this case vendor equity helps to finance a project in return for the vendor's technology being deployed in the new facility. However, technology vendors do not have infinite balance sheets to allow them to invest in unlimited projects. They may only invest in the most advanced projects that are likely to succeed, that will allow them a return on their investment in the shortest time and allow them to exit the project at the earliest opportunity. Compared to the Mankala model, vendor equity illustrates a higher level of vertical integration along the value chain i.e., it is not the electricity consumer joining the generator, but the power plant components manufacturer joining the generator. This could be particularly interesting in the context of SMRs, where a new layer in the value chain would have to emerge, the layer of reactor factories.

3.2 Strategies to mitigate risk

For the two main models to finance the construction of new nuclear power plants (i.e. the government and corporate models as discussed above) upsides, downsides and long-term electricity price uncertainty. Therefore, different mechanisms and strategies are put in place to secure revenues and reduce the market risk for investors. Such a dynamic risk-based approach to financing using contractual incentives may offer innovative solutions. The most known mechanisms designed to complement the uncertain revenues are feed-in tariff

67 https://www.neimagazine.com/news/newsfinnish-government-says-yes-to-tvo-and-fennovoima

(FIT), contract for difference (CFD), power purchase agreements (PPAs), and the regulated asset base model (RAB).

Feed-in tariff (FIT)

FIT have been **extensively used for developing renewable projects** within the EU Member States. Electricity producers are guaranteed a fixed price for the electricity generated for a predetermined number of years, regardless of the actual market electricity prices. In some Member States too generous levels were set by the administrations, rather than through a competitive bidding process. Therefore, despite their recent popularity, FITs have become unaffordable for consumers in some Member States. In addition, FITs may keep prices up due increasing take up and decreasing production costs as seen for renewable energy[68] Therefore, in many case FITs are being replaced with other mechanisms such as CFDs.

Contract for difference (CFD)

The CFD is an **instrument widely used in the UK to support low carbon technologies**[69]. Competitive CFD schemes have been very successful in driving substantial deployment of renewables at scale whilst rapidly reducing costs. CFDs used for the Hinkley Point C (HPC) power plant were an important innovation in promoting a sustainable market-oriented electricity system that embeds a transition to low-carbon energy in a way that is technologically neutral with international significance[70]. It is a mechanism that mitigates market risk by reducing the exposure to electricity price volatility[71]. The HPC CFD is used as an example (see table below).

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68 The Czech Republic had a mandated FIT for solar power of CZK 12 ($0.63) per kWh, about ten times the cost of power generated by CEZ. This was threatening grid stability and was reduced to CZK 5.5 for new PV projects over 100 kW and CZK 7.5 for smaller ones after the end of 2010.

69 Developed in Britain in 1974 as a way to leverage gold. CFDs were initially used by hedge funds and institutional traders to cost-effectively gain an exposure to stocks on the London Stock Exchange because they required only a small margin.

70 Response by the World Nuclear Association to the Public Consultation initiated by the European Commission in connection with State aid SA 34947 (2013/C) concerning Hinkley Point C (UK). World Nuclear Association, 2014.

71 Contracts for Difference for Low Carbon Electricity Generation. Consultation on proposed amendments to the scheme. The Department for Business, Energy & Industrial Strategy (BEIS), 2020.

Table 3.1 The Hinkley Point CFD scheme

Hinkley Point C project	
Project overview	HPC NPP is being developed by EDF in the UK. The development consent order for the project from the UK government was received in March 2013 and the final investment decision on the project was announced in July 2016. The plant's first unit is expected to be operational in 2027. The 3.26 GW plant is predicted to produce 26 TWh of electricity per year during its operational lifetime of 60 years, equivalent to 7% of Great Britain's forecast electricity demand during the 2020s. The project was originally estimated to cost £16bn ($27bn). In February 2023, EDF announced that its cost is likely to increase to between £31bn ($37.2bn) and £32.7bn ($39.3bn) due to inflationary pressures[72].
Strike price	Under the HPC CFD scheme, the government guarantees a "strike price" for the electricity generated by the HPC NPP. The strike price is the price at which the government will pay the project developers for each unit of electricity generated.
Fixed and indexed strike prices	The HPC CFD scheme consists of two phases: • Fixed Strike Price: During the initial phase, the strike price is fixed for a specified period. For HPC, the fixed strike price is £92.50 per MWh in 2012 prices (index-linked with inflation), and it applies for 35 years from the station's commissioning. • Indexed Strike Price: After the fixed period, the scheme transitions to an indexed strike price for the remainder of the project's operational life. This indexed price reflects changes in inflation and energy market indices.
Top-up payments and clawback	The difference between the strike price and the prevailing market price is reconciled through top-up payments or clawback provisions. Top-up Payments: if the market price of electricity falls below the strike price, the government pays the project developers the difference. Clawback: if the market price of electricity exceeds the strike price, project developers are required to pay back the excess to the government.
Government support	The HPC CFD scheme benefits from government support, including loan guarantees and certain financial securities. These measures help secure private investment and reduce the financial risks associated with the project.

Source: Financing the Hinkley Point C project, Steve Thomas, Business School University of Greenwich, 2020

Using the UK example, in a CFD, a strike price is agreed (or awarded via an auction) between the electricity producer and a counterpart, which is generally a governmental entity. The electricity producer sells the electricity in the market and receives the difference between the agreed CFD strike price and a reference price (based on market prices). If the reference price is higher than the CFD, the electricity producer pays the difference to the counterpart, otherwise it receives the difference. Even though the generating company sells electricity (and thus participates) in the market, the CFD mechanism de facto insulates the generating company from market signals, as the combined revenues (market plus CFD compensation) are independent from the actual electricity market price. In this respect, the CFD is like the FIT mechanism. A similar mechanism was used in the Czech Republic (see table below for details).

72 https://www.power-technology.com/projects/hinkley-point-c-nuclear-power-station/

Table 3.2 The Dukovany 5 project in the Czech Republic

The Dukovany 5 project	
Project overview	Construction of a 1200 MW reactor at the Dukovany site, as part of a programme to replace the nuclear reactors currently in operation.
Project financing	The beneficiary of the measure would be the Elektrárna Dukovany II (EDU II). The company is fully owned by the ČEZ Group (the main incumbent in Czechia with the Czech government holding about 70% of the shares). The Czech Republic plans to support the construction through the following measures: • a low-interest repayable State loan expected to cover 100% of the construction costs (approximately €7.5 billion) • a power purchase agreement between EDU II and a State-owned company for the lifetime of the project (60 years) - according to the Czech authorities, this would lower the power purchase price and allow for price adaptations every 5 years • a mechanism to protect the ČEZ Group and the State in case certain unforeseen events occur (if the Czech law changes and makes the realisation of the project impossible). The ČEZ Group contribution to the project will be of approximately €0.18 billion[73] .In order to ensure low-cost financing, the interest rate on the State's stake will be 0% during the construction period and 2% thereafter.
Project framework	A new legislation will define a legal framework to establish a long-term guaranteed price, like the UK CFD model but the European Commission must approve these plans to ensure that they comply with EU State aid rules.

Source: Financing France's new nuclear build. Sfen, 2022

Power purchase agreements (PPAs)

PPAs are the primary contract between sector parties both public and private. They are typically between a (semi-)public sector purchaser (often a state-owned electricity utility, in jurisdictions where the power sector is largely state operated) and a privately-owned power producer. Under a PPA, an electricity purchaser commits to buy all, or a predetermined fraction of electricity generated by a power plant at an agreed fixed price for an extended period. It usually provides the primary revenue stream which underwrites the project. Therefore, the structure and risk allocation regime under the PPA is central to the private sector participant's ability to raise finance for the project, recover its capital costs and earn a return on equity.

Regulated asset-based model (RAB)

A principal feature of the RAB model is that an independent regulator sets a regulated rate of return. The rate is less volatile compared to market rates if is perceived less risky by investors. A nuclear developer may receive a license from an independent regulator following due diligence to confirm a proposed plant's viability and value. In addition, the license would **allow the developer or operator to pass costs onto its customers** in exchange for the provision of the asset (and the supply of electricity from it). The model distributes risks between multiple stakeholders and aligns incentives for the power plant to remain efficient and cost-effective for the consumers.

[73] https://ec.europa.eu/commission/presscorner/detail/en/IP_22_4244

Under this framework, investor revenues based on their expenditures are periodically reviewed by an independent regulator that estimates whether capital investment expenditures are consistent with previously accepted forecasts. Thus, it provides bankable revenue in much the same way that a long-term contract does, reducing risk for investors, and reducing the cost of capital.

In the UK it has been proposed that future nuclear power plants could be financed using the RAB model. The UK Government consulted on a RAB funding model for new nuclear in July 2019 and published its response in December 2020, which confirmed its assessment that the model is credible for financing large-scale nuclear projects[74]. The model is already used for monopoly infrastructure for example in the UK[75], Australia and the majority of EU Member States, but has not been widely used for electricity generation projects. The table below provides an overview of the RAB model used on the Sizewell C project.

Table 3.3 The Sizewell RAB scheme

The Sizewell C project	
Project overview	The project aims to extend the Sizewell nuclear power station and includes the construction of two new EPR reactors.
Project financing	In September 2022 the UK government announced it will provide GBP 700 million in funding. It is part of the GBP 1.7 billion of new direct government funding that was granted for the project in January 2016[76].
Project framework	In June 2022 the Department for Business, Energy & Industrial Strategy published a case for company operating Sizewell C to receive funding under the RAB model. According to the UK government under the scheme, private investors receive greater certainty through a lower and more reliable rate of return in the early stages of a project, lowering the cost of financing it, and ultimately helping reduce consumer electricity bills. However, the Act is still in the consultation phase and at the time of writing no updates were published by the government.

Source: GOV.UK, June 2022

As discussed in this chapter there is a variety of models and ways of financing new nuclear power plants. The table below compares three selected schemes to illustrate the main differences.

74 Nuclear RAB model: Statement on procedure and criteria for designation. BEIS, 2022.

75 It is generally used across multiple assets; the first time it was used to support a single asset construction project was the £4.2 billion Thames Tideway Tunnel sewage project in the UK, in 2016 (BEIS, 2022).

76 https://www.bloomberg.com/news/articles/2022-09-01/uk-to-invest-700-million-in-edf-s-sizewell-nuclear-plant#xj4y7vzkg

Table 3.4 Selected examples of financing models

		Hinkley Point C (2018-2026)	Sizewell C (2022 - ?)	Dukovany (2029-2036)
Financing model and sources		Private financing	RAB model	Majority State financed
Risk allocation	**Construction and Operating risk**	Industry	Shared between investors, consumers and the State	Unconfirmed
	Market Risk	Consumers	Consumers	Consumers
State role and involvement	**Direct financial**	-	Possible	State 70%
	Indirect financial	Loan guarantees	-	-
	Non- financial	Guaranteed electricity price over 35 years	Financial guarantees covering cost ceiling overruns and ROI during construction and operations	Guaranteed electricity price over 30 and 60 years
Discounted cost of production (EUR/MWh)		102 EUR/MWh	44-66 EUR/MWh	48-70 EUR/MWh

Source: Financing France's new nuclear build. Sfen, 2022

New nuclear power plants are unlikely to **be built by the private sector without some form of government support.** When looking at different strategies, evaluation methods, and the advantages and disadvantages of each financing model it must be applied on a project specific basis and should be always compared against the prevailing alternatives at the time. It is important to take the market conditions and regulatory environment into account. The specific type of government support offered could determine how the risks are distributed among the private sector, electricity consumers, and taxpayers. This distribution of risks ultimately affects the project's potential value for money and its overall financial feasibility. The following table compares the CFD and RAB strategies to mitigate risk.

Table 3.5 *Comparison of CFD and RAB model*[77]

Financing models	**Overview**	
CFD	Consumers pay a price per MWh of electricity which is agreed in advance of construction and compensates the developer for its expected expenditure and financing costs and is fixed for a period of time. Risks in construction, from cost overruns or time delays, remain with the developer and its investors. Under the CFD model, construction risk (the risk of cost and time overruns in construction) is entirely held by the developer. Once the project is completed, wholesale market price risk is held by consumers (over the duration of the contract) and, it is assumed, that demand risk, i.e., whether there is sufficient demand in the market for the electricity generated, is also held by consumers. The developer also retains operating cost risk and decommissioning cost risk.	
	Advantages	**Disadvantages**
	• Risk sharing: CFDs allow risk sharing between the government and the private sector. The government ensures revenue stability by guaranteeing a certain price for the electricity produced,	• Government liability: The government may bear the risk if electricity market prices rise above the agreed price in the CFD, potentially resulting in higher costs for the government and taxpayers[78].

77 Estimating comparable costs of a nuclear regulated asset base versus a contract for difference financing model. National Infrastructure Commission, 2019.

78 https://www.fornybarnorge.no/publikasjoner/horinger/2023/public-consultation-revision-of-the-eus-electricity-market-design/

	thereby reducing the market risks of the project. • Cost control: CFDs typically include fixed price agreements, allowing for better cost control and predictability during project development and operation. • Bankability: CFDs can increase the bankability of projects by providing income security, making it easier to secure project financing from lenders.	• Limited market exposure and lack of flexibility: CFDs may limit the project's exposure to market dynamics and price fluctuations. While this can reduce risks, it also means the project may not fully benefit from potential market price increases. • Global cost of the project and LCOE • Administrative complexity: Setting up and managing can be administratively complex, requiring effective monitoring and enforcement to ensure compliance with contractual obligations.
Overview		
RAB	The government-protected RAB model changes risk allocation (and thus changes project financing options) and provides investors with a stable long-term revenue stream, which in turn provides the potential for a lower cost of capital. However, changing the risk profile involves trade-offs that need to be evaluated to ensure comparison with alternative options. • Under the RAB model, construction risk is shared between the developer, consumers, and the taxpayer. • Once the project is completed, wholesale market price risk and demand risk are assumed to be held by consumers. • The developer therefore retains a share of construction risk (up to a cap), operating cost risk and decommissioning cost risk.	
	Advantages	**Disadvantages**
	• Investment certainty: RAB allows for a regulated return on investment, providing investors with long-term certainty and a stable revenue stream, making it attractive for infrastructure projects[79]. • Incentives for alignment: RAB facilitates aligning the interests of investors and regulators by linking returns to efficient and cost-effective project performance, incentivizing efficient project delivery and operation. • Enhanced project control and potential for reduced costs: RAB models involve regulatory oversight, ensuring that the project is delivered and operated efficiently, with appropriate cost controls in place, potentially leading to reduced costs for consumers.[80]	• Limited flexibility: RAB models may have strict regulatory controls and predetermined returns, limiting the project owner's flexibility to respond to changing market conditions or adapt to emerging technologies. • Lengthy regulatory processes: Establishing and implementing RAB models often involves lengthy regulatory processes, which can cause delays in project development and implementation. • Consumer impact: RAB models may result in higher costs for consumers if the regulatory returns are set too high or if the project's efficiency and cost-effectiveness are not adequately monitored[81].

Discussions to reform the EU electricity market are ongoing[82]. In March 2023 the European Commission proposed an electricity market design reform proposal which is also a part of the Green Deal Industrial Plan aimed to enhance the competitiveness of the EU's net-zero industry and accelerate the transition to

79 https://www.nortonrosefulbright.com/es-es/knowledge/publications/55726950/nuclear-energy---briefing-8-july-2022

80 RAB Model for Nuclear. BEIS, 2020.

81 https://www.gov.uk/government/news/future-funding-for-nuclear-plants

82 The European Commission made proposals to reform the electricity market that may impact the possibilities to financing nuclear projects. Until 16 June 2023, the European Commission made first announcements for reforms which have been considered for this report reflecting the ongoing debates and as benchmark to assess possibilities and challenges with the study's stakeholders group. Actual reforms could not be considered for this study due to ongoing dicsussions.

climate neutrality[83]. It proposes measures that incentivise longer term contracts with non-fossil power production. The proposal encourages suppliers to manage price risks at least to the extent of the volumes under fixed contracts, to be less exposed to price spikes and market volatility. To enhance the competitiveness of EU industry and to reduce its exposure to volatile prices, the European Commission proposed to facilitate the deployment of PPAs. In addition, to provide power producers with revenue stability and to shield industry from price volatility, all public support for new investments in infra-marginal and must-run renewable and non-fossil electricity generation could be in the form of CFDs.[84]

3.3 Notification procedure

As discussed in the state-aid and state guarantee sections, government support to the nuclear energy sector increased in the last decade. In parallel to this increase controversy about giving state aid to nuclear energy has surged. The EU´s competition law aims to facilitate the EU's internal market and prevent distortions caused by private undertakings or Member States. The energy sector, as one of the sectors that receives most state aid is therefore frequently debated. The situation is further complicated as nuclear energy is not included in the Guidelines on State aid for environmental protection and energy 2014-2020[85]. That coupled with the existence of the Euratom Treaty[86] gives nuclear energy a very specific role within the EU. Furthermore, the European Commission published a Commission Notice on the notion of State aid as referred to in Article 107(1)[87] as the final act of the state aid modernization initiative launched in 2012.

The notification procedure[88] allows the European Commission and EU Member States to examine the technical regulations other EU Member States intend to introduce for products (industrial, agricultural and fishery) and for Information Society services before their adoption[89]. The date of notification of the draft triggers a three-month standstill period,during which the notifying Member State cannot adopt the technical regulation in question and enables the European Commission to examine the notified text and to respond appropriately.

The notice is intended to give guidance on:

- what can be considered as illegal State aid under the Treaty rules,
- case laws of the European courts and the decision-making practice of the EU Commission,
- subsidies to be exempted for a pre-defined policy objective (e.g., protection of the environment) and thus supporting national courts, granting authorities and entities, which are operating in the market.

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83 https://ec.europa.eu/commission/presscorner/detail/en/IP_23_1591

84 The proposed reform will have to be discussed and agreed by the European Parliament and the Council before entering into force. The final reforms and their implications to nuclear financing are therefore not known at the time of the analysis.

85 https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52014XC0628%2801%29

86 Treaty establishing the European Atomic Energy Community.

87 Commission Notice on the notion of State aid as referred to in Article 107(1) of the Treaty on the Functioning of the European Union [2016] OJ C 262 (The Notice on the notion of State Aid).

88 The procedure was set up in 1983 through Council Directive 83/189/EEC.

89 https://ec.europa.eu/growth/tools-databases/tris/en/about-the-20151535/the-aim-of-the-20151535-procedure/?QueryText=nuclear+notification

If notified drafts create barriers to the free movement of goods or to the free provision of Information Society services or to EU secondary legislation, the European Commission and the other Member States may request clarifications or updates from the drafting Member State or block state support all together[90]. The approval process of new nuclear power plants falls under the same notification procedure, but the timeline is significantly longer, partly due to requirements put forward in the Taxonomy Complementary Climate Delegated Act[91].

In must be added that in line with Article 194(2) TFEU[92], Member States may determine the conditions for exploiting their energy resources, their choice between different energy sources and the general structure of their energy supply, which does not preclude that choice from being nuclear energy. Moreover, the current nuclear regulatory framework appeared in the 1960s and since then it has undergone substantial modifications because of major nuclear accidents and in response to challenges but given the increasing importance of nuclear energy state aid cases and the growing controversy around these cases, there is an increased need to deal with nuclear state aid case law as a whole to understand accurately how the European Commission and the Courts assessed the relationship between state aid and nuclear energy in those cases[93]. However, on average it still takes about two to three years for the approval process for new nuclear power plants.

3.4 Conclusions and recommendations

The scale, cost and development time needed for nuclear projects are so complex that finding a solution to **financing remains a challenging issue** for developers and governments. This applies especially for upfront investments. Therefore, most nuclear projects apply a mix of different financing mechanisms, to reduce risks. This mix depends on the project, the regulatory regime, and available options.

Electricity market risks are generally more limited in regulated markets due to predictability of revenues for financing. This is not the case in liberalised markets, where the electricity price can fluctuate depending on demand and supply. Wholesale electricity prices can be at very low levels for some prolonged periods, as experienced in many liberalised markets during the last decade. If not appropriately mitigated, long-term electricity price uncertainty is a significant risk which can impact on what financing is available and hinder new investments in nuclear.

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90 The detailed opinion has the effect of extending the standstill period by an additional three months for products and by one additional month for services. It can also block a draft for a period of 12 to 18 months if EU harmonization work is to be undertaken or is already underway in the same field.

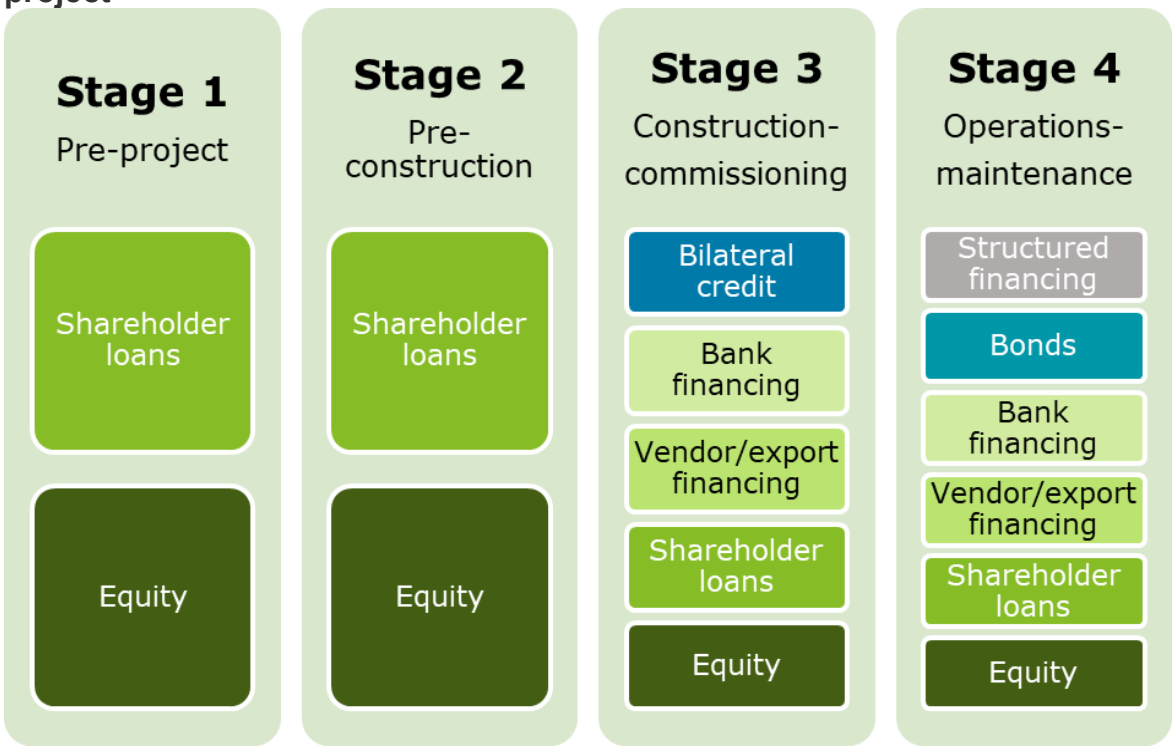
91 In 2015, Austria filed a complaint with the European Court of Justice (ECJ), arguing that the approval of state aid for Hinkley Point C was a violation of EU law, as it distorts competition and fails to promote renewable energy sources. In 2018, the ECJ ruled in favour of the EC and dismissed Austria's case. The court concluded that the Commission's decision to approve the state aid for HPC was lawful and did not violate EU competition rules.

92 Treaty on the Functioning of the European Union.

93 For example, the ECs in-depth investigation into Czech support for new nuclear power plant in Dukovany. It is looking into whether public support that Czechia plans to grant for the construction of a new nuclear power plant in Dukovany is in line with the EU State aid rules based on the notification by the Czech government from March 2022 of its plan to support the construction and operation of a new nuclear power plant.

Additionally, nuclear investments come with specific risks in various stages. The first stages, pre-project and pre-construction[94] are the riskiest stages. During these stages, loans and equity are the most probable for potential investors. Another significant phase is during pre-investment. An industrial management framework for nuclear projects at the level of project development and ownership level is a key success factor in managing financial risk. As can be seen from the graph below, at the operational stage the risks are much lower, the investments base is broader, and refinancing is possible.

Figure 3.5 Financing sources available at different stages during the project



Source: © IAEA, 2021

Financing models vary depending on the location and maturity of the project. Financing nuclear power plants aims primarily to secure finance at an efficient and low cost. These objectives also facilitate state aid compliance. Providing incentives for long-term, high-capital investment in deregulated markets driven by short-term price signals presents a challenge in securing a diversified and reliable electricity supply system. For investors, the confidence provided by clear, long-term governmental commitment to a nuclear power programme remains critical. Most combine a long-term power purchase contract, to reduce revenue risk, and a means of capping investor exposure, for example through loan guarantees. While CFDs may raise the final cost of energy to the consumer, depending on prevailing wholesale prices, they also provide the energy producer with the guarantee of a

94 These are, for example, changes in political direction and priorities, licensing period over run, the deal financial falling through etc.

known price for the electricity and reduce the risk created by volatility in wholesale energy markets.

Nuclear public investment, including state guarantees could likely continue to increase as energy markets become more competitive, thus creating more options for private investors to choose from. Furthermore, when it comes to financing from a company's own resources it is only an option for the largest utilities and developers. To carry such a large capital commitment over the average construction period of five to seven years and factoring in expected delays before the plant starts producing revenue, is a huge challenge for even the most established companies with a strong balance sheet.

To access a variety of sources of capital, **multiple financing mechanisms are required**. That coupled with a stable and long-term investment policy framework could optimise the distribution and allocation of risks for the sake of the community of stakeholders with a view to ensure consumer value for money. More efficient financing opportunities would result in lower overall financing costs and improved economics for nuclear power plants. It is important to understand the best practices for nuclear power plant financing, investment structures, contractual approaches, and risk allocation options currently available on the market. It is also important that the calculation of the profitability of the project demonstrates a sufficient surplus of funds under any stress scenarios. This requires a reasonable forecast of expected cash flows.

Moreover, having projected contractual milestones which need to be reached is important to monitoring financing. Furthermore, policy clarity, coherence, and consistency are key building blocks of the policy risk assessment when launching infrastructure projects. To progres towards achieving low financing costs reporting frameworks and transparent frameworks could be proposed to investors. The inclusion of nuclear energy in the taxonomy as a transitional source of energy is a step in the right direction

The more Capital expenditure (Capex) an asset requires the more important it is to be clear about the framework and regulations in which the project is being developed. The cost of capital is crucial, and depends directly on the risks involved, which in turn depend directly on the proposed policy framework.

For nuclear power, in addition to the difficulties of an electricity market design focused on the short term and profoundly affected by the decorrelation between production capacity and electricity needs, there are other issues. These include a lack of clear messages from policymakers, the means of financing NPPs and, more generally, the place of nuclear in the long-term vision as mentioned by the stakeholders. As a result, strong governmental support is needed for any new nuclear project in Europe, from the financing and construction phase, as demonstrated by projects in Hungary, the Czech Republic, and the UK.

The problem of financing is not only a question of the scale of the resources to be mobilized for 2050, but also of the need for visibility and coherence. In that context, there is a question of availability of funds largely due to this uncertainty.

The analysis of input collected from the study's stakeholders identified the following recommendations[95] to consider to support the financial landscape for NPPs:

European Level

- **Include nuclear energy in all European relevant regulation in a technologically neutral approach, i.e. the Net-zero industry act could provide a clear statement that is necessary for a long-term stable and predictable environment. In addition, funding initiatives could be further aligned with the established Taxonomy e.g., ensuring coordination with the Green Deal and Just Transition Funds.**
- Conclude a reform of the electricity market and give long term signals and incentivise the development of new capacities.
- Create access to European funds, such as EIB loans, Just Transition Fund, Innovation Fund etc. by including nuclear in the technologies that can be financed from European funds.
- Launch a proposal to examine a standardised template to show how nuclear power projects would be financed and streamline the process of notification (i.e., if the state aid is less than 95% then the notification could be simpler and faster).
- Support stakeholders to explore different options of financing, notably for SMRs, such as Important Projects of Common European Interest (IPCEI), European funds or Recovery and Resilience Facility (RRF) (i.e., financing of the first of a kind (FOAK)). SMRs could also be financed through pension funds as they have a long investment period which could be complimentary for nuclear projects.
- Enhance clarity on what is acceptable in the case of state aid support by introduction of a clear set of rules that define the state-aid support across all member states.
- Consider all relevant aspects of a project - industrial, strategic, economic, and climate – when assessing the compatibility of state aid support.
- Promote current market-based frameworks to strengthen competitive proof testing and improve the acceptability of investment in nuclear projects at the levels of off-takers and investors. CFD and RAB, among others, schemes are viewed as appropriate, proportionate, and non-distortive measures to remedy a clear market failure in the context of a deregulated electricity market.
- Describe support mechanisms to decarbonisation in technological neutral terms to remain indifferent on technical means to decarbonization and depoliticize the discussion on nuclear investments.

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95 Chapter 11 presents a list of priorities. These are concrete recommendations which require immediate actions, as discussed with the study's stakeholder group, Member State representatives and NGO representatives during a workshop 5-6 September 2023.

- Consider various financing schemes which could be used, not only for nuclear power projects but also for front-end and back-end industrial capacities.
- Interact with financing institutions (public and private) and other stakeholders (investors and utilities) to establish a fair treatment of the discount rate for nuclear energy on equal footing with other decarbonized means of producing electricity.

Member States

- **Provide a regulatory landscape and long-term perspective on nuclear energy to ensure a stable and predictable environment for pricing and investment options.**
- Enhance public support throughout various phases of nuclear energy production:
    - Different agreements could be concluded between the government and the nuclear industry. For instance, financial support for front-end spending would help advance the project toward the construction phase.
    - During the development phase, government support could be envisaged with a view to reducing the risk profile associated with the development period.
    - During financing, governments may be involved in risk allocation through the provision of explicit government guarantees.
- **Design a revenue model, price, and volume limitations (cap and/or floors), which act as key risk mitigation factors.**
- On national level interact with financing institutions (public and private) and other stakeholders (investors and utilities) to ensure a fair treatment of the discount rate for nuclear energy on equal footing with other decarbonized means of producing electricity.

4 Regulatory environment – Is it ready for wide deployment of current and advanced reactors?

This chapter discusses the deployment of current and advanced reactors from a regulatory perspective. Several regulatory challenges should be addressed to facilitate the construction and decommissioning of many nuclear reactors in the next years and make best use of technological advancement. In addition, licensing processes, waste management, public perception as well as proliferation concerns should be addressed.

To meet the decarbonisation target as presented in chapter 2 by considering new construction, long-term operation and the deployment of Small Modular Reactor (SMR), the regulatory framework should remain relevant and adequate. Moreover, the regulatory environment could provide a framework to unleash the development of new technologies, including SMRs and AMRs, and facilitate safe nuclear energy provision. The analysis and stakeholder inputs resulted in several key findings.

Key findings

- Overall, the **existing regulatory framework is well set up** and plays a crucial role in ensuring the safe and efficient operation of nuclear power plants and in engaging with the public. However, in view of the wide deployment of current and advanced reactors including SMRs/AMRs, it faces several regulatory challenges and issues that must be addressed.
- These challenges are well understood by the international and European nuclear community, **steps could be taken to prepare robust and more efficient legislation, however, the path to improvement is slow-paced.**
- The cooperation between national, EU and international regulatory communities is pivotal for its success but may need to be enhanced to further align frameworks.
- A **key challenge** to develop cohesive regulation for **SMRs/AMRs** in the EU is **the variety of the new prototypes and technologies.** This could slow down their development and deployment at large scale, hampering possibilities for flexible power generation.
- The **graded approach** could be an adequate way of developing the licensing procedure for SMRs/AMRs, however, **the level application of graded approach is uncertain**.
- **A phased licensing approach and increased public engagement are key factors** in facilitating the licensing and deployment, in particular, of Generation IV reactors.

4.1 Status of the regulatory environment in the EU

10 out of 15 members of the study's stakeholder group assess ***the EU's and Member States' licensing processes for enabling newly build Nuclear Power Plants as robust but not efficient*** to ensure timely development of nuclear power. 4 stakeholders assess the licensing process as robust and efficient enough and 1 stakeholder assesses the processes as efficient but not robust. Indeed, EU Member States that operate nuclear facilities have appropriate legislation to ensure their safe operation. However, the requirements are largely based on older generation nuclear power plants and Member States have little experience with latest generation nuclear power plants. Therefore, legislation may not be efficient enough to address latest technological developments. This becomes, among others, visible when regulatory bodies evaluate and approve reactor safety cases. The worldwide experience spans over the last 60 years with current Generation II+ and III. Experience with Generation III+ is mainly present outside the EU as in the EU only two nuclear power plants[96] were licensed. Globally the experience concerning advanced reactors, including SMR and AMR is limited.

The EU and its Member States, as well as the industry have long understood the importance of a **predictable and adaptable regulatory structure** and have worked co-operatively to ensure the safety of civilian nuclear energy throughout the lifetime of nuclear projects. The EU has a comprehensive framework for **nuclear regulations that governs the safety, radioactive waste and spent fuel management, basic safety standards and safeguards of nuclear installations and activities** established through a legal framework via the **Euratom Treaty.** A key document is the **Nuclear Safety Directive (2014/87/Euratom)**[97]**,** which requires EU countries to give the highest priority to nuclear safety at all stages of the lifecycle of an NPP.

The main requirements are:

- To strengthen the role of national regulatory authorities by ensuring their independence from national governments. EU Member States must provide the regulators with sufficient legal powers, staff, and financial resources.
- "Article 8a Nuclear safety objective for nuclear installations" and "Article 8b Implementation of the nuclear safety objective for nuclear installations" and the principle of continuously improving nuclear safety.
- To create a system of peer reviews, EU Member States choose a common nuclear safety topic every 6 years and organise a national safety assessment. They then submit their assessment to other countries for review. The findings of these peer reviews are made public.
- To require a safety re-evaluation for all nuclear power plants to be conducted at least once every 10 years.
- To increase transparency by requiring operators of nuclear power plants to release information to the public, both in times of normal operation and in the event of incidents.

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96 Olkiluoto in Finland and Flamanvile in France.

97 https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32014L0087

Key Directives are listed in the table below:

Table 4.1 Key nuclear regulations in the EU

Name	Description
Radioactive Waste Directive (2011/70/Euratom)	It establishes a legal framework for the safe and responsible management of radioactive waste, including requirements for waste classification, storage, disposal, and the financing of waste management activities.
The Basic Safety Standards Directive (2013/59/Euratom)	It establishes the fundamental safety standards for radiation protection in the EU. It establishes dose limits, sets requirements for occupational and medical exposure, and outlines the responsibilities of member states in monitoring and controlling radiation levels.
Nuclear Safety Directive (2014/87/Euratom)	It is establishing a community framework for the nuclear safety of nuclear installations
The Euratom Safeguards Regulation (302/2005/Euratom)	It establishes requirements for the reporting, verification, and control of nuclear material in EU member states.

Source: Study team

EU Member States have the responsibility to regulate nuclear safety within their territories. Each Member State has its own independent national regulatory authority responsible for overseeing nuclear safety and security. **These authorities are responsible for granting licenses, conducting inspections, and enforcing regulatory requirements in accordance with EU directives, regulations, and international standards**. Ensuring an independence of each Member State comes with a range of challenges such as a lack of harmonisation and varying expertise which might impact resources available for overseeing regulatory licensing processes, and inconsistencies in the regulatory framework. These combined can lead to inconsistencies and gaps, hampering effective cooperation in nuclear safety.

Case study: Regulatory organisations at the EU level

The Western European Nuclear Regulators' Association (WENRA) is a network of chief regulators of EU countries with nuclear power plants and Switzerland, with membership from 17 countries. Other interested European countries have observer status. It was formed in 1999 and has played a major role in coordinating safety standards across Europe.

The European Nuclear Safety Regulators Group (ENSREG) is an independent expert advisory group to the European Commission, in which all EU Member States are represented by senior officials from their national regulatory authorities or nuclear safety authorities. Senior representatives of the European Commission are also part of the group. In addition, the Council of the European Union, the International Atomic Energy Agency, OECD Nuclear Energy Agency, Western European Nuclear Regulators Association, Norway, Switzerland, and Turkey have observer status in the group.[98]

There are also a number of initiatives in different fields to establish a common understanding and approach in NPP licensing, operation, and decommissioning, e.g. **ETSON – European Technical Safety Organisations Network, WANO – World Association of Nuclear Operators**.

the International Atomic Energy Agency (IAEA) sets international standards for nuclear safety, which also influence the national regulatory frameworks. The EU also cooperates with non-EU countries and international organisations on nuclear safety. In 2013, the European Atomic Energy Community (EURATOM) signed a Memorandum of Understanding (MoU) with the IAEA to further strengthen the cooperation through expert peer reviews, emergency preparedness and response. In 2022, the EURATOM signed a new MoU with the IAEA on nuclear safety cooperation, updating the previous agreement from 2013, and extending activities to include emerging areas of common interest, such as education and training, SMR and the safety of fusion installations.[99]

Furthermore, it is **pivotal that all regulatory levels address the public opinion jointly.** Its perception and acceptance play a vital role in any new nuclear deployment. The nuclear sector is subject to public scrutiny due to concerns about safety. Therefore, providing transparent information and addressing any misconceptions surrounding nuclear technology should be done continuously. Furthermore, effective communication and engagement can help build public trust and support in nuclear power, which is vital for successful and timely licensing (the public can attend and comment on the EIA, siting permission and other discussions, which can prolong the licensing process). A transparent licensing process supports public involvement and encourages harmonized licensing processes. At European level this may be support by the Group of European

98 ENSREG at a glance | ENSREG

99 https://commission.europa.eu/news/euratom-and-iaea-sign-memorandum-understanding-nuclear-safety-cooperation-2022-09-27_en

Municipalities with Nuclear Facilities (GMF), a not-for-profit association of municipalities with nuclear facilities across European countries[100]. Currently supported by municipalities with nuclear facilities from Belgium, Bulgaria, Czech Republic, France, Finland, Hungary, Netherlands, Norway, Romania, Slovakia, Slovenia, Spain, Sweden, Switzerland and the United Kingdom. Another example are more local citizen committees such as ANCCLI in France whose role is to inform the public and develop citizens' expertise on nuclear activities[101].

The rapid increase in the international technological, environmental, and economic developments are forcing the nuclear sector to rethink its regulatory framework and licensing process. Innovation brings new and unknown risks and a plethora of challenges to the existing framework. **Overall, the existing regulatory framework is well set up and plays a crucial role in ensuring the safe and efficient operation of nuclear power plants and in engaging with the public. However, in light of the wide deployment of current and advanced reactors such as SMRs/AMRs it faces several regulatory challenges and issues that must be addressed.**

Licensing current nuclear reactors (Generation III, III+)

The study's stakeholders see a need to further harmonise the licensing processes and reduce its duration[102]. **Most of the study's stakeholders perceive the current legislation as sufficient** which has been demonstrated in the previous subchapter. The current nuclear regulatory framework emerged in the 1960s for licensing early nuclear power plant designs and since then it has undergone substantial modifications. At the beginning, a comprehensive safety assessment is carried out before a nuclear reactor is licensed in the EU and this evaluation includes a **detailed review of the reactor design, safety features and operating procedures.** It also assesses potential hazards and analyses the measures put in place to mitigate the risks[103]. The licensing process consists of four stages - pre-construction, consent for construction, commissioning and operation and is generally based on the IAEA Safety Guide[104].

100 http://gmfeurope.org/about-us/

101 https://www.anccli.org/anccli-mission/

102 When asked in the questionnaire, "*What steps need to be taken to prepare robust and efficient legislation for current reactors (Gen III & Gen III+)?"* the common theme voiced by the study's stakeholders was that the current landscape must be more harmonised, efficiency has to be improved, and that progress can be made to streamline and reduce the duration of the licensing processes.

103 Nuclear Power Plants. Instrumentation and Control Important to Safety – General Requirements for Systems. IEC, 2001.

104 Safety Guide No. SSG-12, Licensing Process for Nuclear Installations. IAEA,2010.

Table 4.2 New reactor application stages[105]

Phase	Description
Pre-construction	Pre-construction involves siting, site evaluation, Preliminary Safety Assessment, and other aspects for environmental assessment and site selection.
Consent for construction	Consent for construction involves detailed site evaluation and design review for issuing a permit to start construction.
Commissioning	Commissioning involves progressive transition from construction to operation of the plant and Final Safety Assessment
Operations	Phase of the NPP being in operation.

Source: IAEA, 2010

To restate, the nuclear safety directive emphasised the fundamental principle of prime responsibility for the licensee regarding nuclear safety. The amendment approved in 2014 introduced a **high-level EU-wide nuclear safety objective** and aims to prevent nuclear accidents and limit their consequences as well as to address the safety of the entire lifecycle of nuclear installations. On top of that, the amendment established a set of rules to support the independence of Member State regulators and a new peer review system. The landscape across the EU differs in how Member State governing bodies are set up and the extent of their role in the licensing process as can be seen from the table below. In some countries, the decision is a simple consent while in others, a full licence is needed. The authorisation is usually granted by the government (often the Ministry of Environment), but in some cases the authorisation is granted through a regulatory decision, e.g. the decision for commissioning. The applicant can be a company requesting a licence, an existing operator requesting a new licence or a company that has a site licence and would like to apply for a construction licence or to start commissioning. In addition, there are conventions such as Espoo (which sets out the obligations of parties to assess the environmental impact of certain activities at an early stage of planning)[106] and Aarhus (grants the public rights regarding access to information)[107] that apply to all EU Member States.

Regulatory reviews may last three to eight years and on occasions even longer as can be seen from the table below. Many Member States use Technical Support Organisations (TSOs) to assist them in the reviews and oversight. In some Member States, the TSO function is part of the nuclear regulatory organisation. Skilled professionals with a minimum of an engineering degree or equivalent are commonly required by all regulators to perform the task. During the pre-construction phase the expertise of geologists, meteorologists, hydrologists, seismologist, civil engineers, project managers and environmental project managers is required. For the basic design review, the expertise needed were in structural, civil, mechanical, electrical, nuclear, chemical, and material

105 All regulators perform construction oversight during the construction stage. Some regulators, such as Finland, also review and approve the detailed design. All regulators begin commissioning reviews during construction, which continues well beyond construction. The regulators are directly involved in issuing the licence for operating and loading of fuel during commissioning.

106 https://www.oecd-nea.org/jcms/pl_29146/convention-on-environmental-impact-assessment-in-a-transboundary-context-espoo-convention

107 https://aarhus.osce.org/about/aarhus-convention

engineering, and project management. When construction begins, through commissioning and beyond, oversight is necessary by qualified inspectors, specialists, and technical experts in addition to standard staff. **A rough estimate of the level of effort needed, including technical support, averages between 25 to 50 person-years throughout the processes**[108]**.**

Table 4.3 Average time for licensing before construction and commissioning*

Average time (years)			
Country	**Pre-construction**[109]	**Consent for construction***	**Commissioning and operating licence***
Czech Republic	3 (P)	1 (RR)	0.5 (RR)
Finland	2 (P), incl. 1 (RR)	3 (P), incl. 1.5 (RR)	1.5 (P), incl. 1 (RR)
Hungary	0.5 (RR)	0.5 RR	0.5 (RR)
Poland	2 (P)		1.25 (P)
Slovakia	0.4 (RR)	1 (RR)	0.5 (RR)
Slovenia	4 (P)	2 (RR)	3 (P)

Notes: *Estimates do not include the time frame of construction or commissioning but some reviews by the regulator that may be performed during the construction stage. (RR) A regulatory review is carried out for each step (indicated as RR for regulatory review). (P) The regulatory review involves the entire licensing process (indicated as P for process).

Source: NEA/CNRA

There is also a requirement to submit supporting documentation. The list is provided by the regulatory body and in most EU Member States information submitted early in the process should provide environmental and design-related information. The regulatory authority uses this information as the basis for its siting and construction decisions. Although the information required from the applicant may differ in scope and the level of detail, the information required by Member States is similar. Typically, as construction is completed additional documentation is submitted to show that the as-built plant meets the design requirements.

The common themes across the international and the EU Member States' landscape is the duration of the regulatory review of the **licensing process.** Time is necessary to ensure the safety of the public. Therefore, the process can become lengthy which could have negative effects for the project. For example, it can affect the applicant's ability to obtain funding. **The issue in this case is a lack of harmonisation in the EU regulatory landscape**. While in some Member States (Hungary, Poland, Slovakia etc.) the regulator is the sole authority to grant a licence for new nuclear power plants in others, government ministries, parliament, local authorities, technical support organisations, the public, and neighbouring countries may also be involved in the licensing process (see also the example on Espoo above).

108 Summary Report on the Licensing Process of New Reactor Applications. NEA/CNRA, 2020.

109 Pre-construction involves environmental assessment or licence for site preparation and a general design licence.

4.2 Readiness for SMRs and AMRs licensing process

During our data gathering process the 86% of the study's stakeholders assume a need from large and small modular reactors (SMR) to contribute to net-zero targets[110]. Stakeholders specified that large nuclear power plants could support the baseload electricity market while SMRs could support hybrid systems, decentralisation of sources, heat generation, hydrogen production, process steam etc. Overall, it is believed that SMRs could provide additional flexibility on smaller local scale clearly identified by the EU. In addition, the common view was that SMRs can be easily scalable, eliminate the need for energy transfers, outages and maintenance should not take too long compared to large reactors.

Seven out of 15 members of the study's stakeholders group answered that legislation **needs to be completely reworked** to ensure implementation of SMRs/AMRs and seven answered that **legislation needs minor updates** to be ready for implementation of SMRs[111]. Stakeholders report a lack of experience with SMRs, as none of the MS is currently equipped with SMRs and stakeholders see a need to **harmonise licensing processes** to allow scaling of SMR deployment. Currently the licensing is done per Member State, by the local safety authority, using the guidelines from IAEA and EURATOM. The whole licensing process is repeated whenever a new reactor is considered making licensing a lengthy, repetitive, and costly process. Harmonization of the process is expected to decrease both time and cost of the licensing process and could result in faster deployment of nuclear power according the study's stakeholders.

The current wording of the legislation already allows the licensing of SMRs. However, the development of SMRs should lead to a re-evaluation of existing legislative norms so that the area of SMRs licensing is legislated in detail, as advocated by the study's stakeholders. They see a need for a more agile licensing process to facilitate production of SMRs in series. The international guidelines are already in use for nuclear safety and are broadly applicable but there is not a common view on whether licensing could be done on the EU or Member States level. The experience from historical regulatory and approval processes singularly points out that approval times for conventional nuclear reactors are long and exhaustive[112]. This is also demonstrated in subchapter 5.2. Moreover, on numerous occasions, the process results in project delays as well as cost increases (i.e., delayed licensing at the Paks II project or the Hanhikivi project)[113]. It is thus pivotal to draw lessons from these examples. However, with new technology emerging at much faster speed than industry is historically accustomed to, developing a supportive regulatory environment that keeps up with this fast pace is of highest concern. According to IAEA, there is currently very limited

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110 Study's stakeholders were asked "Do you see the contribution of nuclear to net zero mainly in large reactors or in Small Modular Reactors and why?" 13 stakeholders replied "both". Two stakeholders assume mainly contributions by large reactors, and believe that SMRs are not very economic and more suitable for special purposes only (see also Annex I).

111 When asked "Do you consider the legislation ready for licensing and operation of Small Modular Reactors?" in the stakeholder questionnaire (see also Annex I)

112 A shorter licensing process could be possible if SMRs are to be built on the same site as existing reactors.

113 World Nuclear News. 2023.

international experience in regulating and licensing SMRs and very few regulatory bodies have issued a construction or an operating licence[114].

One of the key arguments on how the licensing process can be improved is through better cooperation between regulatory bodies and SMRs developers. The regulator must stay updated on the new developments in the SMR field and this without adequate support can prove difficult. The regulatory bodies must also ensure that the path to design, construction and operation is as efficient as possible, even more so considering the new and innovative designs and manufacturing processes which some SMRs could introduce. Thus, dialogue and cooperation are pivotal and must accelerate.

Case study: European SMRs pre-partnership[115]

In July 2021, in response to the call of the European nuclear industry and the R&D&I community, the EC organized the first EU Workshop on SMRs. This event showed a growing interest across the EU in this technology. In January 2022, the European SMR pre-Partnership was established and the main objective of one of its workstreams was to identify the elements for establishing a European pre-licensing process based on commonly accepted safety assessments from different ENSREG members interested in the licensing of the same SMR design. ENSREG Members nominated 20 experts from 15 EU countries.

The main activities were:

- First review of NPPs licensing processes in different EU countries interested in SMR licensing (Czech Republic, France, Finland, Romania, Poland, Sweden).
- Establishing a clear state of play of activities in other fora (IAEA NHSI, SMR Regulatory Forum, NEA Committees, WENRA, EUR, ENISS, CORDEL, etc.) in relation to SMR licensing.
- Interacting on Codes & Standards.
- Interacting on different topics and reviewing the outcomes of some Euratom H2020 projects related to the licensing of SMRs.

In view of further supporting efforts to facilitate SMR pre-licensing in Europe several steps forward emerged:

- Engage in early dialogue between designers -licensees and regulators on main elements of the design options.
- Promote cooperation of interested regulators to carry out a joint safety pre-assessment on a mature design and its dissemination with other regulators confronted with that design at a later stage.
- Identify in an early phase potential blocking points in the safety requirements or licensing processes and arrangements for convergence.

Source: European SMR pre-Partnership – Workstream 2 – Licencing

As mentioned, there are regulatory aspects related to larger nuclear power plants which could be adjusted to better apply to the expected reduced source term and thus potentially emergency planning zone influence anticipated by SMRs, the so-called **graded approach**. These aspects are already well discussed in international fora. What is a potentially far greater challenge is the predicted range

114 Lessons Learned in Regulating Small Modular Reactors. IAEA, 2022.

115 Following the submission of this study's script, the European SMRs Industrial Alliance was inaugurated on 29-30 May 2024. The Alliance aims to facilitate and accelerate the development, demonstration, and deployment of SMRs in Europe by the early 2030s.

of new designs to be assessed. The volume of new builds anticipated by the net zero emissions scenario presented in the World Energy Outlook 2022 by IEA could stretch regulatory resources and add pressure as is demonstrated in subchapter 5.2.

Depending on the technology there is some existing experience. For example, for SMRs based on light water and only the specific design has to be assessed but for other technologies (see examples provided in the table below), and concepts, more work may be required to demonstrate feasibility and robustness.

Table 4.4 Examples of SMRs[116]

Rector type	Description	Examples
Light Water Reactors (LWRs)	LWRs are similar to most of the existing NPPs but on a smaller scale. They use regular water as both a coolant and a neutron moderator.	NuScale Power Module™, GE-Hitachi, NUWARD, R&R
High-Temperature Gas-Cooled Reactors (HTGRs)	These reactors use helium as coolant and graphite as a moderator. They can achieve higher temperatures than LWRs, allowing for more efficient power generation and the potential for high-temperature industrial heat applications.	X-energy's Xe-100
Molten Salt Reactors (MSRs)	MSRs use a mixture of salts as both the coolant and fuel, allowing for operation at higher temperatures and atmospheric pressure.	ThorCon, Terrestrial Energy IMSR® NAAREA
Liquid Metal Cooled Reactors	These reactors use a metal or metal alloy (like sodium or lead) as coolant and can operate at high temperatures without high pressure.	GE Hitachi PRISM Newcleo

Source: Study team

To complicate the matter even further, licensing of multiple designs is currently assumed to be done at the Member State level. It is well understood by the nuclear community as well as by the European Commission that various harmonisation initiatives are under way:

- IAEA NHSI Regulatory and Industrial Harmonization for SMR Deployment | IAEA
- OECD and NEA publication: “Harmonising the nuclear licensing process for emerging technologies: A global path forward”
- Projects ELSMOR and HARMONIZE (Coordination and Support Action in Horizon-Europe programme) ELSMOR – Towards European Licensing of Small Modular Reactors
- European SMR pre-partnership

In our questionnaire we also asked, “*What steps need to be taken to prepare robust and efficient legislation for small modular reactors?” The principal feedback received on this question relates to* ensuring that all stakeholders in the nuclear ecosystem (such as developers, researchers, industry, supply chain on one side and licensing authorities, regulatory bodies and waste agencies on the other side) **collaborate from the onset to ensure a synchronised evolution.** According to

116 The list non exhaustive.

the study's stakeholders, this is a path that could guarantee efficiency, save time, and potentially save costs.

Finally, there are great foundations on which the new licensing process could be built. However, the proposed collaboration that could lead to harmonisation might experience challenges. One possible way forward is to enhance the European SMR pre-Partnership Workstream 2 on licencing, a group of high-quality subject matter experts that aim to ensure most up to date knowledge transfer amongst key stakeholders. The same group of regulators could work on harmonising regulations between Member States, make designers aware of regulatory requirements and encouraging everyone to stick to an internationally harmonised and accepted basic set of requirements. Deep understanding of safety and technology is vital, cooperation between regulators, between regulators and SMR producers-designers would further aid the flexibility and agility that could be improved. A solution must be found to fit in with the existing framework while respecting the role of MS regulatory bodies as well as understanding that it is highly unlikely that all Member States will reach a common view on the matter and agree on a set of common licensing rules.

To conclude, regulators are very well-suited to adjusting to small incremental changes in technologies they regulate but today **they are faced with truly disruptive technologies** for the first time since the commercialisation of nuclear energy. EU regulators started to work on harmonised and standardised legislation, and build a harmonised set of licensing rules, while workstreams were set up to team-up several MS regulatory bodies to commonly and timely assess together a specific design to reach a consensus in as many safety cases as possible.

Generation IV reactors and AMRs are nuclear reactor technologies that are envisioned as successors of existing Generation III, III+ reactors. They are designed to address limitations of Generation III, for example increased fuel utilisation or reduced waste production, while still ensuring efficiency and safety. They come in diverse designs (e.g. gas-cooled fast reactors, lead-cooled fast reactor, molten salt reactor)[117]. According to the Nuclear Energy Agency (NEA) the **deployment of advanced reactors incorporating emerging technologies is highly anticipated**. The regulatory framework must be appropriately positioned to independently analyse and evaluate the safety implications and existing regulations. Today they are not sufficient because the traditional regulatory framework is not tailored to fit the novel features of Generation IV. According to the study's stakeholders **the regulator should seek to modify the existing regulations or develop new ones** with an outlook towards harmonisation within the EU and global nuclear regulatory community. However, given the stagnant nuclear development in the EU and globally over the last few decades there is only limited information available about international regulatory experience in the licensing process of advanced reactors. When we asked the study's stakeholders "*Do you consider the legislation ready for licensing and operation of Generation IV reactors?"* the answer that legislation needs to be completely reworked to ensure

117 https://world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/generation-iv-nuclear-reactors.aspx

implementation of Generation IV reactors was selected by nine of the study's stakeholders, five stakeholders stated that legislation needs at least minor changes, however, it was also highlighted that there is no common approach on how to move forward.

The feedback is the same as with SMRs regulatory bodies at the Member States, EU and global level which could be engaged in evaluating and developing new licensing approaches to accommodate advanced reactor technologies. Regulatory requirements should be harmonised so that minimal design changes are required to meet specific national regulations and the technical reviews of a lead national authority can be validated in a straightforward manner by other competent regulatory authorities. The new generation of reactors and further technological developments must entail corresponding changes in legislative regulations and the regulatory framework. This will depend on the specificity of the legislation of the different Member States. The emergence of an advanced reactor industry seems to be embraced by governments as well as the private sector but due to the innovative nature of advanced reactors, it is crucial to ensure a transparent and inclusive decision-making process which includes the public. Emphasising the importance of public participation is key to building public trust and confidence in these new technologies.

An example of an Advanced Modular Reactor (AMR) start-ups is NAAREA. The objective of this start-up's XAMR (eXtrasmall Advanced Modular Reactor) project is to design a low power molten salt Generation IV nuclear reactor. This French deep-tech pioneer in 4th generation micro-nuclear power, and Assystem, an independent international engineering group, signed a cooperation agreement to build an ultra-compact micro-nuclear power generator, the XSMR. NAAREA expects the first units to be produced by 2030[118]. Another example is a start-up called Newcleo, whose aim is to reduce the environmental impact of nuclear fission and providing safe and clean energy, by creating a Small Modular Generation IV reactors based on lead cooled technology[119].

Overall, the outlook for advanced reactors in the licensing process is promising but remains challenging. Their potential is undeniable, and the interest can be seen amongst a wide portfolio of stakeholders but so far, the path to a properly evolved regulatory framework and licensing procedures is slow-paced.

4.3 Conclusions and recommendations

To meet the EU climate and energy objectives, 80 new nuclear power plants should be constructed which are most likely going to be -LWR-SMR or AMRs. Regulation and licensing are currently mostly based on older generation reactors, with a well establish framework. To make full use the potential of next generation reactors substantial changes to the existing framework are needed. The international and EU regulatory landscape is well established. However, with the increase of innovation and the speed at which it happens it is truly disruptive to the slow-paced nuclear industry. Almost overnight the nuclear regulators had to face an environment where they were asked to re-evaluate their processes, standards,

118 https://www.naarea.fr/fr/rejoignez-notre-equipe
119 https://www.newcleo.com/

and requirements to determine whether they are appropriate for the new technologies which is a task that was not required in over six decades. Maintaining regulatory excellence requires that regulators evolve with the technology. Policymakers and national regulators should ensure nuclear licensing and regulations are not impediments to technical progress. Effective communication with industry is also required to ensure regulatory approaches are appropriate and conducive to innovation.

The current legal framework and procedures applied in the field of nuclear power are to some way limiting the introduction of new types of nuclear power plants (Generation III+, SMRs, advanced reactors). While regulatory authorities are typically risk averse, it is mandatory for them to maintain operational awareness of rapidly changing technologies and the increased pace of license requests in line with the newly set up EU objectives. As was discussed throughout this chapter, if regulators do not maintain awareness and understanding of the innovations, they could be unprepared for any attempt by industry to adopt the technologies. The establishment and maintenance of an agile regulatory system that is conducive to the introduction of innovative technologies requires the regulator to consider the existing regulatory framework before developing new regulations and to consider any lessons learnt from other national and international regulators in other industrial sectors. Regulators, both at the Member State and the EU level, need to be flexible, accessible, enabling, and willing to work in a collaborative manner both domestically and internationally. Further collaboration between Member States, such as the European SMRs pre-Partnership Workstream 2 on licensing, could speed up regulating next generation reactors and ensure coherence of regulation in the EU. Legislation is the same, but licensing requirements differ, and it could continue to grow as the technology matures outside the regulatory context.

The current licensing process is designed in a way that the licensing of the large new reactors (Generation III+) should not be an issue. However, the experience with licensing such reactors is missing in the EU, only two reactors of Generation III+ underwent the licensing process and were granted the license. With the increasing construction, this could change, and the process of licensing could become more efficient. The potential issue could arise with the licensing of SMRs and AMRs. The SMRs licensing process is very well mapped, and the issues are identified, the nuclear community is aware of that and is working on a solution through several international initiatives (such as the European SMR Partnership). This situation becomes more complicated with advanced reactors where the regulation must be significantly updated or completely reworked to reflect the novel approaches. To conclude, the regulatory environment is capable of licensing Generation III+ reactors, it is only missing experience and efficiency. The regulatory environment is not prepared for AMRs and their licensing, however, the issues are identified, and the solution is being worked on. Licensing of advanced reactors is the largest issue, as regulation must be considerably updated to allow the operation of advanced reactors. Their deployment is not expected in the next 20 years, but this period allows for necessary updates.

When asked "*Do you consider unified European guideline for licensing process of Small Modular Reactors and Gen IV reactors to be a good idea?"* the consensus among the study's stakeholders was that it is possible but might not be the best

solution. With 27 Member States, to achieve a certain level of harmonisation would be very challenging. All members of the study's stakeholder group believe there should be greater activity by the European Commission to support SMRs pre-licensing and licensing. The European Commission could incentivise, the dialogue, platforms, one stop shops for knowledge sharing among regulators and promote some success stories.

It is necessary to re-analyse licensing processes and their compliance with technological developments. The expected lack of experts could also be a problem. The allocation of more resources could ensure more effective project approval outcomes. The anticipated development of nuclear energy will furthermore run into the issue of the current lack of expert capacity as further discussed in chapter 7.

There are several requirements that are needed such as positive conducive policy and efficiency in the implementation processes that could result in simplification of implementation processes, improved efficiency and competence of processes ensuring efficiency of the licensing process and thus speeding up the process. Other requirements include:

- Harmonisation and mutual recognition of national safety agencies and their approach to the licensing process.
- Continuity and stability in the regulatory framework and a long-term vision.
- Unified licensing processes, construction and permitting standards[120], financial terms and legislation in EU Member States associated with the deployment of newly built nuclear power plants.
- Reduced number of entities with the right to raise objections.

Addressing these regulatory issues comprehensively would pave the way for the widespread deployment of nuclear reactors and harness the potential benefits of this important energy source without compromising the highest level of nuclear safety.

While the EU publicly remains committed to ensuring **responsible, safe and secure development** of peaceful uses of nuclear energy[121] its support must be clearly communicated. The importance of a predictable and adaptable regulatory structure, working co-operatively to ensure the safety of civilian nuclear energy throughout the lifetime as well as sustaining independence and transparency, is essential to enhance trust between the public, regulators, and industry. Building a basis for mutual trust involves inviting the public to collaboratively participate in the review, revision and promulgation processes for regulations. Stakeholder engagement is critically important and must occur early, often and continuously. Both positive and negative aspects of innovation must be discussed in full transparency to build a robust regulatory system.

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120 Permitting process around administrative tasks such as obtaining permits for buildings, land etc. that are not related to nuclear safety could be improved in terms of speed.

121 Stated at the IAEA Board of Governors on Nuclear Technology Review 2023 in Vienna.

The analysis of inputs by the study's stakeholder group provided us with the following recommendations[122] to ensure an effective regulatory landscape:

European Level

- Initiate processes to update current legislation to better match needs for SMRs and AMRs.
- **Facilitate an exchange of experiences and lessons learnt among EU Member States regarding permitting and licensing and encourage sharing of information by Member States for transparent processes.**
- Provide the enabling conditions for the exchange of experience and lessons learnt and create a repository for information and case studies.
- **Keep nuclear energy in policy and strategic documents to ensure overarching objectives for Member States and stimulate joint activities.**
- Initiate cooperation processes between EU member States to streamline and accelerate the procedures required to license and build new nuclear power plants.

Member States

- Participate actively in European Commission activities and exchange of experience between EU regulators to harmonise legislations and licensing/permitting processes as much as possible.
- **Streamline licensing and permitting processes without regression of the level of effective control, to accelerate the execution of nuclear projects.**
- Improve transparency, cooperation, and public engagement to address these challenges effectively.
- **Provide a stable regulatory framework following a long-term vision for nuclear energy.**

Industry

- Express the need for harmonised rules and licensing procedures.
- Cooperate with regulatory bodies to follow the update of regulatory processes and support their continuous improvement.

[122] Chapter 11 presents a list of priorities. These are concrete recommendations which require immediate actions, as discussed with the study's stakeholder group, Member State representatives and NGO representatives during a workshop 5-6 September 2023.

5 Supply chain – Can the industry fulfil the expected demand?

The nuclear supply chain is a complex field that includes suppliers, contractors, manufacturers, and service providers. All stakeholders interact to provide services and deliver materials and equipment for safe and reliable construction, operation, and maintenance of nuclear power plants. Assessing the readiness of the supply chain to deliver the decarbonisation targets, to ensure installed nuclear capacity of 100 GW in 2050, is a crucial task in answering the overarching question, of whether the supply chain is ready to support the construction and operation of new nuclear power plants and facilitate long term operation and development of Small Modular Reactors (SMRs). Several key findings emerge from the analysis, stakeholder inputs, and industry questionnaire:

Key findings

- **Since the beginning of the century, the supply chain in Europe has mainly relied on the operation and maintenance of operating plants**, and very little on construction, in particular, of European Pressurized Reactors - EPRs (in France, the UK, Finland and China).
- Possibilities to enhance the value chain and support the construction of new nuclear power plants differ across the EU. In France, the UK and Finland, core capabilities are present due to ongoing construction projects. At the same time, in most other EU Member States, the nuclear supply chain is under-developed due to a lack of construction in the last 20 years.
- The supply chain at the EU scale already allows for adequate services to older plants, as exemplified over the past 10 years by the successful implementation of post-Fukushima safety upgrades at all nuclear power plants in Europe. Therefore, some stakeholders perceive European companies to be among the most competitive, both for maintenance of the existing fleet or for industrial supply of new builds.
- The current capacity needs to be ramped up to deliver **100 GW or in the advanced scenario 150 GW of nuclear power by 2050.**
- **Companies are prepared to ramp up their production.** A clear statement and commitment to nuclear from policymakers, government and utilities as well as concrete actions and contracts from the customers would support this ramp up.
- Following the announcement of the new French nuclear programme, a series of measures was launched to support the French nuclear industry (industry organisation and coordination with EDF and GIFEN, heavy investment in industrial facilities, development, and recruitment plan).
- In the EU and due to recent announcements in a growing number of countries, nuclear companies exchange through dedicated partnerships to meet challenges posed by new nuclear projects and prospects.
- There are some components/materials that are imported into the EU. For example, the steel for pressure vessels, which could present a potential risk in the future when several reactors could be built, and demand may overtake supply.
- **Standardisation of the industry is key for speeding up construction** and attracting new companies to the sector. The use of non-nuclear graded components is widely discussed; however, this decision may require further examination and discussion.

5.1 Status of the EU nuclear industry

Over the past two decades the nuclear industry in the EU has undergone several developments and transformations. After a relative decline, the situation starts to shift the other way. The recognition of nuclear power as a low-carbon source in the Taxonomy (see chapter 4) facilitates this transformation and strengthened the ecosystem's role in the decarbonization of the EU. Currently, the perception of nuclear power is thus positively changing, but a range of challenges still needs to be tackled such as unstable political environments, safety concerns, public perception, or policy debates. These challenges relate to the industry's diverse group of key stakeholders, that are presented in the table below.

Table 5.1 Main stakeholders in nuclear power plant construction and operation

Stakeholder	Responsibilities
Government	The national government sets the policy framework for the role of nuclear power within the overall energy policy. This includes a legislative framework, some of which is determined through international treaty obligations. The government may also own the utilities and set the policy conditions for industrial participation and the skills required to construct and operate nuclear plants.
Regulator	The regulatory authority is responsible for setting objectives for the safe operation of nuclear power plants and for enforcing them. The regulation of nuclear power is a national prerogative and there are differences between how regulation is applied. However, according to European Directives, the regulator must have effective independence of government and industry, must have the capability to assess nuclear safety and must be able to enforce its decisions.
Owner/Operator	The owner/operator procures the plant and is the licensee for operating it. Typically, it is either a utility (publicly owned or private) or a consortium including a utility. It is the owner/operator's responsibility to demonstrate to the regulator that it has the necessary management, organisational and financial resources to safely operate a nuclear plant.
Vendor	The technology vendor owns the reactor design. They usually also have manufacturing capabilities for the major nuclear steam supply system components such as reactor pressure vessels (RPVs), reactor core internals (possibly including the first fuel core), steam generator and pressuriser (for a PWR). In addition, they will usually have the engineering capability to translate high-level reactor designs into the detailed design and delivery schedule for construction of a plant. Conversely, they may supply the reactor design under licence and leave the engineering and construction to a third party.
Engineering Procurement and Construction (EPC) contractor	An EPC contractor will take overall responsibility for construction and delivery of a power plant. In practice, there is a range of contractual arrangements for risk sharing among the parties.
Equipment suppliers	There are certain major components of an NPP, some of which may be heavy engineering components that are critical to the design and construction of an NPP. These may be supplied by the vendor or by third parties although there are often strategic relationships in view of the criticality of these components.

Source: *Nuclear new build: Insight info financing and project management*. OECD-NEA, 2015

Since the 2000s several EU Member States decided to phase out nuclear. This had a significant impact on the supply chain. Some manufacturers ceased to exist, and some stopped producing critical components. This resulted in a significant decrease of capacity in the EU. Finding a new supplier that would manufacture nuclear graded components or would deliver to nuclear nowadays can be sometimes challenging. The study's stakeholders perceive the market **as too small and too complicated with an immense focus on strict quality assurance**, thus posing a high financial risk for any new potential entrant.

While the supply chain in the EU is shrinking the historical expertise and experience is remaining within its territory, enabling an increase in capacity as and when a clear signal is sent to EU's industrial players. To prepare the industry for the construction of several nuclear power plants in the next decades a clear communication and commitment to nuclear is needed as stated by study stakeholders.

For this study the nuclear supply chain is divided into two parts, the nuclear power plant components and the fuel cycle. The fuel cycle has its dedicated chapter 8 where the main issues and the outlook is described. The nuclear power plant components can be further divided into two segments according to their use in the nuclear power plant. The reactor, steam generator, main coolant pumps and pressurizer are called **the primary circuit**, the turbine, generator, and condenser are called **the secondary circuit**. The other parts such as energy evacuation and galleries are called the balance of plant (BOP).

Table 5.2 PWR material input requirements per kW

Material	kg / kW
Concrete	180–560
Carbon steel	10–65
Wood	4,7 – 5,6
Stainless steel	1,56 – 2,10
Galvanized iron	1,26
PVC	0,80 – 1,27
Insulation	0,70 – 0,92
Copper	0,69 – 2,00
Uranium	0,40 – 0,62
Manganese	0,33 – 0,70
Zirconium	0,20 – 0,40
Chromium	0,15 – 0,55
Nickel	0,10 – 0,50
Inconel	0,10 – 0,12
Brass / bronze	0,04
Lead	0,03 – 0,05
Aluminium	0,02 – 0,24
Silver	0,01
Cadmium	0,01
Boron	0,01
Indium	0,01
Total	**195–635**

Source: *Materials and the Environment*. Michael F. Ashby, 2013

The primary circuit's main items are the reactor and steam generator. The EU landscape is almost fully covered by suppliers residing within its territory. There are, however, some exceptions like very large forgings that are required to assemble a reactor which are today sourced from suppliers outside of Europe. The rest of the forgings are mainly produced in Europe especially in facilities like

Framatome Le Creusot, France for the EPR. As of today, other capacities are existing in Europe and could be reactivated to face the increase of constructions. National or EU support could ease the relocation of very large forgings. The current landscape of companies that are supplying the nuclear sector is presented in Annex F.

Other parts of the primary circuit (main coolant pumps, pipes, valves, and others) are and can be manufactured within the EU, but the existing capacity might not be sufficient to meet future demand since the construction could increase eight times compared to the construction in the past 20 years. The situation could become even more challenging with the increasing construction of new nuclear power plants in the future when the capacities will be utilized for 100% and there will not be enough manufacturers to ensure timely and effective delivery.

Within the secondary circuit the steam turbine is the main component to be manufactured. There are currently two companies manufacturing steam turbines for the nuclear sector in the EU: GE and M&M Forgings[123]. Other companies that manufacture nuclear turbines are located outside of the EU. Additional capacities may be needed to serve the EU Nuclear Alliance ambitions. Other components where there might be a capacity challenge are the generator, condensers[124], valves, pumps, or steam generators[125].

In addition, beyond the primary and secondary circuits, the other important part is the balance of plant (BOP), which consists of all the supporting and auxiliary components needed to produce energy, which can be divided into mechanical BOP and electrical BOP. There are several companies that are providing the needed components for the mechanical BOP, these components are needed for various systems ranging from the water treatment, through air conditioning and ventilation to residual heat transport systems. The study's stakeholder assume that those services can be provided by EU-based companies, however, since many of the services are crucial for the nuclear power plant safety, rigorous certifications are needed. The number of companies that have the certification and can provide these systems/components is relatively limited. Also, since the construction in recent years was not extensive, some companies turned their focus to other sectors. The components forming the electrical balance of a plant (transformers, switchyards etc.) can rely on a large supply chain, not specific to nuclear. It is important to address the potential shortages in capacities holistically, as each supplier can switch from one market to another.

In the operation phase of a nuclear power plant, maintenance plays a major role which is highly connected to the long-term operation of the plant. Maintenance requires inspections and changes of some specific components (control rod drives, detectors, IONEXes etc.) further increasing the necessary capacity of the industry. The maintenance services are provided by several companies throughout the EU as there has been constant need for them. Thus, with a projected capacity of 100 GW of nuclear in 2050, the companies that are in the market today should

123 NEI Magazine. 2023.
124 Manufacturing currently done by only four companies in the EU.
125 Manufactured by six companies within the EU.

be able to provide the necessary services in the future without significant expansion needed. In the advanced scenario (chapter 2), where capacity could be increased to 150 GW in 2050 expanding these stable activities could be required. In addition, as mentioned in chapter 2, the majority (83%) of reactors are older than 30 years and are expected to go through the LTO programme which is presumed to expand the market with maintenance services. **Therefore, the study's stakeholders assess maintenance services to be well set up to support the requirement for installed capacity in 2050.**

The final part of the supply chain that is crucial for the development of nuclear power in the EU is the decommissioning industry. As further described in chapter 9, **decommissioning services are provided by a handful of companies and the experience is not extensive.** However, since the number of shutdown reactors is increasing fast[126], decommissioning is a phase that could grow in importance. With 83% of reactors older than 30 years and the decision from some Member States to phase out nuclear[127] the decommissioning market could be expanding rapidly in the near future. The global decommissioning market is expected to be worth 9.5 billion EUR by 2027[128]. **The EU is expected to become the largest market for decommissioning in the world and it is estimated that it could be worth about 60 billion EUR**[129]. The potential of the decommissioning market is growing, and it can provide a long-term pipeline of work throughout the EU's nuclear sector. It is expected that the market could become very competitive with new players entering[129] (please note that this is covered in more detail in chapter 9).

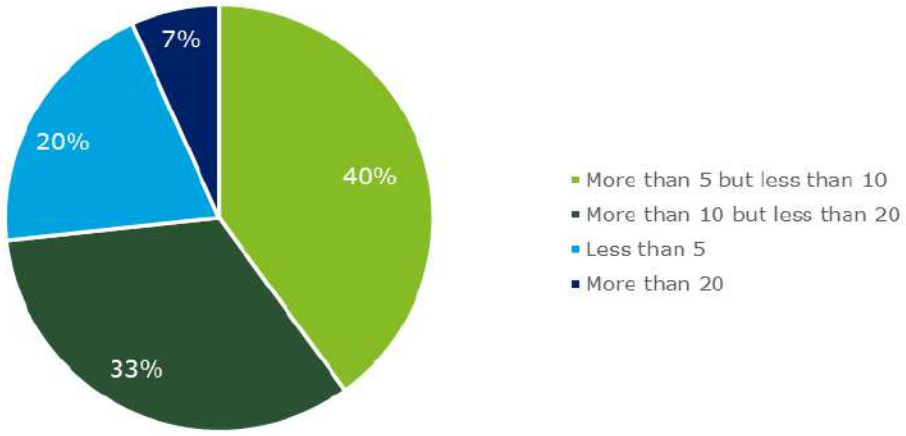
5.2 The readiness and outlook of the industry

The supply chain plays a vital role in the development of nuclear power in the EU, particularly when assuming the plan to have 100 GW of nuclear power by 2050. As mentioned in chapter 2, according to data collected until June 2023, there are plans for 40 new nuclear power plants (combined capacity of about 59 GW) to be constructed by 2050. That, however, is still not fulfilling the set goal of 100 GW. With 59 GW[130] to be built, 17 GW of LTO plants there is still a current gap of 24 GW that must be constructed. Therefore, **the industry must be prepared to build around 80 GW of new NPPs by 2050.** Looking at Figure 2.5 in chapter 2 describing the length for an NPP construction, and using the data provided by projects developers, on average, it takes almost ten years to build a new nuclear power plant. If the assumption that one nuclear power plant equals 1.2 GW of installed capacity is made, it means that 1.2 GW takes ten years to build in the case of building just one nuclear power plant at a time. The needed capacity to be built by 2050 is around 80 GW (almost 70 reactors). This results in the necessity **to build 25.3 GW (22 reactors) of new nuclear capacity simultaneously** and

126 Currently there are **71 NPPs** that are shut down and waiting to be decommissioned.
127 Only in Germany 30 reactors are waiting for decommissioning.
128 Nuclear Decommissioning Services Market Size Worth $9.43 Billion, Globally, by 2027 at 6.3% CAGR - Exclusive Report by The - Bloomberg
129 Decommissioning Europe's nuclear fleet | Energy Focus (the-eic.com)
130 MS questionnaires, interviews.

this is if construction were to start immediately with every further year of delay increasing this number. The magnitude of the problem was confirmed by the study's stakeholders when asked *"What do you think is the possible number of nuclear reactors to be built in Europe simultaneously given the current manufacturing capacity?"* **40%** answered more than five but less than ten, **33%** answered more than 10 but less than 20, **20%** answered less than five and only one stakeholder thinks it is possible to build more than 20 reactors simultaneously. The task that awaits the industry is challenging, but achievable, with the same dedication, alignment of parties and commitment as shown in the past.

Figure 5.1 Stakeholder's opinion on the number of reactors that can be built simultaneously in the EU given the manufacturing capacity



Source: Stakeholder questionnaire

As already stated, the supply chain was and is already preparing for the future construction, but it needs to ramp up its manufacturing capacities as well as human resource competences described further in chapter 6 and closely monitor a potential risk of a lack of strategic materials. In past years, during the construction and operation of nuclear power plants in the EU, the nuclear industry experienced significant delays, cost overruns and even shutdowns. To change this, a coordinated effort in the construction process and project management is necessary. The study's stakeholders mentioned that to ensure faster and seamless construction, standardisation is key. Standardisation of products, components and of processes helped by the high number of projects could improve efficiency, quality, and timing of delivery. Moreover, standardisation and the use of industrial grade components (increase of volume and decrease of efforts for development and qualification) could ease access to the nuclear market and attract more companies to enter. This is where the proposed Net-Zero Industry Act (NZIA) in March 2023[131] could have an impact as it proposes to help strengthen the European manufacturing capacity of net-zero technologies and overcome barriers to scaling up the manufacturing capacity. It also proposes increasing the competitiveness of the net-zero technology industrial base and improve the EU's energy resilience.

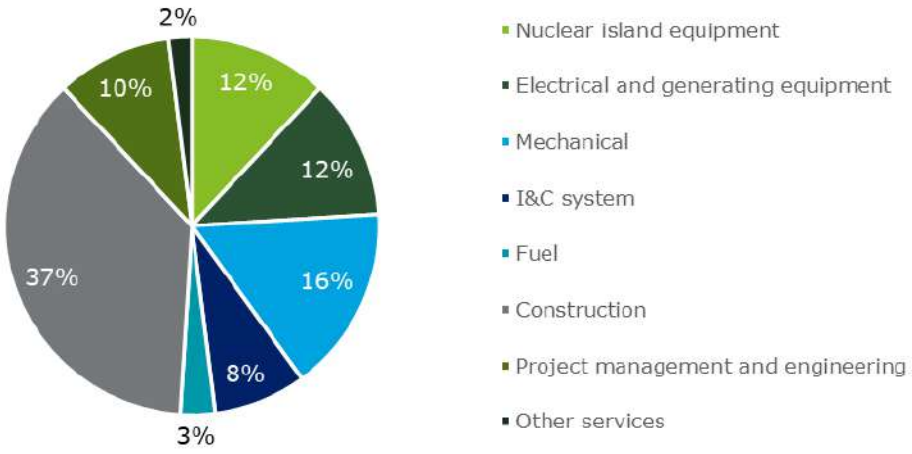
131 https://single-market-economy.ec.europa.eu/industry/sustainability/net-zero-industry-act_en

Additionally, the use of industrial grade components in areas of nuclear power plants without jeopardising the safety is believed to result in faster construction times. Achieving standardisation may need individual companies to cooperate extensively to find a common standard that could be used on the EU level. The benefits of doing so should be promoted and communicated by the European Commission, according to the study's stakeholders.

As explained, the parts of the supply chain that are facing potential capacity challenges are construction and decommissioning. Construction was also identified as the main area where the focus should be put in terms of skill set development. To the question *"On which skills set should training programmes be focused most:"* **eight out of 15** members of the study's **stakeholder group answered: construction**. This need to extend construction capacity is further supported by the situation observed over the past 20 years. The involvement of new companies in the nuclear sector should be supported but as of now the field is perceived as too complicated and companies are hesitant to enter the sphere. During the interviews the study's stakeholders were further asked about what can be done in Europe to attract companies to the nuclear sector. In this regard stakeholders agreed that **it is important to have a stable and long-term commitment to nuclear power.** Overall, the number of companies manufacturing for the nuclear sector may have to increase to meet the decarbonisation goals.

A critical part of the construction phase is the manufacturing of large components such as pressure vessels or steam generators. It is estimated that **equipment cost can make up 48%**[132] **of the overall overnight costs**[133]**.** According to the study's stakeholders only a few companies can make these components.

Figure 5.2 Cost breakdown for nuclear power plants



Source: *Nuclear new build: Insight info financing and project management*. © OECD-NEA, 2015

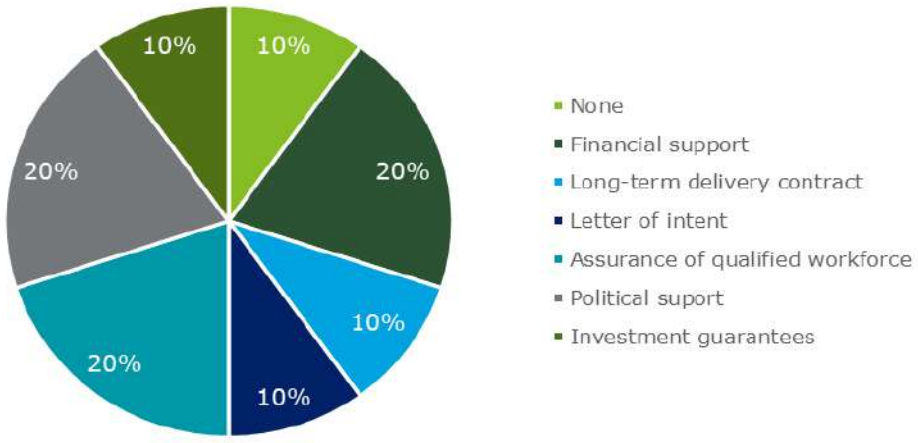
132 Nuclear island equipment – 12%, Electrical and generating equipment – 12%, Mechanical – 16%, I&C system – 8%.

133 Nuclear new build: Insight info financing and project management. OECD-NEA, 2015.

As of today, the nuclear industry is largely located in Europe. To maintain this and, in particular, to manufacture large components in the EU, the capacity may need to increase, otherwise a dependence on non-European suppliers could ensue. Although pressure vessels are the main component of nuclear reactors, they are not the only critical part. Other large components include steam generators, pumps, condensers etc. Like the pressure vessel these components take years to produce and the capacity in the EU is limited. The support from the European Commission and EU Member States toward these companies is critical to maintain Europe's sovereignty on these components.

The European industry has the ability to grow rapidly and meet the capacity challenge: To the question: *"By what percentage would your company be able to increase production capacity over the next 5 years for nuclear industry?"* from the 11 answers received **four companies answered that they could increase their capacity by 100%**, other companies stated the increase is possible **for 60%, 50%, 30% and 25%, each answer having one vote**[134], the rest did not provide a specific number. This shows the commitment and capacity of the companies to ramp up their production capacity if market conditions require it. What was also discussed in the questionnaire was the support needed to double their capacity. Answers that were repeated the most were **the financial support, the assurance of qualified workers and political support**[134].

Figure 5.3 Industry answers to the question: What kind of support would be needed to double your production capacities in the next 5 years?



Source: Industry questionnaire. 2023

To achieve decarbonisation goals[135] the supply chain requires a substantial transformation, considering that only nine reactors were built in Europe, and only five in the EU, in the past 20 year. This transformation or rather the increasing of capacity of the supplying industry for nuclear energy production and the

134 Industry questionnaire. 2023.
135 Building 80 GW of nuclear power by 2050.

development of nuclear power plants is a long-term process. To initiate such a transformation, industry players require financial and political support, assurance of qualified workers, a clear and stable environment, and a commitment to targets and contracts. Without this, only few companies would invest in their expansion to fulfil the required capacity to support the nuclear development. Moreover, the long-term process of developing a nuclear project (before the construction starts) increases uncertainties for industry players.

Currently some parts of the supply chain are ready as confirmed by the study's stakeholders. For example, France has maintained a strong nuclear supply chain thanks to the needed maintenance and evolution of the 56 operating reactors and the construction of 6 EPRs. This new construction programme was an opportunity to better organise the industry with the creation of GIFEN and reinforce the dialogue between major contracting parties and contractors. It allows to give a better view of coming projects and of needed competencies and industrial capacities. Within main companies in the nuclear sector high investments have been and will be made to modernise industrial capacities and to ensure quality, delivery time and a higher volume. For example, ongoing investments could allow to reach the capacity of manufacturing components for up to 2 EPRs per year. Uniformization of processes and the simultaneous launching of 6 EPRs allows to increase massive manufacturing of standardized components. At the European scale several partnerships were initiated for the new build projects. All these efforts need to be supported and accelerated by the implementation of the recommendations mentioned in subchapter 5.4, especially those related to giving visibility and showing commitment.

5.3 SMRs and advanced reactor supply chain

The Small Modular Reactors (SMRs) deployment is widely discussed in the nuclear sector and is expected with anticipation. SMRs are expected to be manufactured in series in factory production. Individually preassembled modules should be transported to the site for final assembly. The manufacturing of SMR modules brings several challenges. Firstly, many SMR designs proposed to EU Member States are not of an EU origin. The European Commission could encourage an EU SMRs market, maintaining a high-level of resilience within the EU, according to the study's stakeholders. Secondly, the variety of designs proposed to EU Member States could put at risk any standardisation ambition. Thirdly, as for the existing supply chain, the capacity of this EU SMR supply chain should be able to sustain the EU decarbonisation ambition. It is important for the industry and component suppliers to cooperate and engage early in discussion with SMR vendors, to prepare for the manufacturing of SMR components. The standards, individual components, timeframe, and necessary processes should be the topic of these discussions.

A European SMRs partnership will be launched by 2024 to coordinate the efforts and ensure smooth integration. Discussion between vendors and manufacturers are progressing. This development and coordination must be supported and encouraged to ensure a progressive ramp up to ensure a sovereign capacity and to prove beneficial to the EU economy.

AMRs are facing even more uncertainties than SMRs, the designs are using completely different technologies, different materials and methods. The main issues identified are the use of different steel materials for molten salt reactors, the use of molten salt with different characteristics, manufacturing of different fuels, the use of molten metals and others. These could require a completely different approach of manufacturing, different processes ensuring the integrity of the materials and components used. Even though the deployment of advance reactors is still years, even decades away, this issue should be investigated in more detail. This is what has been done by the newly founded initiative, the European SMR pre-partnership[136], that is examining mainly the LWR SMRs but also the challenges that the advanced reactor supply chain poses for the EU's industry.

5.4 Conclusions and recommendations

The supply chain plays a **vital role in the construction, operation, and decommissioning of nuclear power plants**, its **efficiency, effectiveness and capacity are crucial to ensure smooth construction** of planned projects. In recent years, the European supply chain was shrinking due to the decreasing number of new build projects and the anticipated shutdown of reactors. The few projects that were or are in the construction phase had **significant issues, including delays, cost overruns and quality problems**. This was further confirmed by the study's stakeholders when asked "*Do you consider the current supply chain for delivering new nuclear units as healthy and ready for maintaining the same capacity as today?*". To this 47% answered that they consider it unhealthy and not ready, 33% consider it as healthy and ready, and 20% answered that the supply chain is only healthy.

During the last few years, and since several Member States reiterated their commitment to nuclear, the supply chain has been preparing for new projects. In France, an organisation has already been put in place and heavy investments have been launched to modernise and secure an engineering and manufacturing capacity. In Europe several partnerships have been made in preparation of the awaited projects.

The current **capacity of the industry needs to ramp up to be able to deliver the decarbonisation target** of 100 GW to 150 GW of nuclear capacity by 2050, as was confirmed by the study's stakeholders and analysis provided in this chapter.

Members of the study's stakeholder group believe that **it is possible to ramp up the capacity of the industry and fulfil the goal**. Ramping up the capacity **requires commitment, a stable environment, cooperation among the key players and support from the European Commission and EU Member States.** Considering extending LTO (up to 80 years) would smoothen the need to ramp up and should be one of the main levers to achieve the objectives. Considering a non-EU supply chain contribution can be seen as a possibility to ensure the sovereignty of the energy supply. To ensure a secure supply of materials, **the key**

[136] Partnership in the form of a collaboration scheme involving industrial stakeholders, research & technological organisations, interested customers (i.e., utilities and even Member States), European policymakers and regulators with the aim at creating enabling conditions for the first European SMRs.

is diversification and domestic supplies where it is possible, as in the case of the fuel cycle. Regarding the supply chain of SMRs, it is important to pay attention to maintaining opportunities for the EU industry. Current suppliers should (and some already do so) cooperate with SMR vendors to discuss the needed capacity, individual component, and standards. Overall, the preparation for the deployment of SMRs, and a recommendation is for the European Commission to promote the development of an EU SMR supply chain.

The nuclear supply chain **would require a transformation**, mainly in the sense of **increasing the capacity, effectiveness, and by becoming a competitive industry for qualified workers**. Using innovative procedures could help decrease the manufacturing time of components and thus ensure a better utilization of the capacity. The study's **stakeholders believe that with concrete support, increase of the production and assurance of a sufficient number of qualified workers this could be possible**. In terms of these updates, **the European Commission, MS and industry must cooperate.** To achieve this in a fast and efficient manner, **targeted support and strong commitment are key**.

The analysis of inputs provided by the stakeholder group allowed us to identify the following recommendations[137] whose aim is to ensure a successful supply chain landscape:

European Level

- **Support a clear and long-term commitment to nuclear power to create a stable environment in which the industry could invest and increase its production.**
- Provide targeted support to the industry for ramping up their capacity and increasing the effectiveness of their processes.
- Show commitment to a European design for SMRs/AMRs, for example by supporting initiatives such as the European Industrial Alliance on SMRs[138] to establish a dialogue between the key SMRs players and the industry and promoting European solutions.
- **Support processes to increase standardisation throughout the EU or some smaller regions. Open the dialogue about using industry-grade (instead of nuclear-grade) components where possible while ensuring the appropriate level of safety.**
- Establish an initiative focused on the supply chain of advanced reactors to help development and deployment as well as assess the needed changes in manufacturing processes and methods, and to ascertain which facilities are missing in the EU.

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137 Chapter 11 presents a list of priorities. These are concrete recommendations which require immediate actions, as discussed with the study's stakeholder group, Member State representatives and NGO representatives during a workshop 5-6 September 2023.

138 European Industrial Alliance on Small Modular Reactors - European Commission (europa.eu)

Member States

- **Develop a long-term nuclear power strategy that emphasizes the commitment toward nuclear power.**
- Support the industry with regard to the expansion of capacities, hiring new talent and increasing the effectiveness of processes while allowing international suppliers to enter the scene.
- Prepare a supporting programme for the cooperation between universities and the industry to ensure a sufficient number of qualified workers.
- Support processes to increase standardisation throughout the EU or some smaller regions.

Industry

- **Develop a strategy for increasing the capacity and effectiveness of processes. Streamline project management to ensure that projects are completed on time and on budget.**
- Cooperate with universities and Member States to support a sufficient supply of qualified workers.
- Ensure a diversification of the material and components supplies, if possible, use domestic supplies within the EU but allow and support international supply chain collaboration.
- Explore the possibility of standardisation throughout the EU or some smaller regions, such as central and eastern EU Member States. Open the dialogue about using industry-grade (instead of nuclear-grade) components where possible while ensuring the appropriate level of safety.

6 Human capacities – Do we have enough experts to construct and operate nuclear power plants?

This chapter presents the main challenges and potential of the EU nuclear ecosystem in the field of human capital. This includes the number of workers, their skills and expertise needed to meet changing demand for nuclear power until 2050. Desk research and stakeholder consultations highlight potential risks of an ageing workforce considering the required increase in the number of nuclear power plants until 2050. At the same time, measures are needed to ensure transfer of knowledge and expertise to new workers in the field of nuclear energy.

The assessment illustrates the importance to increase the attractiveness of the nuclear sector to young people. Today the nuclear sector is competing with other fields that are perceived as more attractive to young people. These fields include IT, aviation, space engineering etc. Another point that was discussed with the study's stakeholders is the importance of collaboration between the three main types of stakeholders: industry, academia and government. In this context, industry could enhance collaboration with academia to align on required skills and the number of new capacities. Also, cooperation in the field of mentorship, industry lectures and other initiatives should be promoted. The government should support academia and the nuclear energy sector.

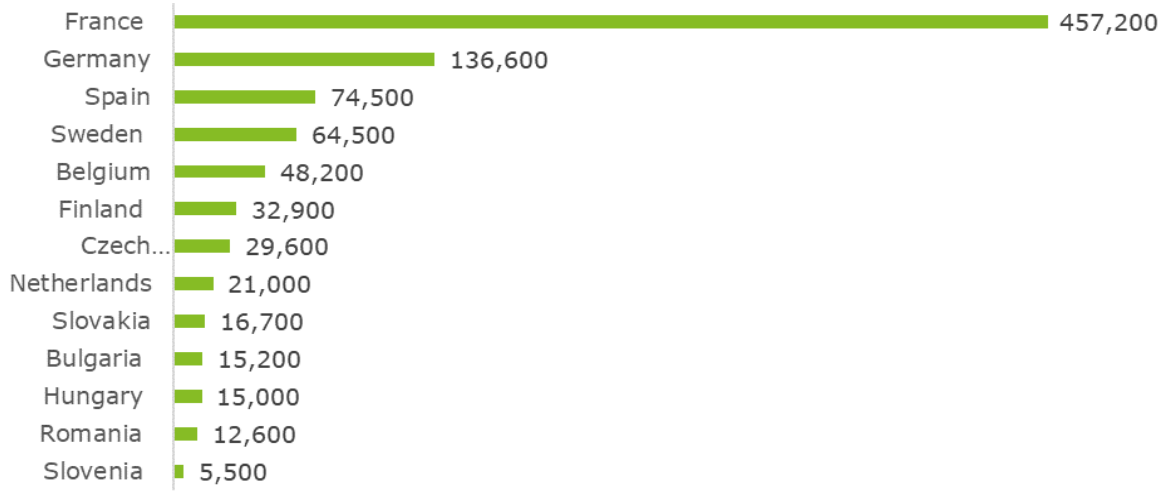
Key findings

- **The ageing workforce** is a main issue for the nuclear ecosystem that is characterised by a large share of professionals currently reaching retirement age.
- **A Lack of young professionals** coming to replace the existing cohort of experts is another issue. Young professionals have limited interest in nuclear, other sectors are far more attractive.
- **Educating nuclear professionals is a long and demanding process** and it only deepens the gap between young and retiring experts.
- A lack of young professionals and the long duration to educate professionals increases risks of **diminishing nuclear expertise and knowledge transfer in the EU**.
- The nuclear industry **is not seen as a field with perspective and upside potential**, and thus it is **competing with other industries** for the already deficient pool of professionals and talents.
- Seen from the industry, the development and maintenance of human resources with the expected skills, competencies and experience, is a **matter of anticipation**, early contracting and long-term planning.
- **The SMRs and AMRs could play a major role in solving these issues**, since young professionals are showing a large interest in these areas.
- **Digital transformation** of the nuclear industry could also support the ramping up of human capacities. Large invest programmes at national scale need to be supported to deal with interoperability, data management in a secure digital environment or skills development.

6.1 An ageing workforce for the EU's nuclear ecosystem

In 2019 the whole nuclear ecosystem sustained more than 1.1 million jobs throughout the EU labour market force139,140. Out of the 1.1 million jobs in the nuclear ecosystem 351,900 jobs were directly attributed to the nuclear industry and 777,900 jobs were attributed to the sector's supply chain. Employment was highest in France, followed by Germany, Spain and Sweden141 as can be seen in the figure below.

Figure 6.1 Total employment in countries operating nuclear power in 2019[142]



Source: Study team, based on *Economic and Social Impact Report,* prepared for ©nucleareurope (former FORATOM), April 2019

The nuclear sector in the EU employs a variety of professionals. Being so diverse and multidisciplinary, the sector offers a wide range of possibilities. The opportunities are ranging from working directly at the nuclear power plant, to research institutions, medical facilities, supply chain companies and back-end facilities. The portfolio of opportunities in the nuclear sector is summarised in the figure below.

Considering the diversity of jobs related to nuclear energy, it is estimated that the ecosystem generates 2.2 indirect jobs per 1 job in the nuclear sector[139] (subcontractors, secondary technology suppliers, steel manufacturers etc.). These jobs can be found throughout EU Member States and the global supply chain as well.

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139 Economic and Social Impact Report. report prepared for nucleareurope (former FORATOM), April 2019.

140 Also including United Kingdom.

141 Figure 6.1 only illustrates employment in Member States that had nuclear power in 2019. There are up to several thousand jobs in countries that do not have operational nuclear power. Examples of such job's focus on nuclear science, nuclear medicine, and the supply chain.

142 Direct + Indirect employment.

Figure 6.2 Range of nuclear opportunities in the EU

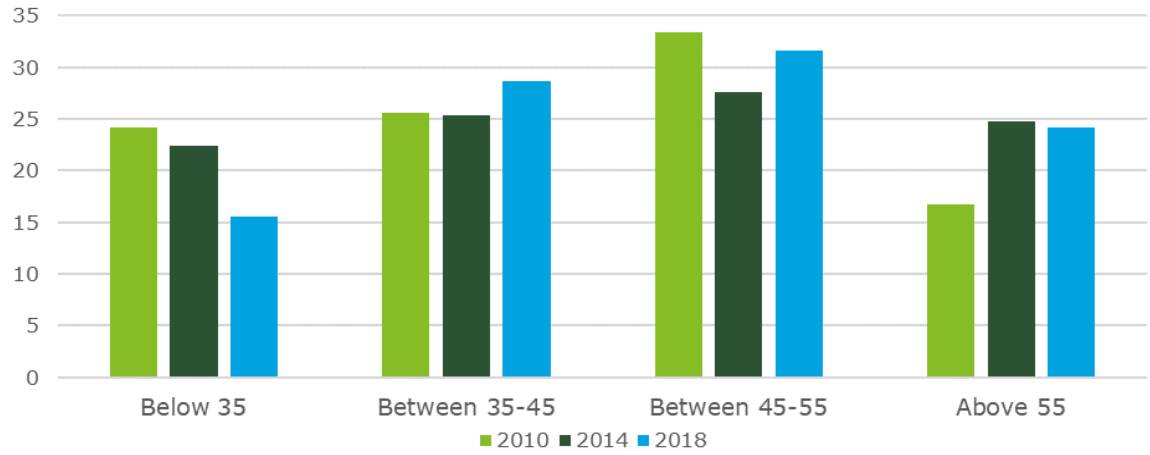


Source: *Nuclear: Investing in a competent workforce for the benefit of society*, © nucleareurope (former FORATOM), 2020

The distribution of workers in the nuclear ecosystem by age group depicts an ageing workforce[143]. The share of nuclear professionals below the age 35 declined between the years 2010 and 2018. While in 2010 there were almost 25% of professional below the age 35 in 2018 it was only 15%. An opposite trend can be seen in the age group of above 55 with the share of the nuclear energy workforce aged 55 and older increasing: In 2010 the number of professional above 55 was approximately 16% while in 2018 it was around 23%. Professionals between the age 45 – 55 in 2018 made up more than 30% of all nuclear professionals[143]. These trends have likely continued to evolve until today, which is also confirmed by the study's stakeholders.

143 Results of surveys of the Supply of and Demand for Nuclear Experts within the EU-28 Civil Nuclear Energy Sector, EHRO-N, 2019.

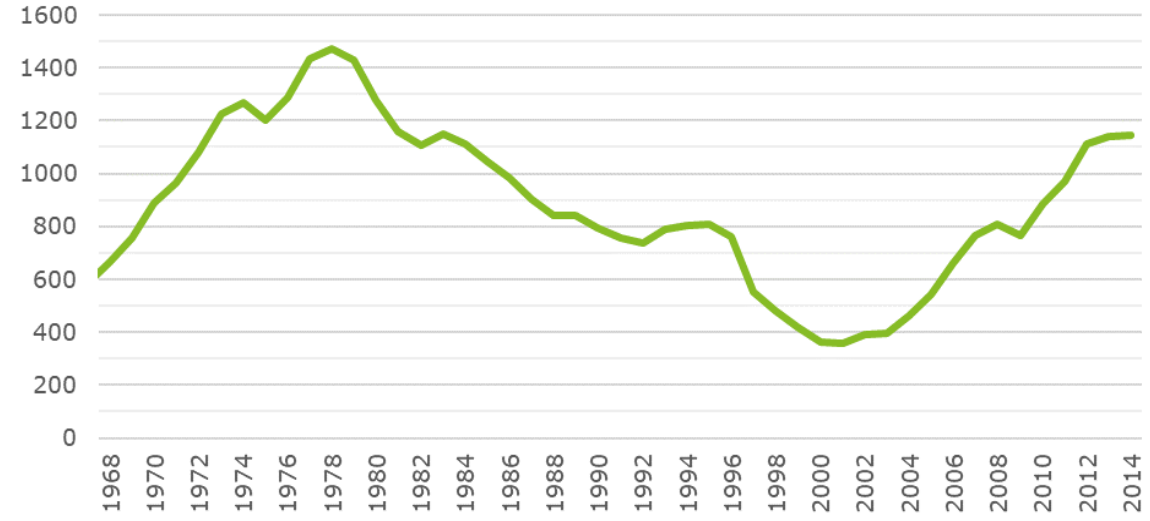
Figure 6.3 Normalised age span for nuclear experts in different years [%]



Source: Results of surveys of the Supply of and Demand for Nuclear Experts within the EU-28 Civil Nuclear Energy Sector, © EHRO-N, 2019

The ageing of the EU's nuclear energy workforce is a result of a combination of factors. Firstly, many of the skilled professionals were recruited in the 1970s and 1980s, during a period of rapid growth of the nuclear industry. Inevitably, these workers are now approaching retirement age. Secondly, the nuclear industry has experienced a decline in popularity in recent years, with many young people opting for careers in other industries, such as renewable energy or technology, it led to a lack of human capital to replace the existing workforce. To further illustrate the decline in popularity of nuclear education, the graph below illustrates the total number of nuclear engineering degrees awarded annually in the US between 1966 and 2015. Even though the numbers are for the US market, the graph illustrates the declining trend, followed by renewed growth and increasing interest from 2001 onwards. It is assumed that the situation in the EU is similar.

Figure 6.4 Awarded nuclear engineering degrees in USA



Source: © Oak Ridge Institute of Science and Education

The ageing workforce and the decline in the number of nuclear professionals under the age of 35 presents a significant risk for the future construction and operation of newly built nuclear power plants and decommissioning of old ones. At the same time, increasing popularity in nuclear engineering degrees may suggest a potentially additional, growing workforce in the coming years. Data from the USA illustrates an increase in the awarded nuclear engineering degrees between 2000 and 2012 (approximately 400 degrees awarded in the year 2000 vs. almost 1 200 in 2012). A similar trend in the EU may require specific steps to leverage this potential to address a possible decline of the nuclear workforce as result of ageing.

6.2 Increasing number of nuclear jobs until 2050

Considering the assumed changes in the nuclear energy system as discussed in Chapter 2, 46% of consulted stakeholders for this study assume a lack of several professionals for the construction, operation, and maintenance of nuclear power plants.

- **Construction**: Current studies estimate that the construction of a nuclear power plant employs 7,000 people at peak times[144]. If we assume that for the construction on average 4,000 workers will be needed than the intended construction of 100 GW or approximately 80 reactors will require 320,000 workers. Of course, the workers could be moved across Europe and the reactors could not be constructed at the same time but even after taking this into account, the industry may **require a significant number of additional workers** in the coming years. Planned constructions support the assessment of a number of workers required simultaneously. For example, Poland is planning to build six reactors, France decided to build six reactors plus an additional eight for which feasibility studies are being prepared. In addition, the Czech Republic is in the middle of the tendering process for one reactor with the plan for potentially three more, the Netherlands started the discussion about the construction of new reactors. During the stakeholder interviews it was reported that France alone may need 5,000 – 10,000 new nuclear professionals to construct and operate the new NPPs. If we assume that the construction in Poland, the Czech Republic, France, and the Netherlands will be done almost simultaneously, **the sector may need at least 100,000 – 150,000 workers to cover the construction of new nuclear power plants in five EU Member States simultaneously.** Importantly, however, the planned construction in these Member States does not cover the required number of reactors to meet the EU energy and climate objectives. Therefore, more workers are likely required.
- **Operation & Maintenance**: During the operation phase a similar number of workers is needed. On average, one nuclear power plant employs 500 to 800 people[144] in administrative, operations, and maintenance. If we assume 80 new reactors to be operated, the industry must hire between 40,000 to 64,000 new workers throughout the lifetime of the NPP (60 – 80 years). During the operation phase workers are stationary, so mobility in this case is not an

144 Nuclear Energy Institute

option. Thus, **all the 40,000 to 64,000 workers are necessary to safely operate and maintain the future power plants.**

- **Decommissioning:** Other areas where a significant number of new professionals may be needed relates to decommissioning and waste management[145]. With the increasing number of reactors shut down, decommissioning could play an important role in the nuclear ecosystem of the future. **The industry of decommissioning nuclear power plants could be rapidly expanding in the future.** Several Member States, with France at the forefront, could shut down multiple reactors in the coming decade, if we assume a LTO of 60 years[146]. Germany already shut down all their reactors as part of the "Energiewende". In total Germany operated 33 reactors, out of which three have already been decommissioned, and 30 reactors are left to be decommissioned in the coming years. As mentioned in chapter 2, between 2040 and 2050, 78 reactors may end their operation if 60 years of operation is assumed. On average **decommissioning a nuclear power plant takes 10-20 years and employs 500 people annually**[147]. With 500 people employed per plant, the sum of required experts in the next 30 years could be approximately 40,000. To find and train such a large group of experts could be a challenging and time-consuming task. Thus, in the upcoming years **the need for decommissioning expert workers may increase.**

Considering the above points, the **nuclear sector may need an additional 180,000-250,000 new professionals until 2050.** Approximately **100,000-150,000 professionals may be required to cover the construction phase** of the planned new nuclear power plants. Another **40,000 to almost 65,000 professionals are necessary to operate and maintain the planned nuclear power plants**. Lastly the **decommissioning may require a further approximately 40,000 professionals**. The ecosystem therefore faces a challenging task of finding and training the professionals. This challenge is even more complex given largely different profiles required ranging from construction workers and civil engineers, mechanical, electrical engineers and reactor operators to experts on decommissioning and dosimetry.

6.3 Enhance education and attract new professionals

The stakeholder consultation illustrates different ways to address the challenges of an ageing workforce and attract sufficient additional workers to meet the changing demand of the nuclear ecosystem until 2050. The study's stakeholders propose to promote the sector and make it attractive to young people. This can, for example be achieved by enhancing **education and awareness campaigns**. To do so, the study's stakeholders recommend combining educating young people about the role of the nuclear sector and illustrating the importance of nuclear energy in meeting Europe's energy demands while highlighting available opportunities. Another possibility would be to enhance internships or offering scholarships as further detailed below.

145 Stakeholder interviews
146 see also the assumptionjs in Chapter 2
147 Measuring Employment Generated by the Nuclear Power Sector. NEA, IAEA, 2018.

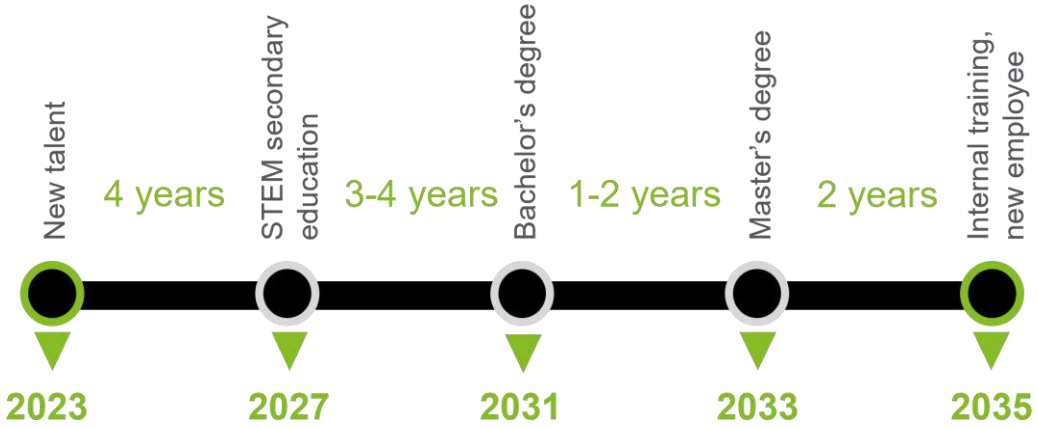
Nuclear professionals

The nuclear energy ecosystem consists mostly of highly skilled jobs; 47% of the 1.1 million jobs in the field[139]. This is relatively more than in the electricity sector in general, where the share of highly skilled jobs varies between 25% and 36%.

Currently, too little nuclear energy professionals enter the market yearly to meet the needs of the planned new builds. As mentioned previously, France alone would need approximately 5,000 to 10,000 nuclear professionals for their intended new NPPs to be build. According to the study by EHRO-N from 2019 the total number of students graduating from 90 universities in 2017 with **nuclear related education was 2,167,** of which 828 Bachelor students, 1,094 Master students and 245 Doctoral students[148]. These numbers illustrate a lack of professionals for developing the nuclear ecosystem. Moreover, the study's stakeholders point at a possible competition among employers to attract the available nuclear professionals.

Also, there is a likely time lag for education providers to contribute to delivering a sufficient number of nuclear professionals. It takes between six to eight years from entering university education (Figure 6.5). Looking at a scenario where the education starts with Science, Technology, Engineering, Mathematics (STEM) secondary school[149], continues with university and work training it takes 10 to 12 years to become a skilled nuclear professional.

Figure 6.5 Becoming a nuclear professional timeline



Source: Study team

148 Results of surveys of the Supply of and Demand for Nuclear Experts within the EU-28 Civil Nuclear Energy Sector. EHRO-N, 2019.

149 Takes four years to complete.

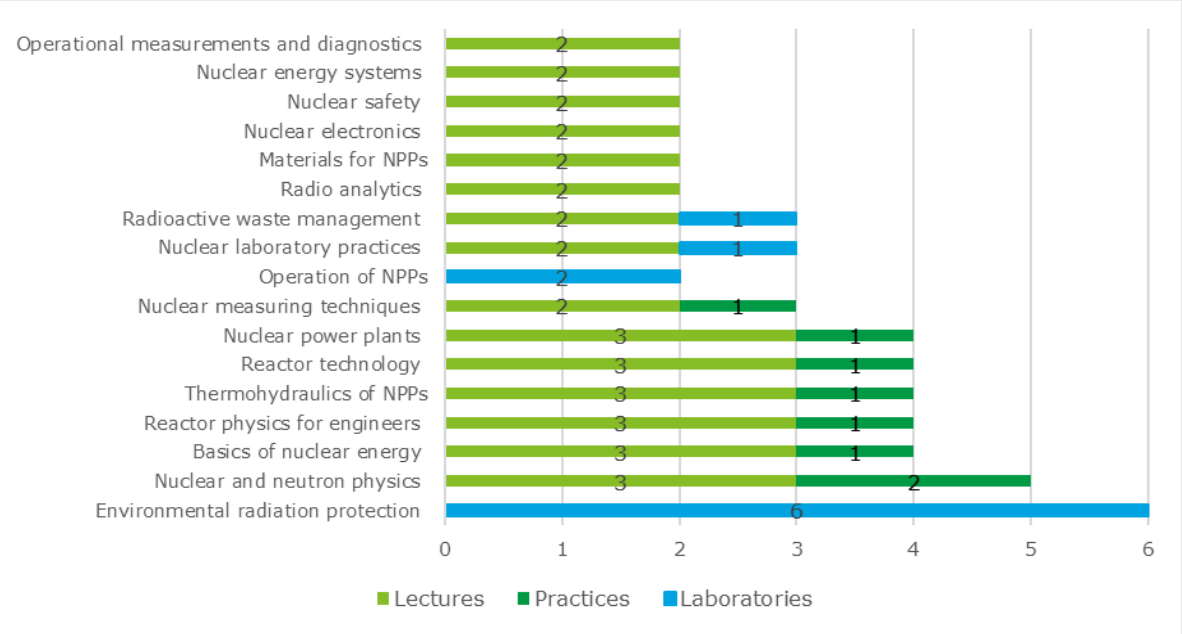
The time required to become a nuclear professional further emphasises the challenges to provide sufficient professionals to meet the changing demand as discussed in previous sections. However, it has to be added that a large number of professionals in the industry have their background in other engineering fields such as electrical, structural, mechanical etc. and are trained to become nuclear professionals without a need to have nuclear specific education. If retiring professionals are to be replaced by new young professionals the entire value chain must understand that it **takes over a decade to prepare a replacement**. Assuming that educating a new cohort begins in 2023 the first individuals prepared to work in the industry could be ready in 2035. If the goal is to have 100 GW of nuclear power in 2050, mainly in new builds, **it is crucial to start training the experts as soon as possible**, otherwise there could be a lack of skilled resources to construct and operate the NPPs.

Attracting nuclear experts from regions outside the EU could provide a solution to meet the demand for human capital. However, this is relevant only to some specific positions. For instance, in some Member States nuclear reactor operators are obliged to have a security clearance, which is difficult to obtain for individuals from other countries. In this study this possibility was not further examined.

Case study: the path to become a nuclear professional in Hungary

Since high level of education and specialised training in nuclear science and technology is required the path to become a nuclear professional is long and demanding. A first step to become an expert in the nuclear field is to obtain a bachelor's degree. Most nuclear experts have bachelor's degree in physics, nuclear engineering, chemistry, material science or mechanical engineering. In Hungary it takes between two and six years to obtain a bachelor's degree and obtain the necessary background in STEM principles[150] (Figure 6.6).

Figure 6.6 Number of nuclear related subjects in the energy engineers BSc at the Roland Eötvös University Budapest



Source: Status and trends in nuclear education, © IAEA, 2011

The next steps on the path to become a nuclear professional is to obtain a master's degree. Usually, the same fields are applicable as for a bachelor´s degree – i.e. nuclear engineering, nuclear physics, chemistry, mechanical engineering, or material science. Examples of **the need for graduates** in these fields for the Hungarian nuclear programme are shown below.

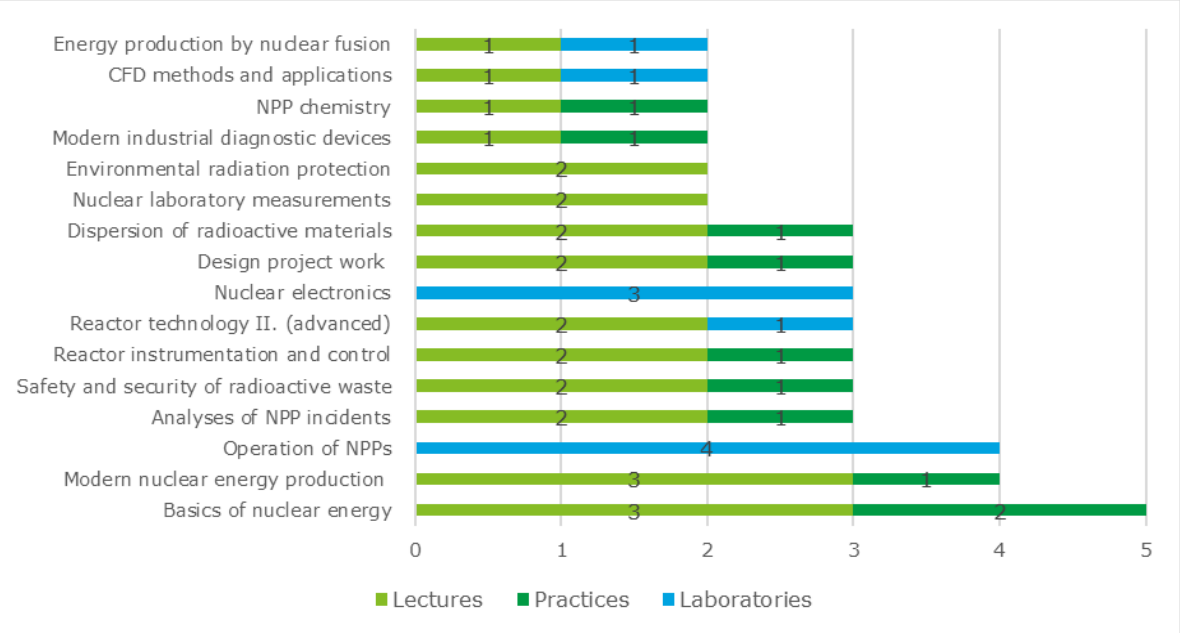
Specialization	BSc	MSc	Total
Energy engineers	69	75	144
Mechanical engineers	148	131	279
Electrical engineers	111	110	221
Chemical engineers	77	61	138
Other (physicist, information technology, environmental engineer, civil engineer etc.)	161	176	337
Total number of personnel required	**566**	**553**	**1119**

Source: Status and trends in nuclear education, © IAEA, 2011

150 STEM principles encompass Science, Technology, Engineering, and Mathematics, emphasizing integrated learning, problem-solving, and interdisciplinary thinking.

The degree provides the graduate with necessary specialized knowledge that is required in the nuclear sector. Obtaining a master's degree takes between two and six years but it varies (Figure 6.7).

Figure 6.7 Number of nuclear related subjects in the energy engineers MSc



Source: Status and trends in nuclear education, © IAEA, 2011

The academic path starts to differ after a master's degree. Some graduates might opt to start working at a nuclear power plant. This is typically followed by further education, with a specific focus on the relevant field of expertise provided by the employer. This varies greatly, as some roles will require specialized training that might last from six months to one year. For example, in the Czech Republic a graduate who wants to become a Nuclear Operator needs to undertake a two-year mandatory training[151]. Only after the training scheme is completed the graduate can start working, gain further work experience and be part of the knowledge sharing process.

To sum up, it takes between four and twelve years to become a nuclear professional, not counting further education and specialised training, for example offered by the operator.

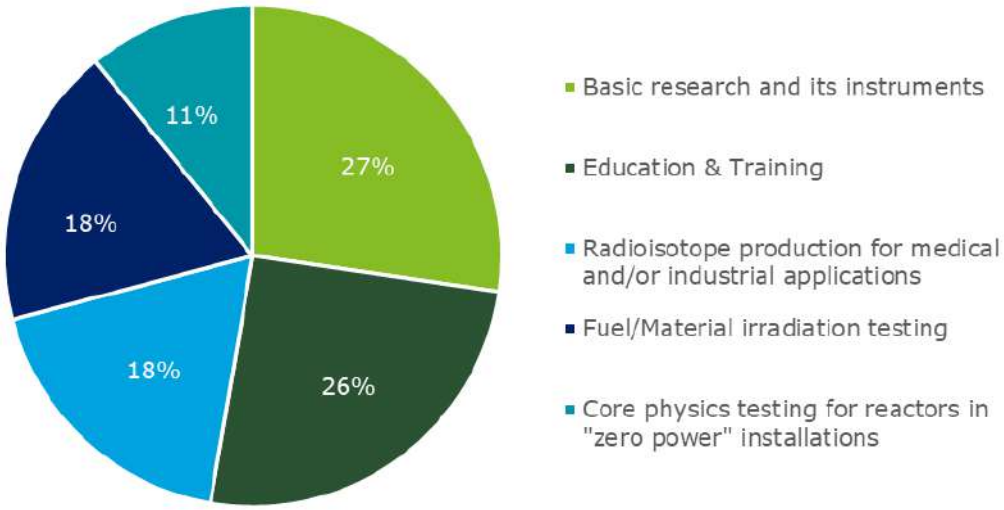
Few initiatives exist to increase the number of education providers and the number of new talents for the nuclear energy ecosystem. For example, the European Nuclear Education Network (ENEN) assists universities to establish new programmes[152]. Therefore, it is possible that the number of universities offering nuclear education could increase in the next years, providing more possibilities to increase the number of nuclear energy professionals in the years to come. ENEN is also providing a mobility programme, where students can study a course in different universities throughout the EU.

Besides universities, also research centres and educational reactors are important to providing new highly skilled labour for the nuclear energy ecosystem. This may enhance the required number of professionals to some degree. However, no data is available on the number of annual graduates from research centres and educational reactors. Moreover, only 14 out of the 30

151 For example, at Czech company ČEZ a.s.
152 Stakeholder interviews

research reactors are used for education[153]. Also, the number of research reactors has declined in the last 20 years and new ones are not being build, apart from the Jules Horowitz Reactor in Cadarache, France. Therefore, the total number of potential additional new professionals from these institutes is assumed to be little.

Figure 6.8 Focus of research reactor



Source: *Towards Optimized Use of Research Reactors in Europe* (TOURR), © ENEN, 2021

Other expertise and skill required to construct, operate, maintain and decommission nuclear power plants

In addition to nuclear experts, other workers are required to operate nuclear power plants. In total, 4 million students graduated in the EU in 2018. Out of which 15.2% graduated in the engineering, manufacturing, and construction fields[154]. Another 6.4% graduated in natural sciences, mathematics, and statistics[154]. Combined this makes a share of approximately 21% of graduates that can work in the nuclear sector. However, as discussed with the study's stakeholder group, it is likely that these students choose different sectors that are currently more popular, including professions related to net-zero economies e.g., renewable energy, hydrogen, or the circular economy. Continuous effort to highlight the advantages of nuclear energy to contribute to climate and energy objectives are therefore required to attract these students, according to the study's stakeholders.

Furthermore, the industry needs a high number of welders, technicians, electricians to meet the demand for the changing ecosystem in 2050. These professionals are necessary to ensure safe and reliable construction and operation of nuclear power plants. As for the experts above, these professionals are needed in other sectors as well, thus nuclear must offer better conditions to ensure the needed workforce. Educating such professionals and attracting them to the nuclear sector could be the key to the development of the successful nuclear power ecosystem in Europe.

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153 Towards Optimized Use of Research Reactors in Europe (TOURR). ENEN, 2021.

154 In which subjects do EU students graduate? - Products Eurostat News - Eurostat (europa.eu)

Case study: Walter Tosto's training programme

The nuclear industry is currently grappling with a critical shortage of young professionals and the imminent retirement of seasoned experts, a challenge highlighted in Chapter 6.1. Walter Tosto, a prominent manufacturer of industrial components, has responded decisively to this industry-wide issue by crafting a dedicated training program. This program involves collaborative efforts with multiple universities and educational institutions, aiming to bridge the prevalent skills gap. Under this initiative, aspiring young professionals interested in launching their careers with Walter Tosto are granted the opportunity to engage in a series of comprehensive training programs and activities designed to equip them with essential skills.

Walter Tosto's collaborative endeavours with schools and universities encompass a diverse array of educational levels, spanning from professional and technical school students to university graduates. These collaborations take various forms, commencing with the direct involvement of Walter Tosto's engineers and technicians in shaping the curriculum. Additionally, the program includes specialized training conducted at the company's facilities, encompassing both theoretical lessons and hands-on laboratory activities. Presently, Walter Tosto is actively collaborating with institutions such as the Technical Institute "Luigi Di Savoia" of Chieti, the Professional Institute "Umberto Pomilio," and the Professional Institute "Di Marzio-Michetti." Remarkably, this initiative has seen over 300 individuals benefit from the training program over the past decade, with an impressive employment rate of over 60% among program participants.

Walter Tosto SpA extends its support to students enrolled in local Technical and Professional Institutes through the implementation of dual learning programs, also known as the Program for Transversal Skills and Orientation (PCTO) in Italy. This innovative approach merges classroom education with practical, hands-on experiences within the company. It offers students valuable insights and real-world applications that enhance their understanding of theoretical concepts learned at school and allows them to engage in work activities, guided by experienced mentors, even before they graduate. These programs play a pivotal role in seamlessly integrating young talents into the company's workforce upon completion of their studies.

The 400-hour training programs are designed for students in their 3rd, 4th, and 5th years of study, focusing on specialized areas such as Welding, Machine Tools, Mechanical Workshop, and Electrical Maintenance Workshop, with the guidance of company technicians who are experts in these domains. Walter Tosto's mentors extend their support beyond the company premises, actively assisting and training students within their school laboratories. To facilitate this, the company has generously provided cutting-edge workstations equipped with state-of-the-art safety measures and protective gear. Within these modern laboratories, students gain hands-on experience and mastery of welding techniques, including wire (CMAW/FCAW), electrode (SMAW), and Tig (GTAW) welding. Notably, Walter Tosto's instructors conduct weekly welding lessons, simultaneously instructing both students and the laboratory technician teachers. This collaborative approach ensures that even the educators acquire the necessary skills to effectively transmit knowledge, including the fundamentals, to students in their first and second years of study.

Another pivotal initiative at Walter Tosto is its International Welding School, which has been in operation since 1997. This comprehensive training program comprises 220 hours of instruction, divided between extensive practical training (200 hours) and classroom lectures (20 hours). Each class accommodates approximately 20 students, and attendance is entirely free of charge, emphasizing the company's commitment to fostering talent. The primary objective of this initiative is recruitment, and over the years, it has successfully trained more than 400 individuals, with an impressive 280 of them securing employment opportunities within the company.

Furthermore, Walter Tosto has periodically organized, since 2010, Master courses in partnership with universities to offer post-graduate specialization in the field of critical process equipment. This six-month program is tailored to train technical professionals in the design and manufacturing of pressure metal components. It also incorporates specialized modules for attaining the prestigious title of International Welding Engineer (IWE).

Figure 6.9 ***Walter Tosto's training programme***



Source: © Walter Tosto's Training Programme report

6.4 Maintaining the know-how

Besides attracting new professions, stakeholders consulted for the study highlight a need to **retain skilled professionals** already working in the industry. This can be achieved by offering competitive compensation and benefits packages.

Case study: MATCH programme – a capacity building tool

Led by Gifen, which represents companies involved in the nuclear industry in France, MATCH provides the necessary structure and governance to lead collective mobilisation according to the ambition set by the French government and the European Nuclear Alliance. The goal is to ensure that human, industrial and financial capacities match the level of resources required to deliver on the needs of these nuclear activities via a ten-year roadmap for the industry.

It is a part of the wider **Excell plan** launched in 2020 to enable the nuclear sector to return to the highest standards of diligence, quality and excellence. EDF and Gifen set out 30 clear commitments from 5 focus areas (governance, standardisation, supplier relationships, manufacture and construction, and skills). 26 of the 30 commitments have been met or have seen their targets exceeded.

The MATCH programme will identify discipline by discipline the skills requirements over the next 10 years, and the Nuclear Industry University will further support the regional training actions to ensure sustainably that the right resources are at the right place at the right time.

MATCH is structured in 20 operational activities specific to nuclear (piping, civil work, engineering, electrical components, instrumentation, and non-destructive testing, control, etc). It has identified 84 relevant types of skilled jobs and specified their training requirements in terms of lead-time-to-full-operation.

Source: Gifen

Nuclear energy is a complex and highly specialised field, and as such, it requires a significant amount of knowledge and expertise to ensure safety and efficiency. The professionals that commissioned and operated existing NPPs have extensive know-how in the field, and it is essential that expertise and experience is passed on to the next generation of nuclear professionals.

Consulted stakeholders present transfer knowledge between generations through **mentorship programmes** as one of the most efficient ways[155]. In this way experienced professionals can be paired with younger colleagues and work with them on a one-on-one basis to share knowledge and provide guidance. Mentor programmes are widely used across other fields as well, such as medical, oil & gas, aviation or automotive. One example is the Volkswagen apprenticeship programme, where the apprentice is working together with more senior colleagues and has a dedicated coach and training team. In this programme the apprentice becomes acquainted with the environment of the facility and has the opportunity to learn from more senior colleagues which ensures knowledge transfer to the younger generation. With the COVID-19 pandemic, the mentorship programs evolved, today several companies offer an online mentoring. This route was chosen by Boeing, currently Boeing uses the platform Tallo[156] to conduct an online mentoring for their proteges. Using the Tallo platform graduates can connect with

155 Knowledge Management for Nuclear Industry Operating Organizations, IAEA, 2006
156 Boeing Launches Mentorship Program Powered by Tallo | Business Wire

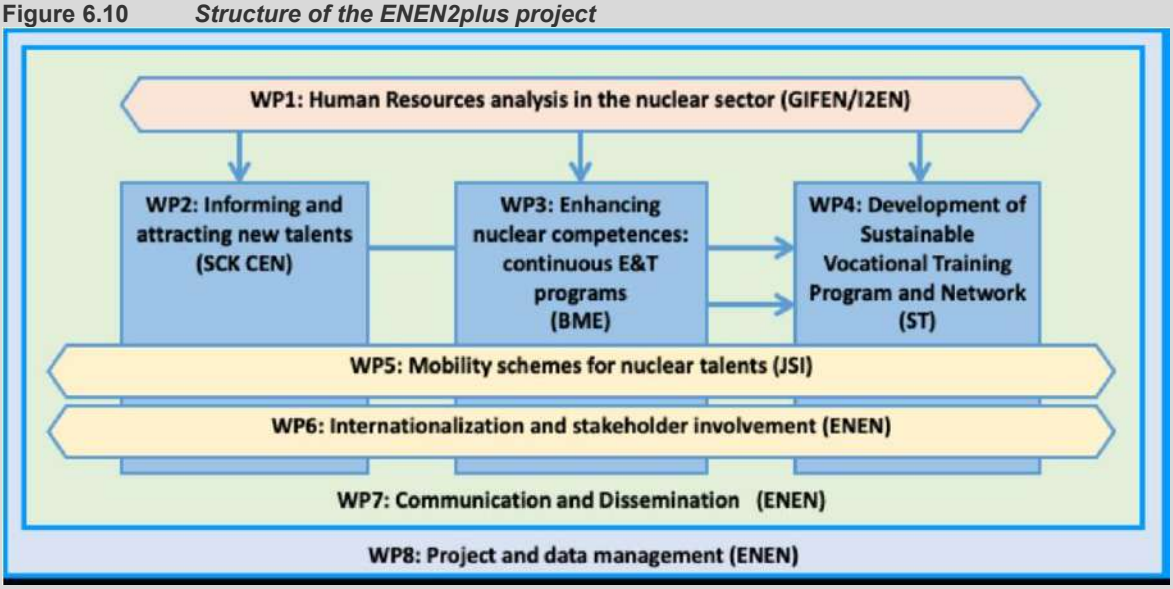
senior colleagues and conduct a virtual meeting to discuss their career and work that is expected of them. A mentoring relationship can help to ensure that critical skills and knowledge are passed on to the next generation and can also help to establish a culture of continuous learning within the nuclear industry as suggested by the IAEA.

Another important approach is the use of formal **training programs**. These programs can include classroom instruction, hands-on training, and simulation exercises to provide younger professionals with a thorough understanding of the principles and practices of nuclear energy. These training programmes can be designed to incorporate the latest technology and best practices, ensuring that the next generation of nuclear professionals is well-equipped to meet the challenges of the industry. In this field a great effort is made by the **European Nuclear Education Network (ENEN)**, their mission is to preserve and develop the nuclear expertise. ENEN is offering an opportunity for students to study courses at European universities, and it helps universities that want to open a nuclear programme to create one. The institution is helping the nuclear education for 20 years and several students and universities used their expertise and the possibilities ENEN offers. An important aspect for further development of training programmes is standardization, the programmes should be standardized across the EU to allow sharing among the universities, MS, and industry. Maximal emphasis should be put sharing of good practices among the stakeholders in terms of training programmes.

Case study: ENEN2plus project

The ENEN is currently running several projects focused on education, one of them being the ENEN2plus project. The project is one of the largest and integrative nuclear education and training effort existing today. Excellent professionals are the key for safe and reliable operation of the NPPs. For this reason, the project is focusing on attraction of new talents, that is followed by the necessary development through education and training, cross-disciplinary and cross-cultural activities. The project is providing career-related events and competitions for high school and university students as well as for teachers, postdocs and lifelong learners to achieve a higher number of nuclear talents.

Figure 6.10 ***Structure of the ENEN2plus project***



Source: ENEN2plus project. © ENEN, 2023.

The project has a strong mobility programme to support the cross-disciplinary and cross-cultural activities. All together it will support more than 100 person-years of nuclear career enhancing experience to about 1 000 learners. During the project a centralized platform for providing the information on vocational training programmes will be established to ensure further education of participants. The project is welcomed in the nuclear society which is illustrated by the number of organizations that take part in it. Altogether, 51 organisations throughout the nuclear sector, involving academia, research centres and industry are part of the project.

What is very important for the retention of know how is support and funding. The EU provided support through the Horizon 2020 Research and Innovation (R&I) framework that ran from 2014 till 2020. A part of the means was dedicated to the Euratom, specifically 1.6 billion EUR[157]. All **Euratom Horizon 2020 R&I projects included a part focused on education and training** to ensure the know how is maintained and the expertise is not vanishing from the EU. The opportunities for training and career development were also included in the **Marie Sklodowska-Curie actions in the Horizon 2020 framework**. Currently the Horizon Europe, a R&I funding programme that runs until 2027 is providing support for Euratom and its R&I and education and training activities.

[157] Horizon 2020 in brief. European Union, 2014.

Thirdly, it is essential to create **opportunities for collaboration and knowledge sharing** between nuclear professionals of different ages and experience levels. Conferences, workshops, and other networking events can help to foster these relationships and provide a platform for professionals to share their expertise and learn from one another. A perfect networking opportunity is offered through a dedicated summer programme such as the World Nuclear University organized by the World Nuclear Association or the Intercontinental Nuclear Institute summer programme, both supported by the IAEA.

Finally, the industry must **embrace innovation and technology** to further address the shortage of skilled professionals. Advancements in technology, such as automation and artificial intelligence, can help increasing efficiency and productivity, while also reducing the need for skilled professionals in some areas.

In summary, knowledge transfer between generations of nuclear professionals and attracting new talent is crucial for ensuring the commissioning of new NPPs and their safe and efficient operation. Mentorship programmes, formal training, and networking events are all effective ways to facilitate this transfer of knowledge and expertise.

6.5 Conclusions and recommendations

The assessment of the nuclear ecosystem depicts an increasing lack of **human capital.** The ecosystem is already challenged by a lack of nuclear professionals, a challenge that is likely to become more persistent until 2050 due to an ageing workforce, an insufficient number of new talents educated in the EU and competition with other sectors for nuclear professionals and other staff.

Increasing the sector's attractiveness is a possible way to mitigate the lack of human capital. A few plausible paths to increase the attractiveness of the sector include improving public relations and visibility of nuclear power, incentivising and investing in schools and research centres, offering competitive conditions and salaries, and improving the overall industry and government involvement in education and management of new talent. Focusing on these four points could help the nuclear industry build the perception of a promising field for young professionals and other employees considering a career change.

A long-term and coherent strategy on the contributions of nuclear energy to the EU energy and climate objectives would further support increasing the sector's attractiveness. The study's stakeholders propose that the perception of the nuclear industry could be improved by focusing on decarbonization. Top-down and bottom-up approaches are required to communicate about the sector's attractiveness.

Seen from the industry, the development and maintenance of human resources with the expected skills, competencies and experience, is a **matter of anticipation**, early contracting and long-term planning. Industry and academia could also benefit from the **increased interest in SMRs** as mentioned by the study's stakeholders. Similarly, a long-term stable strategy on how to attract young people with SMRs is needed. For example, academia could cooperate with the industry to prepare nuclear programmes more focused on SMRs and their

deployment, this way universities could attract more people that would then be relevant for the industry[152]:

- **Top-down** - Clear political support provides stability and confidence in the sector. On top of that, industry should provide a clear vision and outline available opportunities for young professionals.
- **Bottom-up** - Provision of opportunities to illustrate mitigated risks to dealing with nuclear power by the industry, e.g., by providing onsite visits.

Coherent and long-term policies and strategies facilitate furthermore **sustainable education and training** in nuclear science and technology, as most education is required for nuclear energy professionals is publicly funded in the EU. Member States play a vital role in formulating policies and providing funding to facilitate the development and functioning of the nuclear industry and academia. While the specifics of public policies and their engagement with universities and industries may differ across Member States, it is widely recognised that policies have a significant impact on universities' choices regarding the provision of nuclear-oriented programmes as mentioned by the study's stakeholders.

Support to non-governmental organizations such as ENEN, that help universities and the industry to establish education and training programmes, is another important point. The European Commission already provides such support which helps new talents and academia, creates a budget for mobility and offers access to research infrastructure. However, from the conducted interviews the message is that budgets must be increased to ensure a sufficient number of professionals for the nuclear sector.

Close cooperation between the industry, universities and government has been recognized as a vital feature in both improving nuclear education and in attracting young talent. To further stipulate the argument, communication between academia and the industry is also beneficial. Effective communication between academia and the industry yields mutual benefits. It helps better match the needs of the industry, and industrial training can be more focused on specific requirements. Firstly, it guarantees that the knowledge and skills acquired by graduating students are sufficient and align with the current needs of the industry, enabling more targeted and efficient industrial training. Secondly, it facilitates the identification of specific areas for collaboration, including industrial apprenticeships, joint research projects, engagement of visiting professors, and advisory support to university staff involved in curriculum design and teaching.

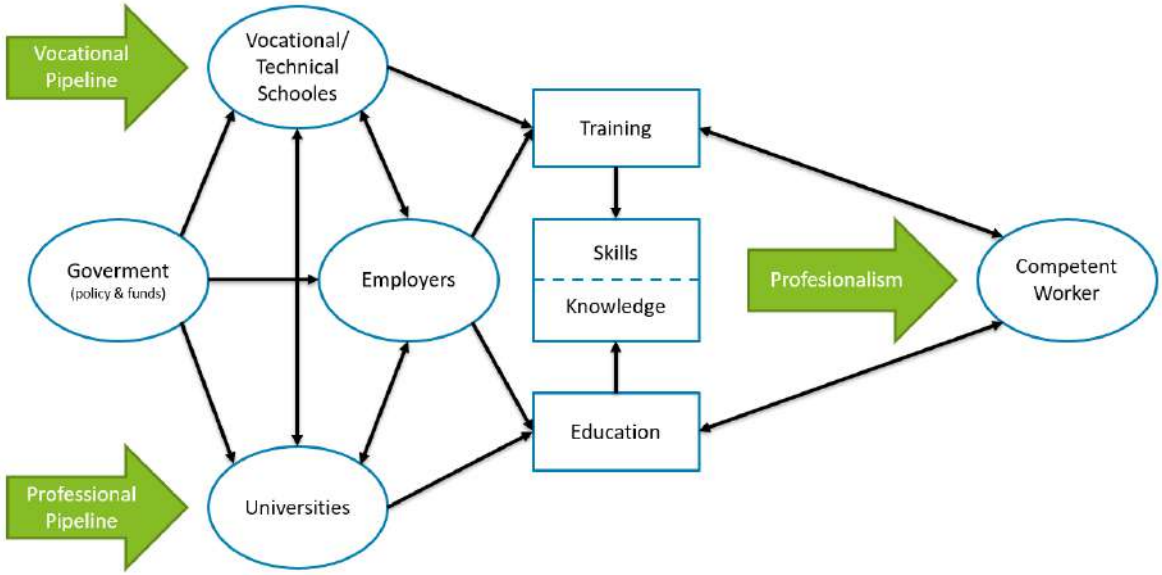
To improve the situation the whole value chain of nuclear power must be engaged. On the one hand, universities need to know what kind of professionals are relevant for industry and what number of professionals are necessary. On the other hand, **students and graduates must know that they are needed**, and that the work is there for them (e.g. by regularly discussing open positions with students). This can be done by **more frequent discussions between industry and academia (hosting lectures, workshops, industry apprenticeship, mentoring)**.

The industry could also support independent scientific centres outside their companies. The current situation is that companies have in-house research, but the public does not know about it. This could be one of the reasons why there are

currently not more students enrolled in nuclear programmes (which has also identified by the study's stakeholders). More students could bring more potential workers to the industry, a crucial point in regard to the planned development of nuclear.

The collaborative model as described in the IAEA document "Status and trends in nuclear education"[158] provides an example to shape the cooperation between industry, universities, and government. The close cooperation between these three entities is essential. This model recognizes that a significant portion of the nuclear workforce enters the industry through vocational routes, mainly technical colleges and local or national training schools.

Figure 6.11 The interaction between government-industry-academia



Source: © IAEA

The analysis of feedback and inputs from the study's stakeholders provided us with the following recommendations[159] to consider to ensure successful human capacity landscape:

158 https://www.iaea.org/publications/8514/status-and-trends-in-nuclear-education

159 Chapter 11 presents a list of priorities. These are concrete recommendations which require immediate actions, as discussed with the study's stakeholder group, Member State representatives and NGO representatives during a workshop 5-6 September 2023.

European Level

- Keep/enhance nuclear energy in policy and strategy documents to provide a stable, predictable environment for the ecosystem.
- Communicate about the efforts delivered to ensure highest safety standards for nuclear energy to “democratize” the topic and to attract more people.
- **Communicate that nuclear is part of the decarbonization energy mix, to ensure that young people see a future in nuclear, otherwise, they may choose a different sector.**
- Initiate a programme to enable non-European competent workers to obtain necessary licenses and diplomas to work in the EU.
- Encourage a focus on nuclear energy relevant mobility programmes for students – encouraging participation of beneficiaries of Member States where the construction/licensing is happening to obtain the knowledge.
- Support educational organizations such as ENEN that can help universities with the establishment of a nuclear programme.
- EURATOM could support more projects like SMRs or advanced reactors, now focused mainly on safety and regulations.
- **Support a knowledge sharing** programme/initiative/organization to ensure **knowledge preservation in the EU**.
- Map the necessary capacities of human capital throughout the EU until 2030, 2040 and 2050.

Member States

- **Keep/enhance nuclear energy in policy and strategy documents to provide a stable, predictable environment for the ecosystem.**
- Actively participate in collaboration programmes between Member States to ensure a consistent increase in workers in the nuclear sector at EU level.
- Include nuclear in policies and long-term strategies for decarbonizing the energy mix.
- Provide funding for universities that want to establish nuclear sciences or nuclear engineering related courses.
- Establish a nationwide knowledge sharing programme/initiative to ensure knowledge preservation in the Member State.
- **Simplify the recognition of education, diplomas, license, and others across Member States**.
- Communicate with young people and highlight that nuclear is about high professional knowledge. Easy to stay in nuclear and also easy to switch careers.

Industry

- **Cooperate more with universities, academia, etc. to establish graduate and university programmes, stating what kind of skills and competences are needed and under which timeframe.**
- Host lectures, workshops, industry apprenticeships, and mentoring programmes. Let the students know that they are needed.
- Provide internships for students, showing them how the company works, treat them like regular employees in training. If they start working in the company, they already have some or all training completed, which may lead to time and cost saving.
- Support independent research centres that could be a source of new employees.
- Hold public presentations and lectures about the company, people are not knowing what exactly nuclear companies manufacture, and therefore may not pursue an education in nuclear.
- **Establish a robust knowledge sharing programme across the company ensuring knowledge transfer and attract new talents**
- Communicate to the graduates about the possible routes to grow in the company (within 5-10 years), provide attactive salaries and carrier development perspectives.
- Prepare a hiring plan/programme until 2030, 2040, and 2050 to ensure sufficient capacity of skilled human resources.

7 Fuel cycle – Can the EU ensure a reliant fuel supply chain?

This chapter discusses the nuclear fuel cycle in the EU and whether the EU can ensure a reliable fuel supply. The fuel supply chain is a complex and global field that is maintained through a small number of companies. These companies operate globally, hence a global view on the fuel cycle is required. The study's stakeholders assume sufficient conversion and enrichment capacities in the EU to meet the demand for the own market in the baseline scenario. Capacity would need to be increased for the advanced scenario[160] and to address increasing global demand[161]. The EU's fuel fabrication capacity is another challenge to meet 2050 decarbonisation capacities. Another challenge relates to the risk concerning securing supplies for Russian VVER type reactors. This potential threat is currently being solved by individual utilities that are contracting other fuel suppliers. Furthermore, it is important to keep monitoring EU supplies, diversify suppliers' portfolios and protecting the EU internal market.

A factor to consider in the fuel cycle until 2050 is the development of SMRs and AMRs. Some SMRs/AMRs are planning to use HALEU and TRISO fuel. The production capacity of HALEU is currently missing in the EU since there is no relevant demand, however, the process of manufacturing HALEU is known and should not pose any significant risk. In the USA, a significant effort to support a high production of HALEU has been launched without waiting for the progressive increase of market demand.

Also, a potential lack of human capital is another point to consider when assessing the development of the fuel cycle until 2050. As in the case of the construction and operation, the fuel cycle also suffers from lack of professionals.

The analysis and insights from the study's stakeholders are presented below in the form of several key findings.

160 See chapter 2 for the description of the baseline and different scenarios.

161 Consulted stakeholder in the fuel cycle for this study assume an increase in global demand in the coming years. This issue can be solved by building additional capacity which the suppliers are prepared to do if they will see a clear commitment to nuclear power from policy makers, government and utilities and market demand as mentioned by stakeholders

Key findings

- The **nuclear fuel cycle is maintained through few multinational companies**. In case of limited development in the ecosystem, these companies might be able to provide sufficient conversion and enrichment to meet assumptions of the baseline scenario.
- Fuel fabrication could pose a potential risk, especially for VVER type reactors. Some Member States are working on diversifying their supplies. Westinghouse and Framatome together with EU partners are developing solutions to provide reliable supply[162].
- Companies are prepared to increase the capacities and invest in new facilities considering a clear outlook on commitments from Member States.
- Some **SMRs/AMRs** designs plan to use **HALEU/TRISO fuel,** that is currently **not present anywhere in the EU** (neither enriched Uranium, nor the fuel technology), mainly because of the lack of demand. The manufacturing process of HALEU is known and future production is expected.
- Other **AMRs or GEN IV plants** are under development and their **fuel development should be anticipated** even if their nuclear output is not assumed until 2050.

7.1 Front end of the fuel cycle – nuclear fuel supply chain requirements and capacity

The front end of the nuclear fuel supply chain is a global, diverse, and complicated field. To obtain the final product of enriched uranium, natural uranium must undergo several technologically demanding processes as described in Annex G.

7.1.1 Uranium production

The first step in the nuclear fuel supply chain is the production of uranium. The global **uranium demand in 2021 was approximately 66,528 tU, the EU demand of 11,975 tU accounts for approximately 18% of that**[163]. The supply of uranium has been sufficient in meeting the world demand for several decades. To cover this demand several means are used, uranium mining being the primary one, followed by the use of stockpiled natural and enriched uranium, reprocessed used fuel, diluted weapons-grade uranium, re-enrichment of depleted tails, and underfeeding[164]. Production of uranium **was 47,472 tU in 2021 from sources in 17 countries**[165]. Kazakhstan remains the world's largest producer of uranium in 2021 with a 46% share of the world's uranium production. Together with the five following producers (Namibia, Canada, Australia, Uzbekistan, and Russia), they

162 In Hungary VVER 1200 reactors are still planned to be used.

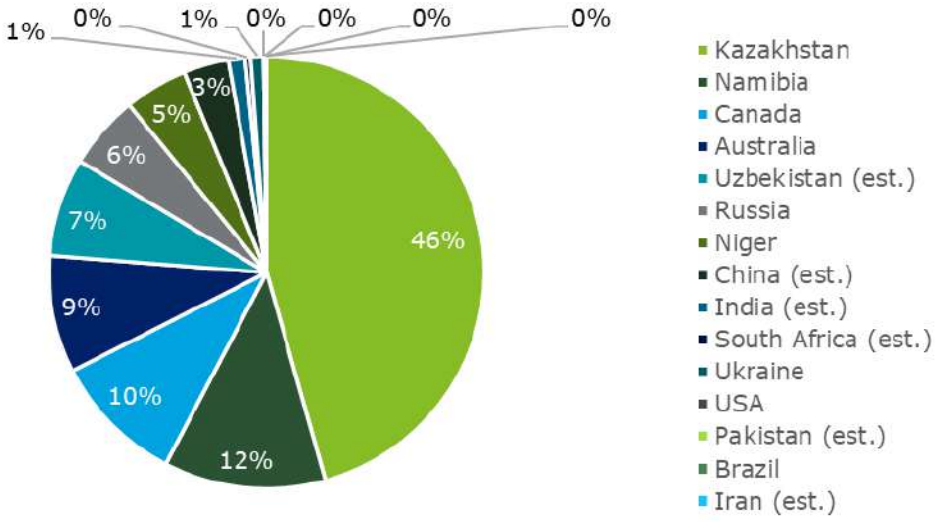
163 Annual Report 2021. EURATOM Supply Agency, 2022

164 Operating enrichment plant the way it has lower operational tails assay, meaning less natural uranium is needed to manufacture the same amount of enriched output.

165 Uranium 2022: Resources, Production and Demand. IAEA and NEA, 2023

account for 88% of global production. In the EU, Sweden has a significant resource of uranium, however, currently it has a ban on exploration and mining of uranium. The shift in perception towards uranium production in the EU can be observed. The Swedish government has obtained the majority to lift the ban on uranium exploration and mining from 2018[166], meaning there might be a uranium production in the EU once again. The Finnish company Terrafame may produce about 200 tU/year as a by-product, starting from 2024[167].

Figure 7.1 Uranium mine production in 2021



Source: © World Nuclear Association

There are uranium resources in the EU and several companies are trying to utilise them to produce uranium. The production is facing several issues including the regulatory framework as in the case of Sweden. Therefore, supplies to the EU are mainly from non-European countries, confirming the global nature of the fuel cycle market. The largest suppliers for the EU market in 2021 were **Niger and Kazakhstan, together accounting for almost 50% of supplies**. The third place in the suppliers list was taken by **Russia which supplied almost 20% of uranium** to the EU[163]. The REPowerEU document presents the need to limit the dependence on Russian supplies of fossil fuels, it also states that **the Member States currently depending on the supplies of Russian nuclear fuel should diversify their options** (currently 5 Member States are dependent on Russian supplies of uranium). However, the fuel cycle market is very dynamic, and market driven and because of its global nature diversification can be achieved. Another possible solution could be stating a long-term objective at the EU level to reduce the Russian market share.

166 Swedish Minister of Energy Provides Update On Uranium Mining Ban In Sweden - Investing News Australia

167 Terrafame to start uranium recovery by the summer of 2024 - Terrafame

Figure 7.2 Origins of uranium delivered to EU utilities in 2021[168]

Origin	Quantity (tU)	Share (%)
Niger	2,905	24.25
Kazakhstan	2,753	22.99
Russia	2,358	19.69
Australia	1,860	15.54
Canada	1,714	14.31
Re-enriched tails	196	1.64
Uzbekistan	162	1.36
EU	21	0.17
South Africa	5	0.04
Other[169]	17	0.14
Total	**11,975**	**100.00**

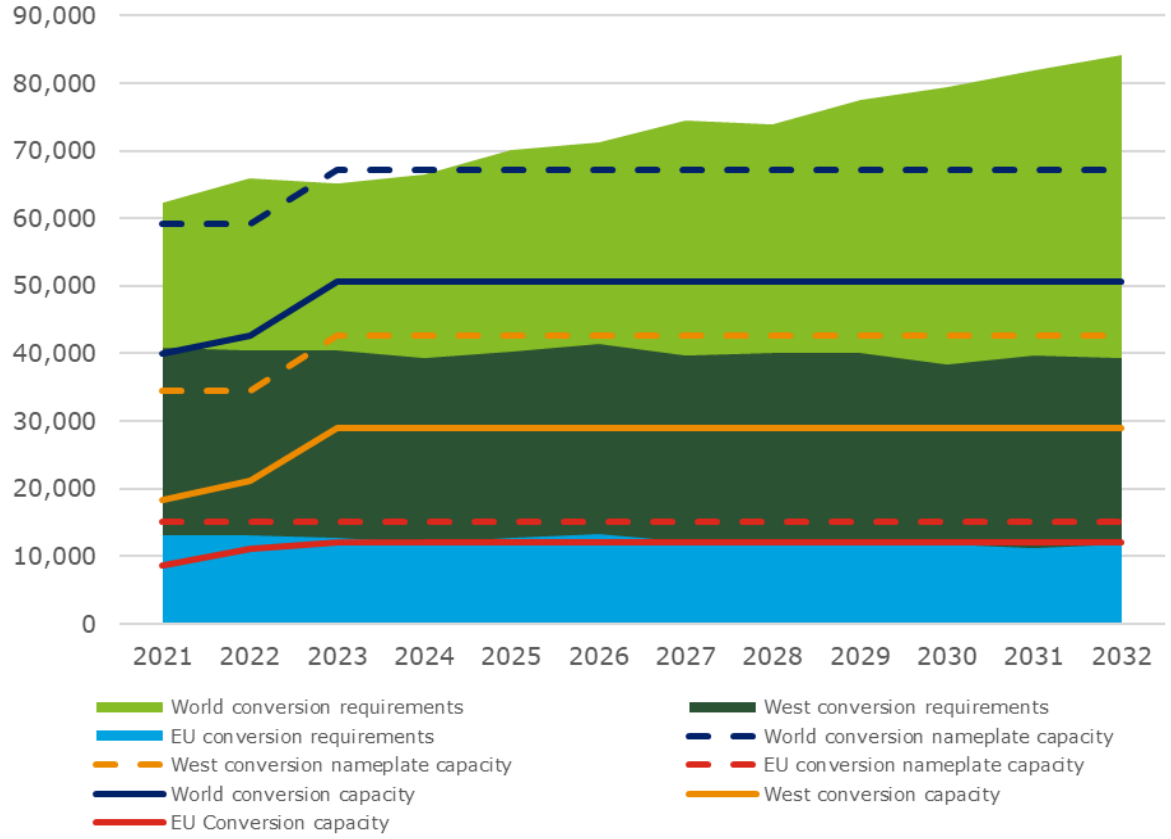
Source: EURATOM Supply Agency - Annual Report 2021

7.1.2 Uranium conversion

Uranium mining is followed by the conversion of Triuranium octoxide (U_3O_8) to Uranium hexafluoride (UF_6). The Euratom Supply Agency (ESA) analysed in their 2022 3rd quarterly report the global conversion capacity. They assess a potential lack of sufficient capacity already as of 2024. This can result in a more competitive market, increasing the prices and potential lack of western conversion capacity. The global conversion requirements, excluding China[170], were 43,203 tU in 2020. This is projected to increase to reach almost 90,000 tU by 2035[171]. The conversion requirement in the EU was 12,850 tU/year[172] in 2020. **The potentially missing capacity in the EU can be ramped up after the Philippe Coste[173] plant in France would increase its capacity.** The fuel cycle is very dependent on market conditions, companies are prepared to increase their capacities if there is a clear commitment and specific actions. The investment into new facilities can be supported by long term contracts and possible support from the European Commission. Since the fuel cycle is a global market, supplies can be delivered from non-European companies supporting the diversification of supplies. The situation of conversion services in the EU is therefore dependent on the suppliers' reaction to the market situation and altering their capacities as necessary. As an alternative secondary supplies, such as government-held or commercial inventories of uranium in any form could complement the potentially missing conversion capacity, the same approach was used after the Fukushima accident.

168 Because of rounding, totals may not add up.
169 Material saved through underfeeding, mixed origin and unknown.
170 According to WNA, China has become self-sufficient an most aspects of the fuel cycle, including conversion.
171 Quarterly Uranium Market Report, 3rd quarter 2022, ESA.
172 Euratom Supply Agency - Market Observatory.
173 The Philippe Coste plant is a conversion plant operated by Orano located at the Tricastin site, that was commissioned in 2018.

Figure 7.3 ***Global conversion requirements and capacity****



Source: *Quarterly Uranium Market Report*, 3rd quarter 2022,

ESA

*Conversion capacity in this graph represents a continuation of present levels. Therefore, it illustrates conversion demand to exceed conversion capacity without price correction.

Conversion capacities throughout Europe vary extensively with the largest share being in France, followed by Russia[174]. In 2020, the EU nominal conversion capacity represented 24% of the global market, and Russia alone represented 20%. An important aspect is not only the nominal capacity but also the utilisation of that capacity. In 2020, the market was dominated by Russia because of the lower price, their conversion services accounted for almost 40% of the global conversion market. In the EU, the largest share of the supplies was used by the Canadian company Cameco, followed by French Orano and Russian Rosatom. The Russian conversion services to the EU accounted for almost 24% of all services, this could pose a risk to the security of supplies in the future. As mentioned, the risk could be lowered by diversification of the supplies using the western markets especially by long-term contracts with European producers. Long-term contracts could secure the supplies and also give a clear signal to the producers that capacity increases might be needed.

174 Currently not possible to use.

Table 7.1 Global conversion capacity and provision of conversion services to the EU in 2020

Country	Nominal conversion capacity (tU/year)	Quantity supplied to the EU (tU)	Share (%)
France (Orano)	15,000	3,651	28.41
China (CNCC)	15,000	-	-
Russia (Rosatom)	12,500	3,040	23.66
Canada (Cameco)	12,500	3,993	31.07
USA (ConverDyn)	7,000	1,970	15.33
Unspecified	-	196	1.52
Total	**62,000**	**12,850**	**100.00**

Source: EURATOM Supply Agency – Annual Report 2021, Euratom Supply Agency – Market Observatory

7.1.3 Enrichment

The enrichment process, increasing the concentration of U-235, is the next part of the fuel supply chain. Worldwide, enrichment is done by a handful of companies. The largest share of the global enrichment capacity[175] is held by Russia's Rosatom, in total, they account for 46% of the market in 2020. The situation, however, changed in 2022 with the Russian invasion of Ukraine and utilities are starting to diversify the enrichment services and use the services of different companies. Rosatom is followed by URENCO with a share of almost 30%[176]. In the EU, only three MS have an enrichment capacity - France, Germany, and the Netherlands. Another European country that has the enrichment capacity is the United Kingdom. The facilities in the Netherlands, Germany, and the UK are operated by URENCO, and the one in France is operated by Orano. The combined capacity of URENCO facilities in the EU and the UK is 13,300 tSWU/year[177], excluding the UK the URENCO enrichment capacity in the EU is g8,800 tSWU/year[177]. The enrichment plant operated in France by Orano has a total capacity of 7,500 tSWU/year.

Table 7.2 Global enrichment capacity in 2020

Country	Nominal enrichment capacity (tSW/year)	Share (%)
Russia (Rosatom)	27,933	46.0
France (Orano)	7,500	12.0
China (CNCC)	6,750	11.0
Netherlands (URENCO)	5,100	8.5
USA (URENCO)	4,600	7.6
UK (URENCO)	4,500	7.5
Germany (URENCO)	3,700	6.2
Others (Brazil, Japan)	55	0.0
Total	**60,138**	**100.0**

Source: Euratom Supply Agency - Market Observatory, URENCO

175 Enrichment capacity refers to the maximum amount that can be enriched by the market which is differentiated from the utilisation of these capacities. The utilisation refers to the extent to which these enrichment capacities are being used. It's the actual level of output as a proportion of the maximum possible output. The utilisation rate can be lower than the capacity for various reasons such as operational issues, lack of demand, or other external factors.

176 Combined capacity of all facilities (NL, DE, UK, USA)

177 URENCO

In 2021, 62% of enrichment services were done within the EU[163] and 31% of services were delivered from Russia[163]. The market demand for enrichment in the EU is relatively stable and is projected to remain stable in the upcoming years oscillating around the value of 11 000 tSWU/year[172]. This represents approximately 67.5 % of the available enrichment capacity within the EU (16 300 tSWU/year). Assuming an installed capacity in 2050 to be 100 GW, similar to the situation today, the enrichment capacity should not be an issue in the future. If one considers the advanced scenario aiming to reach 150 GW, the enrichment capacity might need to be increased, which is something the companies are prepared for. It requires extensive investments in new facilities. It is important to note, that there is a risk involved with these investments related to the return of Russian supplies to EU nuclear operators. Since the costs are lower in Russia, the EU nuclear operators might re-evaluate the supplies and in future return to the use of Russian enrichment services. This is already affecting the investment appetite into new facilities within the EU and the viability of such projects. There are two solutions to this situation: either the EU could limit the supplies from Russia to the EU market or, since the fuel cycle is a global market, stimulate EU nuclear operators to use the capacity of western producers. Also, to support the decision of new investments, long-term contracts from customers are important. The enrichment services market is of global nature and since the majority of the capacity is in the EU, the EU has a chance to become a global leader. If there will be a demand in the global market and there will be a clear signal at EU level, for example in the form of long-term contracts, producers can invest in increasing their capacity. Increasing the capacity by building new facilities will also help the EU to remain self-sufficient in enrichment services. Companies are prepared to invest in new facilities or increase the capacity of old ones. Several announcements were already made - Orano decided to increase the capacity of the Georges Besse II enrichment facility[178], URENCO decided to expand the enrichment plant in the USA[179] and Westinghouse was awarded three grants from the U.K. Government's Nuclear Fuel Fund to upgrade and expand the Springfield fuel fabrication facility[180] and another grant from the UK Department of Business, Energy and Industrial Strategy to explore the development of uranium conversion services at the Springfield location[181]. These activities are an answer to the growing demand from customers that no longer wish to obtain fuel cycle services from Russian suppliers.

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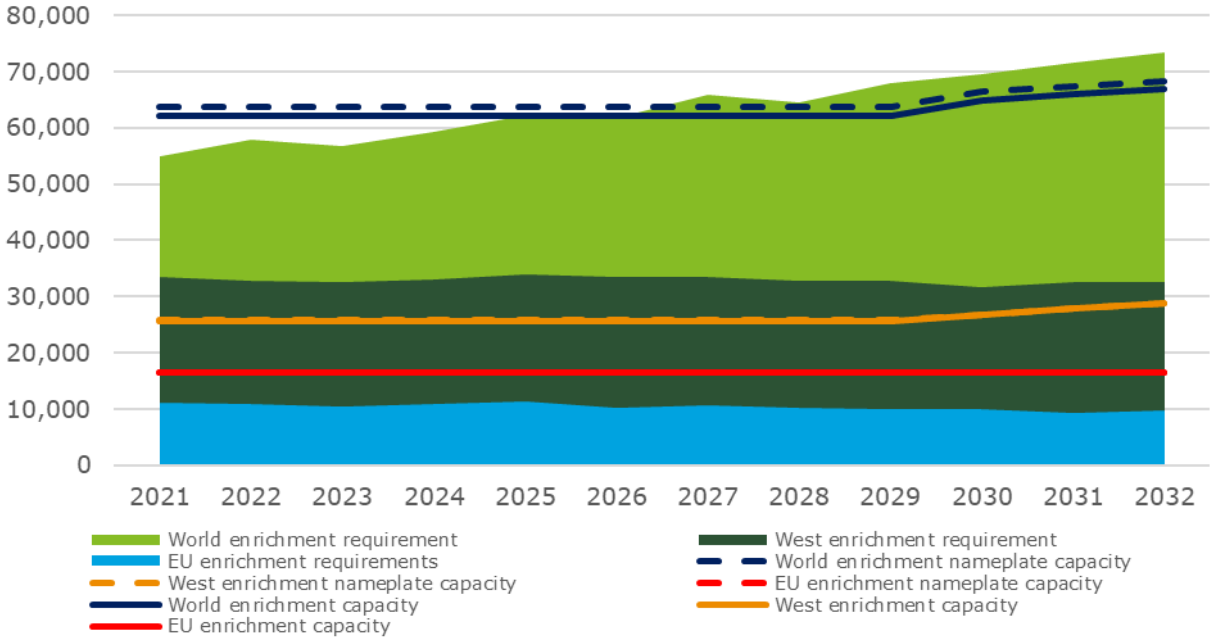
178 Orano to increase uranium enrichment capacity - Nuclear Engineering International (neimagazine.com)

179 Urenco to expand US enrichment plant: Uranium & Fuel - World Nuclear News (world-nuclear-news.org)

180 Westinghouse Awarded Trio of Grants from UK Nuclear Fuel Fund (westinghousenuclear.com)

181 Westinghouse Receives UK Government Grant to Explore Uranium Conversion Services (westinghousenuclear.com)

Table 7.3 ***Global enrichment requirements and capacity***



Source: Quarterly Uranium Market Report, 3rd quarter 2022, ESA

7.1.4 Fuel fabrication

The last step in the value chain is fuel fabrication, a phase where the pellets and the fuel assemblies are manufactured. In this phase depending on the type of reactor different types of fuel assemblies can be manufactured. Fuel fabrication is significantly different from the other three front-end fuel cycle processes. Nuclear fuel is not a commodity or a service but a high-tech product specific to each reactor type that requires specialist support. The specifications are determined by several factors: the fuel cycle management strategy, reactor operation strategy, physical characteristics, and national or sometimes regional regulatory requirements. Fuel assembly is a product that incorporates design, licensing, and R&D activities.

The nuclear fuel demand is made up of two requirements, the requirements for first cores and the requirements for reloads. Even though the first cores have different characteristics and volumes (usually three times more than a reload depending on the type of reactor because for each reload only a limited number (usually 1/3) of assemblies are replaced), the majority of the demand remains for reloads. Fabrication of reloads can be easily planned and managed since it is directly linked to the operation of the nuclear power plant. The fabrication of the first cores can be more demanding for the fabricator since the full core (a large number of fuel assemblies) must be fabricated and ready at the time of reactor start-up. Nevertheless, fuel fabrication is rarely on the critical path of the construction.

Fresh fuel fabrication is maintained in only five EU Member States[182] plus the United Kingdom. The total capacity of light-water reactor (LWR) fuel assemblies within the EU in 2021 was 3,150 tHM/year[183] (more than 4,000 tHM/year with the UK included), the pressurised heavy water reactors (PHWR) (CANDU) fuel assemblies can be manufactured in the amount of 232 tHM/year.[183] The United Kingdom can also manufacture fuel for gas-cooled reactors in the amount of 240 tHM/year[184],however, there are currently no gas cooled reactors operated in the EU and demand is expected to quickly decrease with the progressive shutdown of UK advanced gas-cooled reactors (AGR). The EU has the second largest capacity for fuel fabrication in the world following the USA.

Table 7.4 ***Nominal LWR fuel fabrication capacity[185]***

Country	Nominal LWR fuel fabrication capacity (tHM/year)	Share (%)
USA (Framatome, Global Nuclear Fuel, Westinghouse)	4,354	28.1
Russia (TVEL)	2,760	17.8
Japan (NFI, Mitsubishi, Global Nuclear Fuel)	1,604	10.4
China (CJNF Jianzhong, CBNF, CNNFC)	1,400	9.0
France (Framatome)	1,400	9.0
UK (URENCO)	860	5.5
Korea (KNFC)	700	4.5
Germany (Framatome-ANF)	650	4.2
Sweden (Westinghouse)	600	3.8
Spain (ENUSA)	500	3.2
Others (Brazil, India, Kazakhstan)	648	4.1
Total	**15,476**	**100.0**

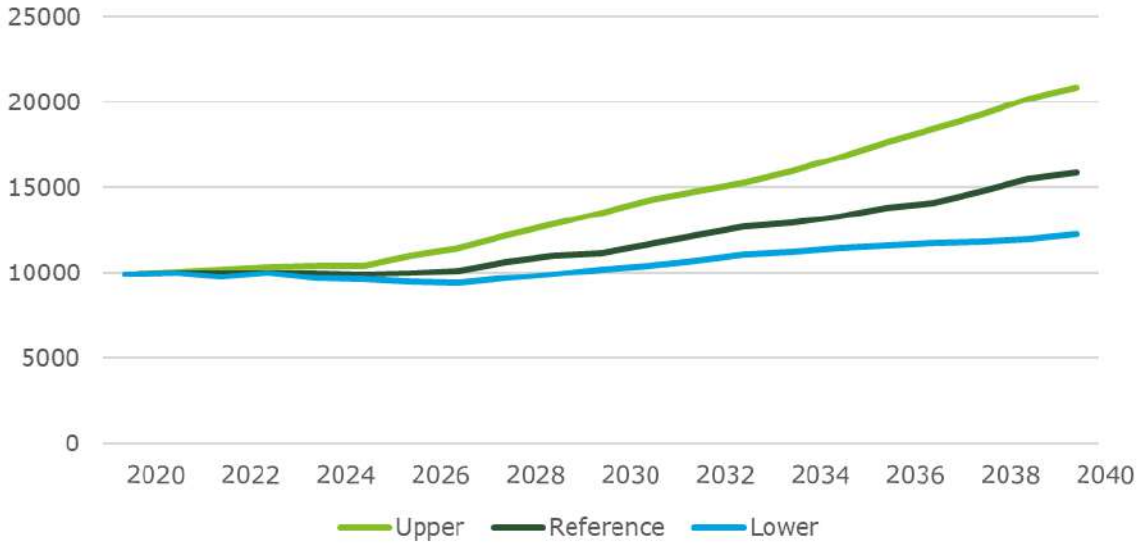
Source: World Nuclear Association

The World Nuclear Association (WNA) assumes possibilities to increase global requirements for reload assemblies until 2040. The WNA defined three scenarios to assess future demand and supply. Government and utility targets and objectives informed a reference scenario, a lower scenario considers possible delays to implement these plans and an upper scenario reflects targets set to meet net-zero emissions[186]. The reference scenario assumes an increase of 38% between 2020 and 2040, reaching 16,000 tHM/year. One can see that the available global capacity may not be sufficient to meet the demand in the future, additional fabrication plants may be required. The situation is a little bit different with the first cores since the first loading of the reactor requires approximately three times the amount of nuclear fuel needed for reload, it could create temporary demand peaks as new reactors may be commissioned. The global peak of demand may occur in 2036 in the reference scenario, following the increase around 2030.

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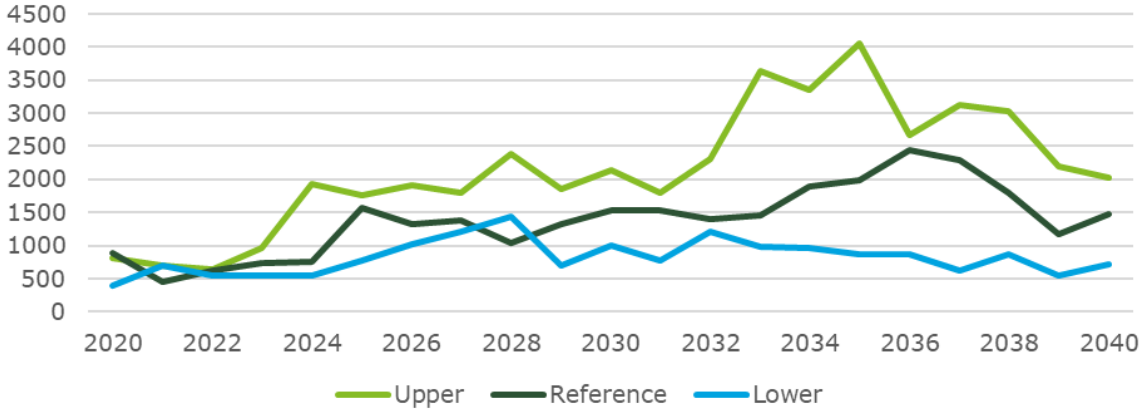
182 Germany, France, Romania, Spain, Sweden.
183 Eurostat. EU, 2023.
184 Nuclear Energy Data 2021, OECD-NEA, 2022
185 Because of rounding, totals may not add up
186 The Nuclear Fuel Report: Global Scenarios for Demand and Supply Availability 2021-2040, WNA, 2022. Please note: these scenarios are independent from this study's scenarios for the entire nuclear energy economy described in chapter 2.

Figure 7.4 ***World reload requirement scenarios to 2040, tHM***



Source: *The Nuclear Fuel Report: Global Scenarios for Demand and Supply Availability 2021*-2040. © WNA, 2022

Figure 7.5 ***First core fabrication demand by scenario, (tHM)***

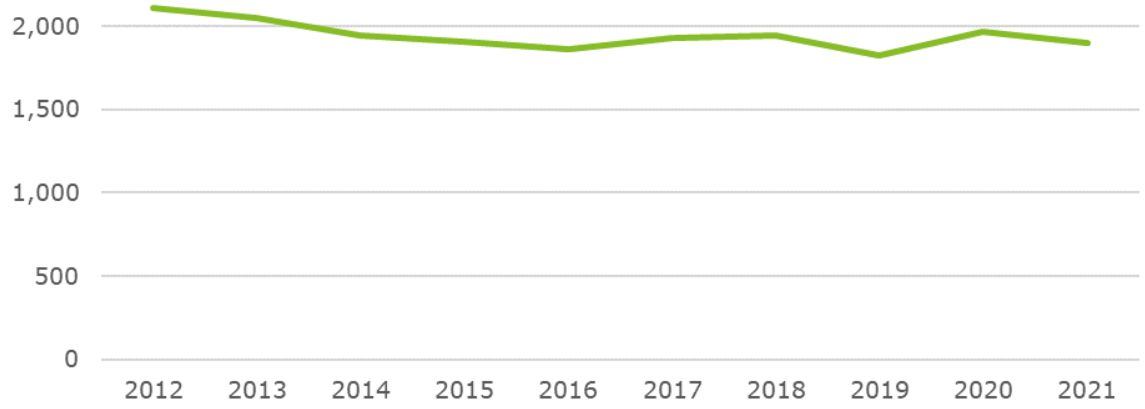


Source: *The Nuclear Fuel Report: Global Scenarios for Demand and Supply Availability 2021*-2040. © WNA, 2022

Global fuel fabrication requirements are to increase in the next 20 years. This growth could be driven mainly by construction outside the EU. Within the EU, the total installed capacity may be oscillating around 100 GW when considering the baseline scenario. The production of fuel assemblies in the EU was relatively stable between 2015 and 2021, it oscillated between 1,800 – 1,950 tHM/year[183]. As discussed above, the total capacity of light-water reactor (LWR) fuel assemblies within the EU in 2021 was 3,150 tHM/year. Therefore, the requirements were well below the available capacity within the EU as only approximately 62% were used. **Therefore, if the assumption of the installed**

capacity of 100 GW in 2050 is considered, fuel fabrication capacity in the EU should be sufficient[187].

Figure 7.6 ***Production of fresh fuel elements in the EU (tHM/year)***



Source: Eurostat. EU, 2023

An issue in terms of fuel fabrication that was mentioned by the study's stakeholders during the interviews and the first workshop concerns the diversification of supplies for VVER type reactors. This type of fuel was almost solely manufactured by Russia and some Member States are dependent on Russian supplies. After the Russian invasion of Ukraine, individual operators started to discuss with other manufacturers the possibility of manufacturing VVER fuel and accelerated stockpiling plans. Westinghouse and Framatome are competing to address this new market developing solutions (incumbent fuels or own design fuels) for VVER 440 and VVER 1000[188]. They already won several contracts in the Czech Republic, Slovakia, Bulgaria, Finland while enlarging capacities through partnerships. Another development in the area of fuel fabrication is the agreement between Fortum and Westinghouse for the design, licensing and supply of a new fuel type for the Loviisa nuclear power plant[189]. The growing number of fuel fabrication agreements shows that the diversification can be done easily and the dependence on Russian supplies is becoming less significant.

7.2 Back end of the fuel cycle

In terms of fuel cycle an important part is the back end i.e. handling the spent fuel. There are currently several solutions how to handle spent fuel. The so-called open fuel cycle utilises the disposal of the spent fuel, meaning there is waste generated that needs handling. Currently, this is the most discussed solution, and deep geological repositories (DGR) are under construction in several Member States. The second option is the closed fuel cycle where uranium and plutonium are

187 Similar requirements – 1 843 tHM/year in 2040 – are presented in the document Nuclear Energy Data 2021 by OECD-NEA

188 At the time of drafting this report, no solutions have been identified for Hungarian VVER1200 reactors yet.

189 Fortum and Westinghouse Electric Company sign an agreement for the design and supply of a new fuel type for the Loviisa power plant | Fortum

further reused. An important and already used option is reprocessing, where more than 95% of the spent fuel is recycled and then used to make new fuel (usually MOX). The remainders are separated and stored; this process significantly decreases the amount of radioactive waste. Further options supplementing the reprocessing are currently in the R&D phase and once commercially deployed they could close the fuel cycle, they require fast reactors. Fast reactors are part of the Generation IV reactors and are researched extensively. The EU cloud focus on closing the fuel cycle and thus support this research on an EU level. Closing the fuel cycle should be one of the priorities under the European Union in terms of minimising the amount of radioactive waste.

7.2.1 Spent nuclear fuel disposal

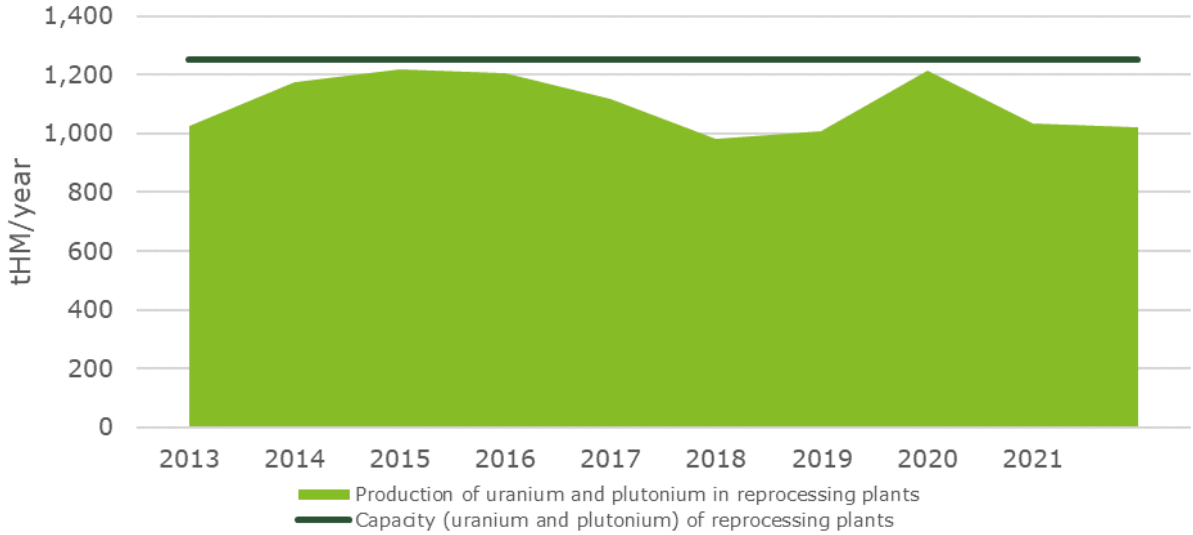
The open fuel cycle generates a certain amount of radioactive waste that must be securely stored in Deep Geological Repositories (DGR). The path of the spent fuel from the reactor to the DGR may take several years. The spent fuel could be unloaded from the reactor and is stored in the spent fuel pool for a period between 5 to 10 years immediately afterwards. After that period of time the fuel is safe to move into the spent fuel container. Once it is in the container, it is stored in the interim storage, waiting to be put into the DGR, where it will be safely stored for several thousands of years. Please note that radioactive waste management is described in more detail in chapter 8.

7.2.2 Reprocessing

When discussing the back end of the nuclear fuel cycle, one must also look at the reprocessing capacities and requirements. The process of reprocessing described in Annex G consists of conversion, enrichment, and fuel fabrication processes. The EU's capacity of the reprocessing plant in terms of production of uranium and plutonium is 1 250 tHM/year[183]. The entire capacity is covered by the La Hague facility in France operated by Orano, the only reprocessing facility in the EU. Production since 2012 has never reached the maximum capacity of the facility. It is important to note that the La Hague facility is in operation since 1966, thus significant future investments in refurbishment are expected to maintain the industrial capacity and to cover the market demand. Since the nuclear sector is very dynamic and the situation is changing every day, it is possible that there could be an increase in the use of reprocessed fuel. If this would occur, there is not a lot of leeway in terms of available capacity, in 2021 the capacity of the reprocessing facilities in the EU was utilised at 81%. Reprocessing, as any other part of the fuel cycle, is a global market but the La Hague facility covers a large part of this market[190]. Thus, this parameter must be monitored and if necessary, investments into increasing capacity must be materialized.

190 Other commercial capacities are found in Russia, Japan, the UK and India: Processing of Used Nuclear Fuel - World Nuclear Association (world-nuclear.org)

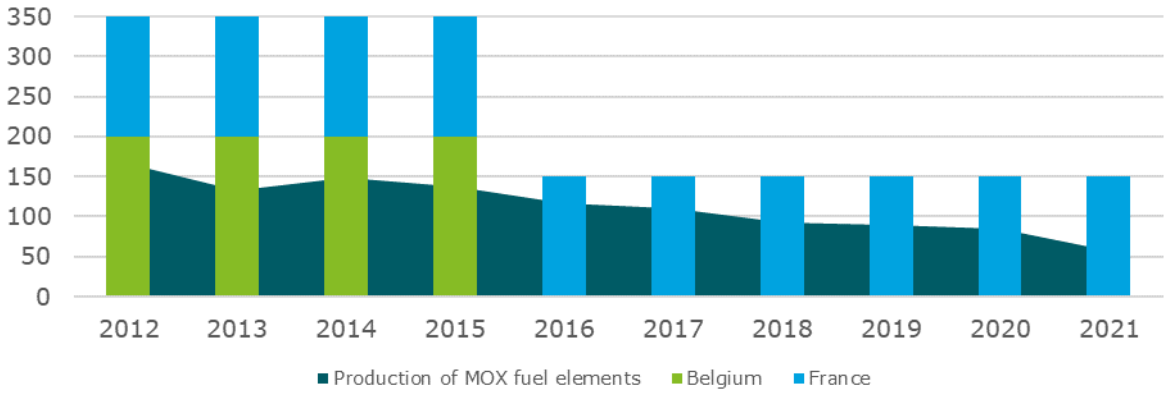
Figure 7.7 Reprocessed uranium and plutonium production capacity and requirements (actual production)



Source: Eurostat. EU, 2023

In terms of the capacity of MOX fuel fabrication, since the reprocessed uranium and plutonium are radioactive, special safety features and processes must be in place to ensure the safe handling of the fuel. Thus, currently only France has the capacity to manufacture MOX fuel assemblies in the EU. Historically there was a facility operated in Belgium, but that was shut down in 2015. However, the capacity of the French facility is sufficient to meet the demand of the EU's customers. In 2021, the facility was operating below the nominal capacity, because it is sized for the current demand. The facility is expected to ramp up the production in the future if required by market demand. Future growth in demand should not, therefore, present a significant issue.

Figure 7.8 MOX fuel production capacity and requirements (actual production) in tonne per year



Source: Eurostat. EU, 2023

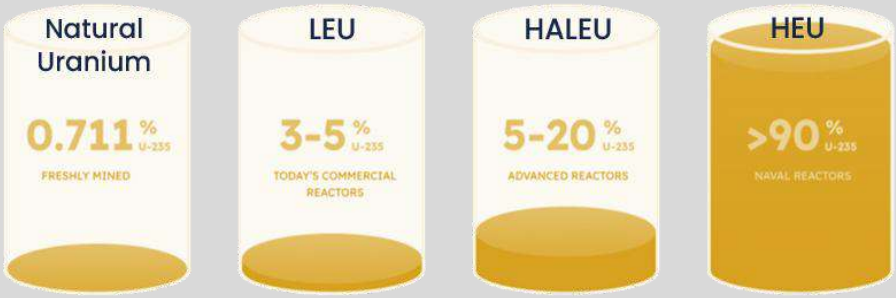
A critical issue highlighted by the study's stakeholders is that there is an operating MOX production facility, but the EU is lacking a conversion facility for reprocessed uranium (RepU). If one considers the global situation and the security of supplies, it would be beneficial to build such a facility in the EU. The know-how and expertise would be maintained within the EU, and this facility could help save natural uranium and decrease the dependence on non-European supplies.

Case study: SMR & AMR fuel fabrication

SMR fuel cycle manufacturing varies significantly. Some of the water-cooled SMRs plan to use a standard LWR fuel enriched up to 5% of U-235. These designs do not pose any problems in terms of conversion or enrichment. In terms of fuel fabrication, some adjustments will be necessary, but these can be easily solved.

Other designs of water-cooled SMRs are expected to use fuel enriched to higher levels to ensure longer operation of the fuel and less frequent changes. This enrichment can go up to 20% of U-235, using high-assay low-enriched uranium (HALEU). HALEU is currently used in research reactors and can be produced with the current infrastructure. While it is not technically difficult to enrich it to higher levels, some arrangements will need to be done. Currently, the EU research reactors rely fully on supply of HALEU from Russia and the US[191]. Members of the study's stakeholder group pointed out that the demand for HALEU will not be seen in the next 10 to 20 years, thus there is time to develop European based supply. The good news in terms of HALEU production is that the European industry has extensive know-how and expertise to develop a HALEU supply chain and meet the current[192] and future demand.

Figure 7.9 ***Different levels of enriched uranium[193]***



Source: © Nuclear engineering international

Although the demand might take 10 to 20 years investments in R&D must be done at the earliest convenience, securing HALEU production which will be crucial for some AMR designs.The situation is complicated for some types of AMRs that are using different types of fuel ranging from HALEU, through TRISO fuel, all the way to molten salt fuel. Some designs even plan to use a thorium cycle, utilizing Th-232 and U-233. Historically there was experience with manufacturing TRISO fuel for an experimental high temperature reactor (HTR) in Julich, Germany. However now only China and Japan are operating an HTR, thus the expertise is lacking in the EU. In terms of manufacturing advanced reactor fuels, the study's stakeholders stated that extensive R&D activities and investments will be necessary to ensure the safe production and deployment of such fuels. Such investments should be supported on the EU level. AMRs are expected to be deployed between 2040-2050. This timeframe gives time for inventing new procedures and ways to produce these fuels.

Source: WNA, Stakeholder questionnaire and interviews

191 HALEU report May 2022 05072022 for printing.indd (europa.eu)
192 Currently HALEU is used in research reactors across the EU.
193 Naval reactors are used as propulsion in ships, submarines and aircraft carriers.

Case study: Accident tolerant fuels

Accident tolerant fuel (ATF) is a term that received attention after the Fukushima Daichi accident. ATF is a technology that increases the safety of nuclear fuel together with increasing its performance. The ATFs are expected to have different parameters incorporating the use of novel materials and designs for cladding and pellets.

Currently, the ATFs are in the phase of development, several concepts are in the market but none of them are manufactured regularly. Individual companies like Framatome, GE Hitachi, Westinghouse, and Rosatom are in various phases of research. Some are already testing their fuel in reactors for example Framatome loaded two fuel assemblies into Calvert Cliffs 2 in 2021. Since the ATFs are still in the research phase the time of actual deployment is uncertain, the USA have a programme that expects the first commercial installation of ATFs in the mid-2020s.

In the EU, ATFs are one of the conditions stated in the taxonomy. The technical screening criteria require the use of ATFs after 2025 with the exception that the fuel is not yet commercially licensed for use across the EU. To use ATFs in the shortest amount of time, individual projects must be supported.

Source: WNA, Japan Moving Forward on Nuclear Accident Tolerant Fuels (powermag.com), EU taxonomy: Complementary Climate Delegated Act

7.2.3 Actinide burning in fast reactors

Actinide burning in fast reactors is **an innovative approach to deal with radioactive waste**. Fast reactors, distinguished by their use of high-energy neutrons, offer the potential to transform actinides into shorter-lived or stable isotopes through nuclear reactions. It can bring several opportunities for waste reduction and resource utilization but there are significant technical challenges that must be overcome to fully harness the potential of actinide burning in fast reactors[194]. By efficiently transmuting actinides, the volume and hazard of long-lived radioactive waste can be substantially reduced. This contributes to enhanced environmental protection and minimizes the burden on future generations.

Also, the design and operation of fast reactors must be optimized to achieve efficient actinide transmutation while maintaining reactor stability. This requires sophisticated neutron control mechanisms, precise fuel management, and effective safety measures. Another challenge lies in the fuel cycle management. Extracting actinides from spent nuclear fuel and reprocessing them for reuse in fast reactors demands advanced fuel handling and separation technologies. Safely managing and isolating the remaining radioactive waste streams generated during the process is of paramount importance. Moreover, actinide burning improves the utilization of nuclear fuel resources. By recycling actinides, the energy potential of spent nuclear fuel is maximized, reducing the need for new uranium mining. This helps mitigate resource scarcity concerns and enhances long-term sustainability.

Furthermore, the economic viability of actinide burning needs careful consideration. The costs associated with fast reactor technology, fuel fabrication, waste management, and infrastructure development must be evaluated to determine the feasibility and competitiveness. It comes with a significant promise as a potential solution to the challenges in radioactive waste. While technical

194 World Nuclear Association. Fast reactors, 2023. Link

challenges exist, ongoing research and development efforts are addressing these issues. Continued innovation and collaboration are essential to overcome these challenges and successfully deploy fast reactors.

7.3 Other materials

Nuclear fuel is a complex technology that requires a specific material, not only uranium (or uranium and plutonium in the case of MOX fuel). The cladding of fuel rods is made of zirconium, the control rods are made from hafnium, and another important part of the fuel are the burnable absorbers, mostly made from gadolinium. These materials are crucial for the safe and reliable operation of nuclear power plants, however, only hafnium is produced in the EU.

Zirconium

Zirconium is a metal that is extracted from the mineral zircon and is used as a cladding of the fuel rods thus it is a vital component in fuel manufacturing. Zirconium is not produced extensively in Europe, the major producers are Australia, China, South Africa, and Indonesia. Zirconium is almost solely used in the nuclear field, its properties make it perfect for cladding, it withstands high temperatures, is resistant to corrosion, and absorbs very few neutrons.

Table 7.5 Worldwide zirconium oxide reserves

Country	ZrO_2 Reserve (tonnes)
South Africa	14.3
Australia	9.1
Ukraine	4.0
USA	3.4
India	3.4
China	0.5
Brazil	0.4
All other	0.9
Total	36.0

Source: The metallurgy of Zirconium, IAEA, 2022

It can be seen that the majority of reserves are not in Europe, it is therefore important to monitor the global market and diversify the portfolio of supplies. Nevertheless, the main production of Zirconium sponge has been maintained in Framatome Jarrie in France while the material supply (Zirconium Oxyde) is carefully followed.

Hafnium

Hafnium is a material that is used for manufacturing nuclear reactor control rods. Its ability to absorb neutrons are making it ideal for this purpose. Also, it is corrosion-resistant and has exceptional mechanical properties. Hafnium is not existing on its own in nature, it is always found with zirconium, and it is a by-product of zirconium extraction. Hafnium is produced in several countries, the major producer being France with a share of 45%, followed by the USA with 41%, Ukraine with 8% and Russia 6%. Even though it may look like the situation is stable in the EU since 45% of the world's hafnium is produced in France, it is

important to consider that hafnium, unlike zirconium, is used also for other applications, the major one being super alloys for the aerospace industry. This can pose a risk in the future, where the expansion of the aerospace industry could utilize the majority of hafnium produced and increase the price of hafnium. As in the case of zirconium it is important to have long-term contracts for supplies or to increase the production capacity of France.[195] The main production in France is performed by Framatome as a side product of Zirconium in its Jarrie plant.

Gadolinium

Gadolinium is the most often used material to make burnable absorbers for nuclear reactors. It is used in the form of oxide Gd_2O_3 because of its neutron absorption ability. Gadolinium is found in the monazite and bastnasite ores but in small quantities. An important producer of gadolinium is China, other notable producers are India, Brazil, USA, and South Africa. The global reserves of gadolinium are expected to be more than one million tonnes with an annual production of about 7,500 tonnes. Gadolinium as other mentioned materials is not found in the EU, thus dependence on other countries needs to be considered and to ensure security of supplies, diversification is key[196].

7.4 Conclusions and recommendations

Manufacturing nuclear fuel is a complex process that involves several very high-tech steps, that are performed by a handful of companies in the world. The nuclear fuel cycle consists of five main phases, the front end of the fuel cycle involves four of them: uranium production, conversion, enrichment, and fuel fabrication. The last phase is the reprocessing consisting of conversion, enrichment, and fuel fabrication processes and which is part of the back end of the fuel cycle. Stakeholders in the EU's fuel cycle may see increasing demand by 2050, mainly due from stakeholders outside the EU and stakeholders outside the nuclear ecosystem.

To facilitate sufficient supply of uranium for the fuel cycle until 2050, Member States (and industry players) could explore sourcing uranium from multiple sources. This may be particularly relevant for Member States depending on Russian uranium[197]. **The reserves of uranium are spread across the world, and none are exploited in the EU today.** Major suppliers are Niger followed by Kazakhstan who has the largest reserves of uranium in the world, followed by Russia ranking third.

Today conversion capacities in the EU are sufficient. However, in the future there is a high risk of increased global competition for conversion capacity. In the EU the annual conversion capacity is rather stable, and the study's stakeholders assume it to remain stable around the value of 12,850 tSW/year. The annual capacity of the EU conversion facility is 15,000 tSWU/year. The study's stakeholders assume therefore that future demand can be met. At the same time, a lack of global conversion services estimated as of 2024 may require EU

195 Hafnium, Critical Raw Materials Alliance, Hafnium | CRM Alliance
196 Gadolinium - MMTA
197 REPowerEU Plan. European Commission, 2022.

producers to increase their capacity and make new investments. To this end, stakeholders highlight a need for long-term contracts or by limiting Russian imports to the EU, which already pose a significant risk to these investments.

Global enrichment capacities are dominated by the Russian Rosatom who holds 46% of the global capacity. The EU holds a capacity of more than 27%, through two companies Orano and URENCO. Even though Rosatom has a 46% share in the global market **the majority of enrichment services (62%) delivered to the EU in 2021 was provided by domestic capacities. The second largest share (31%) was provided by Russia.** While this can pose a potential risk in the future, the global nature of the market and the willingness of companies to ramp up their production if needed leaves the EU in a good position. **The EU enrichment capacity is utilised at about 68%** with current demand of 11,000 tSWU/year. The demand should be relatively stable in the coming years assuming the installed capacity to be roughly the same as today's – 100 GW. If there was an increase in demand in the global market, the potential for increasing the capacity of enrichment facilities is undeniable. Companies are prepared to invest in new facilities or increasing the capacity of old ones. Several announcements were already made - Orano decided to increase the capacity of the Georges Besse II enrichment facility[178], URENCO decided to expand the enrichment plant in the USA[179] and Westinghouse plans to upgrade and expand the Springfield fuel fabrication facility[180] and to explore the development of uranium conversion services at the Springfield location[181]. These activities are an answer to the growing demand from customers that no longer wish to obtain fuel cycle services from Russian suppliers. These investments, however, pose a risk for the suppliers in the situation when Russian suppliers would start to supply to the EU again.

The EU has the second largest capacity of fuel fabrication in the world, which puts it in a strong position on the global market. Since fuel fabrication is a high-tech process specific to each reactor type, it is important to maintain the fuel fabrication for all types of reactors operated within the EU. This is posing a **specific problem for Member States that operate VVER reactors, where the fuel was almost solely manufactured by Russian TVEL.** These **Member States** and manufacturers are, however, already in the process of solving this situation, as **many Member States are discussing with Westinghouse and Framatome to replace the supplies from TVEL**. Westinghouse reached an agreement with the Spanish company ENUSA and together with the Westinghouse facility in Västerås, Sweden will manufacture VVER fuel. Also, Framatome signed a memorandum with Slovenske Elektrarne to manufacture VVER[198]. Fortum and Westinghouse made an agreement for the design, licensing and supply of a new fuel type for the Loviisa NPP[189]. **Therefore, in terms of capacity the EU should be self-sufficient to meet future requirements.**

Reprocessing consists of two main parts, the production of uranium and plutonium and the MOX fuel fabrication. The production of uranium and plutonium is covered by the French La Hague facility and the capacity is sufficient for current supplies. If

198 https://www.framatome.com/medias/framatome-signs-memorandum-of-understanding-with-slovenske-elektrarne-to-extend-long-term-partnership/

the requirements for reprocessed fuel could increase, which is expected by 2050, the capacity might need to increase. **It is therefore recommended to monitor the future requirements and if necessary, the producers should be prepared to increase the capacity to meet the demand.** The MOX fuel fabrication is currently not utilized to a large extent. In this regard, **MOX fuel fabrication should not be a problem** in the future. The study's stakeholders identified a potential problem, **that the EU is lacking a facility for conversion of reprocessed uranium**, as most of the global capacity is in Russia. **This issue should be further examined, and the assessment should be made whether it would be beneficial to build such a facility.**

Another aspect that was further investigated are fuel supplies for SMRs/AMRs and research reactors. In terms of SMRs, the designs used are **standard LWR fuel** (just with different geometries). **Therefore, supplies should not pose a problem**. What could be potentially an **issue are the designs that are using HALEU**, a fuel also used in research reactors. Even though it is technically possible to manufacture such a fuel, **some adjustments are necessary**. This field should be closely monitored to have an appropriate timeline in place to meet the requirements for SMRs and research reactors when they occur. The first SMRs to be deployed are expected in 2030s, so the space for adjusting the manufacturing processes is there and this should not pose a significant risk. **The fuel cycle of AMRs or Gen IV large reactors is mostly in the R&D phase**. Since the types of fuel for advanced reactors are significantly different (i.e., molten salts, TRISO etc.), new processes are required. **This effort should be supported by EU Member States** to make sure manufacturing processes are ready in the time for the deployment of advanced reactors.

As a final part of this chapter materials that are necessary for the operation of the reactor but are not fissionable were investigated. These include zirconium, used for cladding, hafnium used for control rods and gadolinium used as a burnable absorber. Out of these three, **hafnium is produced in the EU**. France covers 45% of the production of hafnium. Zirconium oxide and gadolinium are not produced in Europe but are vital for the reactor operation. **This results in a strong dependence on non-European countries** for the sourcing of these materials. To ensure the security of supply, **suppliers should be diversified, and the EU should not rely on only one producer**.

To conclude this chapter, the fuel cycle in the EU can ensure a reliable fuel supply for current and future demand. The deliveries of uranium are well diversified, and this part should not pose any significant issues in the future. There are, however, several risks that must be monitored such as the Member States that are **reliant on Russian uranium who should diversify their supplies** as soon as possible, the Member States that are **dependent on Russian fuel assemblies delivery**, those operating VVER reactors, **should also diversify their supplies**[199]. Looking at reprocessing the **MOX fabrication capacity is sufficient in the EU** but the **facility for conversion of reprocessed uranium is currently missing**, a point that should be further examined. On the fuel cycle

[199] This is already happening to some extent.

readiness for SMRs and advanced reactors, one can say that the supply chain for **LWR types of SMRs that are using standard fuel (up to 5% of U-235) is ready**, only minor adjustments may be required in terms of fuel fabrication. The situation becomes more complicated with HALEU and even more complicated with advanced fuel. The **HALEU needed for SMRs, and research reactors can be manufactured within the EU, but a specific capacity in the EU must be built because it is not possible to manufacture HALEU using the current enrichment facilities in the EU.** Some Generation IV and AMR designs are fast neutron reactors. They use reprocess fuel which is complex to manufacture and for which a completely new fuel supply chain would need to be developed. Their advantage is to close the fuel cycle and decrease the dependence on natural and enriched uranium supply. Even if these reactors may not contribute to reach the 2050 target, R&D has to be supported to ensure long term, reliable and sovereign electricity supply in the future.

The analysis of inputs from the study's stakeholders provided us with the following recommendations[200] to support a successful fuel cycle landscape:

European level

- **Monitor the market situation to ensure there is sufficient capacity for the EU requirements.**
- **Support the R&D of SMRs and AMRs fuels to facilitate preparedness of manufacturing capabilities when the deployment happens.**
- Investigate the possibility and capabilities of manufacturing HALEU for production.
- Further examine the benefits of establishing a reprocessed uranium conversion facility, currently lacking in the EU.
- Monitor the situation with Accident Tolerant Fuels (ATFs) whether they are ready for licensing and wider deployment, in set intervals.

Member States

- **Support the utilities in diversification of uranium supplies and fuel cycle services, if possible, provide favourable conditions for EU supplies.**
- Support the fuel cycle R&D of Generation III, III+ reactors.
- Investigate the SMRs/AMRs designs that are planned to be built, and their fuel cycle options, how easy is it to manufacture the fuel.
- Support the R&D of SMR and advanced reactor fuels to facilitate preparedness of manufacturing capabilities when the deployment happens.

[200] Chapter 11 presents a list of priorities. These are concrete recommendations which require immediate actions, as discussed with the study's stakeholder group, Member State representatives and NGO representatives during a workshop 5-6 September 2023.

Industry

- Closely monitor the situation on the global fuel cycle market to adjust capacities.
- Flag any obstacles to investing in capacity expansion to policymakers to initiate research on potential market failures.
- Investigate the benefits of establishing a reprocessed uranium production facility, currently lacking in the EU.
- **Cooperate closely with the fuel designers to ensure faster deployment of ATFs, SMRs fuel and fuel for advanced reactors.**
- Start establishing long-term contracts for fuel cycle services whenever possible.

8 Radioactive waste and spent fuel management – What's the best solution for it?

Radioactive waste management is a topic that resonates across the entire ecosystem. Each EU Member State is ethically and legally responsible for its own waste. Clear governance structures, safety protocols, and operating procedures are established to ensure compliance with regulations and to maintain the security and integrity. **11 out of 15 study stakeholders believe that a sufficient waste management strategy is set up by the Council Directive on radioactive waste and spent fuel**[201]. However, to ensure safe handling, storage, and disposal of radioactive waste generated by Member States still comes with a range of challenges which are discussed in this chapter.

Key findings

- **The long-term high-level waste storage of radioactive waste, the legal framework, transport between countries and radioactive waste from other than nuclear power plants** are among the most urgent challenges.
- The **long-term high-level waste storage is technically solved,** however, there are **political, public perception, and in some Member States, regulatory issues.**
- The political and social acceptance for nuclear is highly polarised across the EU making radioactive waste management issues challenging and lengthy.
- There are options on how to deal with waste management and **storage is the most used option.**
- **A shared repository is the preferred solution** for Member States that operate a small number of reactors and do not have a significant amount of waste, but comes with several challenges such as public acceptance, regulatory harmonisation, cross border transportation, funding, and international cooperation.
- National legislative frameworks differ between Member States making cross-European collaboration less efficient and sometimes impossible.
- **The preferred solution for storage of nuclear spent fuel is currently a Deep geological repository, several such sites are being developed in various Member States. Finland has come the furthest and is aiming to commission their DGR by the mid-2020s.**
- Waste management of AMRs/Generation IV reactors (high temperature reactors, fast reactors, molten salt reactors, liquid metal cooled reactors) is uncertain today. This uncertainty should be addressed before the development and deployment of these types of reactors.

201 https://www.ensreg.eu/nuclear-safety-regulation/eu-instruments/Spent-fuel-and-radioactive-waste-directive#:~:text=The%20Directive%202011%2F70%2FEURATOM,and%20requirements%20in%20this%20field.

8.1 Classification and sources of radioactive waste

Procedures for the safe management of radioactive waste differ considerably according to the specific nature of the waste, notably the level of radioactivity of radioactive waste is differently classified per EU Member State. These classes are established in the framework of national programmes, considering their potential risks and the management options currently in place or under development. While different waste classification systems are used, for illustration, the classification system used by the IAEA is described in the table below.

Table 8.1 ***Radioactive waste classification system***

Exempt waste (EW)	Waste that meets the criteria for clearance, exemption or exclusion from regulatory control for radiation protection purposes.
Very short-lived waste (VSLW)	Waste that can be stored for decay over a limited period of up to a few years and subsequently cleared from regulatory control according to arrangements approved by the regulatory body, for uncontrolled disposal, use or discharge
Very low-level waste (VLLW)	Waste that does not necessarily meet the criteria of EW, but that does not need a high level of containment and isolation and, therefore, is suitable for disposal in near surface landfill type facilities with limited regulatory control.
Low-level waste (LLW)	Waste that is above clearance levels, but with limited amounts of long-lived radionuclides. Such waste requires robust isolation and containment for periods of up to a few hundred years and is suitable for disposal in engineered near surface facilities.
Intermediate-level waste (ILW)	Waste that, because of its content, particularly of long-lived radionuclides, requires a greater degree of containment and isolation than that provided by near surface disposal. However, ILW needs no provision, or only limited provision, for heat dissipation during its storage and disposal.
High-level waste (HLW)	Waste with levels of activity concentration high enough to generate significant quantities of heat by the radioactive decay process or waste with large amounts of long-lived radionuclides that need to be considered in the design of a disposal facility for such waste. Disposal in deep, stable geological formations, usually several hundred metres or more below the surface, is the generally recognized option for disposal of HLW.

Source: IAEA Safety Standards, Classification of Radioactive Waste, IAEA, 2009.

Radioactive waste is generated through several applications not only nuclear power but also industry, medical and research application and others. Regarding nuclear power, the waste is generated throughout the whole fuel cycle (described in detail in chapter 7), starting with uranium mining and finishing with reprocessing of spent fuel.

8.1.1 Nuclear power waste

Uranium mining and milling generates tailings that contain naturally occurring radioactive elements found in uranium ore. The tailings are collected to prevent the leakage of radon gas. These tailings are not classified as radioactive waste. During conversion of UO_2 to UF_6 and back, very low-level waste (VLLW) and exempted waste (EW) is produced. Enrichment generates depleted uranium, uranium that has a concentration of U-235 lower than natural level, thus it is not always classified as waste. However, it is safely stored (usually in a chemical

state) since it can be used for down blending of high enriched uranium or as a resource for MOX fuel. There are several Member States that classify depleted uranium as waste if the reuse does not ensure the use up of all depleted uranium. Fuel fabrication generates radioactive waste that contains uranium that is classified as VLLW. Radioactive waste is also generated during reprocessing of used fuel. Reprocessing generates all types of radioactive waste. Fission products that are generated in the reactor during the use of the fuel are extracted and stored in glass matrix (high-level waste - HLW). Reprocessing produces intermediate level waste (ILW) in form of claddings and structural components of the fuel assembly. During operation and maintenance low level waste (LLW) and VLLW are also generated.

The major source of waste in terms of radioactivity is generated during the reactor operation. Electricity generation produces HLW – fission products and transuranic elements, that are contained within the used fuel. Regarding the nuclear reactor 99% of radioactivity is associated with the fuel. During the operation of the reactor ILW and LLW are also generated. These are mainly parts of equipment used for the maintenance. Another source of radioactive waste related to reactor operation is decommissioning of shut down nuclear power plants. The waste comes mainly from “activation products” such as steel components that has been exposed to irradiation.

8.1.2 Non-nuclear power waste

Radioactive waste from research, medical and industrial use can be referred to as non-nuclear power waste. Since radiation is used in many aspects of life, radioactive waste can be generated in a range of activities such as use in national laboratories and university research, industrial gauges, radiography sources and nuclear medicine. These wastes are generated also in EU Member States that do not produce electricity with nuclear power, such as Austria. Although most of the waste is short-lived, proper management of non-nuclear power radioactive waste is required.

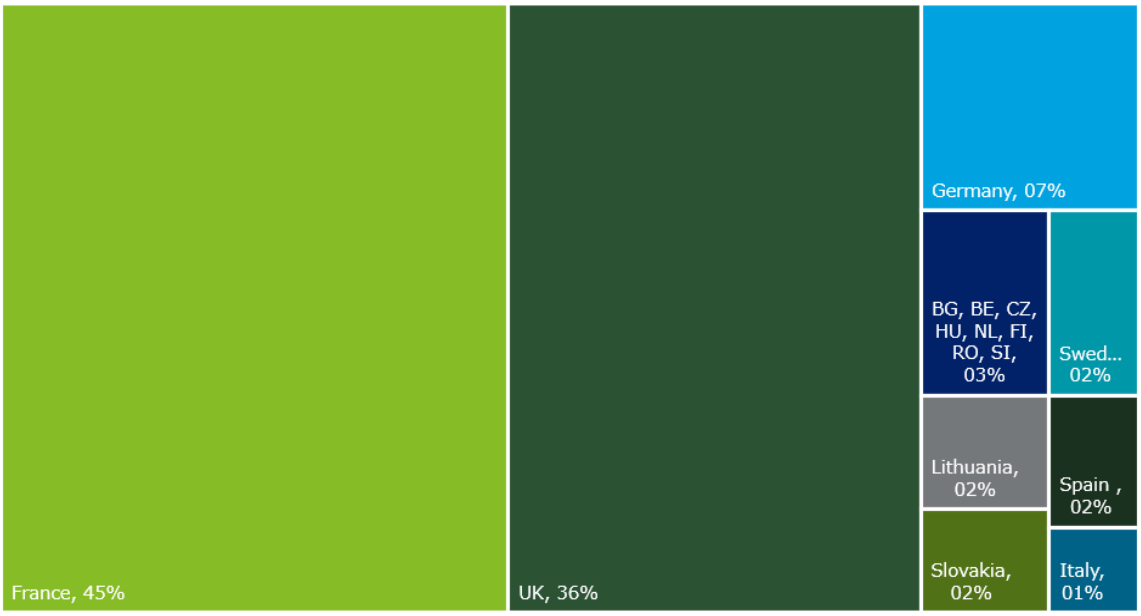
8.2 Waste management in Europe

The **Council Directive 2011/70/EURATOM of 19 July 2011 establishing a community framework for the responsible and safe management of spent fuel and radioactive waste**[202] sets the requirements for each Member State to have a national policy for radioactive waste and spent fuel management and implement programmes for the management of these materials. Member States shall further carry out self-assessments and invite international peer reviews of their national framework, competent regulatory authority and/or national programme at least every ten years. The national programmes should cover all radioactive waste and spent fuel as well as **all stages of radioactive waste management from generation to disposal.**

[202] Council Directive 2011/70/EURATOM of 19 July 2011 establishing a Community framework for the responsible and safe management of spent fuel and radioactive waste https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32011L0070

Furthermore, since 2015, Member States submit national reports on the implementation of the Directive to the European Commission every three years. Based on these national reports, the European Commission drafts a report on the overall implementation of the Directive and an inventory of radioactive waste and spent fuel[203]. All Member States with nuclear power plants generate radioactive waste[204], and some of them also manage spent fuel on their territory. In addition, export of radioactive waste for disposal in countries outside the EU is allowed only under strict conditions[205].

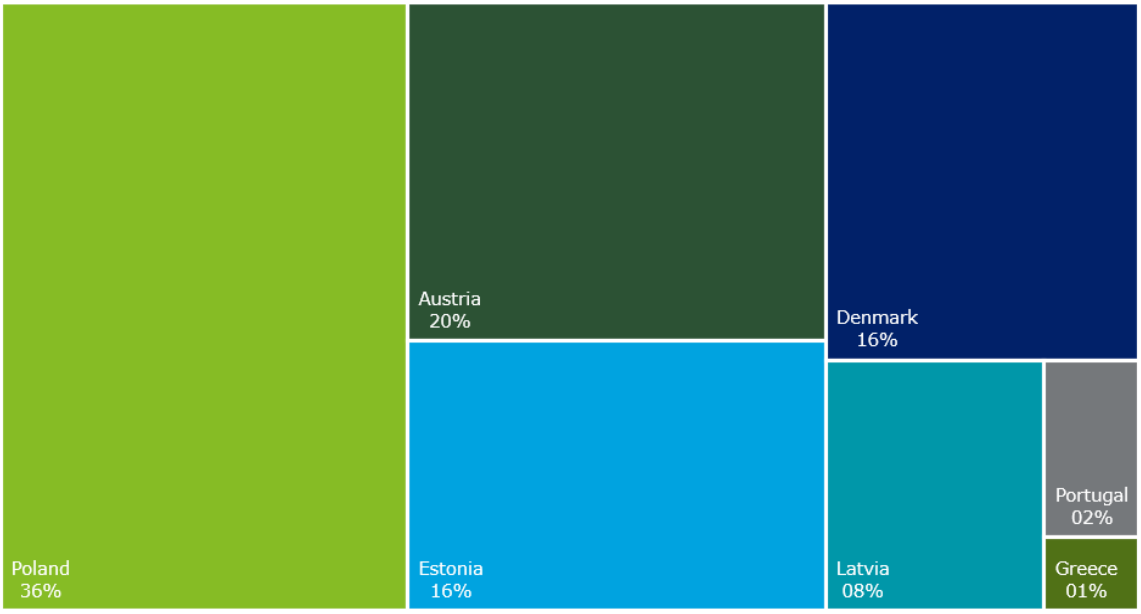
Figure 8.1 Distribution of total volumes of radioactive waste in Member States with nuclear power programmes, end of 2016



Source: COMMISSION STAFF WORKING DOCUMENT Inventory of radioactive waste and spent fuel present in the Community's territory and the future prospects Accompanying the document REPORT FROM THE COMMISSION TO THE COUNCIL AND THE EUROPEAN PARLIAMENT on progress of implementation of Council Directive 2011/70/EURATOM and an inventory of radioactive waste and spent fuel present in the Community's territory and the future prospects, 2019

203 https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1581949250178&uri=CELEX:52019DC0632
204 https://energy.ec.europa.eu/topics/nuclear-energy/radioactive-waste-and-spent-fuel_en
205 https://energy.ec.europa.eu/topics/nuclear-energy/radioactive-waste-and-spent-fuel_en

Figure 8.2 Distribution of total volumes of RAW in Member States without nuclear power programme, end of 2016 (HR, LU, CY, IE and MT have together 0.1%)



Source: COMMISSION STAFF WORKING DOCUMENT Inventory of radioactive waste and spent fuel present in the Community's territory and the future prospects Accompanying the document REPORT FROM THE COMMISSION TO THE COUNCIL AND THE EUROPEAN PARLIAMENT on progress of implementation of Council Directive 2011/70/EURATOM and an inventory of radioactive waste and spent fuel present in the Community's territory and the future prospects, 2019

There are several possibilities for radioactive waste management, each with its advantages and challenges, but the way the industry tackles waste disposal is **based on the level of radioactivity described in the previous subchapter**. The current options include the disposal and reprocessing. In the future there may be another possibility making use of fast reactors to burn the minor actinide.

8.2.1 Near surface disposal

Near-surface disposal refers to the management of waste either at ground level or below it and is typically used for VLLW, LLW. In some Member States it is also used short-lived ILW under specific requirements. Near-surface disposal facilities feature a protective cover that is typically a few meters thick. Waste containers are placed in specially constructed vaults, which are subsequently filled and sealed. Ultimately, these vaults are capped with an impermeable membrane and covered with topsoil. These facilities may also include drainage systems and potentially a mechanism for venting gases. The way of disposal is dependent on the classification of the waste and the legislation of each Member State. Several near-surface disposal facilities are in operation today in individual Member States (e.g. Sweden, Finland, the Czech Republic). In Finland, an underground repository has been in operation at Olkiluoto for low-level waste and intermediate-level waste

since 1988. Additionally, a similar facility was commissioned in Loviisa. These repositories are approximately 100 meters deep[206].

Within the EU, progress has been made in safely disposing of very low-level and low-level radioactive waste.

Case study: COVRA waste management facility serving as an art gallery

An interesting approach to increase the public acceptance of radioactive waste was done in the Netherlands. The radioactive waste of the Netherlands is stored in an above-ground facility (COVRA), it will remain there for at least 100 years. The repository of low and intermediate-level waste is isolated and has a controlled climate, in fact it fulfils the condition needed for storing art. Therefore, COVRA has decided that the space that is unused for the storage of waste will be made available to Zeeland museums for storing their unexhibited art. For the next 100 years art will be stored in the waste storage facility.

Figure 8.3 ***COVRA waste management facility***



Source: © COVRA n.v.

206 World Nuclear Association, 2023.

Case study: SKB's final repository in Sweden

SKB handles the final repository for short-lived radioactive waste in Sweden. The site has been in operation since 1988. The repository stores **low and intermediate-level radioactive waste**, which does not require cooling and is dominated by short-lived radionuclides.

Situated beneath the Baltic Sea it consists of four 160-meter rock vaults and a bedrock chamber with a 50-meter-high concrete silo. Two parallel kilometre-long access tunnels connect the facility to the surface.

The waste must remain isolated from humans and the environment for a minimum of 500 years, during which most of the radioactivity will naturally decay. SKB ensures the long-term safety of remaining substances through regular and repeated safety assessments, demonstrating their stability over ten thousand years.

Key info:

Operational start: 1988

Capacity: Approx. 63.000 cubic metres

Receiving capacity: Approx. 600 cubic metres per year

Staff: Approx. 30 workers

Above ground: Offices and workshops, terminal building, ventilation plant

Underground: Four rock vaults, one silo, control room

Operating costs: Approx. SEK 40 million per year

Given its classification as a nuclear installation, the SFR is subject to strict controls and monitoring by the authorities.

8.2.2 Deep geological disposal

Deep geological repository (DGR) disposal is used for HLW and spent fuel. Each Member State determines a regime to distribute the waste-streams over near-surface and DGR disposal alternatives.

Deep disposal facilities situated in underground caverns are unlike the near-surface disposals, excavated underground. A DGR facility is positioned at a depth of several hundreds of meters below the surface and can be accessed via a drift. The concept of **deep geological disposal** in stable geological formations has emerged due to the necessity to maintain control of the long-lived radioactivity in certain types of waste over geological timeframes. The **objective is to achieve isolation from the biosphere by utilising a combination of engineered and natural barriers** which will be discussed in depth later in the chapter.

For example, in France the most radioactive waste is currently conditioned in stainless steel containers and placed in intermediate storage at the La Hague plant. There are plans to build a DGR to create a place for longer term storage. It is scheduled to open in 2035. Waste will be stored in drifts hollowed out 500 metres below ground, in a stable geological environment, embedded in impermeable claystone. Different types of stable geological formations have been assessed for DGR's in different Member States, including crystalline granite, different types of clay and claystone, and in salt domes. Hence, the French Callovo-Oxfordian claystone solution is only one among others.

The goal of deep geological disposal is to develop safe, sustainable, and socially accepted solutions for the storage of radioactive waste. Such solutions could be

associated with substantial costs[207]. Depending on the size of the deep geological disposal, the costs are usually billions of euros. The responsibility for covering the total cost for the management of spent fuel and radioactive waste rests with those who generated those materials[202]. The ultimate responsibility for radioactive waste lies with the Member State. According to the study done by the European Commission on disposal and decommissioning of plants in the EU's 16 Member States, 130 billion EUR may be required for the management of spent fuel, radioactive waste, and deep geological disposal processes[208]. For example, Finland's deep underground repository's expected costs are about 3 billion EUR[209] for it to be in operation by the mid-2020s. The costs associated with radioactive waste management and related activities represent significant expenses. In Germany, the cost of radioactive waste management is expected to amount to almost 48 billion EUR[210]. The estimated total cost for developing a future DGR in the Czech Republic, which includes construction, operation, and eventual closure, currently stands at around 5.5 billion EUR, according to the Czech Radioactive Waste Repository Authority, SÚRAO. On the other hand, the unit cost for consumers is negligible. In the case of Sweden, their back-end system, which to a great extent is already built/planned, would have cost the electricity-users less than 0.3 cent (€)/kWh had the costs been linearly distributed over the complete production period.

Table 8.2 ***Estimated decommissioning and waste management cost in Germany without discounting (million EUR)***

	Undiscounted costs 2015-99 in prices of 2014 (mil. EUR)
Decommissioning and dismantling	19 719
Casks, Transport, Operational Wastes	9 915
Interim Storage	5 823
Low and Medium Waste Disposal (Schacht Konrad)	3 750
High Level Waste Disposal	8 321
Total costs	**47 527**

Source: Decommissioning of nuclear power plants Regulation, financing, and production. DIW,2023

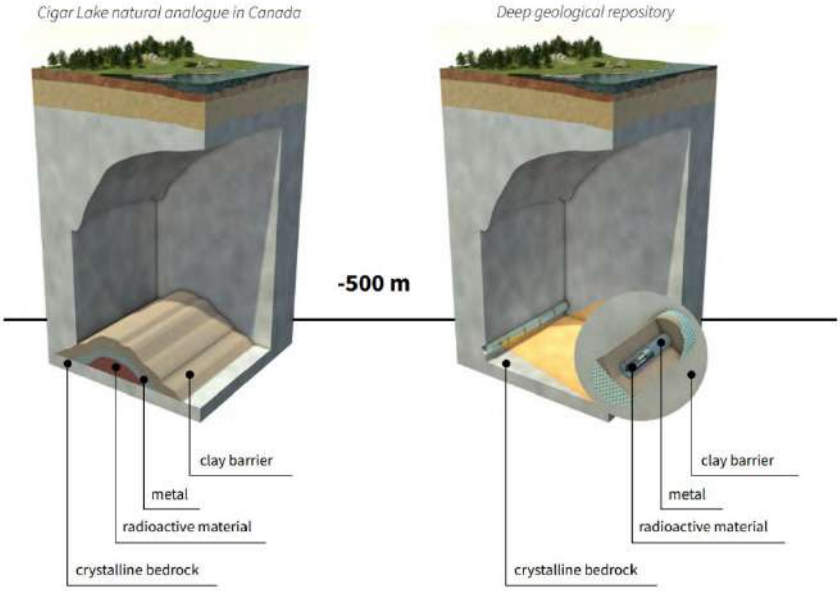
207 DGRs have been used cost effectively for storage of non-radioactive substances such as chemically toxic materials. The risk/cost analysis is much different for the nuclear DGR; thus the costs are higher.

208 https://www.theguardian.com/environment/2016/apr/04/europe-faces-253bn-nuclear-waste-bill

209 Why Finland now leads the world in nuclear waste storage | Nature

210 https://www.econstor.eu/bitstream/10419/268719/1/1833051734.pdf

Figure 8.4 ***Types of the deep geological repository – natural vs synthetic repository***



Source: © SURAO, 2020[213] CC.BY.NC-ND-4.0

Other key factors alongside finding appropriate sites to consider include engineering design, proposing correct radioactive waste packaging, addressing transportation and emplacement techniques. Once the radioactive waste is in place, it must also be monitored and measured for safety reasons[211]. Continuous monitoring is a crucial aspect of DGR operations thus robust monitoring systems are put in place to track various parameters, including temperature, pressure, radiation levels, groundwater conditions, and structural integrity. The DGR is subject to strict regulatory oversight and is typically operated by a responsible government agency or a designated organization thus institutional control and governance is a key requirement. Institutional control applies during repository operations, i.e., until the repository site is sealed and closed. Thereafter (for the next 10 000 - 100 000 years) the site is designed for passive safety, that implies that it should be possible to leave the repository without any long-term onsite control.

The mentioned deep repository is intended to be approximately 500 meters deep and serve for the disposal of highly radioactive waste and spent fuel. The total mass of the stored radioactive waste should correspond to approximately 9,000 metric tons of heavy metal. To accumulate funds for the construction of the DGR, a designated account has been established at the Czech National Bank, overseen by the Ministry of Finance. Each year, the operator of the Czech Republic's two nuclear power plants, CEZ as well as other producers of radioactive waste (Medical Facilities, Nuclear Research Facilities, and Industrial Facilities) pay an

211 These containers are designed to withstand the test of time and prevent the release of radioactive materials. Multiple layers of barriers, such as overpacks and buffers, may be used to provide additional protection and ensure the integrity of the waste packages.

agreed amount based on the total electricity generated[212]. Each year almost 41 million EUR (one billion CZK) are deposited into the nuclear account. Apart from financing the construction of the DGR, the funds from this account are also allocated for the operation, reconstruction, and closure of existing repositories[213].

Deep geological disposal is widely regarded as the preferred method for managing radioactive waste across the EU Member States as is apparent from the table below.

Table 8.3 ***Planned Deep Geological Disposal Facilities in EU Member States***

MS	Siting	Commissioning	Closure	Responsible organization	Comment
BE	No date defined pending national policy	Not available	At least 100 years after construction and operating license	ONDRAF/NIRAS	The disposal cost is for waste category B and category C
BG	Prefeasibility study ongoing and 6 potential sites selected	-	-	SERAW	No concepts as yet for ILW / HLW other than interim storage
CZ	Site selection by 2030.	2050	-	SÚRAO	Ongoing site selection. Two sites to be selected.
DE	Site selection by 2031	2050	-	BGE since July 2016	The cost is for a new geological disposal facility
ES	Site selection 2023-2027	2069	-	ENRESA	
FI	Eurajoki (Olkiluoto) site	mid 2020s	2110	Posiva	Preparations ongoing for operations in mid 2020s
FR	Cigeo: sited in the Border of the Meuse and Haute-Marne	2035	After 2125	ANDRA	100 year reversibility. Concept for submission for authorization.
HR	Site selection process is expected to be completed by 2032.	2068 or 2088	-	The Fund (via its RAW Management Centre)	Possible agreement with Slovenia by 2023
HU	Site selection ongoing	2064	2084	PURAM	Research activities are planned – laboratory in operation in 2038
LT	Site selected by 2033	2066	2072	Ignalina NPP	From 2019 Ignalina NPP takes over all

212 NPP operator pays approximately 2.3 EUR per MWh, other producers pay almost 1 500 EUR per one stored container

213 surao_brozura_HU_EN_online.pdf

MS	Siting	Commissioning	Closure	Responsible organization	Comment
					responsibilities of RATA
NL	Decision in 100 years	About 2130	-	COVRA	Cost estimate updated in the OPERA research programme (costs discounted to 2130, real term 2017)
PL	22nd century	22nd century	Mid-22nd century	ZUOP	
RO	2025	2055	2150	ANDR	Siting not started yet
SE	Forsmark site	2030-2032	2072-2073	SKB	Licence application for construction under review
SI	Site to be selected (2045-2055)	2065	2075	ARAO	Agreement with Croatia pending
SK	Site selection first stage (2013-2016) Site selection in 2030	2065	2105-2115	JAVYS	3.7 bn for 40 years NPP operation and 4.4 bn for 60 years NPP operation
UK	England and Wales SF and HLW	2040	2140	NDA	

Source: COMMISSION STAFF WORKING DOCUMENT Progress of implementation of Council Directive 2011/70/EURATOM Accompanying the document REPORT FROM THE COMMISSION TO THE COUNCIL AND THE EUROPEAN PARLIAMENT on progress of implementation of Council Directive 2011/70/EURATOM and an inventory of radioactive waste and spent fuel present in the Community's territory and the future prospects. 2019, World Nuclear Association, 2022

Case study: Deep geological repository Onkalo, Finland

The construction started in 2004 and the operation should start in the mid-2020s.

The repository will be constructed at a depth of 400-430m, it consists of a spiral-shaped access tunnel, personnel shaft, canister shaft and two ventilation shafts, technical rooms, and tunnels (approximately 10 km of tunnels have been excavated by 2020). It is expected that during the final disposal operations, another 40 km of tunnels will be created.

Posiva, a company that is constructing the repository, expects the operation for about 100-120 years. At the end of this period, the tunnels should be full of nuclear spent fuel, that will be isolated there for thousands of years.

Onkalo DGR is a nuclear installation and is subject to strict controls and monitoring by the authorities.

Key info:

Operational start: mid-2020s

Capacity: Approx. 6 500 metric tons of spent nuclear fuel

Total area: Approx. 2km^2

Above ground: Offices, encapsulation plant, ventilation, and service shafts

Underground: Test tunnels, storage tunnels,

Cost estimate: Approx. 3,5 billion EUR

8.2.3 Shared repository

Based on what was discussed in the previous chapter, the only accepted and secure method for handling spent fuel and high-level radioactive waste has been their disposal in DGR, contingent upon the presence of suitable geological formations. However, some of the Member States have a small amount of radioactive waste and thus building a costly national DGR could be inefficient. To address this issue, the concept of a shared repository emerged as a potential solution. When asked whether they think each Member State should be obliged to construct and operate a DGR for radioactive waste, or whether they would prefer shared capacities, **12 out of the 15 study stakeholders answered that a shared capacity would be better.** There are several key benefits for a shared repository:

Key benefits of shared repository

Economic advantages

Smaller countries, in particular, tend to favour the concept of shared multinational repositories due to economic considerations. By participating in a collective endeavour, each country can realize significant financial benefits derived from the economies of scale involved in constructing and operating a single repository, as opposed to multiple smaller facilities.

Access to safe disposal facilities

Certain countries may lack the financial resources to independently establish safe disposal facilities, leading them to save funds for several decades before undertaking repository construction. A shared repository could grant these countries earlier access to secure disposal options, driven by economic motivations.

Enhanced global nuclear security

Constructing one large state-of-the-art disposal facility instead of several smaller alternatives diminishes the proliferation risk and thereby the risk for misuse of nuclear materials by terrorists or as potential weapons[214]. This consolidation contributes to bolstering global nuclear security.

Environmental protection

A single, high-quality facility can significantly minimize the adverse environmental impacts that multiple individual facilities might have. This approach could be better for environmental protection in comparison to decentralized alternatives.

Expanded range of geological options

In the context of a shared repository involving multiple countries, a broader geological area can be explored, providing a wider selection of geological formations.

Increased technical capacity

Collaboration among scientists and specialists from multiple countries can be deepened and further foster the sharing of knowledge and experience, thereby enhancing technical capabilities in pursuit of a common objective.

Source: World Nuclear Association, 2020

When looking at shared DGR, the challenges that come with it should be discussed. The diverse views of Member States might hinder progress and finding a common ground for this solution. Also, economically weaker Member States may become "waste dumps" for other Member States making the nuclear industry contribute to polarisation of the EU. In addition, the capacities to respect safety management may be reduced over time for Member States “exporting” their waste to other Member States. Finally, from a regulatory point of view, currently transport of radioactive waste across borders is only possible in special cases and under very strict conditions.

Transport is an integral part of radioactive waste management and some waste disposal facilities are located adjacent to the facilities that they serve. Typically, used fuel is stored onsite for at least five months before it can be transported. This considers many different radioactive materials and related potential hazards. Packaging standards developed by the International Atomic Energy Agency (IAEA) consider these characteristics and potential hazards[215]. The guidelines are

214 Also managed by the IAEA and Euratom safeguards.

215 https://www.iaea.org/publications/12288/regulations-for-the-safe-transport-of-radioactive-material

complex but identify five different categories of primary package based on the activity and physical form of the waste being transported[216]. The categories are: excepted, industrial, Type A, Type B, and Type C.

In addition, the EU's Directive on Shipments of Radioactive Waste and Spent Fuel (2006/117/Euratom) establishes a system of prior authorisation for shipments of radioactive waste in Europe. The transport of low-level waste to waste treatment facilities and storage sites is common, however, it is only transported within the country where it is produced, given the relative ease of storage and disposal of it.

A plethora of challenges come with cross border transfer such as multiple layers of regulations and a lack of international consistency. Efforts to address issues include stringent safety standards, secure container designs, careful route planning, public outreach and education, and ongoing research to develop safer and more efficient transportation methods[217]. Nonetheless, the transportation of radioactive waste remains a contentious and challenging aspect of radioactive waste management. If the shared repository were deployed, an update of the regulatory framework would be necessary. Shared capacities will ultimately be national decisions but for example they are not legally possible in France with the present legislation[218]. However, these legislative limitations could be changed if required.

Discussions on shared repositories among Member State representatives are ongoing. In addition, to the challenges discussed above, this requires negotiations focused on regulatory aspects. Following the advantages of a shared repository as defined by the World Nuclear Association (see the box above), certain Member States seem to be open to exploring possibilities for shared repositories[219]. They perceive this solution to contribute to enhancing global safety and security by providing timely disposal options to a broader range of countries.

The global advantages of multinational repositories are clear, and they offer substantial benefits to all parties involved when the benefits and responsibilities are equitably shared. However, it is crucial for each country to thoroughly assess the advantages and disadvantages of participating either as a host or a partner, considering the decisions made by their national governing bodies.

8.2.4 Reprocessing (separating plutonium and uranium from the waste)

The principal **reason for reprocessing used fuel is to recover unused material** such as plutonium, along with less immediately useful unused uranium and **to reduce the volume of used fuel** which is discussed in greater detail in Chapter 7. This way the level of radioactivity in the waste from reprocessing is much smaller and it contributes to national energy security. However, the HLW created after reprocessing is more challenging to dispose of than the original spent UO_2 fuel.

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216 As with other hazardous materials packages of radioactive materials are labelled in accordance with the requirements of national and international regulations. These labels not only indicate that the material is radioactive by including a radiation symbol, but also give an indication of the radiation field in the vicinity of the package.

217 Any substantial quantity of radioactive material is generally transported by specialized companies.

218 World Nuclear Association, 2022.

219 https://www-pub.iaea.org/MTCD/Publications/PDF/te_1413_web.pdf

The total content of radionuclides is lower when the actinides are removed but the most challenging nuclides for a repository remain in the waste stream (i.e., the nuclides that most easily become dissolved and spread into the groundwater whilst having a half-life long enough to reach the biosphere, typically Iodine-129). Hence the lower total activity is not a guarantee that the waste is less problematic. **It is important to state that fuel can be reprocessed only a limited number of times as heavy Pu-nuclides accumulate and become neutron poisons in the reactor.** Also, in Member States with reprocessing, large amounts of nuclear spent fuel will have to be disposed in a DGR.

The reprocessing involves chemically separating the usable uranium and plutonium from the waste. About 1% of plutonium can be retrieved from used fuel and plutonium is subsequently combined with depleted uranium oxide at a MOX fabrication facility to produce new fuel as mentioned in Chapter 7. This approach enables an additional 25-30% of energy to be derived from the initial uranium source and significantly diminishes the volume of high-level waste.

There are existing commercial reprocessing facilities, but these are sparse as can be seen in the table below. Japan is currently in the process of commissioning a new facility and China has plans to construct one as well. In the EU only France provides reprocessing services which are also available for international utilities[220].

Table 8.4 ***World commercial reprocessing capacity (tonnes per year)***

LWR fuel	France, La Hague	1 700
	Russia, Ozersk (Mayak)	400
	Japan (Rokkasho)	800
	Total LWR	**2 100**
Other nuclear fuel	UK, Sellafield (Magnox)	1 500
	India (PHWR, 4 plants)	260
	Total other	**1 760**
Total civil capacity		**3 860**

Source: World Nuclear Association, 2022

France embraced reprocessing as part of its nuclear programme, opting for a closed fuel cycle to recover uranium and plutonium from used fuel. Orano produces 1 110 tonnes of spent fuel annually, with reprocessing occurring after several years of cooling. France currently stores 58 tonnes of civilian plutonium, 26% of which is foreign owned. Used MOX and recycled uranium fuels are stored for future reprocessing and use in Generation IV fast reactors, amounting to approximately 130 tonnes per year. At present, used MOX fuel is not reprocessed[221].

220 For example, significant portion of Japan's fuel has been reprocessed in France.
221 World Nuclear Association, 2023.

8.2.5 Waste management of SMRs/AMRs and advanced reactors (Generation IV)

SMRs waste management

When looking at the radioactive waste management we have to take into consideration newly emerging technologies such as the AMRs and Generation IV large reactors. SMRs are compact nuclear reactors designed for easy transportation, installation, and operation. These reactors provide flexibility in the energy sector and can be used for decentralised electricity production. While SMRs are commonly regarded as having advantages in terms of cost and safety when compared to larger reactors, there has been limited research conducted to evaluate the impact of SMRs on the later stages of the nuclear fuel cycle. Light water reactors (LWR) are the type of SMR most likely to be built until 2050. For these types of SMR, the radioactive waste management could be similar to the currently operated large reactors. A slight increase in the mass of the waste generated by the SMR might be assumed, but this may not be significant. The NuScale SMR VOYGR was analysed, and the conclusion is that in the front end of the cycle it generates 23% more of depleted uranium mass, due to higher enrichment. In the back end of the cycle the amount of HLW in the form of spent fuel increases by only 10%. It can be concluded then that there appear to be no major challenges to the radioactive waste management of SMRs when comparing to conventional LWRs and it has limited impact on long-term repository isolation[222].

222 Nuclear waste attributes of SMRs scheduled for near-term deployment. T.K. Kim, L. Boing, W. Halsey, ANL B. Dixon, INL, 2022.

AMRs and Generation IV large reactors waste management

When it comes to AMRs/Generation IV nuclear reactors, these represent a new generation of nuclear reactors that is increasing efficiency and as a result, reducing radioactive waste. These reactors utilise advanced technologies and materials to provide a sustainable and environmentally suitable means of nuclear energy production. According to the NEA[223], Generation IV reactors are expected to achieve higher fuel burn-up, which could result in lower amounts of radioactive waste produced per unit of energy generated. It also has shorter half-life of the waste, meaning that the radioactivity of the radioactive waste decreases more rapidly, simplifying long-term storage requirements and reducing the need for complex disposal facilities. Some fourth-generation reactor concepts, such as Sodium-cooled fast reactor (SFRs), have the capability to use spent fuel from previous generations as fuel for further reactions. This way, they can transform spent fuel, which would otherwise be considered radioactive waste, into a source of energy. However, it also comes with associated challenges. While fourth-generation reactors can reduce waste volume and radioactivity, addressing the issue of long-term storage for the remaining radioactive waste is still necessary. The deployment of AMRs/Gen IV reactors is currently uncertain and could happen after 2050, that is why this study is not exploring the issue of AMRs/Gen IV waste management any further.

8.3 Conclusions and recommendations

The storage of radioactive waste is a complex issue that presents several challenges, among others around long-term management and safe containment. The storage containers must withstand natural disasters, human errors, and potential terrorist threats. Robust engineering and monitoring systems are necessary to minimize the risk of leaks or breaches. This goes hand in hand with the requirement for a strong regulatory framework, a comprehensive and consistent regulatory framework for radioactive waste storage is crucial. Concerns about safety can lead to opposition and hinder the implementation of storage solutions. Thus, building public trust through transparency and engagement is essential. In Bure, France, a DGR for radioactive waste was proposed. The project faced protests and opposition from residents and environmental organizations[224]. On the other hand, a DGR is expected to start operation in Finland in the mid-2020s with wide societal acceptance. In Sweden DGRs also have wide public support.

Assuming the baseline scenario[225], the amount of radioactive waste produced could be the same in 2050 as today[226]. The total radioactive waste flux in the

223 https://world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/generation-iv-nuclear-reactors.aspx

224 https://www.reuters.com/article/uk-france-nuclearpower-waste-idUKKBN1HP1S7

225 100 GW installed capacity in 2050, similar as the installed capacity today. See also Chapter 2.

226 The amount of radioactive waste per year may change depending on the number and type reactors in operation, as well as depending on the possibilities to recycle waste. Further details on Member State's expectations and plans are required to fine-tune this assessment, as presented in the EU waste report.

Member States could increase to some extent as old reactors are simultaneously replaced by new ones leading to an increasing flux of decommissioning waste. There are currently two ways for handling radioactive waste; disposal or reprocessing:

- Disposal is dependent on the classification of the radioactive waste and the legislation of each Member State. There are two types of disposal, the near-surface disposal (for VLLW, LLW and in some Member States for short-lived ILW) and the deep geological repository (DGR) (for HLW and spent fuel). Several near-surface disposal facilities are in operation today, the first DGR to be operated is being constructed in Finland and the commissioning is expected in mid 2020s. Different possibilities such as burning minor actinides in fast reactors are still in the R&D phase and the deployment time is uncertain. The commercial deployment of fast reactors might not happen before 2050, as the focus could be on building the conventional reactors and SMRs in the EU, thus no change is expected.
- Reprocessing, may continue to run as it does today. It could, however, happen that the amount of reprocessed radioactive waste could increase when more Member States use reprocessed fuel in their reactors.

International cooperation, sharing of best practices, and learning from existing DGR projects can help overcome some of the challenges discussed within this chapter and ensure the safe long-term disposal of radioactive waste.

The analysis of stakeholder's inputs provided us with the following recommendations[227] to consider in order to support a successful radioactive waste management landscape:

European level

- Continue the monitoring and communication about radioactive nuclear waste management.
- **Use monitoring and communication to increase public acceptance of DGR.**
- **Support the research of radioactive waste management of SMRs and advanced reactors** e.g., through a research organisation such as the European Commission Joint Research Centre.
- Initiate work to standardise and harmonise the back-end nuclear regulation in different Member States cross-EU to support efficient deployment of a new nuclear fleet across Europe.
- Strive for implementation of IAEA standards within nuclear-specific issues, and in other fields work to harmonize the requirements on the nuclear industry with the requirements on other comparable EU industries.
- Gather the pro-nuclear Member States in a separate council and give them active support to build up the competence and capacity needed to meet the 2025-2050 radioactive waste management demands.

[227] Chapter 11 presents a list of priorities. These are concrete recommendations which require immediate actions, as discussed with the study's stakeholder group, Member State representatives and NGO representatives during a workshop 5-6 September 2023.

- Initiate processes to set up a framework to pre-qualify and license different reactors considering their radioactive waste management on the EU level. This may facilitate de-risking the licensing phase.
- **Explore the possibility to use the shared repository in the EU and provide similar support (R&D, feasibility studies, etc.) as for the national repositories.**
- Facilitate research and host discussions on shared repositories, mainly on the regulatory aspects of shared repository and the feasibility of such a project.
- Remove administrative boundaries to allow for efficient radioactive waste management across Member States' borders (incl. joint repositories, international waste management services, etc.).

Member States

- **Continue the monitoring and communication about radioactive nuclear waste management and to increase public acceptance of DGR**
- Explore funding mechanisms that could be controlled and can be reviewed every few years. It is crucial that the funds for DGR are in place.
- Review available funding for DGR regularly to ensure sufficient funds when needed for construction, operation, and maintenance.
- Develop plans and realize a national repository programme that encompasses radioactive waste from non-nuclear activities (such as medical, industrial, R&D, etc.).
- Develop a risk/reward-sharing structure associated with the national back-end programme that distribute long term regulatory and financial risks between the state and the nuclear industry.
- Stimulate general competence build-up within radiotechnology and nuclear. Initiate programs within the academy and give support to expand competence and capacity within the nuclear supply chain (traineeship, etc.).

Industry

- Cooperate with the waste management authority to ensure a timely deployment of the repository.
- **Design the nuclear components with the thought of future decommissioning and radioactive waste management to ensure easier handling of this waste.**
- Develop an end-to-end plan for the supply of resources and competence to the back-end system. The plan should remain solid in light of competitive nuclear activities (i.e., the need for resource and competence for newbuild, refurbishment programmes, standard ops., and decom programmes).
- Develop partnering solutions across the nuclear industry to stimulate early growth of capacity and competence within the nuclear supply chain.
- Stimulate radioactive waste management competence build-up by dedicated employer activities (trainees, internal re-schooling/back-end academies, etc.).

9 Decommissioning – Are we ready for dismantling several nuclear power plants at once

According to the International Atomic Energy Agency (IAEA) decommissioning refers to the administrative and technical actions taken to remove all or some of the regulatory controls from an authorised facility to reuse the site and facility. Decommissioning is a complex process that **requires careful planning, sufficient resources, expertise, and adherence to strict safety and regulatory requirements as well as social, and political support**[228].

The EU may become a global hotspot for decommissioning, as 78 reactors might end their operation between 2040 and 2050, following the study's assumptions (see chapter 2). As a result, multiple dismantling projects may need to be performed at the same time, which raises concerns and challenges that necessitate careful assessment.

This chapter presents the status of the nuclear decommissioning landscape and an overview of the range of issues to consider when decommissioning several nuclear power plants at once. The analysis and the study's stakeholder inputs resulted in several key findings.

Key findings

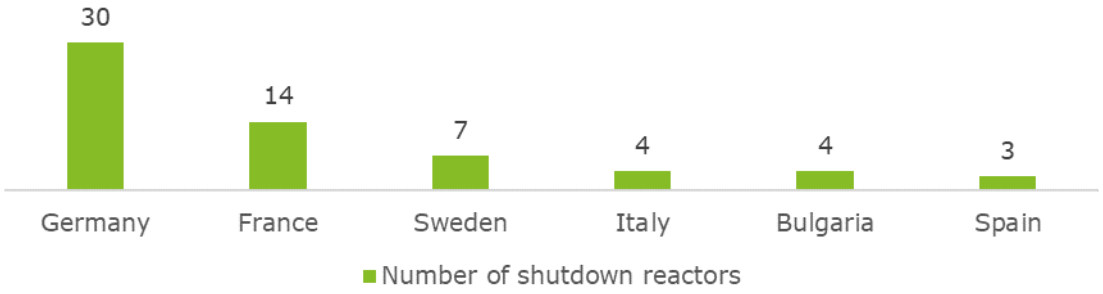
- The EU's **fleet of nuclear reactors is ageing.** Even under the assumption that nuclear power plants have an operation lifetime of 60 years, **decommissioning may steadily increase in the coming decades and the number of shutdown reactors grows.**
- The decommissioning process is **lengthy, costly, and often exceeding initial cost estimates**. At the same time, cost estimates may become more accurate based on growing experience from an increasing number of decommissioning projects that are being realised.
- There is **risk of insufficient financial resources** in place at the time of decommissioning.
- **Collaboration between Member States and other relevant stakeholders must be promoted, to ensure transparent knowledge exchange** regarding decommissioning practices.
- **Ensuring the availability of qualified personnel and expertise** is one of the primary challenges. The simultaneous decommissioning of multiple plants could stretch the existing workforce thin.
- The **readiness of the nuclear supply chain i.e. business involved in the sphere of decommissioning** and their capacity and capability **must be further assessed.**

228 Financial aspects of decommissioning. IAEA, 2005.

9.1 Scope of decommissioning in the EU

Decommissioning becomes a domain of growing importance and could inevitably increase in scope in the coming decades. The average age of a nuclear power plant in the EU is 35 years and 83% of reactors in the EU is older than 30 years. With the assumption of an operating lifetime of 60 years (see chapter 3), 78 reactors might end their operation between 2040 and 2050. The World Nuclear Association confirms this increased scope for decommissioning in Europe. According to their study approximately 200 of the 411 operating nuclear power plants worldwide are coming to the end of their operational and economic lifetimes and may need to be decommissioned in the coming two decades[229]. This adds to the already shut down reactors in Europe. As of May 2022, there are 103 operational reactors and 62 shutdown reactors in various stages of decommissioning in the EU, with 18.6% of them in Germany, followed by France.

Figure 9.1 ***Number of shutdown nuclear reactors in EU in 2022***



Source: © IAEA, 2022

Long Term Operation (LTO) Programmes may reduce the decommissioning scope in the EU. Extending the operating lifetime of reactors through significant maintenance operations may delay decommissioning. It is common for operators to apply for license extensions to extend the lifetime of reactors beyond the initial period[230]. Moreover, energy market volatility and increasing emphasis on maintaining a stable source of power supply might further increase interest in LTO programmes.

Nuclear authorities authorise these extensions following strict controls, economic considerations and verifying safety standards. The International Atomic Energy Agency (IAEA) created a safety review service: Safety Aspects of Long-Term Operation (SALTO) to advise nuclear power plant owners on lifetime extensions. In the EU it provided a comprehensive safety review in several Member States, including Bulgaria, Sweden, Belgium, Spain and Slovenia[231].

Further prolonging the operation lifetime may additionally reduce the decommissioning scope. Some countries are considering LTO programmes of 80

229 https://world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-wastes/decommissioning-nuclear-facilities.aspx

230 https://www.iaea.org/newscenter/news/advising-nuclear-power-plants-on-lifetime-extensions-the-iaeas-salto-service

231 The team comprised experts from the Czech Republic, Slovakia, Spain, and the United Arab Emirates, and three IAEA staff members.

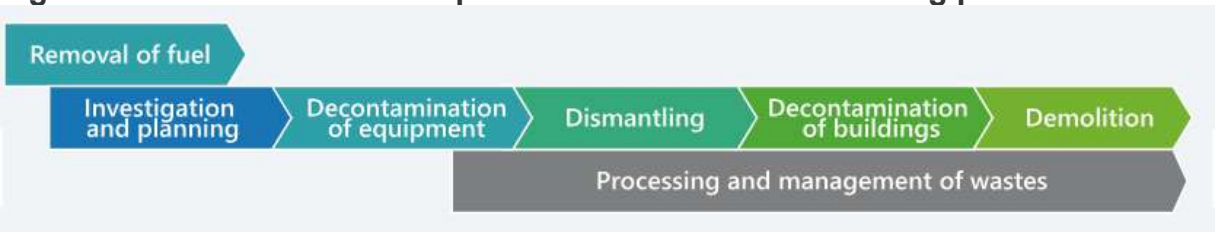
or 100 years, for example the US[232]. This may further reduce decommissioning challenges presented in this study.

Regardless of LTO, it is assumed that decommissioning remains a key challenge for the nuclear energy ecosystem.

9.2 Decommissioning possibilities

Decommissioning of nuclear power plants is a lengthy and resources intensive phase in the life of the NPP. The long process involves **activities from shutdown and removal of nuclear material to environmental restoration of the site.** The detailed structuring of the different phases depends on the specific national legal frameworks for decommissioning, but the general overview can be seen from the figure below:

Figure 9.2 Transition from operations into decommissioning phases



Source: © Toshiba

Nuclear decommissioning stages include **dismantling, decontamination, demolition,** and **site restoration** at the end of their lifetime as well as **storage, processing, conditioning, and disposal of radioactive waste and spent fuel.** Detailed approaches to implement these stages depend on the **type, characteristics, and age** of each nuclear power plant as well as the **standpoint of the country**. To ensure that decommissioning is safe and environmentally sound, the EU established a set of guidelines outlining the points for companies to follow.

232 See also chapter 3 for a discussion on the effects of different timeframes for LTO.

Case study: review of the EU's decommissioning regulatory landscape

Within the EU, the most relevant issues concerning nuclear decommissioning are covered either by the Safety Directive or the Radioactive Waste Directive.

Furthermore, two other regulations are providing support for the decommissioning of specific EU nuclear facilities. **Regulation 2021/100**[233] established a financial programme for decommissioning of certain nuclear facilities and managing radioactive waste and **Regulation 2021/101**[234] established a nuclear decommissioning assistance programme in Lithuania. Each Regulation runs from 1 January 2021 to 31 December 2027, but the support started well before and is part of the 2003 Act of Accession[235].

Name	Key points
Regulation (Euratom) 2021/100	• supports the safe decommissioning of the Kozloduy nuclear power plant in Bulgaria and the Bohunice V1 plant in Slovakia[236]. • implements the decommissioning process and manages radioactive waste at four Joint Research Centre (JRC) sites: JRC-Geel (Belgium), JRC-Karlsruhe (Germany), JRC-Ispra (Italy), JRC-Petten (the Netherlands). • supports the JRC to manage radioactive waste, nuclear material and spent fuel safely, explore and develop options for transferring decommissioning and waste management liabilities to the host Member States, develop ties and exchange knowledge among those involved, such as governments, safety authorities, utilities, and decommissioning operators, document knowledge gained and make this available. • has a €466 million budget shared between the programmes as follows: €63 million for the Kozloduy programme, EUR 55 million for the Bohunice programme, EUR 348 million for the JRC. • states that the EU will provide no more than 50% of the costs of the Kozloduy and Bohunice programmes, with Bulgaria and Slovakia covering the rest. • repeals Regulation (Euratom) No 1368/2013[237]
Regulation (EU) 2021/101	• supports the safe decommissioning of the Ignalina nuclear power plant in Lithuania, including dismantling and decontaminating the reactor shafts, managing safely the decommissioning and the legacy waste, implementing the building demolition programme, obtaining the decommissioning licence, downgrading radiological hazards[238] • has a EUR 552 million budget. • states that the EU will provide no more than 86% of the costs involved, with the remainder to be covered by Lithuania and other sources. • repeals Regulation (EU) No 1369/2013[239].

Source: European Commission, EUR-Lex

The requirement for EU Member States to ensure that adequate and audited financial resources for decommissioning and radioactive waste management activities are available for the purpose for which they have been established and are managed in a transparent way is already established. It is therefore necessary that the continued fulfilment of responsibilities is ensured over the whole financing and spending period, including the accumulation of funds during operation and the entire decommissioning period. For this purpose, the European Commission has established the NuBAFA expert group with a mandate that covers both financing of decommissioning and disposal of radioactive waste. With its support it is addressing the challenges faced by the EU and its Member States with regard to the back-end of the nuclear fuel cycle. Close

233 https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32021R0100
234 https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32021R0101
235 https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:12003T/TXT
236 https://www.ebrd.com/what-we-do/sectors-and-topics/nuclear-safety/kozloduy.html
237 Council Regulation (Euratom) No 1368/2013 of 13 December 2013 on Union support for the nuclear decommissioning assistance programmes in Bulgaria and Slovakia
238 https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52018PC0466&qid=1708608122041
239 Council Regulation (Euratom) No 1369/2013 of 13 December 2013 on Union support for the nuclear decommissioning assistance programme in Lithuania

collaboration with experts and shared knowledge of national best practices is assumed to facilitate the implementation of the related requirements of the Radioactive Waste Directive[240]. For the period 2022-2023, the work programme enlists three main activities defined in consultation with the experts and envisaged main outcome of these activities to be a series of recommendations to prime relevant policy initiatives or to support retrofitting of existing acts e.g., Commission Recommendation from 2006.

Source: European Commission

To further aid the selection and determination **of the best decommissioning strategy,** the International Atomic Energy Agency (IAEA) proposed several factors[241] that should be considered:

- the national policies and regulatory framework
- financial resources and cost of implementing a strategy
- spent fuel and radioactive waste management system health, safety, and environmental impacts
- knowledge management and human resources
- social impacts and stakeholder involvement
- suitable technologies and techniques

The global status regarding decommissioning approaches is as varied as the range of sites globally, but when considering decommissioning **two main decommissioning strategies can be considered**[242]:

- **Immediate dismantling (ID)** is a strategy that allows for the facility to be removed from regulatory control relatively soon after shutdown or termination of regulated activities. Final dismantling or decontamination activities can begin within a few months, depending on the facility. Following removal from regulatory control, the site is then available for re-use within a decade. This is proposed in several countries, including France, Italy, Germany, Spain and Slovenia.
- Safe enclosure followed by **deferred dismantling (DD)** is a strategy in which a facility or site is placed in a safe condition for a certain time, followed by decontamination and dismantling. During the deferred dismantling period, a surveillance and maintenance is implemented to ensure the required level of safety is maintained. A few countries have adopted this approach due to the design of the NPP with the delay ranging from 10-40 years in Sweden, to around 100 years in the UK.

The selection of the ID or DD method depends on each nuclear power plant's specific characteristics and predominant approach in the country. Larger nuclear power plants with multiple reactors and supporting buildings generally require more resources and time to decommission and the presence of highly radioactive materials, such as spent nuclear fuel, adds complexity. Additionally, the age of the plant and the technologies used in its construction also influence the decision. The

240 https://commission.europa.eu/system/files/2023-02/ener_mp_2022_en.pdf
241 https://www-pub.iaea.org/MTCD/Publications/PDF/PUB1996_web.pdf
242 Selection of Decommissioning Strategies: Issues and Factors. IAEA, 2005.

table below provides and overview of the assumed duration of phases during various decommissioning projects.

Table 9.1 Assumed duration for typical phases in various decommissioning projects

Country	Number of units	End state	Preparatory work	Dismantling	Decontamination	Conventional demolition/site restoration
Finland	2	Brownfield	2 years	2 years	3 years	Not included
France	4	Brownfield[243]	3 years	7 years	3 years	2 years
Slovakia	2	Brownfield	3 years unit 1 5 years unit 2	3 years	10 years	
Spain	1	Greenfield[244]	2 years	4 years	3 years	
Switzerland	1	Greenfield	5 years	10 to 15 years		

Source: OECD – NEA, 2016

9.3 Decommissioning experience

Worldwide, several countries have gained significant experience in nuclear decommissioning. The USA has decommissioned nine nuclear power plants, and currently 19 nuclear power plants are undergoing decommissioning. This experience also benefits the EU as European actors are active participants in the US market, and vice versa. Within the EU there are just a few examples of countries that have experience in nuclear decommissioning: Germany, Slovakia, Spain, France, and Sweden being at the forefront.

Germany

In 2011, after the Fukushima event, Germany decided to end the commercial operation of NPPs by the end of 2022. This led to the subsequent shutdowns of NPPs and by the end of 2021, Germany had a total of 30 closed commercial nuclear reactors, corresponding to the second largest fleet of closed reactors worldwide. Only three nuclear power plants remained operational after the originally proposed date and were shut down in April 2023[245]. Including prototype and research reactors, it also has the second highest number of fully decommissioned units. German utilities have been decommissioning NPPs for several years and several plants, such as **Stade, Obrigheim, and Mülheim-Kärlich**, have already been decommissioned or are in various stages of decommissioning.

The German decommissioning market is expected to create several opportunities for foreign and domestic actors to provide the necessary expertise to develop the decommissioning market. Germany's decommissioning market is composed of multiple decommissioning projects being carried out in parallel.

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243 In France, all decommissioning projects include conventional demolition of all the buildings on-site up to one meter below ground level.

244 In Spain, greenfield is the target end state. However, the duration of seven years is only an assumption for the cost estimate, planning and financing, rather than a mandate.

245 This political decision was widely accepted for the last ten years, until Europe's energy crisis of 2022. The event resulted in calls for some plants to continue operating. As of October 2022, three plants, Emsland, Isar2 and Neckarwestheim-2, will remain operating until spring 2023 to ensure energy security during the cold winter months.

Table 9.2 Summary of German nuclear power plants

Technology	Age range (years)	Status
9 BWR	9 – 37	9 shutdowns
20 PWR	0.5 – 37	20 shutdowns
2 HTGR	3 – 21	2 shutdowns
1 FBR	13	1 shutdown
1 PHWR	18	1 shutdown

Note: BWR: Boiling Water Reactor, PWR: Pressurized Water Reactor, HTGR: High temperature reactor; FBR: fast breeder reactor; PHWR: pressurized heavy water reactor
Source: © Wimmers, Alexander et al., 2023 CC BY-SA 4.0[246]

France

France currently operates 56 nuclear power plants, of which six are shut down, eight reactors are in the decommissioning phase and several research reactors have been decommissioned.

Table 9.3 Summary of French nuclear power plants

Technology	Age range (years)	Status
60 PWR	23 - 44	56 operating 2 shutdowns 1 under construction
8 GCR	9 -24	8 decommissioning
2 FBR	13 - 36	2 shutdowns
1 HWGCR	18	1 shutdown

Note: PWR: Pressurized Water Reactor, GCR: Gas cooled reactor; FBR: fast breeder reactor; HWGCR: heavy water gas cooled reactor
Source: © Wimmers, Alexander et al., 2023 CC BY-SA 4.0

Sweden

Sweden has a fleet of 13 nuclear reactors at five different nuclear power plant sites, 12 of which are commercial. No Swedish commercial reactors have been fully decommissioned yet, but six are currently undergoing decommissioning. Compared to other countries, Sweden is quite far along in developing solutions for waste disposal and storage processes.

Table 9.4 Summary of Swedish nuclear power plants

Technology	Age range (years)	Status
9 BWR	25 - 46	4 operating 5 decommissioning
3 PWR	40 - 45	2 operating 1 decommissioning
1 PHWR	10	1 decommissioning

Note: BWR: Boiling Water Reactor, PWR: Pressurized Water Reactor, PHWR: pressurized heavy water reactor
Source: © Wimmers, Alexander et al., 2023 CC BY-SA 4.0

246 https://www.diw.de/documents/publikationen/73/diw_01.c.864222.de/diw_datadoc_2023-104.pdf

Within the EU, decommissioning experiences vary among the Member States due to differences in nuclear infrastructure, regulatory frameworks, national priorities, and available resources. The European Commission supports sharing of best practices that contribute to the collective knowledge and continuous improvement in nuclear decommissioning worldwide as will be discussed further in this chapter.

9.4 Funding of decommissioning activities

It is a universal requirement set up by the Nuclear Energy Agency that preliminary decommissioning plans are developed early in the licensing process i.e., well before a nuclear power plant is approved for construction. In general, **funds for decommissioning are required to be set aside from revenue obtained from the sale of electricity** generated by the nuclear power plant during its operating phase, or through a levy on sales of electricity of any origin. This is similar to the **Polluter Pays Principle (PPP),** an environmental principle that consists in "a requirement that the costs of disposing of radioactive waste must be borne by the holder of waste, by previous holders or by the producers of the product from which the waste came", i.e. the nuclear power plant operator should bear the costs associated with remediation and clean-up (decommissioning and radioactive waste management)[247]. A main obligation for the distribution of liabilities through the PPP is broadly accepted, but not fully implemented in every EU Member State. One of the risks associated with unclear key concepts and definitions is the absence of financial security in cases of insolvency[248]. Thus, it is pivotal, that detailed frameworks are put in place to ensure that regulations, policies, and strategies are set out and effectively implemented, and that financial, as well as non-financial responsibilities, are clearly defined and allocated to those responsible for discharging the liabilities.

In the EU, requirements for financing decommissioning liabilities are formally established in accordance with the legal system of each Member State, but overarching regulations exist. The European Council, the European Commission and the Parliament highlighted the importance of decommissioning funds in a joint statement noting that "*separated management of decommissioning funds is essential to secure both the availability of funds to pay for decommissioning and radioactive waste management"*. This is further supported within **the Radioactive Waste Directive** in 2011[249]. To reiterate, **funding of nuclear decommissioning activities is primarily the responsibility of Member States**. However, there are certain mechanisms and regulations at the EU level that provide guidance and support to enhance the requirements for decommissioning funds to be in place on time and encourage a more proactive approach by the Member States.

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247 It is based on the notion that those who benefit from certain activities should also assume the financial responsibility for addressing the environmental consequences, if there are any.

248 https://www.eca.europa.eu/Lists/ECADocuments/SR21_12/SR_polluter_pays_principle_EN.pdf

249 2011/70/EURATOM Council Directive establishing a community framework for the responsible and safe management of spent fuel and radioactive waste. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32011L0070

9.4.1 Funding mechanisms and practices

Legal and regulatory frameworks are established across EU Member States for the creation of **decommissioning funds** and to warrant that they will not be diverted for other purposes. The common themes in such regulations are:

- **Contributions to funds are made by facilities from the beginning of operation** to ensure sufficient funds are available at the time of final shutdown to cover all decommissioning and waste management expenses.
- **Contributions are in line with the nuclear power plant's estimated lifespan** and chosen strategy, to cover decommissioning of the facility.
- **The funds are managed and reviewed periodically** in a manner ensuring liquidity compatible with the timetable for decommissioning obligations.
- **Legal and administrative remedies are available** and enforceable in the event of non-compliance with the above[250].

In general, **decommissioning funds are created from business revenues.** It also has to be highlighted that **nuclear is the only energy source that includes decommissioning and** radioactive **waste management cost in the price of electricity and makes provisions that way.** In almost all cases, the size of the necessary fund is reviewed on a regular basis, generally between one and five years[251]. It is then agreed with the government, either directly or by way of the regulator[252]. However, there are considerable variations between Member States in terms of the details of these formal legal requirements. **Most Member States require that the total funding for decommissioning is provided at shutdown (Belgium, France, Sweden, Slovakia etc.)**, this nevertheless varies among Member States.

The management of decommissioning funds typically rests with the national authorities or entities designated by each Member State. The exact structure and organization vary but generally, the following entities or stakeholders are involved: **nuclear regulatory authorities, government agencies, decommissioning entity, and utility companies.** The actual management of the accumulated assets of the fund may be entrusted to a variety of custodian banks or asset managers, but it is clearly stated by the European Commission that a **secure and prudent risk profile should be pursued** in the investment of the plan, ensuring that a positive return is achieved[253]. The options for asset management include investment in national currency bonds, international currency bonds, national equities and international equities or investment in real estate. The range of options available in any given instance, however, may be restricted as a matter of national or fund policies, and/or fund investment strategy over the accumulated funds. Irrespective of the management approach followed, **mechanisms are needed to address risks** ranging from errors in the assumptions - inflation, the

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250 https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52018PC0467&from=ET

251 The national body should annually review the financial resources gathered and periodically, at least every five years, the decommissioning cost estimates.

252 Member States should set up or appoint a national body capable of providing an expert judgment on fund management and decommissioning cost matters. This body should be independent as regards the contributors to the fund.

253 https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2006:330:0031:0035:EN:PDF

discount rates and market turbulences and **to retain their value**. As the operator has no influence on the financial management of an external decommissioning fund, the EC recommends that the value of the investments **should be guaranteed by the Member State** to ensure that adequate funds are available when required, even if a nominal loss is made by the independent manager of the invested amounts by the time these financial resources are to be used[254]. It is also supporting the view that if the management of an internal fund underperforms, the operator should be responsible for ensuring that adequate funds are available when needed.

A fundamental methodological difference between EU Member States[255] is whether future decommissioning provisions are based on undiscounted costs[256] or on discounted costs[257]. Given the long timescales involved this makes a significant difference to the funds that the operators must set aside and the available funds in case of prematurely or early shutdown of a nuclear power plant.

Furthermore, according to the European Commission, financing decommissioning should focus on the independence of the involved parties to avoid situations where the operator has power of authority to dispose of the decommissioning funds and aim at reducing any possible situation where financial funds obtained by the operator can be used for different purposes[258]. In some Member States funds are provisioned specifically for decommissioning and cannot be used for another purpose. Another issue, mentioned above, that arises even with best practice is that **when premature permanent shutdown for decommissioning occurs**, for example due to political or social pressures, the funds in place might not be sufficient. Therefore, it must be taken into consideration that decommissioning funding arrangements may still be vulnerable to earlier than expected plant closure.

To conclude, **decommissioning funds management and the mechanics used for it are a complex landscape** to manage. It varies significantly across EU Member States, and it is not always clear to which extend these funds are protected against financial crises or variations in the expected returns, or how potential changes in operating times of NPPs could affect the time frame for the build-up of funds. Moreover, it also has to be understood that decommissioning funding comes with other challenges even if the right regulations, policies, and strategies are in place. For example, two opposing trends which impact the timing of when reactors enter the decommissioning phase have been observed: While on the one hand, in recent years operating licence extensions have become more common, on the other hand we see changes to political (e.g., Germany) or

254 https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2006:330:0031:0035:EN:PDF

255 For example, in France a common practice in accounting for long-term provisions is funds accumulated today are discounted to future values. Each operator has a different approach in terms of inflation rates and other measures, but the maximum discount rate value is mandated by the French state. From 2024 onwards, the value may not exceed the real long-term rate published by the European Insurance and Occupational Pensions Authority (EIOPA).

256 whereby the full estimated costs must be accrued)

257 whereby funds are assumed to grow, though investment, over and above the rate of expected inflation

258 https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2006:330:0031:0035:EN:PDF

economic conditions (e.g., Sweden) which impact the timing of decommissioning in a contradictory manner.

9.4.2 Cost estimates

Before nuclear power plants reach the end of their operational lives it is necessary to estimate the costs associated with decommissioning and therefore, ensure the right amount of decommissioning funds is available. As mentioned in the previous subchapter these estimates are crucial for budgeting and financial planning, as well as for ensuring that the decommissioning is carried out in a safe and environmentally responsible manner. While **decommissioning cost estimates are subject to a high degree of risks and uncertainties these may be lower with increasing experience gained by involved stakeholders**. Factors that influence decommissioning cost estimates in the nuclear industry and how decommissioning costs should be estimated were addressed as part of the 2006 EC Recommendation[259]:

- Technical decommissioning of the installation and radioactive waste management should be addressed separately, based on separate cost calculations.
- To ensure that adequate financial resources are available, cost calculations should be based upon a prudent choice from the realistically available alternatives and subject to the external supervision and agreement of the national body.
- All cost estimates should be site-specific and based upon best available estimates.
- If during implementation the decommissioning project proves to be more expensive than the approved cost estimates, the operator should cover the additional expenses. This aspect should be carefully addressed should the operator change during or beyond the lifetime of the nuclear installation.
- When estimating decommissioning liabilities understanding what activities and liabilities are to be covered is essential.

The detailed structuring of the different decommissioning phases depends on the specific national legal frameworks for decommissioning but mainly can be split within the following cost categories or in other words activity groups[260]:

- Pre-decommissioning actions
- Facility shutdown activities
- Additional activities for safe enclosure and entombment
- Dismantling activities within the controlled area
- Radioactive waste processing, storage, and disposal
- Site infrastructure and operation
- Conventional dismantling, demolition, and site restoration
- Project management, engineering, and support
- Research and development

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259 https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2006:330:0031:0035:EN:PDF

260 International Structure for Decommissioning Costing (ISDC) of Nuclear Installations. NEA, 2012.

- Fuel and nuclear material
- Miscellaneous expenditures

Cost estimations vary considerably in format, content, and practice both within and across countries. These differences may have legitimate reasons but make the process of reviewing estimates complicated. Hence the Nuclear Energy Agency, the International Atomic Energy Agency and the European Commission joined forces to standardise itemisation of decommissioning costs either directly to produce cost estimates or for mapping estimates onto a standard, common structure for purposes of comparison. The exercise resulted in the **International Structure for Decommissioning Costing (ISDC)**[261] **which provides general guidance on developing decommissioning cost estimates.**

Thus, **once each cost category is properly established decommissioning plans and estimates can be developed further.** In most EU Member States the designated competent authority plays a major role in reviewing the cost and approving the selected decommissioning strategy. The table below shows an overview for selected countries.

Table 9.5 Mechanism for the review of the decommissioning estimates

Review by mechanism	Country
Utility or decommissioning entity	Belgium, Italy
Both the utility, decommissioning entity and the government and/or nuclear regulator	Finland, France, Netherlands, Spain
Administrative body for the fund, on the basis of estimates produced by the operator	Slovakia
National nuclear regulator	Sweden

Source: OECD – NEA, 2016

There are commonly three types of cost estimates used. Each has a different level of accuracy based on when during the lifespan of NPPs the valuation occurs[262]:

- **Order-of-magnitude estimate:** one without detailed engineering data, where an estimate is prepared using scale-up or -down factors and approximate ratios. It is likely that the overall scope of the project has not been well defined. The level of accuracy expected is -30% to +50%.
- **Budgetary estimate:** one based on the use of flow sheets, layouts and equipment details, where the scope has been defined but the detailed engineering has not been performed. The level of accuracy expected is -15% to +30%.
- **Definitive estimate**: one where the details of the project have been prepared and its scope and depth are well defined. Engineering data would include plot plans and elevations, piping and instrumentation diagrams, one-line electrical diagrams and structural drawings. The level of accuracy expected is -5% to +15%.

261 International Structure for Decommissioning Costing of Nuclear Installations, 2012.
262 https://www.oecd-nea.org/upload/docs/application/pdf/2019-12/isdc-nuclear-installations.pdf

Each of the three types should use cost estimations from other decommissioning projects. For example, estimation handbooks, equipment catalogue, performance data are some of the sources that can be used to develop cost estimates. However, such **data is not very commonly shared and publicly available**.

It is important to understand the design mechanism behind cost estimates to develop realistic and cost-effective decommissioning strategies, both crucial parts of the aforementioned fund management. **There is not a universally one-size-fits-all standard for developing decommissioning cost estimates but sharing experiences and lessons learnt would speed up the process of establishing common practice.** This would lead to more efficiency and potentially even cost savings. The newly established NuBaFA[263] looks exactly at this from three perspectives:

- Cost estimates and their uncertainties
- Cost modelling management
- Risk profile of funds

Firstly, calculations are based on both the estimated decommissioning costs and on the various assumptions made, including the time when the costs may arise, inflation, and the anticipated nominal interest rate on the accumulated capital. The cost estimation process is a complex task that presents a significant challenge. However, many projects were completed or are in an advanced phase of decommissioning in the EU and therefore several lessons can be drawn from that. Yet it is not commonly shared information amongst EU Member States, regulators, operators, and the industry. Member States shall submit reports to the European Commission every three years on the implementation of the Directive, information on cost assessments and financing schemes used but the requirement to review and update is not fulfilled by all.

To restate, the biggest concern around cost estimates is that they are often underestimated and additionally they are not directly comparable across countries and practices. Across the EU, **national policies differ substantially**. Member States have centralised or decentralised facilities dealing with decommissioning activities. Initiatives have been launched by international and intergovernmental bodies, the UK´s Nuclear Decommissioning Authority's Business Plan published in 2022 provides an example[264]. The Business Plan's purpose was to provide a summary of activities for the 17 UK nuclear power plants over the next three years. As part of the plan funds and expenditure figures are reviewed. In the EU, NuBaFA[265] was created with a similar purpose: To look at uncertainties in cost estimates, financing schemes and funds management, and increase transparency toward all stakeholders.

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263 https://www.eumonitor.eu/9353000/1/j9vvik7m1c3gyxp/vljy59t1b7z3

264 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1062302/Business_Plan_2022-2025_220322.pdf

265 Group of experts on financial aspects of nuclear decommissioning and spent fuel and radioactive waste management

The ecosystem would benefit from a **set of enhanced standards, methodologies, and case studies** to be employed in future reviews of cost estimates when addressing residual uncertainties. Secondly, showing and sharing best practices while promoting and providing a set of recommendations to address challenges will help in unifying the management of cost estimates modelling. When further looking at efficient decommissioning funding mechanisms the risk profile is a key feature. Sharing relevant data and detailed examples, with a focus on the risk assessments and costs calculations, for example via the presentation of case studies would contribute to setting a benchmark of the risk profile.

When it comes to an actual **total cost of decommissioning of nuclear power plant facilities across the EU,** there are considerable **differences between Member States,** and it is not commonly publicly available information in all Member States.

In conclusion, decommissioning cost estimates in the nuclear industry depend on a range of factors, including the size and complexity of the plant, regulatory requirements, chosen decommissioning method, site-specific considerations, and public perception. Because there is no universally accepted standard at present for developing decommissioning cost estimates, the existing estimates come with considerable variability in format.

9.5 Recycling of decommissioned components and materials

The decommissioning of nuclear power plants includes the safe removal of radioactive materials, the demolition of infrastructure, and the management of radioactive waste. Thus, the **recycling of decommissioned components and materials in the nuclear landscape is an important aspect of radioactive waste management** as was already discussed in depth in chapter 8. The EU as well as the International Atomic Energy Agency and Nuclear Ener Agency have robust regulatory frameworks in place to promote the recycling and reuse of nuclear materials to the extent possible, while ensuring safety and environmental protection. The Waste Directive requires that all EU Member States have a national policy for spent fuel and radioactive waste management and Member States should submit a national report on the implementation of this Directive to the European Commission every three years[266]. Based on those, the European Commission drafts a report on the overall implementation of the Radioactive Waste Directive and an inventory of radioactive waste and spent fuel present in the Member States and the potential prospects.

The decommissioned components and materials can often contain valuable resources, such as metals and other materials, that can be recycled or reused. **By recycling these materials, the EU seeks to reduce the need for raw material extraction and minimize the environmental impact** associated with mining and processing[267]. This goes hand in hand with the EU´s waste hierarchy approach which prioritises waste prevention, reuse, and recycling over disposal and aligns

266 Since August 2015.

267 National legislation may propose different approaches but keeps the same objective. For example, French legislation does not define levels to release material from radioactive classification but implement a strict process of separating what is in hot areas or not.

with the broader goals of the EU's circular economy, which aims to minimize radioactive waste generation and promote sustainable resource use[268].

The recycling of decommissioned components and materials involves several steps. First, the components and materials undergo classification and assessment to determine their radioactivity levels and suitability for recycling[269]. This process helps identify materials that can be safely recycled and those that require special treatment or disposal due to the type of radioactivity and other characteristics like the difficulty to separate radioactive substances. Once the materials are deemed suitable for recycling, they undergo various treatment processes to remove radioactive contaminants. These processes can include mechanical separation, chemical treatment, and other specialized techniques[270]. **The goal is to reduce the radioactive content of the materials to acceptable levels for recycling or reuse**. To ensure the safe and controlled recycling of nuclear materials, the EU has established stringent regulatory frameworks. **The main legislative framework is the Euratom Basic Safety Standards Directive (BSSD)**[271], which sets the radiation protection standards for the management of radioactive waste, including the recycling of materials. In addition to regulations, the EU supports research and development efforts to advance recycling technologies and improve the efficiency and safety of recycling processes. Funding programmes such as Horizon Europe[272] provide support for research projects focused on radioactive waste management, including recycling and reuse initiatives.

It is worth noting that while recycling plays a significant role in radioactive waste management, **not all decommissioned components and materials can be recycled**. Some materials may have high levels of radioactivity or complex chemical compositions that make recycling impractical or unsafe. In such cases, proper disposal methods, such as long-term storage or deep geological repositories, are employed to ensure the safe isolation of radioactive waste from the environment.

In conclusion, the **EU recognizes the importance of recycling and reusing decommissioned components and materials in the nuclear landscape**. Through regulatory frameworks, research initiatives, and the promotion of circular economy principles, the EU aims to maximize the recycling of nuclear materials while ensuring safety and environmental protection.

9.6 Necessary capacities for decommissioning

When looking at decommissioning capacities, the readiness for dismantling several nuclear power plants at once depends on **four main factors**: unified framework, adequate financing, human capital i.e., qualified personnel and supply chain.

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268 The Waste Framework Directive is the EU's legal framework for treating and managing waste in the EU.
269 https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32011L0070
270 Decontamination Techniques Used in Decommissioning Activities. NEA, 2009.
271 https://eur-lex.europa.eu/eli/dir/2013/59/oj
272 https://commission.europa.eu/funding-tenders/find-funding/eu-funding-programmes/horizon-europe_en#:~:text=Contact-,About%20the%20programme,the%20EU's%20competitiveness%20and%20growth.

Regulatory frameworks and national policies play a vital role in ensuring the safe decommissioning. The capacity and capability to monitor and enforce compliance with safety and environmental regulations for multiple simultaneous dismantling projects is of paramount importance. **Ensuring regulatory bodies have sufficient resources and expertise** to handle the increased workload that comes with simultaneous decommissioning projects has been initiated by mapping and assessing how unified the regulatory landscape is and how the overall industry works. For example, the UK oil and gas industry after the oil price crash in 2015 started to investigate decommissioning. The industry realised the enormous task decommissioning is and created the National Decommissioning Centre (NDC) in the North-East of Scotland. This organisation brought together all relevant parties and is now pivotal for establishing and ensuring best practices. To do so, it regularly reviews decommissioning cost evaluation mechanisms, changes to calculated liabilities, monitors changes to market conditions, as well as the timing of decommissioning to reduce the risks of inadequate decommissioning funding and overall cost. Moreover, in 2022 NDC and the Nuclear Decommissioning Authority (NDA) have signed a three-year collaborative research agreement – the first of its kind – between the nuclear and oil and gas decommissioning sectors.

Another crucial consideration must be given to the financial aspect. Dismantling nuclear power plants is a costly endeavour, and simultaneous dismantling of multiple nuclear power plants may require **significant financial resources**. Adequate funding must be secured to cover all expenses associated with decommissioning, including personnel costs, waste management, site restoration, and long-term monitoring. **Continuous and diligent management of decommissioning funds** and ensuring that adequate financial resources are available is of paramount importance to ensure a successful and safe process and a way to avoid compromising safety or leaving decommissioned sites in an incomplete or unsafe state. The European Commission must carefully evaluate the financial implications of simultaneous dismantling projects and ensure sufficient decommissioning funds are allocated to prevent any shortfall that could hamper the process.

A third factor to consider is the **availability of qualified personnel, expertise and resources**. The decommissioning phase involves a range of specialised tasks, including the handling and removal of radioactive materials, dismantling of structures, waste management, and environmental remediation. Since **the industry of decommissioning nuclear power plants could be rapidly expanding in the future** and the EU could face an increase in the number of shutdown reactors in the coming decade[273]. In the upcoming years **decommissioning may require many professionals**. This long and labour-intensive phase on average takes 10-20 years and employs an average of 500 people per plant. Thus, as stated in chapter 7, over 30 years, up to 40,000 people might be required to decommission nuclear power plants. This number can be significantly reduced through optimisation of the decommissioning sequence and favouring workers' mobility. The experience of decommissioning experts can

[273] As mentioned in chapter 3, between 2040 and 2050 78 reactors will end their operation (assuming 60 years of operation).

afterwards be utilised in other industries that may require decommissioning, such as conventional powerplants, oil and gas platforms and others. Another possibility to tackle this is retraining experts which is a best practice in other industries.

Furthermore, in chapter 7 **knowledge sharing** is stated to be an important aspect when looking at capacities. In the EU the **JRC coordinates the structuring and dissemination of knowledge gained** in the ongoing nuclear decommissioning projects in Europe. Its **nuclear Decommissioning Knowledge Management** (DKM) aims at gathering, screening, storing, and sharing knowledge gained by users and organizations involved in decommissioning programmes. The JRC itself is managing decommissioning of several nuclear research facilities, thus the DKM initiative is of key importance. For example, one of its knowledge products, as a service, is the **training programme** European Learning Initiatives for Nuclear Decommissioning and Environmental Remediation **(ELINDER**)[274]. Another knowledge product, as a media, is aNDy, the virtual nuclear decommissioning narrator[275]. Other knowledge products, like documents, are currently generated by the Nuclear Decommissioning Assistance Programme (NDAP)[276]. There are also the International Atomic Energy Agency and Nuclear Energy Agency who play an important role in the process. These are just a few positive examples showing that the EU is taking the right steps to ensure necessary capacities are available for safe and successful decommissioning.

Simultaneous dismantling projects could inevitably increase the volume of radioactive waste generated in a short time, demanding an increase in required waste management infrastructure, storage facilities, and disposal options. The EU must prioritise the development and implementation of safe and effective radioactive waste management strategies to mitigate any adverse impacts during and after the dismantling process. Thus, another concern of interviewed stakeholders was whether the supply chain for decommissioning can meet the steeply rising demand. The availability of equipment, tools, and radioactive waste disposal facilities must be assessed to ensure it can handle the demands of decommissioning projects but given that as of 2022 worldwide **only eleven commercial nuclear power reactors over 100 MW have been completely radiologically decommissioned,** it is “learning-by-doing”[277]. This learning accumulates slowly, because decommissioning is a lengthy process, but it is already benefitting from the experience gained abroad, in particular in the US. The primary concern regards the readiness of the nuclear supply chain and its capacity and capability to handle an increasing number of dismantling projects simultaneously. This can be answered by closely following the story of Swedish Uniper, who is currently refining decommissioning methods to streamline the work.

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274 ELINDER: The European nuclear decommissioning training programme - European Commission (europa.eu)

275 aNDy the nuclear decommissioning narrator - European Commission (europa.eu)

276 Six knowledge products have been generated so far, with more to come in the coming years.

277 European decommissioning market from 2022 onwards. VTT, 2022.

Case study: Sweden on its path to simultaneous decommissioning

Sweden has been actively involved in nuclear decommissioning projects as part of its long-term strategy to phase out nuclear power. The Swedish nuclear decommissioning project primarily focuses on two nuclear power plants: **Barsebäck and Oskarshamn**.

Out of Sweden's twelve commercial reactors, six are currently undergoing decommissioning and dismantling: Barsebäck 1 and 2, Oskarshamn 1 and 2, and Ringhals 1 and 2.

Decommissioning of Barsebäck 1 and 2 and Oskarshamn 1 and 2 are being conducted in a coordinated 1 programme covering the decommissioning of all 4 reactors in order to leverage experiences, to refine decommissioning methods and to streamline the work when moving from one reactor to the next. The decommissioning strategy is to work from the inside out, so that the most radioactive waste is removed first. Afterwards comes a systematic review of the entire facility, where different parts and systems are decommissioned according to a shared, synchronized timetable. Approximately 6% of the material at the facilities (67,000 tons) is radioactive, most of which is low-level. Around half of these 67,000 tons is expected to be classified free from radioactivity and can therefore be processed like conventional waste and recycled.

The **decommissioning of the closed reactors at Barsebäck and Oskarshamn will continue until 2028**, after which some traditional dismantling will remain. During the 2021-2023 period the technical decommissioning works of the whole programme have been carried out in a partnership between Fortum and Uniper on behalf of the license holders Barsebäck Kraft AB and OKG AB. Fortum and Uniper will continue their close cooperation in the programme also in the future. However, due to changes of Uniper's ownership, that took place in the end of 2022, the parties (Fortum and Uniper) have agreed some changes in the form of cooperation from 2024 onwards. Fortum will thereafter be more focused on decommissioning activities for the Oskarshamn site in a role of owner while the coordination of the whole programme consisting of all 4 units remains under Uniper's responsibility.

Source: Uniper

To conclude, it appears that highly specialised players are emerging in the nuclear industry to assert themselves on the still nascent nuclear decommissioning market potential addressing supply chain bottlenecks. It is essential to assess whether these suppliers and manufacturers have the capacity to meet the increased demand for items such as radiation shielding materials, waste containers, and decommissioning tools. Additionally, evaluating the capability of suppliers to deliver high-quality products and services within the required timelines becomes crucial to ensure the smooth progress of dismantling projects.

9.7 Conclusions and recommendations

The EU's nuclear decommissioning landscape is over the medium-term facing an increasing number of nuclear power plants that are reaching the operational retirement age and this is expected to drive decommissioning. At the same time, the lifetime extension of nuclear power plants with favourable government policies may ease the medium-term challenges.

Current systems and practices in decommissioning of nuclear power plants aim at preserving safety for future generations. However, **policies, legislation and best practices differ** on detailed objectives to be achieved and vary significantly across EU Member States. Thus, **enhancing transparency** and putting in place better methods to collect and share information would contribute greatly to future assessments and improvements. Lessons can be drawn from other industries.

While changes in the regulatory framework may be necessary to reflect the natural evolution, long-term consistency needs to be ensured to provide a better **understanding of the uncertainties affecting decommissioning** activities in

some Member States and how to best take them into account. **Adoption of more homogeneous methodologies** and exchanging experiences has been repeatedly advocated also in the international arena. Regulatory bodies currently in place for establishing policy, legislation, and standards, for decommissioning are adequate, however, it may be convenient to modify practical arrangements by creating new bodies, preferably at higher than national level to maintain and further develop **unified expertise available in one transparent place.** It is recognised that several initiatives already exist such as the NuBAFA or for example the Inno4Graph[278].

Current concerns include the ability to accurately calculate and demonstrate the validity of decommissioning cost estimates[279]. In general, information to the public is restricted in several key areas, including estimates of total decommissioning costs, details of the cost estimation methodology, provisions accumulated per plant, investment strategy of decommissioning funds, and details of payments from decommissioning funds for decommissioning activities. **Through transparent and participatory approaches**, the EU aims to achieve adequate funding because if licensees are unable to pay for decommissioning, the liability and remaining financial responsibility may ultimately fall on the taxpayer. This, however, does not apply to all Member States as some of them fully comply already with the requirement of transparency.

Sufficient human resources with the necessary expertise and training must be available to manage and carry out decommissioning tasks safely and effectively. This coupled with the just emerging supply chain capacities could create several opportunities for foreign and domestic actors to provide the necessary expertise to develop the decommissioning market. The European Commission and JRC also promote knowledge exchange and collaboration among EU Member States regarding decommissioning practices. Experience and expertise gained from previous decommissioning projects are shared to improve efficiency and safety in future endeavours. The European Commission provides platforms for sharing best practices, conducting research, and developing innovative technologies for decommissioning activities.

While there is an extensive understanding of the techno-economic aspects of decommissioning, social aspects remain less investigated. Communication with stakeholders, their involvement and engagement should also be thought of as key enablers for successful decommissioning. Furthermore, public perception and stakeholder involvement can influence decommissioning cost estimates. Stakeholder engagement and public consultation processes are often undertaken to ensure transparency and address concerns, but they can also contribute to project delays and cost overruns.

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278 https://www.inno4graph.eu/

279 Decommissioning costs may also influence investments in new capacities as discussed in other parts of this report. Investments may reduce in the 2040s when there is a decommissioning peak. Possible cost overruns for decommissions may have a negative effect on investors' interest in new nuclear activities or the required risk compensation (i.e., discount rate) may increase.

The readiness for dismantling several nuclear power plants at once depends on a range of factors, including the availability of qualified personnel and resources, financial considerations, regulatory oversight, radioactive waste management capabilities, and stakeholder involvement. Each project must be assessed individually to determine its feasibility and ensure that safety, environmental protection, and public acceptance are prioritized. This ambitious undertaking poses several challenges that demand careful consideration.

The analysis of the input and feedback from the stakeholders of the study provided us with the following recommendations[280] to facilitate and enhance the decommissioning landscape:

European level

- Support activities focused on enhancing decommissioning funds. For example, reviewing the EU regulatory framework or providing further guidance to harmonise decommissioning financing, increase transparency, oversight, and encourage collaboration among EU Member States.
- Assess the possibilities to establish a EU-wide decommissioning fund shortfall insurance. The insurance could balance funds between plants generating surplus funds from life extensions against plants with lacking funds, i.e. due to premature shut down because of political pressure or challenging market environments.
- Define a regulatory framework to further aid and add clarity to the prudence principle, which plays an important role in the field of financial asset management as stated in the 2006 recommendation. It is recommended that further guidelines are also established.
- **Further promote knowledge exchange and collaboration among EU Member States regarding decommissioning practices.** Experience and expertise gained from previous decommissioning projects must be shared to improve efficiency and safety in future endeavours. Thus, the European Commission should continue with facilitating sharing of best experience and practices, as well as further exploring possibilities to set up a community practice while developing innovative technologies for decommissioning activities.

Member States

- **Proactively look at uncertainties in cost estimates, financing schemes and funds management, and at ways to increase reporting transparency toward all stakeholders across Member States, by utilising the NuBaFA initiative.**
- Oversee different regimes for estimating, collecting, and managing decommissioning funds as there are significant differences in the operation, governance, investment, and accessibility of the existing funds across the EU. Thus, some Member States should increase transparency and actively participate in the EU recommended activities.

[280] Chapter 11 presents a list of priorities. These are concrete recommendations which require immediate actions, as discussed with the study's stakeholder group, Member State representatives and NGO representatives during a workshop 5-6 September 2023.

- Follow the European Commission's recommendation to prepare annual reviews of financial resources gathered and periodically, at least every five years, the decommissioning cost estimates.
- Establish more transparent access about ongoing decommissioning activities which may enhance the transparency of information as already proposed by the European Commission.
- Use the same rules for the free release of decontaminated material, in particular resulting from the decommissioning process to reduce the amount of radioactive waste to be treated and thus reduce the overall costs.

Industry

- **Collaborate and share best practices as well as the development of vertically integrated supply chains with specialized staff.**
- Learn from other industries and ensure the exchange is done through the European Commission by the industry in a proactive manner and that lessons continue to be fed back into new facility designs.

10 The ecosystem's contribution to the EU economy

This chapter analyses the macroeconomic effects of the nuclear energy sector, including impacts from the operation of existing and new nuclear power plants as well as impacts related to the construction of new and decommissioning of existing facilities in the future. In addition, the nuclear fuel industry is considered.

The economic analysis considers the contribution of the nuclear energy sector to the overall economy of the EU. It provides an assessment of the current economic benefit generated directly by the nuclear industry as well as the effects of the economic activities of the nuclear sector throughout the EU. The potential of the nuclear ecosystem to contribute to EU energy and climate objectives, to provide economic output in the EU especially in terms of gross value added (GVA) and employment has been analysed.

Key findings

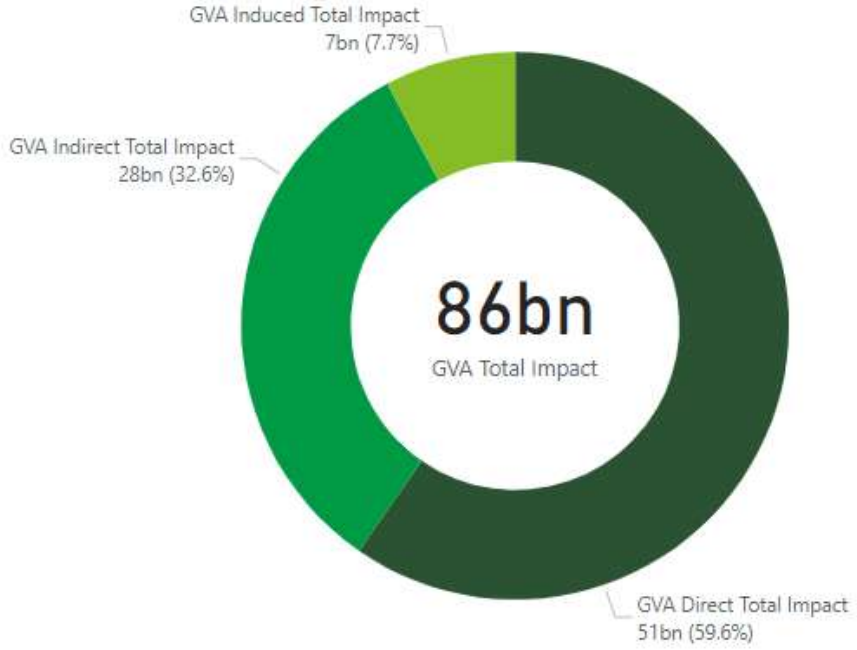
- The **current Gross Value Added (GVA)** of the nuclear energy sector encompasses an **estimated average contribution to GDP of 86 billion EUR** in total in 2023 – compared to a total GDP of around 15 trillion EUR for all EU Member States combined.
- This corresponds to an **estimated 653 thousand jobs** maintained by the nuclear sector in 2023.
- The assumed evolution of the nuclear ecosystem could provide a GVA of, on average **113 billion EUR per year between 2023 and 2050**.
- Breaking down the GVA, a **significant impact on private households** (wages and salaries) is expected, representing an average total employment **effect of around 800 thousand jobs** per year between 2023 and 2050.
- The estimations imply a significant increase in GVA, driven by economic activity **related to construction** of new **and decommissioning** of old NPPs.
- Potential **constraints, especially in the supply chain** and related to the construction of new nuclear power plants **need to be overcome** to capitalize the potential.

10.1 Current contribution to the nuclear energy sector (2023)

In 2023, the nuclear industry encompasses 100 nuclear power reactors operating in 12 MS with a total installed nuclear capacity of approx. 100 GW. The contribution of nuclear power generation to the EU economy can be analysed by looking at two types of impacts. Firstly, there are the direct contributions made by the sector, encompassing its role in fostering GDP growth, generating employment, and yielding tax revenues. Secondly, there are indirect and induced effects, emanating from the contributions of supplier and employees, which in turn sustain and bolster the economies of the Member States.

The current gross value added of the nuclear energy sector encompasses an estimated average contribution to GDP of around 86 billion EUR, including 51 billion EUR through direct means, 28 billion EUR through indirect means, and 7 billion EUR through induced means.[281]

Figure 10.1 Estimated GVA in the EU in billion EUR in 2023

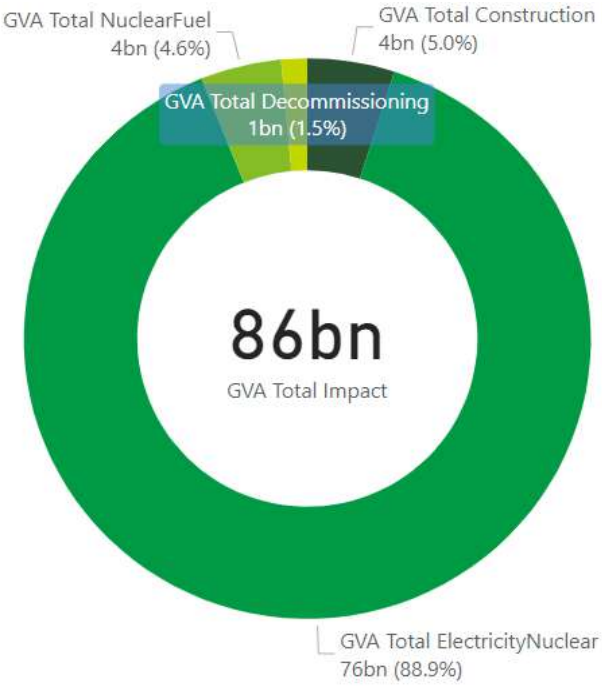


Source: Study team

[281] The direct component measures economic activity directly associated with Nuclear Energy's production of goods and services – that is, the payments to the factors of production. For example, labour is a key input factor in the service provision process, with the total salaries of workers representing a direct measure of the activity generated by industry. The indirect component measures the economic activity generated by the Nuclear Energy industry through its demand for the outputs of other industries. The induced component measures economic activity arising from income being spent when employees of the nuclear energy industry and those in its supply chain spend their wages.

The GVA can be further distributed among the primary subsectors within the nuclear industry that were considered, namely construction, operation, fuel and waste management, and decommissioning:

Figure 10.2 Estimated GVA in the EU in billion EUR in 2023 by primary subsector



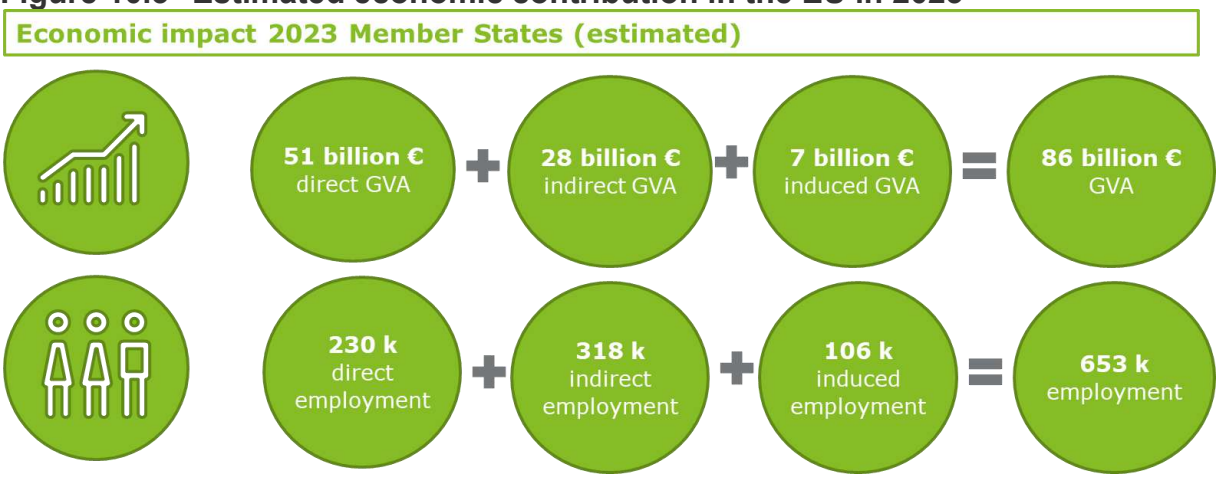
Source: Study team

This contribution to GDP is composed, among others of wages and salaries, which emphasizes the sector's impact on private household income. Currently, the sector generates 28 billion EUR in gross wages and salaries, including for employees directly employed in the industry as well as related to indirect and induced employment effects. This corresponds to an estimated 653 thousand jobs[282] in the nuclear sector in 2023.

Furthermore, the nuclear industry is contributing directly as well as indirectly to fiscal revenues generated in EU Member States. Presently, the industry is estimated to have an impact of 66 billion EUR on fiscal revenues, including contributions to social security systems. Collectively, this underscores the industry's significant financial contribution to fiscal revenues.

[282] The number of jobs/FTE is calculated by using labour coefficients (number of employees/FTE per output).

Figure 10.3 Estimated economic contribution in the EU in 2023



Source: Study team

Figure 10.4 Estimated economic contribution in the EU in 2023



Source: Study team

10.2 Methodological approach and assumptions

This subchapter presents our general approach to economic modelling and the main assumptions, which are used to assess the economic impacts of the EU nuclear ecosystem until 2050. Further explanations of the methodology and the premises, as well as additional, detailed results for various indicators and by Member State are presented in Annex H[283].

The analysis was performed by applying an input-output model. It included an analysis of both the current economic impact of the industry on the EU economy as well as presentation of a measurable projection of its future benefits in the reference period 2023 to 2050. The analysis focused primarily on the EU Member States with operating nuclear facilities.

Our economic impact modelling and the corresponding assumptions are based on relevant literature and the qualitative findings of our study research. Additionally, the analysis incorporates available data and statistics. Our assumptions reflect the current trends and tendencies in the nuclear energy industry at the EU level. Information collected for the baseline of this study enables us to assess the current and potential future contribution to the EU's economy.

Based on the estimation of the total economic impact of the Nuclear Energy Ecosystem as of today (2023), the analysis estimates the potential economic impact until 2050, considering substantial changes (e.g. construction of new and decommissioning of existing power plants, etc.)[284]. Our study covers the investments, as well as the operational activities and the decommissioning activities of the nuclear energy industry in the EU. In this regard it includes a baseline scenario accounting for the potential way of development of the nuclear power industry.

Assumptions for production value of nuclear electricity and nuclear fuel activities

The statistical data and forecast are based on EXIOBASE data[285]. The dataset is used as the basis for the projection of electricity generated from nuclear power for the EU Member States with nuclear power plants. Output (production value) and corresponding gross value added (as a measure for GDP contribution) projections for 2023 - 2050 are conducted using granular plant-level nuclear power generation

283 It should be noted that, as with any economic analysis, the results depend on the modelling approach chosen and the underlying assumptions. For example, the results obtained within this analysis differ from those of the Economic and Social Impact Report from Deloitte, April 2019 (report prepared for nucleareurope (former FORATOM). In the study from 2019, on the one hand, a different methodological approach was chosen, and on the other hand, the aforementioned study has a different scope. In addition, some assumptions differ depending on the context of the analysis. Nevertheless, comparable results can be observed for some of the economic indicators against the background of the deviations outlined above.

284 The impact modelling for the Nuclear Power Ecosystem/Industry will have a time horizon of at least 15-20 years. This time horizon is normally used in our studies as it allows us to determine the concrete impacts at various levels without having the risk of being too imprecise regarding potential future events.

285 EXIOBASE is a global, detailed Multi-Regional Environmentally Extended Supply-Use Table and Input-Output Table. EXIOBASE 3 is the culmination of work in the FP7 DESIRE project and builds upon earlier work on EXIOBASE 2 in the FP7 CREEA project and EXIOBASE 1 of the FP6 EXIOPOL project. https://www.exiobase.eu/

capacity data from the questionnaires as well as publicly available information. Current prices of outputs for the respective sectors were calculated using average consumer price inflation in the Member States over the last 20 years and include a mid-term forecast from the IMF. For the long-term, an average (compound annual) inflation rate of 2.3% was applied. It is further assumed, that all nuclear energy produced is matching demand – at current average utilization rates – and output is limited by capacity. Capacity, respectively output, was modelled on a plant level and on an annual basis, taking into consideration planned decommissioning and new instalments of nuclear power plants. The following table presents the estimated contribution to GDP for the year 2023, which is the starting point of the analysis.

Table 10.1 Estimated Output and GVA Nuclear Electricity (billion EUR)

Member State	Year	Output Direct Electricity Nuclear	GVA Direct Electricity Nuclear
France (FR)	2023	38.71 billion EUR	21.4 billion EUR
Germany (DE)	2023	9.44 billion EUR	7.0 billion EUR
Spain (ES)	2023	8.77 billion EUR	5.3 billion EUR
Slovakia (SK)	2023	4.36 billion EUR	2.7 billion EUR
Belgium (BE)	2023	3.90 billion EUR	3.1 billion EUR
Sweden (SE)	2023	3.76 billion EUR	3.1 billion EUR
Finland (FI)	2023	2.37 billion EUR	1.9 billion EUR
Czech Republic (CZ)	2023	1.87 billion EUR	1.5 billion EUR
Hungary (HU)	2023	1.37 billion EUR	0.9 billion EUR
Slovenia (SI)	2023	0.80 billion EUR	0.4 billion EUR
Belgium (BG)	2023	0.66 billion EUR	0.5 billion EUR
Romania (RO)	2023	0.30 billion EUR	0.2 billion EUR
Netherlands (NL)	2023	0.30 billion EUR	0.3 billion EUR
Estonia (EE)	2023	0.00 billion EUR	0.0 billion EUR
Poland (PL)	2023	0.00 billion EUR	0.0 billion EUR

Source: EXIOBASE, Study team's compilation and calculation

Activities related to construction of new and planned decommissioning of nuclear power plants

The construction of new nuclear power plants and the decommissioning of old nuclear power plants until 2050 was modelled using information from the conducted questionnaires and publicly disclosed information. The associated costs for construction in current prices were allocated linearly between the assumed start and end of construction works, assuming a construction period of 10 years in each case. For decommissioning, the same assumptions have been applied, amongst others a period of ten years. Economic interdependencies were further modelled by dividing the construction and decommissioning costs into sub-

industries from the Global Industry Classification Standard, with an additional geographical allocation to individual EU Member States, based on desk research. The table below summarises the assumptions used for economic impact modelling regarding installed, shutdown and new capacity in the reference period 2023 - 2050 by EU Member State[286].

Table 10.2 Installed, shutdown and new capacity 2023-2050 – assumptions for economic impact modelling

Member States	Installed capacity 2023	Shutdown capacity 2023-2050	New capacity 2023-2050	Installed capacity 2050
Austria	0.0	0.0	0.0	0.0
Austria	0.0	0.0	0.0	0.0
Belgium	4.9	-4.9	0.0	0.0
Bulgaria	2.0	-1.0	2.0	3.0
Croatia	0.0	0.0	0.0	0.0
Cyprus	0.0	0.0	0.0	0.0
Czech Republic	3.9	-1.9	7.8	9.9
Denmark	0.0	0.0	0.0	0.0
Estonia	0.0	0.0	0.9	0.9
Finland	4.4	-2.8	6.0	7.6
France	61.4	-51.4	24.6	34.5
Germany	0.0	0.0	0.0	0.0
Greece	0.0	0.0	0.0	0.0
Hungary	1.9	-1.9	2.4	2.4
Ireland	0.0	0.0	0.0	0.0
Italy	0.0	0.0	0.0	0.0
Latvia	0.0	0.0	0.0	0.0
Lithuania	0.0	0.0	0.0	0.0
Luxembourg	0.0	0.0	0.0	0.0
Malta	0.0	0.0	0.0	0.0
Netherlands	0.5	-0.5	2.4	2.4
Poland	0.0	0.0	8.0	8.0
Portugal	0.0	0.0	0.0	0.0
Romania	1.3	0.0	1.9	3.2
Slovakia	2.3	-0.9	1.6	3.0
Slovenia	0.7	-0.7	1.2	1.2
Spain	7.1	-7.1	0.0	0.0
Sweden	6.9	-6.9	0.0	0.0
SUM	**97.4**	**-80.0**	**58.8**	**76.1**

Source: Member States questionnaire, Stakeholder interviews, IAEA PRIS database

286 Within the economic model, minor deviations from the values presented in the table are due, among other things, to the granular modelling of capacities at the level of individual power plants.

10.2.1 Baseline

The following information collected for the baseline of the economic analysis enabled the assessment of the current and potential future contribution of the nuclear industry to the EU's economy.

Nuclear electricity value chain

The figure below provides information on the nuclear energy value chain. This value chain, as considered in our analysis, consists of 4 main phases, which in turn can be subdivided into several smaller phases, and one longer phase. The four phases reflect the life cycle of a nuclear power plant, from construction to dismantling. We have focused our study on the economic impacts of the following four primary activities of the nuclear value chain: construction including pre-building activities, operation, nuclear fuel, and decommissioning. More specifically, we assess the impact of these four nuclear industry stages on GDP, employment, household disposable income and the trade balance.

Figure 10.5 Nuclear energy value chain

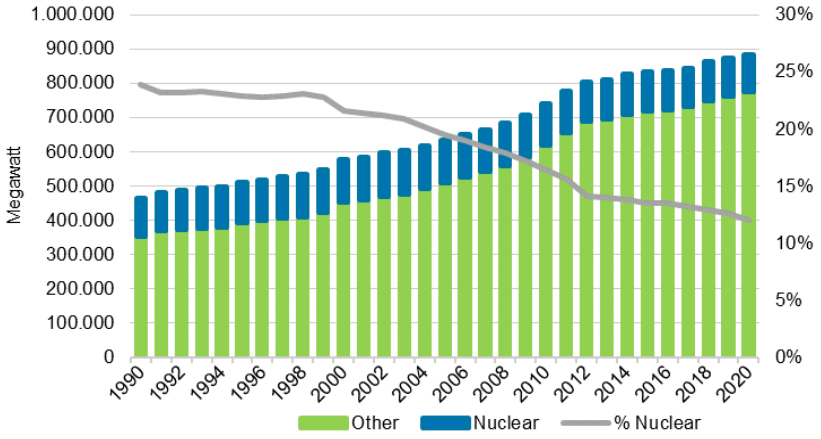


Source: Study team

Electricity production capacities

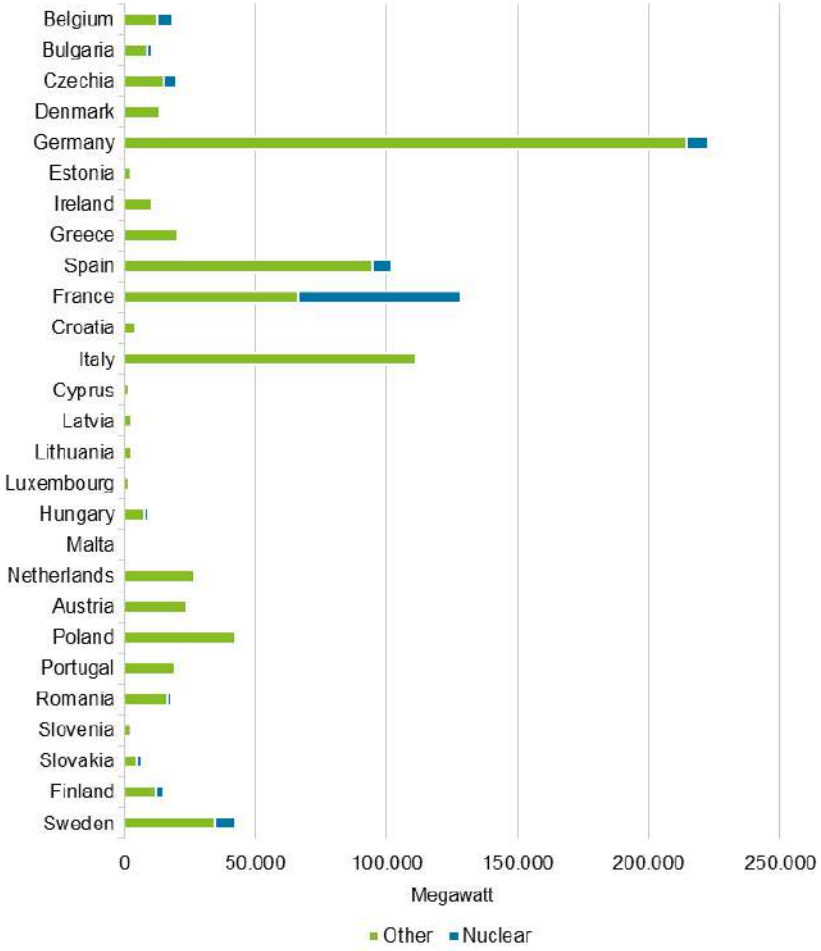
The charts below illustrate the share of the total installed capacity occupied by nuclear power. It can be noted that in the last 20 years the share of nuclear installed capacity decreased by almost ten percentage points. Nevertheless, given that the capacity factor of nuclear power plants is much higher than other sources of fossil-free energy, the actual decrease in the total power generated by nuclear is lower than the above mentioned ten percentage points.

Figure 10.6 Electricity production capacities



Source: Eurostat, study team

Figure 10.7 Electricity production capacities by Member State in 2020



Source: Eurostat, study team

There are currently 100 nuclear power plants in operation in 12 EU Member States, producing approximately 100 GW of electricity. These 100 GW of installed capacity produce around 25% of the EU's total electricity and around 50% of the fossil-free electricity. However, 83% of the reactors producing this energy are more than 30 years old. The model takes the following aspects into account in this respect:

- Effects from the construction of new NPPs;
- Effects from the decommissioning of old NPPs at the end of their service life;
- Effects from the operation of NPPs; the change in the park of NPPs due to new construction (+) and decommissioning (-) is taken into account here on an annual basis.

Assuming a reactor lifetime of 60 years,, more than 80 reactors may be shut down by 2050, most of them between 2040 and 2050. By 2050, 58 GW of new nuclear capacity may be built, 14 new reactors in France alone. However, plans to build new nuclear power plants in MS do not compensate for the potential loss of capacity due to the need to close older reactors by 2050, as indicated by desk research and the results of the Member State questionnaires. There are currently 13 Member States with plans or discussions to build nuclear power plants, either large reactors or SMRs. Taken together, these plans represent almost 59 GW of installed capacity, much less than is needed to achieve the target share of nuclear energy in the energy mix as agreed by EU Member States, taking into consideration decommissioning. Moreover, the construction of nuclear reactors takes about ten years[287].

EU Member States all have their own different nuclear power strategies. Belgium currently has six active nuclear power plants, all of which may be decommissioned by 2035 at the latest. In Germany, the last nuclear power plant was shut down in 2023[288] and therefore no nuclear power plants are in operation. In contrast, Poland, which currently has no nuclear power plants, plans to build two nuclear power plants by the end of the 2030s[288]. In summary, preliminary results show that the amount of installed capacity planned to be built is not sufficient to meet decarbonization targets. The missing approx. 24 GW of installed capacity correspond to about 15-20 reactors. Building an additional 15-20 reactors would generate an additional economic impact but requires availability of resources and is a long-term task.

10.3 Economic impact

Detailed results of the economic analysis for the main macroeconomic indicators, GVA and employment are differentiated according to the three main activities, namely construction (including pre-building), operation, and the decommissioning phase as well as nuclear fuel. Further detailed results are included in Annex H.

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287 As mentioned by one of the stakeholders in this study the construction time can take between 5 to 20 years depending on several conditions.

288 See also chapter 9.3: The event resulted in calls for some plants to continue operating. As of October 2022, three plants, Emsland, Isar2 and Neckarwestheim-2, will remain operating until spring 2023 to ensure energy security during the cold winter months.

10.3.1 Economic impact of constructing a nuclear power plant

A new nuclear power plant represents an investment of 9-11 billion EUR (depending on plant size), including interest during construction, calculated by using a case study from 2019 for a nuclear power plant from Westinghouse[289]. The construction costs were assessed using average historical and projected inflation rates for the EU, and furthermore scaled according to capacity. To forecast the economic impacts of constructing a nuclear power plant, we have allocated the total construction costs to four different industry sectors. These industries were weighted by a country comparison and the construction costs were allocated accordingly. These assumptions have been used as a basis for the estimation of the economic impact of construction activities in our analysis.

Impact on GDP

In the case of constructing new nuclear power plants, the impact on GDP can be substantial. The direct impact of constructing new nuclear power plants is estimated to be around 1.7 billion EUR in the EU in 2023. This includes activities directly related to the construction process itself. This, however, is based on the general assumptions regarding the cost of building a nuclear power plant and their distribution over time. Accordingly, these are statistical values and effects. The actual costs and effects in the EU may differ accordingly. However, the assumed indirect impact is even more significant, reaching around 2.6 billion EUR in total (indirect and induced impact). This indirect impact is generated by suppliers in the construction supply chain, as well as the spending of both the industry's direct employees and the employees of suppliers within the EU economy.

In total, the construction of new NPPs is expected to have an estimated overall impact of 4.3 billion EUR on EU GDP in 2023. This represents approximately 0.03 % of the EU's GDP, indicating the contribution of the nuclear power construction industry on the overall economic output of the EU.

Impact on GDP 2030 - 2050

The table below provides a breakdown of the impact of power plant construction on the EU’s GDP. In the years 2023 - 2030 the impact of activities directly, indirectly and induced related to the construction of power plants is projected to increase by up to 11.37 billion EUR on average per year. In the period 2031 - 2040 the impact of constructions of new nuclear power plants on EU GDP is estimated to remain at a high level with a total effect of 20.37 billion EUR on average, including indirect and induced effects. Between 2041 - 2050 the corresponding annual average is estimated at 15.66 billion EUR on average. Overall, the construction of new nuclear power plants could have an impact of 438 billion EUR on the EU GDP for the entire reference period 2023 - 2050, with an annual average of 15.66 billion EUR accordingly.

It must be noted however, that the results are primarily driven by the assumed path of nuclear capacity additions. The results here - like the other results relating to construction of new NPPs - are primarily due to the assumed construction of

289 U.S Energy Information Administration (2020). Capital cost and performance characteristic estimates for utility scale electric power generating technologies.

new NPPs and the distribution of construction activities over time. The total number or capacity of new builds is shown above in Table 10.2.

Table 10.3 Estimated impact on the EU gross value added due to *construction (billion EUR)*

Period	Direct	Indirect	Induced	Total
2023	1.69	1.88	0.71	4.28
Average				
2023-2030	4.20	5.10	2.06	11.37
2031-2040	7.31	9.41	3.65	20.37
2041-2050	5.23	6.55	2.59	14.37
2023-2050	5.68	7.16	2.82	15.66
Total				
2023-2030	33.57	40.83	16.52	90.92
2031-2040	73.10	94.15	36.49	203.74
2041-2050	52.33	65.48	25.92	143.73
2023-2050	159.00	200.46	78.92	438.38

Source: study team

Impact on employment

Analysing the current impact of nuclear construction activities on employment, it becomes evident that a substantial number of jobs are directly linked to its economic activity, totaling around 59 thousand employees in 2023. Moreover, these construction activities generate an indirect impact, supporting an additional 51 thousand jobs maintained by suppliers on average each year. This implies that for every direct job within the nuclear industry, the economy generates an extra 0.9 indirect jobs.

Furthermore, the indirect impact encompasses the employment opportunities created through the expenditure of both industry and supplier employees in other sectors of the economy. Overall, the construction of nuclear power plants is estimated to contribute to around 132 thousand jobs statistically in 2023. It must be noted, however, that this value represents a statistical estimation, based on the assumptions regarding average annual costs related to the construction of a nuclear power plant. The costs relating to the construction of a power plant are based on publicly available information, expert estimates, industry knowledge and expert opinions. A breakdown by industrial sector and the origin of the goods input (equipment, civil engineering, etc.) by country was considered. This was based on market shares and expert estimates of major global equipment suppliers. A certain outflow from the EU27 through the commissioning of suppliers outside the EU27 has been taken into account. Nevertheless, it should be noted here in particular that the commissioning is not predictable and is also subject to aspects of public procurement law. In practice, it is therefore possible, for example, that there is a higher outflow of value added at the level of individual projects (commissioning of OEMs outside the EU27) or a lower outflow through domestic commissioning (OEMs in the EU27).

Impact on employment 2030 - 2050

According to the projections, the construction of new nuclear power plants is expected to support between 59 to 127 thousand jobs per year directly from 2023 to 2030.[290] These direct jobs could also lead to the sustenance of an additional 51 to 148 thousand jobs provided by suppliers. The overall impact includes jobs created by the spending of both construction industry employees and supplier employees across various economic sectors. Consequently, the construction of nuclear power plants is anticipated to contribute to around 400 thousand jobs annually by 2030 in the EU.

In the years 2030 - 2040 the impact on employment of constructions of nuclear power plants is projected to support between 74 to 127 thousand jobs directly per year, while the additional indirect and induced effect is projected between 136 to 213 thousand jobs per year. In the period 2041 - 2050, the total employment impact is estimated at around 119 thousand jobs annually.

The results are primarily driven by the assumed construction of new NPPs. The results here - like the other results relating to construction of new NPPs - are primarily due to the assumed construction of new NPPs and the distribution of construction activities over time. The total number or capacity of new builds is shown above in Table 10.2.

Table 10.4 Estimated impact on the EU's *Employment due to construction (thousand)*

Period	Direct	Indirect	Induced	Total
2023	59.25	50.86	22.51	132.62
Average				
2023-2030	91.38	91.70	41.39	224.47
2031-2040	103.10	124.39	52.71	280.20
2041-2050	41.10	55.65	22.55	119.30
2023-2050	77.61	90.50	38.70	206.81

Source: study team

10.3.2 Economic impact of operating nuclear power plants

To assess the economic impact from the operation of a nuclear power plant, the total output for the "electricity by nuclear" sector was utilised. In this analysis, the output for each country was scaled based on their respective capacity to calculate the output per MW. Afterwards, the output per MW was multiplied by the respective capacity on an annual basis, taking inflation into account.

290 It is assumed that labour intensity/productivity changes at the same rate as inflation. Further changes due to e.g. automation are not considered.

Impact on GDP

The direct impact of operating a nuclear power plant is estimated at around 48 billion EUR in 2023. The indirect and induced impact is significant as well, reaching an estimated 28 billion EUR in 2023. This indirect impact is generated by suppliers in the operation stage, as well as the spending of both the industry's direct employees and the employees of suppliers within the EU.

In total, the operation of nuclear power plants has an overall estimated impact of around 76 billion EUR on the EU GDP in 2023. This represents approximately 0.5 % of the EU's estimated 2023 GDP, highlighting the substantial influence of the nuclear power industry on the overall economic output of the EU.

For the sake of simplicity, the model assumes a price trend in line with the available long-term inflation forecasts. Individual markets, including the energy markets, are not modelled. In this respect, it cannot be ruled out that output and contributions to GDP (gross value added) may be higher or lower due to price changes.

Impact on GDP 2030 - 2050

The impact of activities directly related to the operation of NPP is estimated to increase to 70 billion EUR in 2040, while the indirect and induced impact could increase to an estimated 44 billion EUR. This indirect impact is generated by suppliers in the operating stage of the supply chain, as well as the spending of both the industry's direct employees and the employees of suppliers within the EU. Overall, the operation of a nuclear power plant could have an overall impact of 114 billion EUR on the EU GDP in 2040.

The table below provides a breakdown of the impact of NPP operations on the EU GDP until the year 2050. In the years after 2030 until 2040 the yearly direct effect is projected in a range between 48 billion EUR to 70 billion EUR. After 2040 the direct effect of NPP operations is expected to range between 47 billion EUR to 68 billion EUR, the total effect is estimated at 95.6 billion EUR annually.

On average over the years 2023 - 2050 the operation of nuclear power plants could contribute 89 billion EUR in total to the EU GDP per year.

The impact is driven in particular by the assumed evolution of the NPP portfolio/park. The decommissioning of old and operation of new NPPs capacities derived and presented in the previous chapters are the decisive factors here.

Table 10.5 Estimated impact on the EU gross value added due to *operating* *(billion EUR)*

Period	Direct	Indirect	Induced	Total
2023	48.27	23.11	5.08	76.45
Average				
2023-2030	44.44	22.74	4.99	72.17
2031-2040	57.99	30.10	6.57	94.67
2041-2050	59.44	29.78	6.36	95.58
2023-2050	54.64	27.88	6.04	88.56
Total				
2023-2030	355.55	181.88	39.92	577.36
2031-2040	579.88	301.03	65.75	946.66
2041-2050	594.36	297.82	63.59	955.76
2023-2050	1529.79	780.73	169.26	2479.78

Source: study team

Impact on employment

Analysing the current employment impact of operating nuclear power plants, it becomes evident that a substantial number of jobs are directly linked to its performance, totaling to estimated 130 thousand in 2023. Moreover, these direct jobs have an indirect impact, supporting an additional estimated 300 thousand jobs maintained by suppliers in 2023. This implies that for every direct job within the nuclear industry, the national economy generates an extra 2.65 indirect employees.

Furthermore, the indirect impact encompasses the employment opportunities created through the expenditure of both industry and supplier employees in other sectors of the economy. Overall, the operation of nuclear power plants contributes to over 430 thousand jobs in the EU.

Impact on employment 2030 - 2050

According to the projections, the operation of nuclear power plants is estimated to support a total of 120 to 140 thousand jobs per year directly from 2023 - 2030. These direct jobs could also lead to the sustenance of an additional 200 to 230 thousand jobs provided by suppliers. The overall impact includes jobs created by the spending of both operating industry employees and supplier employees across various economic sectors. Consequently, the operation of nuclear power plants is anticipated to contribute to between 380 to 420 thousand jobs annually in the EU by 2030.

Projections for the year 2040 until 2050 estimate between 260 to 320 thousand direct jobs yearly. Indirect and induced jobs are expected to contribute to an additional 240 to 360 thousand jobs yearly. In total this adds up to an estimated range of 520 to 660 thousand jobs in the EU for that period. The estimated average annual employment impact is presented in the following table by period.

Table 10.6 Estimated impact on the EU's *employment due to operating (thousand)*

Period	Direct	Indirect	Induced	Total
2023	134.15	228.20	71.09	433.44
Average				
2023-2030	122.83	205.53	62.73	391.10
2031-2040	197.23	241.68	71.64	510.55
2041-2050	279.09	233.96	64.77	577.82
2023-2050	205.21	228.60	66.64	500.45

Source: study team

10.3.3 Nuclear fuel

The nuclear fuel value chain of an NPP encompasses the entire lifecycle of nuclear fuel, from mining and processing to reactor operation and spent fuel management as discussed in chapter 8. Therefore, this lifecycle takes place during all stages of the nuclear value chain. The calculation of the economic impact arising from the nuclear fuel cycle followed a similar approach to that of the operating phase of a nuclear power plant. The output of the nuclear fuel sector was utilized, and subsequently adjusted for inflation over the years until 2050.

Impact on GDP

The direct impact of the nuclear fuel industry amounts to an estimated 0.8 billion EUR in 2023. This includes activities directly related to the nuclear fuel industry itself. However, the indirect impact is even more significant, reaching 3.1 billion EUR. This indirect impact is generated by suppliers in the nuclear fuel industry, as well as the spending of both the industry's direct employees and the employees of suppliers within the EU.

In total, the nuclear fuel industry has an estimated overall impact of 4 billion EUR on EU GDP in 2023. This represents approximately 0.03% of EU GDP.

Impact on GDP 2030 - 2050

The impact of activities directly related to the nuclear fuel industry may reach 1 billion EUR in 2030. Whereas, the indirect impact may be even more significant, reaching 3.7 billion EUR. This indirect impact is generated by suppliers in the nuclear fuel industry, as well as the spending of both the industry's direct employees and the employees of suppliers within the EU. In total the nuclear fuel industry is estimated to contribute on average 5 billion EUR per year between 2023 - 2050.

Impact on employment

An employment impact of the nuclear fuel industry of 31 thousand jobs in total in 2023 is estimated. Moreover, these direct jobs have an indirect impact, supporting an additional estimated 41 thousand jobs maintained by suppliers. This implies that for every direct job within the nuclear fuel industry, the economy generates an extra 1.3 indirect and induced jobs.

Furthermore, the indirect impact encompasses the employment opportunities created through the expenditure of both industry and supplier employees in other sectors of the economy. Overall, the nuclear fuel industry is estimated to contribute to approximately 72 thousand jobs in the EU.

Impact on employment 2030 - 2050

According to the projections, the nuclear fuel industry is expected to maintain an estimated 31 thousand jobs per year directly over the reference period and approximately 72 thousand jobs annually in the EU on average in total, including indirect and induced impacts.

10.3.4 Decommissioning phase

The decommissioning phase involves the safe and systematic dismantling of a nuclear power plant at the end of its operational life. Upon successful completion, the site is released from regulatory control, signifying the conclusion of the decommissioning process[291]. By 2050 a number of approximately 90 nuclear power plants are going to be decommissioned within the EU[292]. The costs incurred in dismantling a nuclear power plant are assumed in a range from 1 to 1.5 billion EUR in total, depending on size and duration[293]. To calculate the economic impact of decommissioning a NPP, the costs were initially determined. Three case studies from recent years were considered to calculate an average. This average was adjusted for inflation and projected over the reference period until 2050. Subsequently, a decommissioning period of ten years was assumed to linearly allocate the decommissioning costs over the years.

Impact on GDP

The direct impact of the decommissioning phase on EU GDP is estimated at 0.5 billion EUR in 2023. This includes activities directly related to decommissioning nuclear power plants. However, the indirect impact is even more significant, estimated with 0.77 billion EUR. This indirect impact is generated by suppliers, as well as the spending of both the industry's direct employees and the employees of suppliers within the EU economy.

In total, the decommissioning industry has an overall estimated impact of 1.27 billion EUR on EU GDP in 2023.

Impact on GDP 2030 - 2050

The impact of activities directly related to decommissioning nuclear plants are estimated to reach up to 0.7 billion EUR per year until 2030. Whereas, the indirect impact may be even more significant, reaching up to 1.2 billion EUR. This indirect impact is generated by suppliers in the decommissioning industry, as well as the spending of both the industry's direct employees and the employees of suppliers within the EU economy.

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291 International Atomic Energy Agency (2022). Decommissioning of nuclear installations. Link

292 World Nuclear Association (2023). Nuclear Power in the European Union. Nuclear Power in the European Union - World Nuclear Association (world-nuclear.org).

293 Nuclear Energy Agency (2016). Costs of Decommissioning Nuclear Power Plants.

In the years 2040 - 2050 the direct effect of decommissioning nuclear plants is projected to be between 0.6 - 3.9 billion EUR per year. The indirect effect generated by suppliers of the decommissioning industry is even more significant with a yearly GDP contribution between 0.8 and 4.7 billion EUR. In total the effect of the decommissioning industry is expected to contribute to EU GDP with up to 10.5 billion EUR per year.

In the years 2023 - 2050 the decommissioning industry could contribute 3 billion EUR on average per year to EU GDP.

Impact on employment

The direct employment impact of decommissioning activities in the EU is estimated at around 5 thousand in 2023. Moreover, an additional indirect impact of 6 thousand jobs in 2023 is estimated. This implies that for every direct job within the decommissioning industry, the national economy generates an extra 1.2 indirect jobs.

Furthermore, the indirect impact encompasses the employment opportunities created through the expenditure of both industry and supplier employees in other sectors of the economy. Overall, the decommissioning industry is estimated to contribute around 15 thousand jobs in 2023 in the EU.

Impact on employment 2030 - 2050

According to the projections, the decommissioning industry is estimated to support up to 32 thousand jobs per year directly until 2050. The additional indirect employment impact is estimated at 36 thousand. The overall impact includes jobs created by the spending of both decommissioning industry employees and supplier employees across various economic sectors, up to an estimated 15 thousand. Consequently, the decommissioning industry is anticipated to contribute up to 83 thousand jobs (in 2048) per year in the EU until 2050.

On average over the years 2023 - 2050 the decommissioning industry could contribute 29 thousand jobs annually in the EU.

10.4 EU Member States' competitiveness and export potential of the nuclear energy sector

Based on the findings above, it can be assumed that increasing demand especially for products and services related to construction and decommissioning of nuclear power plants in the EU could also have a positive influence on the EU nuclear industry's current and long-term position regarding innovation and competitiveness worldwide. Significant effects can be expected from the direct export of nuclear energy related technology outside the EU, if the EU nuclear industry can strengthen its position and market shares on the world market. In summary, there are approximately over 300 proposed reactors worldwide. Many of these planned reactors are concentrated in Asia, driven by fast-growing economies and the increasing demand for electricity. Many countries with existing nuclear power programmes have either formulated plans or are actively

constructing new power reactors. Moreover, approximately 30 countries are currently considering, planning, or initiating nuclear power programmes[294].

Companies within the EU are specialised in various aspects of nuclear power plant construction, such as design, manufacturing of components, and provision of equipment. However, to face the projected demand within the MS and in addition to participate on the growing world market, availability of resources including primary production factors like capital and labour, are an inevitable prerequisite. Furthermore, the expected increase in demand for decommissioning related services, as analysed in this chapter, can enable companies to strengthen their MS-based companies in the industry to also be able to strengthen or maintain their competitive position in the international market by participating in the expected activities in the MS. This applies to their potential to participate in projects expected worldwide regarding the construction of new plants as well as the decommissioning of old ones[295].

Participating in the construction of new nuclear power plants in the EU (including SMR) enables these companies to not only preserve their market position and expertise in the nuclear energy sector but also seize valuable business opportunities. By remaining at the forefront of nuclear technology advancements, these companies could potentially expand their operations and make significant contributions to fulfilling the MS energy demands while ensuring a sustainable energy future.

In addition, effects from the export of other technologies, and general innovation and spill over effects from the supplier industries can be assumed. Nuclear technology could thus increase or at least strengthen further export opportunities including in other industries. However, this analysis does not provide an assessment of the probability of implementation of any international projects and the potential participation of nuclear technology suppliers in EU MS[296].

Another effect is the strengthening of the established reputation of the EU nuclear technology. In general, a nation's reputation influences the competitiveness of its companies and brands. A nation's reputation influences attitudes toward a nation's products and services and its ability to attract investors, companies, and tourists in general.

The positive effect that the application of "state-of-art" technologies – especially locally in EU MS where the respective technologies were developed – has on additional innovation and, by extension, on productivity and growth, can be seen as a kind of "innovation multiplier". This represents a factor regarding the strategic role of the nuclear industry. However, determining the extent of this effect is relatively difficult.

The expected benefits from the implementation – and maintenance – of the nuclear technology in Europe are supported e.g. by Vernon’s product cycle theory,

294 World Nuclear Association (2023). Plans for new reactors worldwide.
295 World Nuclear Association (2021). Heavy manufacturing of nuclear power plants
296 It can be noted that the effects of exports can in principle also be derived based on the input-output model, however, this would require a more detailed database.

according to which the key to successful trade is a nation's domestic market[297]. Early domestic demand allows domestic companies to develop new products early and export them during the early development phase of an industry, and then build foreign production as foreign demand grows. The theory in general illustrates how the domestic market can influence innovation.

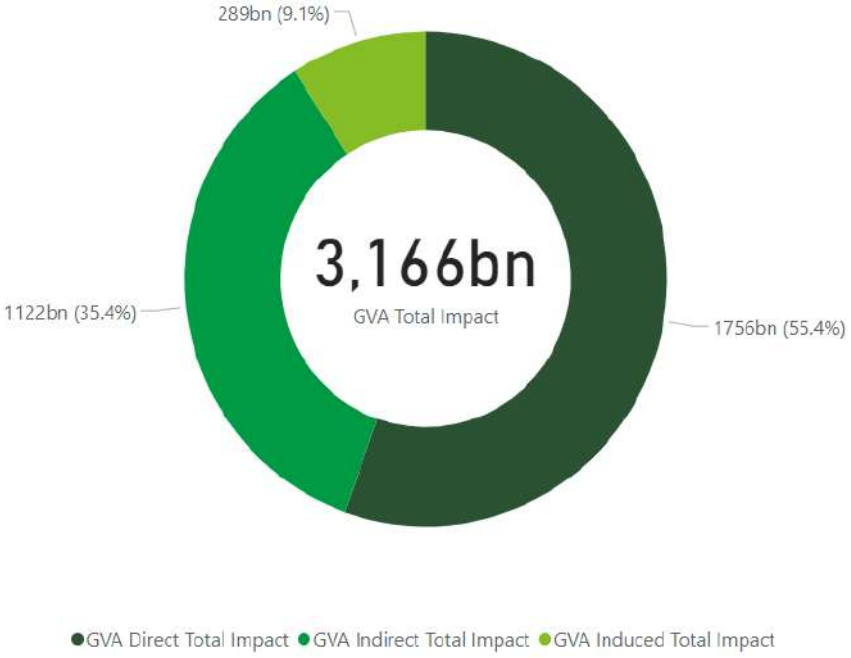
The EU's position as a nuclear technology provider is not unchallenged. Nuclear technology is being intensively researched and developed as well as supplied in various other countries. Success in connection with innovation does not fundamentally depend solely on possessing the best technology. The ability to sell the technology is a prerequisite for success and further development on the innovation path. The sale of nuclear technology in the domestic EU market, i.e., with regard to new power plants, could thus increase export opportunities.

10.5 Conclusions

10.5.1 Total economic impact

The estimated total macroeconomic impacts for the period 2023 - 2050 are as presented below:

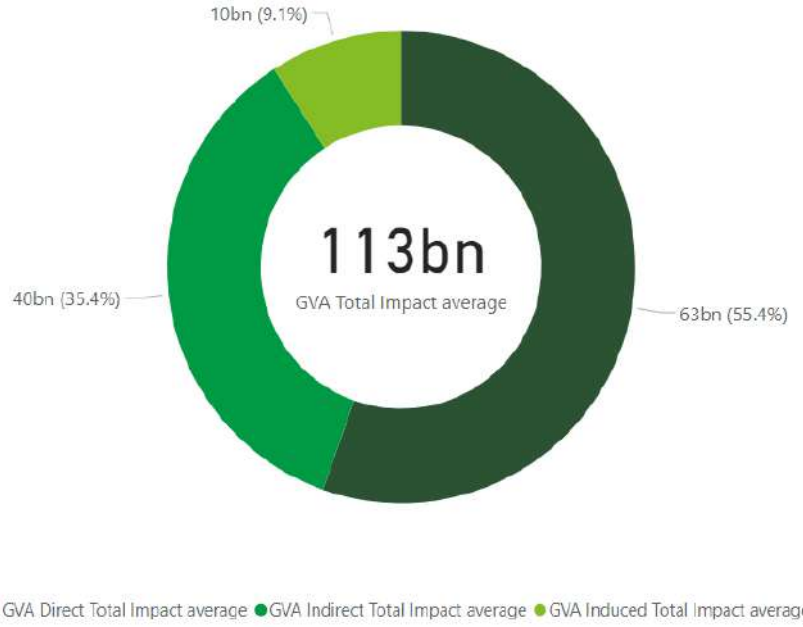
Figure 10.8 GVA by impact (billion EUR) 2023-2050 cumulative



Source: study team

297 Vernon, R. ,1996.

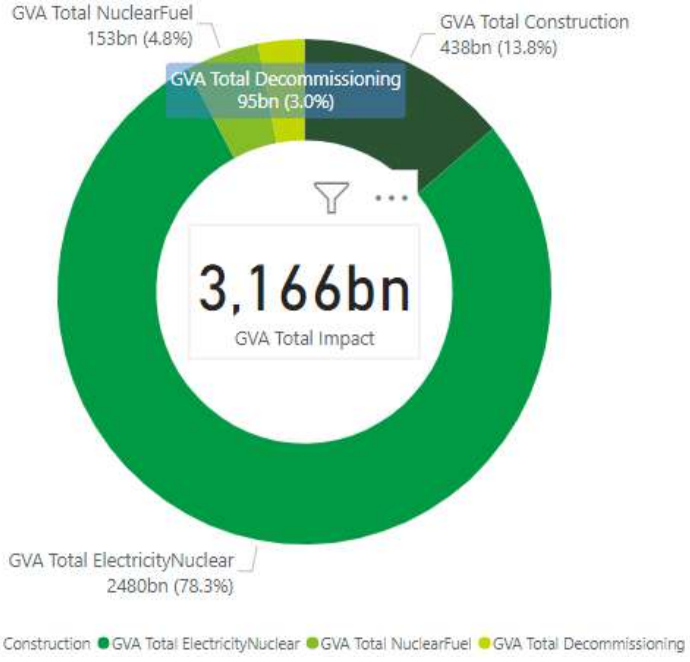
Figure 10.9 GVA by impact (billion EUR) 2023-2050 average



Source: study team

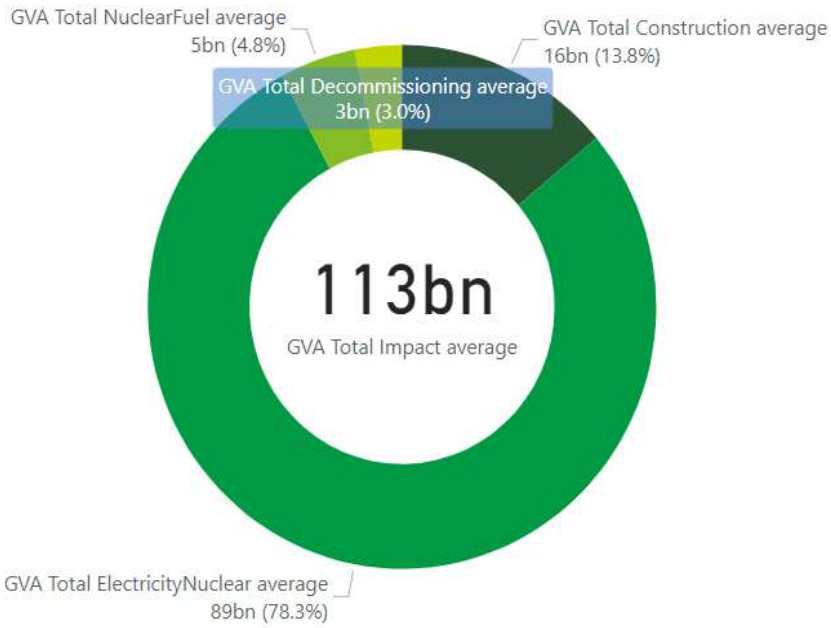
The gross value added (GVA) in total for the period 2023 - 2050 is estimated at 3 166 billion EUR including indirect and induced effects. On average, contribution to GDP is estimated at 113 billion EUR per year over the reference period. The impact includes direct (63 billion EUR), indirect (40 billion EUR) and induced (10 billion EUR) effects on average per year. The GVA can be allocated further to the main phases of the nuclear industry that have been considered, construction, operation, fuel and waste management, and decommissioning:

Figure 10.10 GVA by activity (billion EUR) 2023-2050 cumulative



Source: study team

Figure 10.11 GVA by activity (billion EUR) 2023-2050 average

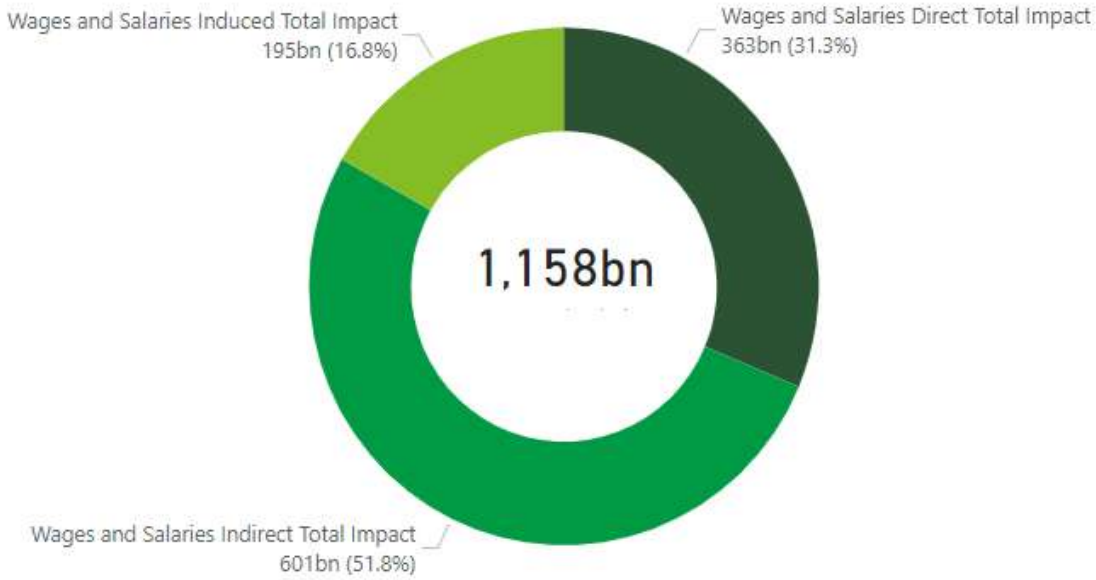


Source: study team

Effects triggered by the operation of nuclear power plants represent the main part of the total impact with an estimated 89 billion EUR on an annual average basis.

Regarding the components of gross value added, a significant impact on private households (wages and salaries) can be noted. Household disposable income refers to the money that households have available for spending and saving after deducting income tax. In total, around 1 158 billion EUR gross wages and salaries over the entire reference period are assumed to be generated. This includes both the direct and indirect impacts. The direct impact accounts for the disposable household income of employees directly and indirectly involved in the industry. The indirect impact considers the incomes of employees throughout the nuclear supply chain, as well as the employees of the industry and its suppliers.

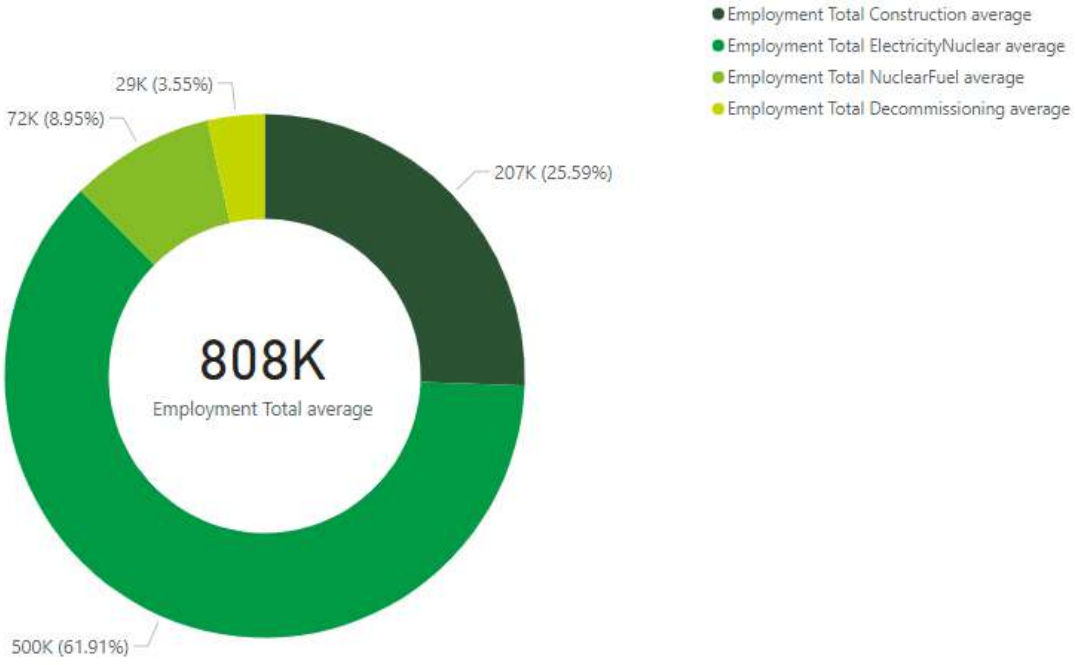
Figure 10.12 Wages and salaries (billion EUR) 2023-2050 cumulative



Source: study team

Labour income of 1 158 billion EUR and a gross employment effect of around 22.6 million over the entire reference period 2023 - 2050 are expected, representing an average total employment effect of around 800 thousand jobs per year and average wages and salaries of around 41.4 billion EUR.

Figure 10.13 Employment impact in the EU (thousand) 2023-2050 average



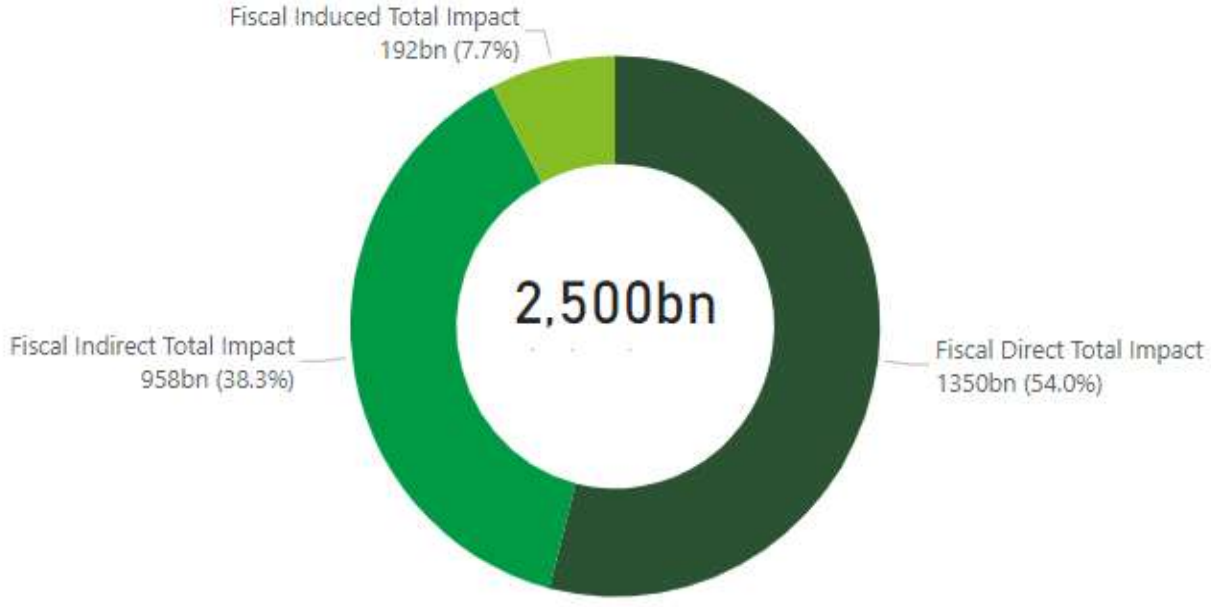
Source: Study team

Furthermore, tax contributions and contributions to social security systems directly support government expenditures. The positive outcomes resulting from the construction and operation of nuclear power plants as well as decommissioning and nuclear fuel activities, including increased output, job creation, and higher wages, could lead to higher tax collections and subsequently contribute to public revenues.

The nuclear industry plays a significant role in contributing to the national budgets of MS through taxes. Over the entire reference period 2023 - 2050, the total cumulative impact of the industry on fiscal revenues is estimated to be 2 500 billion EUR, corresponding to an estimated annual average impact of 89.3 billion EUR. The largest portion of these tax contributions comes from indirect taxes such as value-added tax, excise duties, and personal income tax.[298]

Directly, the industry contributes around 54 % to government revenues through tax payments. Indirectly and induced, the industry has an additional impact of 1 050 billion EUR on government revenues including contributions to social security systems. The following figure includes a breakdown of the impact accordingly.

Figure 10.14 Governmental revenues (fiscal impact) in the EU (billion EUR) 2023-2050 cumulative

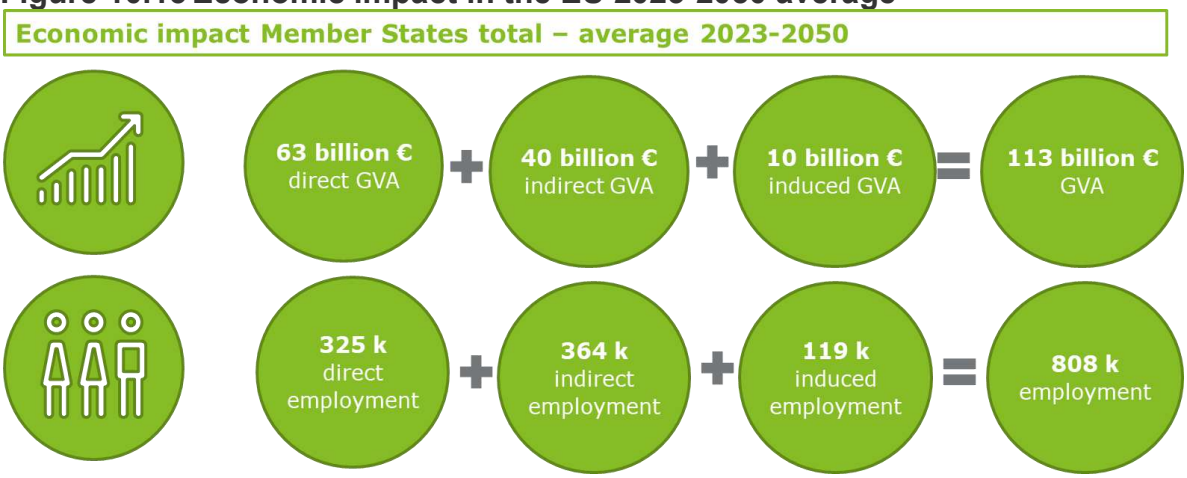


Source: Study team

[298] In this regard the ratio of taxes and social security contributions over GDP has been analysed for recent years. Averages for recent years were used to forecast future inflows. However, it cannot be ruled out that the contributions will vary more strongly in the future - e.g. due to demographic changes.

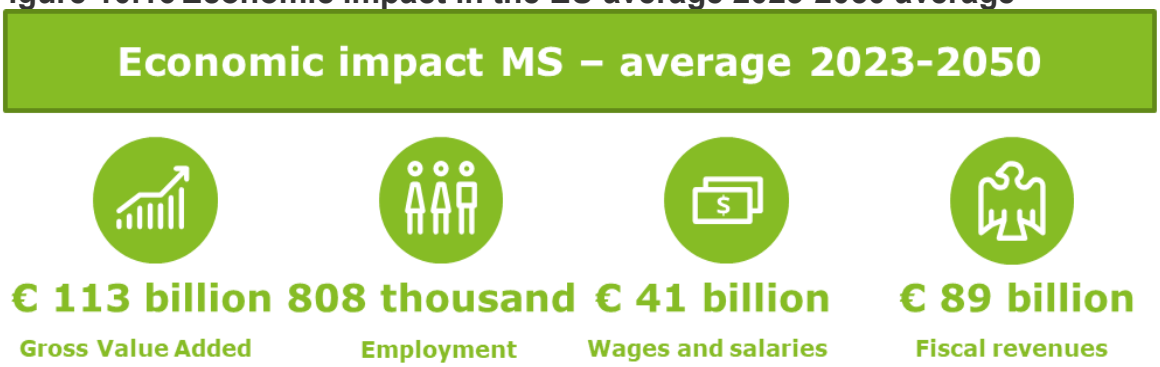
The average impact and the total impact during the reference period are presented below[299].

Figure 10.15 Economic impact in the EU 2023-2050 average



Source: Study team

Figure 10.16 Economic impact in the EU average 2023-2050 average



Source: Study team

The analysis of the future impact reveals that in the period until 2050 the nuclear energy sector generates on average annually 113 billion EUR gross value added, 89 billion EUR state revenues and sustains 808 thousand jobs in the EU economy including indirect and induced effects, as illustrated by the figure above.

299 It must be noted, that the figures below present the average of the total of the EU27 MS, not the average per MS.

10.5.2 Outlook – challenges and opportunities

While the supply of energy, is in general an important input factor in the production across all sectors of economic activity, the nuclear industry is also of considerable importance in terms of industrial policy. The projections for the MS nuclear energy ecosystem have shown its significant contribution to the economies of Member States for the coming decades. Although the economic contribution is highly driven by the operating phase, the projections have shown that the renewal of existing capacity through new constructions has a substantial share of the total economic activity. On average, construction of nuclear power plants has a share of 13.8% in the nuclear industry's total GDP contribution, whereas operating activities contribute to around 78.3%. In comparison, the share of nuclear fuel and decommissioning activities is lower with an estimated share of 4.8% and 3.0% respectively.

However, the projections only reflect specific construction plans, which are currently not in line with the overall 2050 target for the share of nuclear energy in total electricity production.

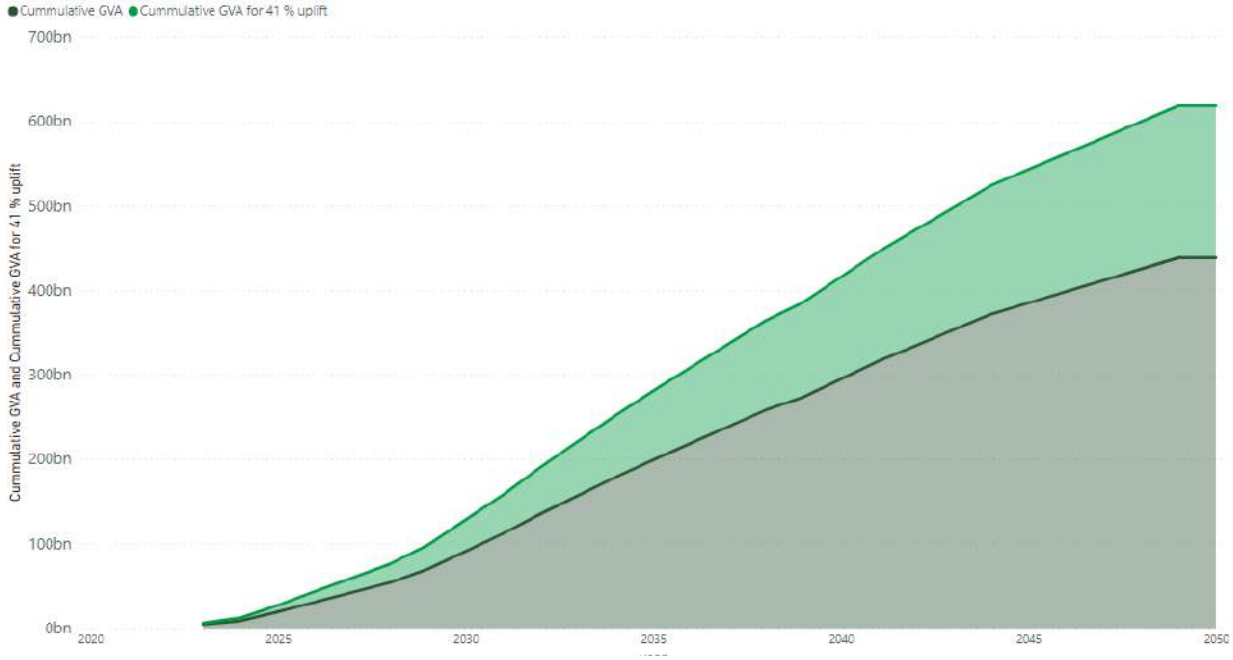
While EU nuclear power plants with a combined capacity of around 84 GW could be decommissioned by 2050, the current construction pipeline adds an estimated 59 GW to a total capacity of approximately 76 GW by 2050. This leaves a 24 GW gap to the target of 100 GW needed for reaching a 15 % share of nuclear power in the EU.

In terms of the economic impact the identified gap of approximately 24 GW represents additional potential for GDP contribution and job creation. Although the lack of existing plans does not allow a granular projection, closing the 24 GW gap would require a 41% uplift of the current construction pipeline by 2050. Regarding the already quantified economic impact of 438 billion EUR cumulative 2023-2050, expanding construction plans to reach the 100 GW target would provide up to 180 billion EUR cumulative in additional GVA. Employment would rise from 207 thousand jobs up to 292 thousand yearly on average for construction. However, the simple extrapolation also demonstrates the scale of the gap and that reaching the 100 GW target would require significant efforts from both, a highly specialized industry with its workforce as well as its suppliers providing resources.

However, it must be noted that the impacts refer to additional potential of the NPP industry/ecosystem of 24 GW. These impacts should be considered as gross effects. The net effects would assumably be lower, because it is probably not realistic to assume that a 24 GW capacity gap would remain in place. An alternative scenario, where the 25 GW gap is not closed by nuclear, would include some other generation technologies to close the gap, e.g. through renewable energy and/or storage. However, the additional construction of these assets would also lead to additional jobs and to additional GVA, which is not quantified here.

The additional 180 billion EUR GVA and employment only apply relative to a comparator scenario where a 24 GW capacity gap remains, which is not filled by other assets.

Figure 10.17 Cumulative GVA construction in the EU baseline and uplift (billion EUR)



Source: Study team

In summary, the following aspects should be noted in particular:

- The EU's nuclear industry generates – including direct, indirect, and induced effects – significant GVA, estimated at about 0.5% of the current level of GDP of the EU.
- Accordingly, the EU's nuclear industry contributes to corresponding employment effects in the EU, estimated at around 800 thousand annually on average, including highly-skilled jobs.
- The major share of the macroeconomic impacts relates to the operation of existing or future, new nuclear power plants. However, the real - price-adjusted - net growth is limited due to the decommissioning of older nuclear power plants. Accordingly, it can be assumed that the share of nuclear-generated electricity in the overall expected electricity demand, which is expected to grow further, could decrease accordingly and that output could thus be limited by nuclear power plant capacities. To achieve the envisaged share of nuclear electricity in the EU's energy mix, additional new nuclear power plants would have to be built on top of those already planned or expected to be built.
- To compensate for the decommissioning of older nuclear power plants, the construction of new nuclear power plants is required. In this context, increasing, significant contributions to GDP of the EU's nuclear industry are to be expected. Nevertheless, it should be noted that corresponding macroeconomic effects within the EU presuppose the participation of domestic companies in such new construction projects. In this context, the availability of resources, including primary production factors such as capital and labour, is a basic prerequisite, in addition to the know-how and knowledge base in this high-tech sector. The corresponding demand, e.g. for employment, was

nevertheless shown and assumed in the context of this analysis. Appropriate framework conditions are a basic prerequisite for this. In this respect, the global input-output model used already takes into account a certain outflow due to supplies/contracts from foreign companies (extra-EU27), which are mapped in the inter-industry links of the model. With regard to investments in connection with new buildings, expert assumptions were made on the volume of imports (extra-EU27) based on expert estimates, industry expertise and market shares of renowned manufacturers, among other things. Nevertheless, it should be noted that there is a relatively large uncertainty factor here, as it is uncertain which companies will be awarded contracts for planned power plants, some of which are still far in the future.

- Provided that the maintenance or expansion of corresponding capacities, resources and know-how is successful, there is also the opportunity for companies in the EU's nuclear industrial sector to participate in the growing global market of the future.
- Regarding the increasing planned decommissioning of older nuclear power plants in the EU, a growing market and corresponding economic contributions can be expected from decommissioning activities. Here, too, the availability or the development of corresponding capacities is a basic prerequisite and was shown in the present analysis. Provided that this is achieved, future participation in the world market is also an opportunity for the nuclear industry in the EU.
- In addition to the upstream effects identified in this analysis, the substantial downstream contribution of the nuclear industry in terms of the supply of electricity as a key production input factor for all sectors of the economy and private households is also important. While this applies equally to all forms of electricity generation, the potential of the nuclear industry regarding decarbonization and competitiveness can be highlighted.

11 Key recommendations – what steps should be taken to ensure seamless decarbonisation?

This study assessed the European nuclear ecosystem and its readiness for the EU's decarbonisation objectives. To make the assessment and formulate recommendations individual parts of the ecosystem were analysed through extensive desk research and stakeholder engagement. Findings illustrate that the **nuclear ecosystem prepares to achieve the EU's climate objectives,** but additional changes and investments are required to improve its readiness.

The main challenges to address have been identified in the supply chain, human capacities, regulatory environment, and the financing environment.

- **Financing environment:** Despite the availability of sufficient funds, the willingness of stakeholders to invest in nuclear is a challenge. Nuclear projects are complex, long-term, and featured with uncertainties and risks, related to regulatory, electricity market, notification processes, and high upfront cost. A possible solution could be the standardisation of the financing options and the full inclusion nuclear in the taxonomy or the net-zero industry act. This would ease up the financing and the whole process of notification.
- **Supply chain:** The main challenges identified in the supply chain are that the industry diminished in the past 20 years due to the lack of construction, and the lack of standardisation. Another important point concerns the possibility to use industry-grade components where the safety standards allow for this.
- **Human capacities:** The lack of human capacities is a long-term challenge for the nuclear ecosystem. Nuclear professionals currently working in the sector are approaching retirement age and young professionals have limited interest in the sector. However, it must be stated that this is not the case for every Member State. These two challenges raise another one: the vanishing expertise and the lack of experience. This calls for specific knowledge retention and knowledge sharing programmes. In this regard an important aspect concerning human capacities and skills is the cooperation between industry, academia and government. This cooperation could bring new opportunities, improve the perception of the nuclear sector among young professionals and ensure enough workers for the industry.
- **Regulatory environment:** From the regulatory point of view the lack of construction and thus licensing is a key challenge. Even though the regulatory environment is well set up for the licensing of current reactors, the capacity of regulatory offices could be an issue. If one assumes 100 GW of nuclear energy in Europe in 2050 and a 60 years of operation maximum for any nuclear power plant, it could be necessary to license and construct a large number of reactors (around 80 GW) within 27 years. Further standardisation of processes facilitates to address this challenge. Also, the regulatory environment requires changes to license SMRs and AMRs. Currently there is no experience with licensing such reactors. The deployment of LWRs SMRs is expected by the mid-2030s, the deployment of AMRs even later. Thus the timescale allows for the changes to be made in time but is it important to start as soon as possible.

The nuclear energy ecosystem may implement the following four actions with accessible outcomes against these challenges:

- The European Commission could **communicate that nuclear is part of the decarbonization energy mix**.
- The European Commission could **use existing networks to encourage knowledge exchange and collaboration among Member States and industry stakeholders** on decommissioning practices.
- The European Commission could **leverage existing partnerships** in the nuclear energy field to demonstrate commitment to the ecosystem and, **bring relevant stakeholders together** to **advance the development of a European design for SMRs**.
- The European Commission could **develop monitoring tool for the market's capacity on required fuel** and share the information with relevant stakeholders.
- Industry stakeholders should express any specific need and possibilities for **harmonised rules and licensing procedures** to policymakers. As such EU level actions could be initiated.
- Industry stakeholders should **identify any obstacles for investing in capacity expansion** and inform policymakers in view to initiate research on potential market failures. This should enable further prioritisation of activities to perform to address supply chain challenges.
- Industry stakeholders should **host lectures**, organise **workshops**, establish **scholarships** and **internship** possibilities, **knowledge sharing** and mentoring programmes **to attract students**.

Beyond these priority actions, the study's stakeholders highlight a general need for **clear political support and commitment to nuclear power in the EU in the long term** to facilitate addressing all the above-mentioned challenges. Member States and the EU could provide a clear and long-term vision of nuclear power being utilised in the EU. If this is provided, the ecosystem can undergo the required changes and be fit for the decarbonisation goals of the EU. Moreover, certain recommendations may be prioritised. The study's stakeholder group together with representatives from EU Member States and NGOs discussed and reviewed the list of recommendations presented per Chapter during a workshop in September 2023 to define a list of prioritised recommendations:

Financing

- **European level** - Include nuclear energy in guidelines on public funding for environmental protection and energy and in the Net-zero industry act to provide a clear statement that is necessary for a long-term stable and predictable environment. In addition, funding initiatives could be aligned with the newly established Taxonomy e.g., ensuring coordination with the Green Deal and Just Transition Funds.
- **Member State level** - Provide a regulatory landscape and long-term perspective on nuclear energy to ensure a stable and predictable environment for pricing and investment options.**Member State level** - Design a revenue model, price, and volume limitations (cap and/or floors), which act as key risk mitigation factors.

Regulatory environment

- **European level** - Keep nuclear energy in policy and strategic documents to ensure overarching objectives for MS and stimulate joint activities.
  - **Member State level** - Streamline licensing and permitting processes without regression of the level of effective control, to accelerate the execution of nuclear projects.

Supply chain

- **European level** – Support a clear and long-term commitment to nuclear power to create a stable environment in which the industry will invest to increase its production.
- **European level** – Support processes to increase standardisation throughout the EU or some smaller regions. Open the dialogue about using industry-grade (instead of nuclear-grade) components where possible while ensuring the appropriate level of safety.
- **Member State level** - Develop a long-term nuclear power strategy that emphasize the commitment towards nuclear power.
- **Industry level**- Develop a strategy for increasing the capacity and effectiveness of processes. Streamline project management to ensure that projects are completed on time and on budget.

Human capacities

- **European level** - Communicate that nuclear is part of the decarbonization energy mix, to ensure that young people see a future in nuclear, otherwise, they may choose a different sector.
- **Member State level** - Keep/Enforce nuclear energy in policy and strategy documents to provide a stable, predictable environment for the ecosystem.
- **Member State level** - Simplify the recognition of education, diplomas, license, and others across Member States.
- **Industry level** - Cooperate more with universities, academia, etc. to establish graduate and university programmes, stating what kind of skills and competences are needed and under which timeframe.
- **Industry level** - Establish a robust knowledge sharing programme across the company ensuring knowledge transfer and attract new talents.

Fuel cycle

- **European level** - Monitor the market situation to ensure there is sufficient capacity for EU requirements[300].
- **European level** - Support the R&D of SMRs and AMRs fuels to make sure the manufacturing capabilities are prepared when the deployment will happen.
- **Member States level** - Support the utilities in diversification of uranium supplies and fuel cycle services, if possible, provide favourable conditions for EU supplies.

[300] Euratom already monitors the EU market situation.

- **Industry level -** Cooperate closely with the fuel designers to ensure faster deployment of ATFs, SMRs fuel and fuel for advanced reactors.

Waste management

- **European and Member State level** - Use monitoring and communication to increase public acceptance of DGR.
- **European level** - Explore the possibility to use a shared repository in the EU and provide similar support (R&D, feasibility studies, etc.) as for the national repositories
- **Industry level** – Design the nuclear components with the thought of future decommissioning and waste management to ensure easier handling of the waste.

Decommissioning

- **European level** – Further promote knowledge exchange and collaboration among Member States regarding decommissioning practices.
- **Member State level** – Proactively look at uncertainties in cost estimates, financing schemes and funds management, and at ways to increase reporting transparency toward all stakeholders across Member States, by utilising the NuBaFA initiative.
- **Industry level** – Collaborate and share best practices as well as develop vertically integrated supply chains with specialized staff.

Annex A Methodology

Desk research

The study commenced with an extensive desk research phase, which involved gathering relevant information. One of the key sources of information were international organizations active in the nuclear field such as International Atomic Energy Agency (IAEA), nucleareurope (former FORATOM), DG ENER, Nuclear Energy Agency (NEA), Sustainable Nuclear Energy Technology Platform (SNETP), International Energy Agency (IEA) and Western European Nuclear Regulators Association (WENRA) etc. In addition, industry reports and databases, governmental publications, official EU, and other reputable online sources were analysed. This provided a comprehensive understanding of the topic and allowed to identify existing perspectives and potential gaps. The findings from this initial phase were instrumental in informing the subsequent stages of the research process as well as formulating conclusions.

Stakeholder engagement

To obtain a diverse range of perspectives, stakeholder engagement played a pivotal role in this study. A stakeholder group was established to follow the study and regularly provide inputs. Key stakeholders were identified based on their relevance and expertise on the subject matter. These included individuals from industry professionals, agencies, policymakers, academia, and representatives from relevant organizations. The stakeholders final list was carefully selected to represents each important part of the nuclear energy and to cover different industry segments. For the high-level strategy discussion representatives from nucleareurope (former FORATOM) and EURATOM were selected. For the more technical aspects of nuclear energy the representatives from SNETP and GIFEN were selected. To cover the industry's largest companies involved in nuclear energy representatives were selected from Framatome, URENCO, Walter Tosto and ENSA. Identified investor companies are Fortum or CEZ. Stakeholders involved in education and talent identification were European Nuclear Education Network (ENEN) and the Jozef Stefan Institute. The final part of selected stakeholder were stakeholders active in regulatory/radioactive waste management, namely representatives from the European Nuclear Safety Regulators Group (ENSREG). Also, the representatives from nucleareurope (former FORATOM) provided insights on this aspect.

Each group was contacted with an explained purpose and scope of the study via email, emphasizing the voluntary nature of the participation.

Questionnaire

To collect data about the current landscape, perceptions, and attitudes, three types of questionnaires were designed. Each questionnaire development process involved careful consideration of the research objectives, ensuring that the questions were clear, concise, and aligned with the study's purpose. The questionnaires comprised both closed-ended questions, which allowed for quantitative analysis, and open-ended questions, which facilitated the gathering of qualitative insights. Prior to employment, the questionnaires underwent a pilot test

to assess its clarity, comprehensibility, and appropriateness. The questionnaires can be found in Annex I. The questionnaires were prepared as follows:

- Initial questionnaire to stakeholders - to provide a first relevancy check on the data collected by the project. From the 17 identified stakeholders, 15 questionnaires were collected and analysed.
- Member State questionnaire – to collect structured data inputs focused on obtaining and validation of relevant data related to MS. In total 17 MS sent their responses, the MS that didn't provided any answers were mainly non-nuclear MS or MS that will phase out nuclear.
- Readiness questionnaire to licensed manufacturers - to assess the readiness and capacity of the industry. In total the questionnaire was sent to approximately 100 stakeholders, the response rate was low, 11 completed questionnaires were collected.

The aim was to extract specific answers from each stakeholder group. Questionnaires were circulated following the approval by DG ENER via MS Excel or via the study team's platform. The outcome from the initial questionnaire further helped with identification of areas for further desk research, and outline interview scripts for stakeholders.

Data collection

The data collection process involved administering the questionnaire to the identified stakeholders. The questionnaires were distributed electronically, utilizing a secure online platform, to ensure ease of access and confidentiality. Stakeholders were given a defined timeframe to complete the questionnaire, and reminders were sent to maximize response rates. The collected data from the questionnaires were stored securely and maintained in accordance with data protection regulations. Once the completed questionnaires were received the processing of gathered data took place. The data were divided into sets of relevant topics and incorporated into the study. After the analysis, the sets of interviews were set to serve as clarification of collected answers and to provide further enrichment and elaboration of certain topics.

Interviews

To further explore the stakeholders' perspectives and gather more in-depth insights, semi-structured interviews were conducted with a selected group of participants. The interviewees were purposefully chosen based on their expertise, experience, and their responses to the initial questionnaire. The first round focused on a basic debriefing related to received answers from questionnaires and related data and was placed shortly after results of initial questionnaires were evaluated. The second collaborative and feedback interviews were developed to further identify areas of interest from the analysis. The aim was to provide further and deeper insights into detailed findings of the AS-IS state of the nuclear industry, supply chain and policy/regulatory environment in Europe. It was targeted on gathering areas of opportunities and risks to be addressed and potential policy changes towards the nuclear industry in Europe.

In total 27 interviews in two rounds were held. The interviews were conducted via video conferencing tools and one face-to-face with duration of approximately one hour. Detailed notes were taken during the interviews to facilitate comprehensive data analysis during data analysis phase. Both sets of interviews contributed for a preparation of workshop phase.

Workshops

The objective of the first workshop was to present the preliminary results (mainly the baseline scenario) of the research conducted and data gathered during the questionnaire phase. The aim of the Workshop was to have a discussion with the stakeholders on the identified and already collected data. During the Workshop addressing and deciding on the relevant topics that should be further elaborated in the study was done. Following feedback received in the Workshop supporting and hindering factors were identified and the areas for further exploration were confirmed.

The second workshop concluded the study and focused on presenting its main findings and key recommendations. The workshop was the last stakeholder engagement activity organised for this study. The workshop allowed us to verify the findings and fine-tune and prioritize the recommendations, notably by highlighting which recommendations need immediate action.

Data analysis

The collected data, both quantitative and qualitative, were subjected to a thorough analysis process. Quantitative data from the questionnaires were analysed using statistical software, enabling to identify patterns, trends, and key messages. Qualitative data obtained from the open-ended questions and interviews were transcribed, coded, and thematically analysed to identify recurring themes, emerging patterns, and nuanced perspectives. The integration of quantitative and qualitative findings allowed for a comprehensive understanding of the stakeholders' perceptions and attitudes. Following the initial data collection, data analysis and identification of missing data also take place. The limitations of the study were in factors that may have affected the study findings which includes sample size limitations.

In conclusion, this study employed a multi-faceted methodology to investigate whether the current ecosystem of the EU nuclear energy sector is fit for the longer-term prospects of carbon neutrality of the EU's energy system. The integration of desk research, questionnaires, stakeholder engagement, interviews ensured a comprehensive and well-rounded analysis about the nuclear ecosystem. The careful implementation of each stage of the methodology laid the foundation for rigorous data collection and analysis, contributing to the validity and reliability of the study's findings.

Annex B Status and outlook of nuclear power in individual MS

Austria

Austria is a country with strong historical opposition to the use of nuclear power. It is among selected countries that legally prohibited the use of nuclear power in their country (in 1978) and actively tries to prevent its development in neighbouring countries and within the European Union.

Table 0.1 Overview of nuclear power - Austria

The total number of operated reactors and installed capacity	1 TRIGA research reactor / 250 kW
Number of new nuclear capacities till 2050	0 MW
New capacity of SMRs till 2050	0 MW
Capacity of shutdown reactors till 2050	0 MW

Source: Member States questionnaire, Stakeholder interviews, IAEA Research Reactor Database

Belgium

Belgium is a country with a long history of the use of nuclear power, in 1962, BR3, an 11 MWe prototype, was the first pressurized water reactor (PWR) in Western Europe to be connected to the grid. Between 1974 and 1985, 7 nuclear power units — all PWRs — were connected to the electricity grid, with a total net generating capacity of almost 6000 Mwe. Due to political reasons in more recent years, the country is seeing a rather downturn in nuclear energy. In 2003, the federal Parliament passed a law prohibiting the construction of new nuclear units intended for the industrial production of electricity by nuclear fission in Belgium, while limiting the operation of existing reactors to 40 years. According to this law, nuclear fission energy was to be phased out between 2015 and 2025. Successive governments have amended the law in order to ensure the security of supply of electricity — extending the operating licences of the three oldest reactors by ten years — but always confirming the decision to phase out all nuclear power reactors by 2025. However, on 18 March 2022, the federal government decided to take the necessary steps to extend the operational life of the two youngest nuclear power reactors, Doel-4 and Tihange-3, by ten years until 2035. Together, these plants can generate about 55% of the country’s electricity needs. In 2021, they produced 47 892 GWh or 50.8% of total electricity production. In accordance with the Belgian nuclear phase-out law, unit 3 of the Doel nuclear power plant has been permanently disconnected from the grid on Friday 23 September 2022. On Tuesday, January 31, 2023, unit 2 of the Tihange nuclear power plant followed. Doel-3 and Tihange-2 are therefore the first Belgian nuclear power reactors to permanently stop producing electricity, after 40 years of operation. Currently, Belgium operates five reactors which produce about 46% of its electricity. The original plan was to shut down all the reactors by 2025 but the country's leadership re-evaluated its decision to ensure the security of supply of electricity. The Belgium government and French utility Engie agreed to extend the operation of two reactors, Doel-4 and Tihange-3, till 2035. The country is currently not planning

to build any new reactors. However, on 18 March 2022, the Federal Government unveiled a transition plan that should eventually enable Belgium to become energy independent and will contribute to the goal of becoming carbon neutral by 2050. As part of this, 100 million euros will be made available to the SCK CEN research centre for research into new generation nuclear energy, in particular into safer, smaller, and modularly deployable reactors (SMR).

The country's energy future will be a mix of more renewable energy with more solar panels, wind turbines, on land and at sea, and hydrogen. But there may also be room for new sustainable nuclear energy.

Table 0.2 Overview of nuclear power - Belgium

The total number of operated reactors and installed capacity	6 power reactors / 4 936 MW 3 research reactors / 101 MW
Number of new nuclear capacities till 2050	0 MW
New capacity of SMRs till 2050	0 MW
Capacity of shutdown reactors till 2050	4 936 MW

Source: Member States questionnaire, Stakeholder interviews, IAEA Research Reactor Database

Bulgaria

Bulgaria operates two nuclear reactors at the Kozloduy site (Kozloduy 5 & 6). Both reactors are Russian VVER designs with a nominal power of 1003 MWe. The share of nuclear power in the energy mix is around 37%. Both operating reactors had their licenses extended by ten years in 2017 and 2019, i.e., until 2027 and 2029. At the same site, four other reactors were in operation in the past, units 1 & 2 were shut down in 2002, and units 3 & 4 in 2006. Dismantling of units 1 - 4 is ongoing and it is planned to be finished by 2030. In 2021 the government approved the plan for new units at Kozloduy, units 7 & 8. Furthermore, in October 2021, Bulgarian Energy Holding signed an agreement with Fluor to examine the feasibility of replacing its five coal-fired power plants with 77 MW NuScale reactors.

Table 0.3 Overview of nuclear power - Bulgaria

The total number of operated reactors and installed capacity	2 power reactors / 2 006 MW
Number of new nuclear capacities till 2050	2 000 MW
New capacity of SMRs till 2050	0 MW
Capacity of shutdown reactors till 2050	1 003 MW

Source: Member States questionnaire, Stakeholder interviews, IAEA Research Reactor Database

Croatia

Croatia is a country with a positive relationship towards nuclear energy even though it doesn't have any nuclear power plant in operation on its land. The Republic of Croatia participated in constructing the nuclear power plant Krško, which lies on Slovenian territory. Both states share liability and ownership of the Krško NPP. The Agreement on the Regulation of the Status and other legal Relationships, Connected with Investments in the Krško NPP, its Exploitation and Decommissioning defines the shared ownership. According to the statement of the minister of economy and sustainable development, Croatia is willing to help with the construction of the intended new nuclear unit in Krško NPP.

Table 0.4 Overview of nuclear power - Croatia

The total number of operated reactors and installed capacity	0 power reactors / 0 MW
Number of new nuclear capacities till 2050	0 MW
New capacity of SMRs till 2050	0 MW
Capacity of shutdown reactors till 2050	0 MW

Source: Member States questionnaire, Stakeholder interviews, IAEA Research Reactor Database

Cyprus

Cyprus is a non-nuclear country, there are not any NPPs or research reactors in operation and there are no plans for the development of nuclear energy in the future. Only nuclear related activities are the use of radioactive sources for medical, industrial, and research purposes.

Table 0.5 Overview of nuclear power - Cyprus

The total number of operated reactors and installed capacity	0 power reactors / 0 MW
Number of new nuclear capacities till 2050	0 MW
New capacity of SMRs till 2050	0 MW
Capacity of shutdown reactors till 2050	0 MW

Source: Member States questionnaire, Stakeholder interviews, IAEA Research Reactor Database

The Czech Republic

The Czech Republic has a long history of nuclear power operations. The first nuclear power plant was entirely designed and built in former Czechoslovakia, commencing operations in 1972. Presently, the Czech Republic operates six power units—four VVER-440 units at the Dukovany site and two VVER-1000 units at the Temelin site. Additionally, there are two research reactors operated by the research center Rez, and two educational reactors at the Czech Technical University in Prague. The government committed itself to expanding nuclear capacities, this was emphasized in the State Energy Policy from 2015. The current

Government Policy Statement indicates plans for the operation of both large new units and SMRs, which will be reaffirmed in the updated State Energy Policy which should be issued by the end of 2023. Progress in the construction of large units is already underway, the partially stat-owned company CEZ is in the middle of the tender for constructing a new power plant at the Dukovany site. The selection of a vendor is expected in 2024, the construction should start in 2026 with the planned commissioning in 2037. Looking ahead to 2050, the Czech Republic aims to construct three additional large plants and several SMRs, solidifying its position as a significant proponent of nuclear energy in the European Parliament.

Table 0.6 Overview of nuclear power - The Czech Republic

The total number of operated reactors and installed capacity	6 power reactors / 3 934 MW 2 research reactors / 10 MW 1 educational reactor / 0 MW
Number of new nuclear capacities till 2050	up to 4 800 MW
New capacity of SMRs till 2050	3 000 MW
Capacity of shutdown reactors till 2050	1 878 MW

Source: Member States questionnaire, Stakeholder interviews, IAEA Research Reactor Database

Denmark

Denmark currently does not operate any NPP. Historically though Denmark played a significant role in nuclear research and even considered constructing a nuclear power plant. Denmark operated three research reactors, that were put into operation between 1957 and 1960. The plan to build nuclear power plant was abandoned in 1985 when the Danish government issued a resolution that prohibits the operation of NPPs. At present there is no prospect of reversing this resolution and thus Denmark will remain a non-nuclear country.

Table 0.7 Overview of nuclear power - Denmark

The total number of operated reactors and installed capacity	0 power reactors / 0 MW
Number of new nuclear capacities till 2050	0 MW
New capacity of SMRs till 2050	0 MW
Capacity of shutdown reactors till 2050	0 MW

Source: Member States questionnaire, Stakeholder interviews, IAEA Research Reactor Database

Estonia

Estonia is currently not operating any NPP. In 2009 Estonia presented a development plan which stated that the country will establish a nuclear power plant by 2023. This plan was not implemented as no nuclear power plant is in operation or construction as of now. However, the company Fermi Energia announced its intentions to build and operate SMR in Estonia, thus making it a nuclear newcomer country. Fermi Energia announced in September 2022 that it will accept bids for the construction of SMR. In February 2023 Fermi Energia selected the GE Hitachi design BWRX-300. The planned commissioning of the plant is scheduled for 2031. The government of Estonia has several scenarios for the electricity supply mix and one of them suggests building three SMRs with a total capacity of 900 MW, so a potential increase in nuclear capacity is possible.

Table 0.8 Overview of nuclear power - Estonia

The total number of operated reactors and installed capacity	0 power reactors / 0 MW
Number of new nuclear capacities till 2050	0 MW
New capacity of SMRs till 2050	900 MW
Capacity of shutdown reactors till 2050	0 MW

Source: Member States questionnaire, Stakeholder interviews, IAEA Research Reactor Database

Finland

Finland is currently operating five nuclear reactors, with the fifth commercially commissioned in 2023, after 17 years of construction. Finland is operating nuclear power since 1977, so it has a long history of using nuclear energy. It relies on nuclear energy and they plan to bring the nuclear contribution to electricity production up to 60% from today's 35%. Construction of a plant was planned at the Hanhikivi site by Fennovoima.. Fennovoima terminated the EPC contract of plant delivery with RAOS Project due to RAOS Project's significant delays and inability to deliver the project in May 2022. In December 2022 the Dispute Review Board decided that the decision to terminate the EPC contract from the Fennovoima side was unlawful. Both parties (Fennovoima and RAOS Project) submitted notices of dissatisfaction after the decision was made. Finland will be the first country to have a DGR in operation. The company Posiva is currently building the repository and it should be in operation in mid 2020s.

Table 0.9 Overview of nuclear power - Finland

The total number of operated reactors and installed capacity	5 power reactors / 4 394 MW
Number of new nuclear capacities till 2050	6 000 MW
New capacity of SMRs till 2050	0 MW
Capacity of shutdown reactors till 2050	2 794 MW

Source: Member States questionnaire, Stakeholder interviews, IAEA Research Reactor Database

France

France operates the largest fleet of nuclear power plants in Europe. Currently, there are 56 reactors in operation which account for more than 70% of electricity generation About 17% of its electricity is generated from recycled nuclear fuel. One reactor is under construction and should be commissioned in 2023. In February 2022 France committed to build another six units with the potential of building another eight (feasibility studies are in the preparation phase). France has a very strong nuclear industry with several large companies focused on nuclear: EDF, Triatome, Orano, Nuvia, CEA, and others. EDF has its design of a Gen III+ reactor - the EPR. Significant focus is put on the nuclear fuel products and services, that are part of France's export. The country is also operating front-end facilities such as enrichment, conversion, and fuel fabrication plant. The back-end facilities such as reprocessing and MOX fuel fabrication plant are in operation as well.

France is also very active in the field of nuclear research, the main research organization CEA is running several research centers throughout France, the main ones being in Saclay and Cadarache. One research reactor is currently under construction in France, the Jules Horowitz Reactor. France is active in the field of nuclear fusion, and together with the European consortium is building the fusion reactor ITER near the CEA's Cadarache site.

Table 0.10 Overview of nuclear power - France

The total number of operated reactors and installed capacity	56 power reactors / 61 370 MW 3 research reactors / -
Number of new nuclear capacities till 2050	24 600 MW
New capacity of SMRs till 2050	0 MW
Capacity of shutdown reactors till 2050	51 440 MW

Source: Member States questionnaire, Stakeholder interviews, IAEA Research Reactor Database

Germany

Germany was historically very strong in terms of nuclear energy; throughout its history, it operated 33 reactors. Before 2011 nuclear accounted for about ¼ of its electricity supplies. After the accident at Fukushima Daichi in 2011 the government decided to phase out nuclear. This decision was not made purely by the impulse of the Fukushima Daichi accident, the German government introduced the plan of phasing out nuclear in 1998, the so-called Energiewende, but it was cancelled by the new government in 2009 and reintroduced in 2011. Eight reactors were shut down immediately and the rest was scheduled to be shut down before the end of 2022. However, in October 2022 the German government decided to prolong the operation of three reactors till mid-April 2023, to account for the reduced gas supplies from Russia. As of now Germany has shut down all its reactors and is not supporting the use of nuclear power.

Table 0.11 Overview of nuclear power - Germany

The total number of operated reactors and installed capacity	0 power reactors / 0 MW 5 research reactors / 0,1 MW
Number of new nuclear capacities till 2050	0 MW
New capacity of SMRs till 2050	0 MW
Capacity of shutdown reactors till 2050	0 MW

Source: Member States questionnaire, Stakeholder interviews, IAEA Research Reactor Database

Greece

Greece does not operate any nuclear power plants. Historically it was operating one research reactor and two subcritical assemblies. The research reactor is in the phase of extended shutdown, one critical assembly is decommissioned, and the other is still in operation . Since Greece is not operating any nuclear power plants, the spent fuel management is relevant only to the operation of the research reactor. Irradiated fuel was repatriated to the USA in 2019. Radioactive waste in Greece is associated with medicine, research, and industry-used isotope sources. Greece is not planning to operate nuclear power in the future, since the region is extremely seismic . However, Greece is discussing the possibility of nuclear cooperation with Bulgaria. The cooperation should be based on a long-term supply contract for energy from a new reactor in Bulgaria .

Table 0.12 Overview of nuclear power - Greece

The total number of operated reactors and installed capacity	0 power reactors / 0 MW 1 research reactor / 0 MW
Number of new nuclear capacities till 2050	0 MW
New capacity of SMRs till 2050	0 MW
Capacity of shutdown reactors till 2050	0 MW

Source: Member States questionnaire, Stakeholder interviews, IAEA Research Reactor Database

Hungary

Hungary has a long history with nuclear energy, the National Atomic Energy Committee was founded in 1956 and the first research reactor was put in operation in 1959. The order for the first nuclear power plant was signed in 1971, and two VVER-440 were commissioned in 1982 and 1984. These two units were followed by another two VVER-440s commissioned in 1986 and 1987. Today nuclear delivers about 47% of electricity in Hungary. The country is committed to operating nuclear power in the future and the plan is to build two additional units of VVER-1000 on the table 1980s, unfortunately in 1989 the project was cancelled. In 2009 the project was renewed when the government gave preliminary approval. The Hungarian Atomic Energy Agency issued a construction license in In August 2022. The construction will be done by the Russian company Rosatom and the reactor type to be built is VVER-1200.

Table 0.13 Overview of nuclear power - Hungary

The total number of operated reactors and installed capacity	3 power reactors / 4 055 MW 1 research reactor / 10 MW 1 Educational reactor / 0,1 MW
Number of new nuclear capacities till 2050	2 400 MW
New capacity of SMRs till 2050	0 MW
Capacity of shutdown reactors till 2050	1 916 MW

Source: Member States questionnaire, Stakeholder interviews, IAEA Research Reactor Database

Ireland

Operating nuclear power plants in Ireland is prohibited by the Electricity Regulation Act from 1999. So today, there are no nuclear power plants, research reactors, or waste facilities in operation in Ireland. However, the plans to build and operate nuclear power in Ireland were prepared in the 1960s. Irish government even selected the site (Carnsore Point) and decided to build 4 reactors there. In the late 1970s and early 1980s, public opinion shifted against nuclear power, and several

anti-nuclear groups were established. Later the government dropped the plan to build nuclear power plants.

Table 0.14 Overview of nuclear power - Ireland

The total number of operated reactors and installed capacity	0 power reactors / 0 MW
Number of new nuclear capacities till 2050	0 MW
New capacity of SMRs till 2050	0 MW
Capacity of shutdown reactors till 2050	0 MW

Source: Member States questionnaire, Stakeholder interviews, IAEA Research Reactor Database

Italy

Italy had four nuclear reactors. Two were closed in 1982 and 1987 and the last two reactors were shut down after the Chernobyl accident. Italy does not operate any nuclear reactors and does not have any plans for the development of nuclear power. There were efforts to revive nuclear ambitions in Italy in 2008 when the government policy towards nuclear changed and the plan to generate 25% of electricity from nuclear by 2030 was introduced. However, a referendum held in June 2011 rejected this ambition. Although Italy does not have nuclear power plants it has very strong nuclear research and industry. Italy is operating five research reactors. The research is led by a research organization called ENEA . Most of the research is focused on waste management and decommissioning but fission and fusion research is done in small measures as well. Several large companies focused on nuclear are Italian, for example, Ansaldo Energy, Walter Tosto, and others.

Table 0.15 Overview of nuclear power - Italy

The total number of operated reactors and installed capacity	0 power reactors / 0 MW 5 research reactors / 1,25 MW
Number of new nuclear capacities till 2050	0 MW
New capacity of SMRs till 2050	0 MW
Capacity of shutdown reactors till 2050	0 MW

Source: Member States questionnaire, Stakeholder interviews, IAEA Research Reactor Database

Latvia

Latvia is currently a country without nuclear power. Its national energy and climate plan is under revision and for the first time it will include nuclear power as an alternative option on how to decarbonize the energy sector by 2050. Historically Latvia was operating one 5 MW research reactor; it was permanently shut down in 1998 and the spent highly enriched uranium was transported back to Russia in 2008. Radioactive isotopes are now used mainly for medical, research, and industrial purposes.

Table 0.16 Overview of nuclear power - Latvia

The total number of operated reactors and installed capacity	0 power reactors / 0 MW
Number of new nuclear capacities till 2050	0 MW
New capacity of SMRs till 2050	0 MW
Capacity of shutdown reactors till 2050	0 MW

Source: Member States questionnaire, Stakeholder interviews, IAEA Research Reactor Database

Lithuania

Historically Lithuania was utilizing nuclear energy, its last reactor was shut down in 2009 as a part of the agreement with the EU.10 Lithuania was operating two light water gas-cooled reactors of Russian design (RBMK-1500), these reactors generated about 70% of generated electricity. Before the shutting down of nuclear power in Lithuania, the country was a major exporter of electricity. Today, the country is a large importer, it imports a significant share of electricity (70% in 2021) . It is also a sizeable consumer of natural gas and biomass. The development plans for new nuclear capacity existed, however, the project of a new reactor in location Visaginas, near the former nuclear power plant Ignalina was cancelled .

Table 0.17 Overview of nuclear power - Lithuania

The total number of operated reactors and installed capacity	0 power reactors / 0 MW
Number of new nuclear capacities till 2050	0 MW
New capacity of SMRs till 2050	0 MW
Capacity of shutdown reactors till 2050	0 MW

Source: Member States questionnaire, Stakeholder interviews, IAEA Research Reactor Database

Luxembourg

Luxembourg does not operate any nuclear facilities. The country is heavily focused on emergency preparedness and response due to the French nuclear power plant Cattenom, which is located about nine kilometres from its borders. Radioactive waste in Luxembourg arises from medical, industry, scientific, and educational purposes. All used sources should be returned to the country of origin and if this is not possible, it should be stored in a foreign waste management facility.

Table 0.18 Overview of nuclear power - Luxembourg

The total number of operated reactors and installed capacity	0 power reactors / 0 MW
Number of new nuclear capacities till 2050	0 MW
New capacity of SMRs till 2050	0 MW
Capacity of shutdown reactors till 2050	0 MW

Source: Member States questionnaire, Stakeholder interviews, IAEA Research Reactor Database

Malta

Malta is not operating any nuclear facilities and the public opinion is not in favour of nuclear power. On the other hand, Malta is a small country with very high energy consumption per capita, in 2019 the consumption was 80,2 MWh per person, compared to the world average of 21,0 MWh per person . Since it is a small country the possibility of utilizing large areas for renewable energy is limited, nuclear power could thus be potentially beneficial for Malta. Currently, though the Maltese government is not planning any development of nuclear energy.

Table 0.19 Overview of nuclear power - Malta

The total number of operated reactors and installed capacity	0 power reactors / 0 MW
Number of new nuclear capacities till 2050	0 MW
New capacity of SMRs till 2050	0 MW
Capacity of shutdown reactors till 2050	0 MW

Source: Member States questionnaire, Stakeholder interviews, IAEA Research Reactor Database

The Netherlands

The Netherlands has a long history of nuclear research and the operation of nuclear power plants. The construction of a research high flux reactor in Petten started in 1955 and was put into operation in 1961. The reactor is in operation for more than 60 years and in the mid-2020s it will be replaced by a new research reactor called PALAIS which is now under construction. The country is operating one power reactor at the Borselle site and has one shutdown reactor at the Dodewaard site.

Nuclear power delivers about 3% of the country's electricity supply. The reactor at the Borselle site is going through the LTO programme and it was given a license for operation till 2033. The government in December 2022 presented a plan to extend the operation of the Borselle plant even beyond the 2033 license expiration. At the end of 2022, the government decided to move forward with increasing the nuclear capacity. It has preselected the Borselle site as the most suitable location for two additional reactors. The final decision will be made at the

end of 2024 at the earliest. The Netherlands is also operating a nuclear fuel enrichment facility at the Almelo site; it is operated by the URENCO company together with other facilities in UK and Germany.

Table 0.20 Overview of nuclear power - The Netherlands

The total number of operated reactors and installed capacity	1 power reactors / 482 MW 3 research reactors / 47,3 MW
Number of new nuclear capacities till 2050	2 400 MW
New capacity of SMRs till 2050	0 MW
Capacity of shutdown reactors till 2050	482 MW

Source: Member States questionnaire, Stakeholder interviews, IAEA Research Reactor Database

Poland

Poland is a newcomer country with a focus on nuclear power and a strong advocate for nuclear energy. It is operating one research reactor – MARIA, which is one of the European research reactors that produces Molybdenum-99. The country's electricity mix is based mainly on fossil fuels, coal, gas, and oil. Apart from a programme to construct nuclear power plants based on VVER soviet technology - abandoned in early 1990's - Polish plans for deploying nuclear energy are dating back to 2005 when the government decided to diversify its energy sources and the introduction of nuclear was one of the possibilities. The strategic documents developed since then for energy sector envisage construction of nuclear power plants in Poland. The current strategy - Energy Policy of Poland until 2040 which was adopted in February 2021 laid plans to develop 6 – 9 GWe of nuclear capacity.

In 2014 the Council of Ministers adopted the Polish Nuclear Power Programme (PNPP) and its updated version was approved in 2020. It is a roadmap for all necessary actions to be taken by the government to implement nuclear power in a safe and sustainable manner.

Poland held talks with three potential suppliers of nuclear technology: Westinghouse, EDF, and KHNP. In November 2022, the Polish government announced that the technology of Westinghouse AP1000 will be used in the country's first nuclear power plant. The commissioning of the first of the six units is foreseen in 2033. Subsequent units will be completed every two years.

In 2022, the companies ZE PAK, PGE, and KHNP signed a letter of intent to explore the possibility of building a nuclear power plant using the Korean APR1400 technology.

There is also an increased interest in SMR technologies from Polish energy and industrial companies.

Table 0.21 Overview of nuclear power - Poland

The total number of operated reactors and installed capacity	0 power reactors / 0 MW 1 research reactor / 30 MW
Number of new nuclear capacities till 2050	7 350 MW
New capacity of SMRs till 2050	608 MW
Capacity of shutdown reactors till 2050	0 MW

Source: Member States questionnaire, Stakeholder interviews, IAEA Research Reactor Database

Portugal

Portugal is a non-nuclear country and it does not operate any nuclear reactors. It operated one research reactor but that is in the permanent shutdown state. The public acceptance of nuclear is very low in Portugal and thus there are no development plans in terms of nuclear power.

Table 0.22 Overview of nuclear power - Portugal

The total number of operated reactors and installed capacity	0 power reactors / 0 MW
Number of new nuclear capacities till 2050	0 MW
New capacity of SMRs till 2050	0 MW
Capacity of shutdown reactors till 2050	0 MW

Source: Member States questionnaire, Stakeholder interviews, IAEA Research Reactor Database

Romania

Romania has currently two nuclear reactors in operation at the Cernavoda site. These reactors are delivering about 20% of their electricity supplies. Both reactors are CANDU type, with an installed capacity of 650 MW, the first being commissioned in 1996 and the second in 2007. The country is committed to nuclear energy and the government support is strong. The development plans cover two new units at Cernavoda, both CANDU reactors, the first being commissioned before 2030, and the second before 2035. Also, Nuclearelectrica signed a memorandum of understanding with NuScale in 2022 and is expected to deploy six VOYGR modules with a total capacity of 462 MW. Romania has also strong nuclear research, the research centre RATEN is operating a TRIGA reactor. The focus of research in Romania is put mainly on the development of the Advanced Lead Fast Reactor European Demonstrator (ALFRED), on which Romania is cooperating with Italy.

Table 0.23 Overview of nuclear power - Romania

The total number of operated reactors and installed capacity	2 power reactors / 1 413 MW 2 research reactor / 16 MW
Number of new nuclear capacities till 2050	1 427 MW
New capacity of SMRs till 2050	462 MW
Capacity of shutdown reactors till 2050	0 MW

Source: Member States questionnaire, Stakeholder interviews, IAEA Research Reactor Database

Slovakia

Slovakia currently has five nuclear reactors in operation and one in construction. Nuclear power accounts for approximately 50% of its electricity supplies and the government is committed to the use of nuclear power. The construction of the first reactor in Slovakia started in 1955 and it was connected to the grid in 1972. It was shut down after an accident in 1977. Currently there is one NPP under commissioning (at 90% of the capacity). The Slovakian government is considering another new unit at the Bohunice site, but the National Energy and Climate Plan for 2021 to 2030 does not expect the reactor to be commissioned before 2035. Decommissioning of the first nuclear power plant is ongoing and decommissioning of the two remaining shutdown reactors is in the preparation phase.

Table 0.24 Overview of nuclear power - Slovakia

The total number of operated reactors and installed capacity	5 power reactors / 2 308 MW
Number of new nuclear capacities till 2050	1 640 MW
New capacity of SMRs till 2050	0 MW
Capacity of shutdown reactors till 2050	932 MW

Source: Member States questionnaire, Stakeholder interviews, IAEA Research Reactor Database

Slovenia

Slovenia is operating one nuclear reactor that is in shared ownership with Croatia (each having a 50% share of the power plant). The reactor was commissioned in 1981 and it is Westinghouse PWR type with a rated capacity of 688 MW. Originally it was designed for a 40-year lifetime, an extension for another 20 years was issued in 2015. The extension is dependent on the result of inspections in 2023 and 2033. Slovenia is considering building a second unit at the Krsko site with similar conditions as the first unit, co-owned with Croatia. The government stated that it will decide about the construction of the second unit by 2027. In July 2021 an energy permit for unit 2 was issued. Slovenia is also operating one research reactor (TRIGA 250 kW) at Jozef Stefan Institute.

Table 0.25 Overview of nuclear power - Slovenia

The total number of operated reactors and installed capacity	1 power reactors / 688 MW 1 research reactor / 250 kW
Number of new nuclear capacities till 2050	1 200 MW
New capacity of SMRs till 2050	0 MW
Capacity of shutdown reactors till 2050	688 MW

Source: Member States questionnaire, Stakeholder interviews, IAEA Research Reactor Database

Spain

Nuclear power in Spain covers approximately one fifth of the country's electricity generation. All together Spain operates seven reactors in five locations. Historically the country operated another three reactors that are now in a shutdown state and the subject of decommissioning. The Spanish government is not pursuing the further development of nuclear energy, so no new units are planned at the moment. The National Energy and Climate Plan issued in 2019 is discussing the complete phase out of nuclear power. Following this decision, the agreement between the government, NPP operators, and ENRESA was made and it was agreed that the nuclear phase out will happen by 2035. Together with the NPPs, Spain is operating the Juzbado plant through the state-owned company ENUSA , this plant produces fuel elements for PWR and BWR. No conversion or enrichment facilities are in operation in Spain.

Table 0.26 Overview of nuclear power - Spain

The total number of operated reactors and installed capacity	7 power reactors / 7 123 MW
Number of new nuclear capacities till 2050	0 MW
New capacity of SMRs till 2050	0 MW
Capacity of shutdown reactors till 2050	7 123 MW

Source: Member States questionnaire, Stakeholder interviews, IAEA Research Reactor Database

Sweden

Sweden currently operates six nuclear reactors at three locations which account for about 30% of its electricity supplies. The development of nuclear power in Sweden began in 1947 when the atomic energy research organization was established. The first experimental reactor was commissioned in 1954. Swedish energy policy toward nuclear power has been changing a lot in history. In 1980 after the three-mile island accident, the government decided to phase out nuclear by 2010 if new energy sources are available, and the further development of nuclear was banned. After the Chernobyl accident, the government decided to speed up the phase out of nuclear and to start shutting down reactors in 1995. This decision was later overturned in 1991.

In 2010 the ban on the construction of new units was dropped, even though new units can be built only on existing sites to replace the existing units. The government has proposed to remove the restriction of only ten reactors in Sweden as well as the restriction to build new reactors at sites other than the three existing ones. Sweden is also operating a fuel fabrication facility owned by Westinghouse, it doesn't have any conversion or enrichment facilities, so it imports the uranium. The country is investigating the potential location of the DGR , the construction should begin in the mid-2020s.

Table 0.27 Overview of nuclear power - Sweden

The total number of operated reactors and installed capacity	6 power reactors / 6 935 MW
Number of new nuclear capacities till 2050	0 MW
New capacity of SMRs till 2050	0 MW
Capacity of shutdown reactors till 2050	6 935 MW

Source: Member States questionnaire, Stakeholder interviews, IAEA Research Reactor Database

Annex C Response rate to the MS questionnaire

Country	Status
Austria	Answers not received
Belgium	Answers received
Bulgaria	Answers received
Croatia	Answers not received
Cyprus	Answers not received
Czech Republic	Answers received
Denmark	Answers not received
Estonia	Answers received
Finland	Answers received
France	Answers received
Germany	Answers received
Greece	Answers received
Hungary	Answers not received
Ireland	Answers received
Italy	Answers not received
Latvia	Answers received
Lithuania	Answers received
Luxembourg	Answers not received
Malta	Answers not received
Netherlands	Answers received
Poland	Answers received
Portugal	Answers not received
Romania	Answers received
Slovakia	Answers not received
Slovenia	Answers received
Spain	Answers received
Sweden	Answers received

Annex D List of Universities

The table below present a comprehensive list of universities that are offering a nuclear or nuclear-related programme. The list shows that the number of universities that offers nuclear courses is not that large.

Country	University	Degree	Programme
Austria	Graz University of Technology	Bachelor's	• Bachelor of Technical Physics
		Master's	• Master of Technical Physics
		Doctoral	• PhD of Physics
	Technische Universitaet Wien	Bachelor's	• Bachelor of Physics with courses on nuclear engineering, reactor physics or radiation protection
		Master's	• Master of Physics with courses on nuclear engineering, reactor physics or radiation protection
		Doctoral	• PhD of Physics
	Atominstitute through TU Wien or University of Vienna	Bachelor's	• Bachelor of Physics
		Master's	• Master of Physics
		Doctoral	
	University of Innsbruck	Bachelor's	
		Master's	• Master of Chemistry
		Doctoral	• PhD of Physics
	University of Natural Resources and Applied Life Sciences	Bachelor's	
		Master's	
		Doctoral	• PhD of Physics
Belgium	University of Hasselt	Bachelor's	• Bachelor of Engineering Technology
		Master's	• Master of Nuclear Engineering Technology
		Doctoral	
	University of Namur	Bachelor's	• Bachelor of Physics with Nuclear Physics courses
		Master's	• Master of Physics with courses on nuclear medicine and radiology
		Doctoral	• PhD of Engineering Technology, specialised in a nuclear research topic linked to the NuTeC research group and the Doctoral

Country	University	Degree	Programme
			School of Sciences & Technology
	University of Limburg and Leuven	Bachelor's	• Bachelor of Energy Technologies with courses on nuclear energy production
		Master's	• Master of Energy Technologies with courses on nuclear energy production
		Doctoral	
	University of Liege	Bachelor's	
		Master's	• Master in Nuclear Medicine
		Doctoral	
	University of Ghent	Bachelor's	
		Master's	• European Master in Nuclear Fusion Science and Engineering Physics
		Doctoral	
	BNEN	Bachelor's	
		Master's	• Master after Master in Nuclear Engineering
		Doctoral	
Bulgaria	Sofia University Kliment Ohridski	Bachelor's	• Bachelor's programme in Nuclear Chemistry • Bachelor Nuclear Power Engineering
		Master's	• Master's programme in Nuclear Chemistry • Master of Nuclear Technique and Technology • Master's Degree Programme: Fusion Science and Technology (FUSENET project)
		Doctoral	• Nuclear Physics • Radiochemistry
	Technical University of Sofia	Bachelor's	
		Master's	
		Doctoral	• PhD Programme in Nuclear Power Engineering
	Medical University of	Bachelor's	

Country	University	Degree	Programme
	Plovdiv	Master's	
		Doctoral	• Nuclear medicine and radiotherapy
	Medical University of Sofia	Bachelor's	
		Master's	
		Doctoral	• Nuclear medicine and oncology
Croatia	University Rijeka	Bachelor's	• Bachelor of Radiologic Technology
		Master's	• MSc study programmes of Electrical Engineering Systems and Technology • Medical Radiology
		Doctoral	
	Polytechnic for Applied Health Studies	Bachelor's	• Courses of Radiology Technology
		Master's	
		Doctoral	
	University of Zagreb	Bachelor's	
		Master's	• Master's in electrical Power Engineering with specialisation of Nuclear Engineering
		Doctoral	• PhD programme in Electric Engineering and Computing with courses nuclear power plant safety analyses
	University of Split	Bachelor's	
		Master's	• Power Engineering
		Doctoral	
Czech Republic	Czech Technical University in Prague	Bachelor's	• Bachelor with specialization Physics and Technology of Nuclear Fusion • Bachelor with specialization Theory and Technology of Nuclear Reactors • Bachelor with specialization Dosimetry and Applied Ionizing Radiation
		Master's	• Master with specialization Physics and Technology of Nuclear Fusion • Master with specialization Theory and Technology of

Country	University	Degree	Programme
			Nuclear Reactors • Master of Radiological Physics • Master in Nuclear Energy Engineering • Bachelor with specialization Theory and Technology of Nuclear Reactors • Bachelor with specialization Dosimetry and Applied Ionizing Radiation
		Doctoral	• PhD programme in Mechanical Engineering • PhD programme in Applied Sciences
	Charles University in Prague	Bachelor's	• Bsc in Applied Nuclear Physics
		Master's	• Magister (MSc.) in Nuclear and Sub nuclear Physics
		Doctoral	• PhD programme of Nuclear Physics
	Brno University of Technology	Bachelor's	• Bachelor's study programme Electric, Electronic, Communication and Control Technology
		Master's	• Master of Electric, Electronic, Communication and Control Technology
		Doctoral	
	University of West Bohemia Pilsen	Bachelor's	
		Master's	• Master's programme of Electrical Power Engineering • Master's study programme Design of Nuclear Power Equipment
		Doctoral	• PhD programme Design of Power System Machines and Equipment
Finland	Aalto University	Bachelor's	• Bachelor of Applied Physics with courses on antimatter and nuclear engineering
		Master's	• Master of science programme in nuclear engineering
		Doctoral	
	Lappeenranta	Bachelor's	• Bachelor's programme in Nuclear Engineering

Country	University	Degree	Programme
	University of Technology	Master's	• Master's Programme in Nuclear Engineering
		Doctoral	• Doctoral programme in Energy Systems
	University of Helsinki	Bachelor's	
		Master's	• Master's Programme in Particle Physics and Astrophysical Science
		Doctoral	• Doctoral programme in Particle Physics and Universe Sciences
	University of Jyväskylä	Bachelor's	
		Master's	• Master's Degree Programme in Nuclear and Particle Physics
		Doctoral	• Doctoral Programme in Nuclear and Particle Physics
France	University Clermont Auvergne	Bachelor's	• Bachelor of Physical Chemistry
		Master's	
		Doctoral	
	École Centrale Paris	Bachelor's	
		Master's	• MSc Nuclear Energy
		Doctoral	
	Université de Paris-Sud	Bachelor's	
		Master's	• The Nuclear Energy Master's Course (M1) • Master's degree in Nuclear Engineering (M2)
		Doctoral	
	Université Pierre et Marie Curie (UPMC) Sorbonne Universités	Bachelor's	
		Master's	• Master of Physics and Application with Nuclear Engineering specialization • Master's Programme: Europlasmi curriculum: Physics of Fusion and Plasmas • Master's degree in basic physics and applications
		Doctoral	
	Mines Paris Graduate	Bachelor's	

Country	University	Degree	Programme
	School	Master's	• Master's in science and Executive Engineering, Nuclear Engineering Minor • Strategic Energy Master's programme
		Doctoral	
	University of Lorraine	Bachelor's	
		Master's	• European Master in Nuclear Fusion Science and Engineering Physics (FUSION-EP)
		Doctoral	
	IMT Atlantique	Bachelor's	
		Master's	• MSc in Safe and Reliable Nuclear Applications • MSc Sustainable Nuclear Engineering – Applications and Management (Waste, Energy Production and Instrustrial Applications and Medical Applications – 3 specialisations.
		Doctoral	
	Grenoble Institute of Technology	Bachelor's	
		Master's	• European Masters in Nuclear Energy • MSc Reactor Physics and Nuclear Engineering Specialty • Master's in engineering of Nuclear Power
		Doctoral	
	Chemistry Paris Tech	Bachelor's	
		Master's	• Masters in Nuclear Energy • Masters in Energy
		Doctoral	
	University Clermont Auvergne	Bachelor's	
		Master's	• Master of Physics and Radiation Technology • Master of Nuclear Engineering
		Doctoral	
	University Bordeaux	Bachelor's	

Country	University	Degree	Programme
		Master's	• Master of Nuclear Physics
		Doctoral	
	University Montpellier	Bachelor's	
		Master's	• Master of Management of Nuclear Decommissioning and Valorisation of the Industrial Site
		Doctoral	
	Polytechnic School Paris Tech	Bachelor's	
		Master's	• Master of Physics with courses of Nuclear Physics • Master's of Physics with Fusion Sciences Track
		Doctoral	
	National High school of Advanced Technics	Bachelor's	
		Master's	• Master of Nuclear Engineering • M2 Nuclear Plant Design • M2 Processes, energy, environment
		Doctoral	
	National High school of Ingenieurs of Caen	Bachelor's	
		Master's	• MSc Electronics and Applied Physics Engineer
		Doctoral	
	Université Paris-Sarclay	Bachelor's	
		Master's	• MSc Nuclear Energy • M2 Nuclear Plant and Design • M2 Nuclear Reactor Physics and Engineering • M2 Decommissioning and Waste Management • M2 Fuel Cycle
		Doctoral	
	Grenoble Institute of Technology	Bachelor's	
		Master's	
		Doctoral	• PhD Physics
	Doctoral School of	Bachelor's	

Country	University	Degree	Programme
	Engineering Sciences Clermont- Ferrand	Master's	
		Doctoral	• PhD programme in Engineering Sciences
	University Bordeaux in the Centre of Nuclear Studies	Bachelor's	
		Master's	
		Doctoral	• PhD programme in Nuclear Energy
	Université Paris-Sarclay	Bachelor's	
		Master's	
		Doctoral	• PhD programme in Nuclear Energy
	GANIL SPIRAL2	Bachelor's	
		Master's	• PhD programme in Nuclear Instrumentation • PhD programme in Theoretical Nuclear Physics
		Doctoral	
Germany	University Augsburg	Bachelor's	• Bachelor and Master of Experimental Plasma Physics
		Master's	
		Doctoral	
	Freie Universität Berlin	Bachelor's	• BSc Chemistry (modules in Radiochemistry)
		Master's	
		Doctoral	
	Dresden Technical University	Bachelor's	• BSc Physics
		Master's	
		Doctoral	
	Heinrichs-Heine University Düsseldorf	Bachelor's	• BSc Medical Physics • BSc Physics
		Master's	
		Doctoral	
	Justus Liebig University Giessen	Bachelor's	• BSc Physics
		Master's	
		Doctoral	
	Leibniz University	Bachelor's	• BSc Power Engineering

Country	University	Degree	Programme
	Hannover	Master's	
		Doctoral	
	Cooperative State University Karlsruhe	Bachelor's	• BSc Security Studies, Radiation Protection
		Master's	
		Doctoral	
	Ulm University	Bachelor's	• BEng Energy Systems Technology
		Master's	
		Doctoral	
	Rheinisch-Westfaelische Technical University Aachen	Bachelor's	
		Master's	• MSc Energy Engineering
		Doctoral	
	University of Applied Sciences	Bachelor's	
		Master's	• European Master of Science in Nuclear Applications
		Doctoral	
	Freie Universität Berlin Sciences	Bachelor's	
		Master's	• Master of Chemistry (modules in Radiochemistry and Radiation Module in MSc chemistry Protection)
		Doctoral	
	University of Cologne	Bachelor's	
		Master's	• Module in MSc chemistry
		Doctoral	
	Brandenburg Cottbus University of Technology	Bachelor's	
		Master's	• MSc Power Engineering • MSc Process and Plant Technology
		Doctoral	
	Dresden Technical University	Bachelor's	
		Master's	• MSc Physics • MSc Medical Radiation Sciences
		Doctoral	
	Heinrichs-Heine	Bachelor's	

Country	University	Degree	Programme
	University Düsseldorf	Master's	
		Doctoral	• International Master Programme in Physics • MSc Medical Physics • MSc Physics
	Center for Radioprotection and Radioecology at the Leibniz University Hannover	Bachelor's	
		Master's	
		Doctoral	• PhD programme Radioprotection and Radioecology
	University of Goettingen	Bachelor's	
		Master's	
		Doctoral	• PhD programme in Physics
Hungary	Budapest University of Technology and Economics	Bachelor's	• BSc Programme in Applied Physics • BSc Programme in Energy Engineering
		Master's	• MSc Programme "Nuclear Techniques" • MSc Programme "Energy Engineering"
		Doctoral	
	Eötvös Loránd University	Bachelor's	
		Master's	• Master programme in Particle Physics • Masters in physics
		Doctoral	• PhD programme in Particle Physics and Astronomy
	University of Pannonia	Bachelor's	
		Master's	• MSc in Environmental Engineering
		Doctoral	
Italy	University of Palermo	Bachelor's	• Bachelor of Energy Engineering with Nuclear Specialisation
		Master's	• MSc degree in Energy and Nuclear Engineering • European Master of Science in Nuclear Engineering
		Doctoral	• PhD programme Energy and Information Technologies

Country	University	Degree	Programme
	University of Bologna	Bachelor's	• Bachelor of Energy Engineering
		Master's	• MSc degree in Energy Engineering • MSc in Physics, curriculum nuclear and subnuclear physics
		Doctoral	• PhD degree in Physics, curriculum nuclear and subnuclear physics
	Sapienza University of Rome	Bachelor's	• Bachelor of Energy Engineering
		Master's	• MSc in Energy Engineering
		Doctoral	• PhD in Energy and Environment with topic in Nuclear Engineering
	University of Pisa	Bachelor's	
		Master's	• MSc programme in Nuclear Engineering and Industrial Safety
		Doctoral	• PhD programme in Industrial Engineering, curriculum in Nuclear Engineering
	Politecnico di Milano	Bachelor's	
		Master's	• MSc programme in Nuclear Engineering
		Doctoral	• PhD programme in Energy and Nuclear Science and Technology
	Turin University	Bachelor's	
		Master's	• Master of Physics
		Doctoral	
	IUSS – University of Pavia	Bachelor's	
		Master's	• Master's programme in Nuclear and Ionising Radiation Technologies
		Doctoral	
Lithuania	Kaunas University of Technology	Bachelor's	• Bachelor of Power Engineering Nuclear Energy
		Master's	• Master of Power Engineering Nuclear Energy
		Doctoral	• PhD in Energetics and Power Engineering
	Vilnius University	Bachelor's	

Country	University	Degree	Programme
		Master's	
		Doctoral	• PhD in radiochemistry • PhD Studies in Nuclear Physics • PhD Studies in Radiation Protection
Netherlands	Radboud University of Nijmegen	Bachelor's	• Bachelor of Natural Sciences and Astronomy
		Master's	• Master Physics and Astronomy • Masters in Nuclear Physics
		Doctoral	• PhD Programme of High Energy
	University of Groningen	Bachelor's	• BSc Honours Medical Sciences (nuclear medicine and radiology electives)
		Master's	
		Doctoral	
	Leiden University	Bachelor's	
		Master's	• Master of Physics (Medical Centre) – Oncology
		Doctoral	• PhD Radiology • PhD Radiation Oncology
	Delft University of Technology	Bachelor's	
		Master's	• Masters in applied physics track Radiation, Radionuclides and Reactors • Masters in chemical engineering track Nuclear Science and Engineering
		Doctoral	• PhD Radiation Science and Technology • PhD Process and Energy
	Utrecht University	Bachelor's	
		Master's	• Master programme of Particle Physics
		Doctoral	
	Eindhoven University of Technology	Bachelor's	
		Master's	• Master's programme in Applied Physics. Plasma Physics and Radiation Technology • MSc Science and

Country	University	Degree	Programme
			Technology of Nuclear Fusion • MSc Electrical Engineering • Master's programme in Applied Physics. Science and Technology of Nuclear Fusion
		Doctoral	
	Free University of Amsterdam	Bachelor's	
		Master's	• Master of Physics
		Doctoral	
	INHOLLAND Graduate School	Bachelor's	
		Master's	• Master of Science Radiation Oncology in Europe
		Doctoral	
	Amsterdam UMC	Bachelor's	
		Master's	• Master's Oncology
		Doctoral	
Poland	AGH University of Science and Technology	Bachelor's	• Medical Physics • Technical Physics • Power Engineering
		Master's	• Medical Physics • Technical Physics • Power Engineering (possible specialisation: Nuclear Energy)
		Doctoral	• Physics • Power Engineering
	Gdańsk University of Technology	Bachelor's	• Power Engineering
		Master's	• Power Engineering
		Doctoral	• Power Engineering
	Institute of Nuclear Chemistry and Technology	Bachelor's	
		Master's	
		Doctoral	• Radiation Chemistry
	Łódź University of Technology	Bachelor's	• Chemical Technology
		Master's	• Chemical Technology (possible specialisation: Biomedical and Radiation Engineering)

Country	University	Degree	Programme
		Doctoral	• Chemical Engineering
	Maria Curie-Skłodowska University	Bachelor's	• Physics (possible specialisation: Nuclear Safety and Radiation Protection)
		Master's	• Physics
		Doctoral	• Physics
	National Centre for Nuclear Research	Bachelor's	
		Master's	
		Doctoral	• Physics • Interdisciplinary PhD programme for new generation reactors* • Interdisciplinary PhD programme RadFarm - Radiopharmaceuticals for molecularly targeted diagnostics and medical therapy
	Poznań University of Technology	Bachelor's	• Power Engineering
		Master's	• Power Engineering (possible specialisation: Nuclear Energy)
		Doctoral	• Power Engineering
	Silesian University of Technology	Bachelor's	• Power Engineering
		Master's	• Power Engineering (possible specialisation: Nuclear Energy)
		Doctoral	• Power Engineering
	The Henryk Niewodniczański Institute of Nuclear Physics	Bachelor's	
		Master's	
		Doctoral	• Applied Physics
	University of Silesia in Katowice	Bachelor's	• Physics
		Master's	• Physics
		Doctoral	• Physics
	University of Szczecin	Bachelor's	• Physics
		Master's	• Physics (possible specialisation: Nuclear Physics and Engineering)
		Doctoral	• Physics

Country	University	Degree	Programme
	University of Warsaw	Bachelor's	• Power Engineering
		Master's	• Nuclear Chemistry • Physics
		Doctoral	• Chemistry • Physics
	Warsaw University of Technology	Bachelor's	
		Master's	• Power Engineering (possible specialisation: Nuclear Energy)
		Doctoral	• Power Engineering
	Wrocław University of Science and Technology	Bachelor's	• Power Engineering
		Master's	• Power Engineering (possible specialisation: Nuclear Energy)
		Doctoral	• Power Engineering
Romania	University Politehnica of Bucharest	Bachelor's	• Bachelor of Science in Power Engineering and Nuclear Technology • Bachelor of Science in Mechanical Engineering with courses in Nuclear Engineering
		Master's	• Master of Science in Nuclear Engineering • Master of Science in Lasers and Particle Accelerators Engineering and Applications • Master of Science in Specialized Termoclasic and Nuclear Equipment • Master of Science in Mechanical Engineering (Major in Maintenance Engineering for ELI-NP-IMent-ELi) – with courses in Nuclear Engineering
		Doctoral	• PhD studies in Lasers and Particle Accelerators Engineering and Applications (in partnership with UPB) • PhD studies in Nuclear Engineering
	University of Bucharest	Bachelor's	• Bachelor of Science in Technological Physics with nuclear related courses

Country	University	Degree	Programme
			• Bachelor of Physics in English or in Romanian
		Master's	• Master of Physics with courses of Nuclear Physics • Bachelor of Physics in English or in Romanian
		Doctoral	• PhD in Nuclear Physics and other Physics related fields • Bachelor of Physics in English or in Romanian
	Ovidius University of Constanta	Bachelor's	• Bachelor of Science in Energy Engineering with Specialisation of Industrial Energy
		Master's	
		Doctoral	
	Babes - Bolyai University	Bachelor's	
		Master's	• Master of Physics
		Doctoral	• PhD in Physics
Slovakia	Slovak University of Technology	Bachelor's	• Bachelor of Nuclear and Physics Engineering
		Master's	• Master of Nuclear and Physics Engineering
		Doctoral	• PhD programme in Nuclear Power Engineering
	Comenius University in Bratislava	Bachelor's	• Bachelor's degree Studies in Physics • Bachelor's degree Studies in Pedagogy with Specialisation Physics • Bachelor's degree Studies with study programme in Renewable Energy Sources and Environmental Physics • Bachelor's degree Studies in Biomedical Physics
		Master's	
		Doctoral	
Slovenia	University of Ljubljana	Bachelor's	• Bachelor's programme with optional courses of Nuclear Engineering
		Master's	• Master's programme in Medical Physics • Master's programme in Nuclear Engineering

Country	University	Degree	Programme
		Doctoral	• Doctoral Programme in Mathematics and Physics • Doctoral Programme in Nuclear Engineering
	University of Maribor	Bachelor's	• Undergraduaten Professionally Oriented Study Programme Energy Technology • Undergraduate Academic Study Programme Energy Technology
		Master's	• Master's Degree in Energy Technology
		Doctoral	
Spain	Polytechnic University of Madrid	Bachelor's	• Undergraduate degree in Energy Engineering
		Master's	• Master degree in Energy Engineering • Master degree in Nuclear Science and Technology
		Doctoral	• PhD Sustainable Energy, Nuclear and Renewable
	University of Huelva	Bachelor's	• BS Energy Engineering
		Master's	
		Doctoral	
	University of Seville	Bachelor's	• Undergraduate degree in Energy Engineering
		Master's	• Masters in Nuclear Physics
		Doctoral	
	University of Oviedo	Bachelor's	• Bachelor's in physics
		Master's	
		Doctoral	
	University of La Laguna	Bachelor's	• Bachelors in Physics
		Master's	
		Doctoral	
	The Autonomous University of Madrid	Bachelor's	
		Master's	• Master Inter-University programme in Nuclear Physics
		Doctoral	• PhD in Physics
	Polytechnic University	Bachelor's	

Country	University	Degree	Programme
	of Cataluña, Barcelona	Master's	• Master in Energy Engineering • Master's in Nuclear Engineering
		Doctoral	• PhD Studies in Nuclear and Ionizing Radiation Engineering
	Complutense University of Madrid	Bachelor's	
		Master's	• Master in Nuclear Fusion Science and Engineering Physics (Erasmus Mundus) • Master in Nuclear Physics • Master in Plasma Physics and Nuclear Fusion (Erasmus Mundus)
		Doctoral	• PhD in Theoretical Nuclear Physics • PhD in Experimental Nuclear Physics • PhD in Nuclear and Particle Physics Applied to Medicine
	Granada University	Bachelor's	
		Master's	• Masters in Physics: Radiation, Nanotechnology, Particles and Astrophysics
		Doctoral	
Sweden	Lund University	Bachelor's	• Bachelor's in physics with specialization in Synchrotron Radiation Based Science
		Master's	• Master's in physics: Theoretical Nuclear Physics
		Doctoral	
	Royal Institute of Technology	Bachelor's	
		Master's	• Master's Programme, Nuclear Energy • Master's Programme, Nuclear Energy Engineering • Master's Programme, Engineering Physics
		Doctoral	• PhD programme managed by Department of Nuclear Reactor Physics
	Uppsala University	Bachelor's	
		Master's	• Masters in Energy Technology

Country	University	Degree	Programme
			• Masters in Nuclear and Particle Physics
		Doctoral	• PhD programme at Nuclear and Particle Physics
	Stockholm University	Bachelor's	
		Master's	• Master's programme in Physics
		Doctoral	• PhD' programme in Experimental Physics with Research programmes in nuclear and particle Physics
	Umeå University	Bachelor's	
		Master's	• Masters courses in Nuclear Medicine • Masters courses in Nuclear Physics
		Doctoral	
	Linnaeus University	Bachelor's	
		Master's	• Masters Programme in Physics
		Doctoral	
United Kingdom	University of Aberdeen	Bachelor's	• BSc Physics
		Master's	
		Doctoral	
	Aston University, Birmingham	Bachelor's	• Undergraduate in Professional Engineering (Nuclear Engineering)
		Master's	
		Doctoral	
	Bangor University	Bachelor's	• Undergraduate in Control and Instrumentation Engineering
		Master's	
		Doctoral	
	University of Bath	Bachelor's	• BSc Physics, with option of medical physics • Undergraduate in Chemical Engineering
		Master's	•
		Doctoral	•
	University of	Bachelor's	• BSc Nuclear Science and

Country	University	Degree	Programme
	Birmingham		Materials • MEng Nuclear Engineering
		Master's	• MSc Physics and Technology of Nuclear Reactors Masters • MSc Nuclear Decommissioning and Waste Management
		Doctoral	
	Birmingham City University	Bachelor's	• BSc Diagnostic Radiotherapy, Radiotherapy
		Master's	
		Doctoral	
	University of Bradford	Bachelor's	• BSc Diagnostic Radiography
		Master's	• MSc Advanced Chemical and Petroleum Engineering
		Doctoral	
	University of Cambridge	Bachelor's	• Undergraduate in Engineering
		Master's	• Mphil Nuclear Energy
		Doctoral	
	University of Central Lancashire, Preston and Burnley	Bachelor's	• Undergraduate in Energy Engineering • BSc Nuclear Engineering Science
		Master's	• MSc Nuclear Safety, Security and Safeguards • MSc Nuclear Science and Technology
		Doctoral	
	Canterbury Christ Church University, Canterbury, Thanet, Tunbridge Wells and Chatham	Bachelor's	• BSc Diagnostic Radiography • Undergraduate in Engineering
		Master's	
		Doctoral	
	Cardiff University	Bachelor's	• Undergraduate in Civil Engineering • Undergraduate in Mechanical Engineering • BSc Physics with Medical Physics • BSc Diagnostic

Country	University	Degree	Programme
			Radiotherapy and Imaging • BSc Radiotherapy and Oncology
		Master's	
		Doctoral	
	University of Chester, Chester and Warrington	Bachelor's	• BSc Physics • Undergraduate in Engineering
		Master's	
		Doctoral	
	University of Chichester	Bachelor's	• Undergraduate in Mechanical Engineering • Undergraduate in Electrical Engineering
		Master's	
		Doctoral	
	Cranfield University	Bachelor's	• Undergraduate in Engineering
		Master's	
		Doctoral	
	De Montfort University, Leicester https://www.dmu.ac.uk/	Bachelor's	• Undergraduate in Engineering
		Master's	
		Doctoral	
	University of Derby	Bachelor's	• BSc Diagnostic Radiotherapy • Undergraduate in Engineering
		Master's	
		Doctoral	
	University of East Anglia, Norwich	Bachelor's	• Undergraduate in Energy Engineering with Environmental Management
		Master's	
		Doctoral	
	University of East London	Bachelor's	• Undergraduate in Mechanical Engineering
		Master's	
		Doctoral	

Country	University	Degree	Programme
	Edinburgh Napier University	Bachelor's	• Undergraduate in Mechanical Engineering
		Master's	
		Doctoral	
	University of Greenwich	Bachelor's	• Undergraduate in Chemical Engineering • Undergraduate in Mechanical Engineering
		Master's	
		Doctoral	
	University of Hertfordshire, Hatfield	Bachelor's	• BSc Radiotherapy and Oncology
		Master's	• MSc Medical Imaging and Radiation Sciences, Radiotherapy
		Doctoral	
	Imperial College London	Bachelor's	• Undergraduate in Chemical Engineering • Undergraduate in Materials or Mechanical and Nuclear Engineering
		Master's	• MSc Advanced Nuclear Engineering
		Doctoral	• Nuclear Engineering
	Lancaster University	Bachelor's	• Undergraduate in Nuclear Engineering
		Master's	
		Doctoral	
	University of Leeds	Bachelor's	• Undergraduate in Chemical and Nuclear Engineering
		Master's	
		Doctoral	
	University of Liverpool	Bachelor's	• BSc Physics with Nuclear Science • BSc Diagnostic Radiography • BSc Therapeutic Radiography and Oncology
		Master's	• MSc in Nuclear Science & Technology (NTEC Programme)
		Doctoral	

Country	University	Degree	Programme
	University of London	Bachelor's	• At St Georges - BSc Diagnostic Radiography
		Master's	
		Doctoral	
	London South Bank University	Bachelor's	• BSc Diagnostic Radiography • BSc Therapeutic Radiography
		Master's	• MSc Diagnostic Imaging
		Doctoral	
	Nottingham Trent University	Bachelor's	• BSc Physics with Nuclear Technology
		Master's	
		Doctoral	
	University of Oxford	Bachelor's	• BSc Physics
		Master's	• MSc Materials MSc by research
		Doctoral	• Science and Technology of Fusion Energy
	University of Plymouth	Bachelor's	• Undergraduate in Mechanical Engineering with Composites • BSc Diagnostic Radiotherapy
		Master's	
		Doctoral	
	University of Portsmouth	Bachelor's	• BSc Energy and Power Systems Management • BSc Diagnostic Radiography and Medical Imaging
		Master's	
		Doctoral	
	Queen Margaret University, Edinburgh	Bachelor's	• BSc Diagnostic or Therapeutic Radiography
		Master's	• MSc Diagnostic Radiography • MSc Radiotherapy and Oncology
		Doctoral	
	Queen's University	Bachelor's	• BSc Physics with Medical Applications

Country	University	Degree	Programme
	Belfast	Master's	
		Doctoral	
	University of Reading	Bachelor's	• BSc Environmental Physics • BSc Physics of the Environment
		Master's	
		Doctoral	
	The Robert Gordon University, Aberdeen	Bachelor's	• BSc Diagnostic Radiotherapy
		Master's	
		Doctoral	
	University of Salford	Bachelor's	• BSc Diagnostic Radiotherapy
		Master's	• MSc Nuclear Medicine Imaging
		Doctoral	
	University of Sheffield	Bachelor's	• Undergraduate in Chemical Engineering with Nuclear Technology
		Master's	• MSc in Nuclear Science & Technology (NTEC Programme)
		Doctoral	
	Sheffield Hallam University	Bachelor's	• BSc Diagnostic Radiography • BSc Radiotherapy and Oncology
		Master's	• MSc Advanced Clinical Practice Radiotherapy and Oncology • MSc Enhanced Diagnostic imaging practice
		Doctoral	
	University of Southampton	Bachelor's	• BSc Physics, module in nuclear physics and atomic physics
		Master's	
		Doctoral	
	University of St Andrews	Bachelor's	• BSc Physics
		Master's	
		Doctoral	

Country	University	Degree	Programme
	St Mary's University, Twickenham	Bachelor's	• BSc Applied Physics
		Master's	
		Doctoral	
	University of Suffolk, Ipswich, Bury St Edmunds, Great Yarmouth, Lowestoft	Bachelor's	• BSc Radiotherapy and Oncology
		Master's	
		Doctoral	
	University of Surrey, Guildford	Bachelor's	• BSc Physics with Nuclear Astrophysics
		Master's	
		Doctoral	
	Swansea University	Bachelor's	• BSc Healthcare Science - Nuclear Medicine • BSc Physics
		Master's	• MSc Medical Radiation Physics • MSc Clinical Science (Medical Physics)
		Doctoral	
	Teesside University, Middlesbrough and Darlington	Bachelor's	• Undergraduate in Chemical Engineering • Undergraduate in Instrumentation and Control Engineering
		Master's	
		Doctoral	
	Ulster University, Coleraine, Jordanstown, Magee and Belfast	Bachelor's	• BSc Radiography • BSc Diagnostic and Imaging
		Master's	
		Doctoral	
	University of the West of England, Bristol	Bachelor's	• BSc Diagnostic Radiography
		Master's	• MSc Nuclear Medicine
		Doctoral	
	University of the West of Scotland, Paisley, Hamilton, Ayr & Dumfries	Bachelor's	• BSc Physics with Nuclear Technology
		Master's	• MSc Physics and Technology of Nuclear Reactors Masters • MSc Nuclear Decommissioning and

Country	University	Degree	Programme
			Waste Management
		Doctoral	
	University of York	Bachelor's	• BSc Physics
		Master's	
		Doctoral	
	University of Brighton	Bachelor's	
		Master's	• MSc Clinical Radiology
		Doctoral	
	University of Bristol	Bachelor's	
		Master's	• MSc Nuclear Science and Engineering
		Doctoral	
	University of Edinburgh	Bachelor's	
		Master's	• MSc Advanced Materials Engineering
		Doctoral	• PhD Nuclear Physics
	University of Manchester	Bachelor's	
		Master's	• MSc in Nuclear Science & Technology (NTEC Programme)
		Doctoral	
	University of Stirling, Bridge of Allan	Bachelor's	
		Master's	• MSc Environmental Management (Energy)
		Doctoral	
	University of Strathclyde, Glasgow	Bachelor's	
		Master's	• MSc Cancer Therapies
		Doctoral	
	University of the West of Scotland, Paisley, Hamilton, Ayr & Dumfries	Bachelor's	
		Master's	• MSc Physics and Technology of Nuclear Reactors Masters • MSc Nuclear Decommissioning and Waste Management
		Doctoral	
	Loughborough	Bachelor's	

Country	University	Degree	Programme
	University	Master's	
		Doctoral	• PhD advanced laser processing control strategies for radioactive decommissioning • PhD Analysing radioactive laser cutting emissions
Ukraine	Vasyl Nazarovych Karazin Kharkiv National University	Bachelor's	• Medical Physics • Experimental Nuclear Physics and Plasma Physics
		Master's	• Medical Physics • Experimental Nuclear Physics and Plasma Physics
		Doctoral	
	Nizhyn Mykola Gogol State University	Bachelor's	• Physics
		Master's	• Physics
		Doctoral	
	Chernivtsi National University	Bachelor's	• Applied Physics
		Master's	• Applied Physics
		Doctoral	
	Taras Shevchenko National University of Kyiv	Bachelor's	
		Master's	• MSc Nuclear Power
		Doctoral	

Source: European nuclear society. 2023.

Annex E Operational research reactors in the EU

Facility name	Member State
TRIGA II VIENNA	Austria
VENUS-F	Belgium
BR-1	Belgium
BR-2	Belgium
VR-1	Czech Republic
LVR-15 Rež	Czech Republic
LR-0	Czech Republic
Cabri	France
ILL High Flux Reactor	France
Isis	France
FRMZ	Germany
AKR-2	Germany
SUR Furtwangen	Germany
SUR Ulm	Germany
SUR Stuttgart	Germany
GR-B Subcritical Assembly	Greece
Budapest Research Reactor	Hungary
Nuclear Training Reactor	Hungary
RSV TAPIRO	Italy
TRIGA RC-1	Italy
LENA, TRIGA II PAVIA	Italy
SM-1 Subcritical Assembly	Italy
AGN-201 Costanza	Italy
HOR	Netherlands
HFR	Netherlands
Delphi	Netherlands
MARIA	Poland
TRIGA II Pitesti - SS Core	Romania
TRIGA II Pitesti - Pulsed	Romania
TRIGA- MARK II LJUBLJANA	Slovenia

Source: Research reactor database, IAEA

Annex F European companies delivering to the nuclear sector

The table below presents a comprehensive list of companies that deliver or provide services to nuclear sector in the EU. The table states the company name and products or services they offer. However, the list is non-exhaustive and there are other companies that specialise in other sector of the nuclear for example design, engineering, manufacturing etc.

Name	Products and services
Assystem Energy & Infrastructure Limited - GB	• Computer aided design and modelling • Consultants • Decommissioning • Design services, civil • Design services, control and instrumentation • Design services, plant • Engineering services • Management consulting and services • Mechanical handling equipment • Nuclear fuel cycle • Project management • Stress corrosion cracking, analysis and treatment
Addgards Ltd	• Safeguards equipment and services
AF Industry	• Decommissioning • Design services, control and instrumentation • Probabilistic safety and risk assessment • Radioactive waste characterisation • Training, general
AREVA NP Services Spain SLU.	• Data acquisition systems • Integrated service and maintenance • Mechanical handling equipment • Project management • Reactor internals
Ansaldo Nucleare SpA	• Architect/engineers • Balance of plant engineering and systems • Crane safety systems and services • Decommissioning • Engineering services • Fuel handling equipment • Instrumentation and control and electrical systems • Modernisation and upgrades • New reactor designs • Radioactive waste handling and management analysis
AF-Consult Switzerland Ltd	• Analysis, regulatory and licensing • Design services, plant • Modernisation and upgrades • Plant life prediction and extension • Siting studies
Alfa Laval Lund AB	• Blowers & fans • Condensers, steam • Heat exchangers • Seawater desalination plant • Strainers, low pressure
Alstom Power	• Balance of plant engineering and systems • Condensers, steam • Feedwater heaters • Heat exchangers • Moisture separators/reheaters

Name	Products and services
	• Pumps • Radwaste treatment, at-reactor equipment • Standby generators • Steam turbines • Turbine generators
Andritz AG - Pumps Division	• Main coolant • Pumps • Pumps, small • Seals and sealing systems
Arc Machines UK Ltd	• Welding equipment • Welding, remote • Welding, waste container
ATB Riva Calzoni SpA	• Pressure vessels, non-reactor • Pressurisers • PWR Reactor Vessel Head Replacement • Reactor pressure vessels • Spent fuel storage and transport casks
Ansaldo-NES	• Analysis, seismic • Containment structures • Control systems • Crane safety systems and services • Cranes & hoists • Fuel handling equipment • Heat exchangers • Mechanical handling equipment • Refuelling services
ARGO Ekspresas	• Radwaste storage and transport containers • Tanks, storage
Ahlberg Cameras AB	• Nuclear Engineering International
Brokk UK Limited	• Decommissioning • Remote vehicles • Robotic arms and manipulators • Robotics, robots and robotic equipment
Belgoprocess	• Decommissioning • Decontamination services • Radioactive waste incinerators • Radwaste treatment, high level • Radwaste treatment, low and intermediate level

Belleli Energy CPE Srl	• Design and Manufacturing of Mechanical Components:
	  ○ Heat Exchangers
	  ○ Reactor Vessels
	  ○ Steam Generators
	  ○ Pressurizers
	  ○ Pressure Vessels
	  ○ Feed Water Heaters
	  ○ Containment Vessels
	  ○ Moisture Separator Reheaters
	  ○ Feed Water Tank
	  ○ Steam Condenser Boundles
	  ○ Mixing Tanks
	  ○ Service Vessels
	  ○ Spent Fuel Casks
	  ○ Special tailor-made components

Bilfinger Noell GmbH	• Hot cells & labs • Liners, stainless steel • Mechanical handling equipment • Radioactive waste compactors • Radwaste treatment, low and intermediate level

Name	Products and services
Boltight - Bolt Tensioning Experts	• Bolt Tensioners • Bolting and stud tensioning services and equipment
Belman A/S	• Bellows, metal • Expansion joints • Field services
Bertin - Technologies	• Access control systems • Environmental monitoring equipment and services • Health physics & personnel radiation dose mgt • Radiation monitoring • Radioactive waste monitoring
Cross Manufacturing Co (1938) Ltd	• Fasteners • Seals and sealing systems • Energising & Realising Springs • Special Rolled Sections • Retaining Rings
Cormet Testing Systems	• Autoclaves • Hot cells & labs • Materials testing equipment • Test loops • Water quality and chemistry, analysis & control eq
Cezus	• Fuel cladding • Neutron absorbing materials • Special metals and alloys • Tubing • Zirconium/zircaloy
Cee Vee Engineering Ltd	• Debris recovery services • Fuel pool equipment • Inspection, in-service • Spent fuel management and backend services • Television inspection services and equipment
ClydeUnion Pumps - an SPX Brand	• Commissioning • Feedwater heaters • Main coolant • Pumps • Spare parts management
Centronic Ltd	• Fission chambers • Geiger-Mueller counters/tubes • Ionisation chambers • Machining services • Neutron detectors • Penetrations, electrical • Radiation detectors, semiconductor solid state
Costain Group Plc	• Civil works • Commissioning • Construction services • Consultants • Control systems • Cooling towers • Design services, civil • Design services, control and instrumentation • Design services, pipework • Design services, plant • Engineering services • Graphite • Instrumentation and control engineering • Integrated service and maintenance • Plant life prediction and extension

Name	Products and services
	• Project management • Radwaste treatment, low and intermediate level
Croft Associates Ltd	• Analysis, regulatory and licensing • Decommissioning • Isotope storage and handling • Leak detection equipment and services • R&D and test • Radioactive waste packaging • Radwaste storage and transport containers • Shielded containers • Transport of nuclear materials • Transport/storage casks
Cavendish Nuclear Ltd	• Air sampling/analysis • Architect/engineers • Construction services • Consultants • Criticality monitors/systems • Decommissioning • Dosimeters • Engineering services • Environmental monitoring equipment and services • Fuel handling equipment • Health physics & personnel radiation dose mgt • In-core monitoring and instrumentation • Inspection equipment • Inspection, in-service • Inspection, pre-service • Leak detection equipment and services • Neutron detectors • Neutron flux mapping • Neutron flux monitoring • Pipe inspection • Post accident sampling and monitoring systems • Project management • Radiation area surveys • Radiation counters • Radiation detectors, semiconductor solid state • Radiation monitoring • Radioactive waste handling and management analysis • Radioactive waste monitoring • Radwaste solidification and encapsulation • Reactor protection and control • Spent fuel storage facilities, engineering and constr. • Training, operator
Clextral - DKM Pumps	• Pumps • Pumps, small
Daher	• Engineering services • Packings and glands • Radioactive waste characterisation • Radioactive waste handling and management analysis • Valves
Denley Hydraulics Ltd	• Actuators • Control systems • Hydraulic equipment • Pipework systems • Valves
Darchem Engineering Ltd	• Fabricated components, ferrous • Fireproofing materials • Insulation, thermal

Name	Products and services
	• Liners, stainless steel • Radwaste storage and transport containers
DMS Nuclear	• 3D laser scanning • Decommissioning • Decontamination services • Design services, control and instrumentation • Engineering services • Fabricated components, ferrous • Fabricated components, non-ferrous • Hoses and couplings • Machining services • Project management • Radioactive waste packaging
ENUSA Industrias Avanzadas, S.A., S.M.E.	• Fuel design • Fuel examination, PIE & PII • Fuel fabrication • Fuel repair and reconstitution • Fuel supply
Emcel Filters Limited	• Filter containment • Filter services • Filtered venting systems for containment • Filters
ENVINET - GmbH	• Data acquisition systems • Environmental monitoring equipment and services • Health physics & personnel radiation dose mgt • Radiation area surveys • Radiation monitoring
Equipos Nucleares, S.A. (Ensa)	• BWR & PWR Reactor Vessels • Decommissioning • Fuel storage racks • Heat exchangers • PWR Reactor Vessel Head Replacement • Radioactive waste handling and management analysis • Spent fuel storage and transport casks • Steam generators
ET Enterprises Limited	• Charged particle detectors • Electron tubes • Neutron detectors • Photomultipliers • Pulse amplifiers
EVAC AG	• Bellows, metal • Couplings • Cryogenic equipment • Seals and sealing systems • Vacuum equipment
EnerMech	• Cranes & hoists • Design services, control and instrumentation • Hydraulic equipment • Mechanical handling equipment • Robotics, robots and robotic equipment
EMERSON	• Valve diagnostic systems • Valves • Valves, pressure relief • Valves, safety and relief • Instrumentation
Fluid Components International - FCI	• Flow indicators • Flow measurement • Flow meters

Name	Products and services
	• Level indicators • Temperature measurement
Fagerstrom Industrikonsult AB	• Consultants • Decontamination equipment
Fine Tubes	• Control rods • Heat exchangers • In-core monitoring and instrumentation • Pipes and tubes • Reactor instrumentation
Fortum Power & Heat Oy - Power Division/Power Solutions	• 3D laser scanning • Analysis, accident and plant transient • Analysis, ageing • Analysis, criticality • Analysis, failure • Analysis, fracture mechanics • Analysis, human factors • Analysis, maintenance • Analysis, reactor physics • Analysis, regulatory and licensing • Analysis, risk • Analysis, seismic • Analysis, shielding • Analysis, stress • Analysis, thermal hydraulic • Analytical services, general • Architect/engineers • Commissioning • Consultants • Decommissioning • Decontamination services • Design services, control and instrumentation • Design services, pipework • Design services, plant • Documentation • Emergency planning services • Engineering services • Environmental and accident modelling • Maintenance • Management consulting and services • Modernisation and upgrades • Outage and maintenance management services • Plant life prediction and extension • Probabilistic safety and risk assessment • Procurement • Project management • Quality assurance • Radioactive waste characterisation • Radioactive waste handling and management analysis • Radioactive waste monitoring • Seismic services • Simulators, training • Spare parts management • Spent fuel storage facilities, engineering and constr. • Training, general • Training, maintenance • Water treatment • New build consultation ○ Feasibility studies related to the new build project

Name	Products and services
	○ Public acceptance strategy and stakeholder involvement ○ Procurement strategy for a new NPP incl. Plant contract ○ Owner/operator in safety and licensing activities ○ Technology provider evaluation and selection ○ Infrastructure of NPP site ○ Contract management ○ Commissioning • Radioactive waste consultation ○ Site selection and survey ○ Site Characterization ○ Environmental impact assessment procedure ○ Operating waste cave and waste management • Nuclear safety consultation ○ Probabilistic Risk Assessment (PRA) ○ Safety culture ○ Risk and security analysis ○ Occupational safety • Performance improvement consultation ○ Operating rate improvement ○ Raise of power generation efficiency ○ Maintenance optimization ○ Outage optimization • Competence management consultation ○ Competence management ○ Training
Flamgard Engineering Limited	• Fire protection equipment • Heating, ventilating, air conditioning equipment
Forsyths Group	• Fabricated components, ferrous • Heat exchangers • Pipework systems • Pressure vessels, non-reactor • Tanks, storage
Framatome	• 3D laser scanning • Access control systems • Acoustic sensors • Actuators • Air sampling/analysis • Analysis, accident and plant transient • Analysis, ageing • Analysis, criticality • Analysis, failure • Analysis, fracture mechanics • Analysis, human factors • Analysis, maintenance • Analysis, reactor physics • Analysis, regulatory and licensing • Analysis, risk • Analysis, seismic • Analysis, shielding • Analysis, stress • Analysis, thermal hydraulic • Analytical services, general • Annealing, reactor pressure vessel • Architect/engineers • Balance of plant engineering and systems • Batteries, battery monitoring, battery testing • Bolt Tensioners • Bolting and stud tensioning services and equipment • Borescopes and fibrescopes

Name	Products and services
	• BWR & PWR Reactor Vessels • Capsules, irradiation testing • Castings • Chemicals, cleaning and protective • Coatings • Commissioning • Comp software, ancillaries & peripherals for C & I • Computer aided design and modelling • Condition monitoring, on-line surveillance, diag • Control rod drives • Control rods • Control rooms and control room instrumentation • Control systems • Coolant level instrumentation (reactor) • Cores, reactor • Corrosion inhibitors • Couplings • Criticality monitors/systems • Data acquisition systems • Data processing systems • Debris recovery services • Decommissioning • Decontamination equipment • Decontamination services • Design services, control and instrumentation • Design services, plant • Digital circuit modules • Documentation • Electrical, cables • Emergency planning services • Emergency response info svcs, systems & facilities • Engineering services • Environmental and accident modelling • Environmental monitoring equipment and services • Fabricated components, ferrous • Fabricated components, non-ferrous • Field engineering services • Field services • Filter containment • Filtered venting systems for containment • Filters • Fire protection services • Flanges, pressure vessel • Flow measurement • Foreign materials exclusion control and parts acc • Forgings • Freeze plugging services • Fuel and fuel cycle management and services • Fuel assembly components • Fuel cladding • Fuel design • Fuel element monitoring • Fuel examination, PIE & PII • Fuel fabrication • Fuel handling equipment • Fuel pool equipment • Fuel repair and reconstitution • Fuel storage racks • Fuel supply

Name	Products and services
	• Fuel, mixed oxide (MOX) • Fuelling machines • Furnaces, fuel sintering • Gaskets • Gauges • Grids, fuel element • Heat exchangers • Heating, ventilating, air conditioning equipment • Hot cells & labs • Hydrogen control, ignition & recombiner equipment • In-core monitoring and instrumentation • Inspection & classification • Inspection and audit, third party • Inspection equipment • Inspection materials • Inspection, in-service • Installations, electrical • Installations, instrumentation • Installations, mechanical • Instrument repair/calibration • Instrumentation and control and electrical systems • Instrumentation and control engineering • Instrumentation cabinets, consoles, panels • Integrated service and maintenance • Ion exchange resin services • Irradiation rigs and capsules • Leak detection equipment and services • Leak detection systems for in-service monitoring • Leak sealing • Level indicators • Lighting equipment • Liners, plastic • Loose parts monitors • Machining services • Main coolant • Maintenance • Management consulting and services • Materials testing equipment • Modernisation and upgrades • Monitors • Motors • Motors, main coolant pump • Neutron flux mapping • Neutron flux monitoring • New reactor designs • Non-destructive testing • Non-destructive testing equipment • Nozzle dams • Nozzles, RPV • Nozzles, steam generator • NSSS, fast reactors • NSSS, thermal reactors • Outage and maintenance management services • Pipe fittings, flanges and union • Pipe inspection • Pipes and tubes • Pipework systems • Piping shock absorbers • Plant life prediction and extension

Name	Products and services
	• Post accident sampling and monitoring systems • Power supplies • Power supply protection systems • Pressure vessels, non-reactor • Pressuriser heaters • Pressurisers • Probabilistic safety and risk assessment • Probes, eddy current • Probes, ultrasonic • Procurement • Project management • Pumps • PWR Reactor Vessel Head Replacement • Qualification and testing services • Quality assurance • Radiation area surveys • Radiation monitoring • Radioactive waste characterisation • Radioactive Waste Management • Radioactive waste monitoring • Radiochemicals • Radiographic equipment • Radioisotopes • Radwaste storage and transport containers • Reactor design, fast breeder • Reactor design, gas-cooled • Reactor design, high temperature • Reactor design, PWR • Reactor instrumentation • Reactor internals • Reactor power monitors • Reactor pressure vessels • Reactor protection and control • Recombiners • Refuelling services • Reliability database services • Remote repair and maintenance devices • Research, test and training reactors • Resins, ion exchange • Resistance temperature detectors (RTDs) • Safety parameter display systems • Seals and sealing systems • Seismic instrumentation • Seismic services • Seismic test equipment • Shake table services • Simulators, training • Siting studies • Spare parts management • Special metals and alloys • Spent fuel storage facilities, engineering and constr. • Spray nozzles • Springs • Steam generator inspection • Steam generator replacement • Steam generator services • Steam generator tubing • Steam generators • Stress corrosion cracking, analysis and treatment

Name	Products and services
	• Stress relief equipment • Switchgear • Temperature measurement • Tensioners, stud and bolt • Test loops • Thermocouples • Training, general • Training, maintenance • Training, operator • Transducers • Transmitters, pressure • Transmitters, temperature • Tubing • Ultrasonic testers and transducers • UPS • Valve and valve actuator maintenance • Valve diagnostic systems • Valve position indicators • Valve repair, in line • Valve testing, on line • Valves, pressure relief • Valves, safety and relief • Valves, solenoid • Vibration/noise measurement • Water quality and chemistry, analysis & control eq • Waterproofing materials • Welding, remote • Zirconium/zircaloy • Pressure Transmitters • Pressure Switches
Galson Sciences Limited	• Analysis, criticality • Environmental and accident modelling • Probabilistic safety and risk assessment • Radioactive Waste Disposal • Radioactive Waste Management
Gamma Technical Corporation	• Doorway monitors • Environmental monitoring equipment and services • Radiation monitoring • Respiratory protection equipment • Scintillators
Goodfellow Cambridge Ltd	• Special metals and alloys • Stainless steel • Steels, special • Surface finishes • Tubing
Georgin	• Gauges • Instrumentation and control and electrical systems • Instrumentation and control engineering • Transmitters, pressure • Transmitters, temperature
GNS Gesellschaft fur Nuklear	• Decommissioning • Engineering services • Radioactive waste compactors • Radioactive waste monitoring • Radwaste treatment, high level • Radwaste treatment, low and intermediate level • Shielded containers • Spent fuel storage and transport casks • Spent fuel storage facilities, engineering and constr.

Name	Products and services
	• Transport/storage casks
Graver Technologies LLC	• Filters • Fuel pool equipment • Ion exchange materials • Strainers, high pressure • Water treatment
GDES	• Cleaning, reactor vessel flange, stud & stud hole • Decommissioning • Decontamination services • Laundry services • Refuelling services
Gradel s.à.r.l.	• Cleaning, reactor vessel flange, stud & stud hole • Decontamination equipment • Fuel pool equipment • Remote vehicles • Spent fuel pool cleaning services
Graver Technologies LLC	• Filters • Fuel pool equipment • Ion exchange materials • Strainers, high pressure • Water treatment
Habia Cable AB	• Cables • Connectors, electrical • Electrical, cables • Fibre optics • Thermocouples
Hamon	• Modern Power Systems • Nuclear Engineering International
Howden Solyvent-Ventec	• Blowers & fans • Compressors • Filtered venting systems for containment • Heat exchangers
Huntingdon Fusion Techniques Ltd	• Freeze plugging services • Oxygen monitoring and trace measurement • Pipe stoppers and stud hole plugs • Welding equipment
IDOM Consulting, Engineering, Architecture S.A.U.	• Project management • Quality assurance
INETEC	• Inspection, in-service • Inspection, pre-service • Non-destructive testing equipment • Probes, eddy current • Probes, ultrasonic • Robotics, robots and robotic equipment
Institute for Energy Technology	• Nuclear Engineering International
Jahrestagung Kerntechnik	• Nuclear Engineering International
James Fisher Nuclear	• 3D laser scanning • Analysis, stress • Balance of plant engineering and systems • Commissioning • Comp software, ancillaries & peripherals for C & I • Computer aided design and modelling

Name	Products and services
	• Condition monitoring, on-line surveillance, diag • Connectors, electrical • Control rooms and control room instrumentation • Control systems • Crane safety systems and services • Debris recovery services • Decommissioning • Design services, control and instrumentation • Design services, pipework • Design services, plant • Dosimeters • Engineering services • Glove boxes • Health physics & personnel radiation dose mgt • Health physics, equipment and supplies • Heating, ventilating, air conditioning equipment • In-core monitoring and instrumentation • Inspection equipment • Inspection, in-service • Installations, instrumentation • Instrumentation and control and electrical systems • Instrumentation and control engineering • Leak detection systems for in-service monitoring • Manipulators • Mechanical handling equipment • Modernisation and upgrades • Non-destructive testing • Penetrations, electrical • Penetrations, mechanical • Pipe inspection • Programmable controllers • R&D and test • Radiation monitor calibration • Radiation monitoring • Radioactive waste monitoring • Radiographic equipment • Radwaste storage and transport containers • Remote repair and maintenance devices • Remote vehicles • Robotic arms and manipulators • Robotics, robots and robotic equipment • Shielding doors • Shielding systems • Simulators, training • Valve position indicators • Welding, remote
JCS Nuclear Solutions	• Health physics & personnel radiation dose mgt • Neutron detectors • Radiation monitor calibration • Radiation monitoring • Scintillators • Shielding materials
JL Goslar GmbH	• Decontamination equipment • Hot cells & labs • Lead and lead products • Radioactive waste packaging • Radwaste storage and transport containers • Radwaste treatment, at-reactor equipment • Radwaste treatment, low and intermediate level

Name	Products and services
	• Shielded containers • Shielding doors • Shielding systems
Kabelwerk Eupen AG	• Cables • Electrical, cables • Fibre optics
Kraftwerksschule E.V.	• Training, general • Training, health physics • Training, maintenance • Training, operator
KUKA Robotics	• Decommissioning • Robotics, robots and robotic equipment
LATTY INTERNATIONAL	• Gaskets • Packings and glands • Seals and sealing systems
Lee-Dickens Ltd	• Coolant level instrumentation (reactor) • Instrumentation and control engineering • Instrumentation cabinets, consoles, panels • Level indicators • Moisture meters and humidity monitoring insts
Lloyd's Register Energy	• Analysis, human factors • Analysis, risk • Inspection and audit, third party • Probabilistic safety and risk assessment • Quality assurance
Lisega SE	• Field engineering services • Pipe hangers & supports • Pipe whip restraints • Piping shock absorbers • Snubbers
Lucideon	• Analysis, failure • Analysis, fracture mechanics • Analysis, stress • Analytical services, general • Non-destructive testing
Mangiarotti SpA	• Heat exchangers • Pressure vessels, non-reactor • Spent fuel storage and transport casks • Steam generators • Tanks, storage
Mauell GmbH	• omputer aided design and modelling • Control rooms and control room instrumentation • Control systems • Fire protection equipment • Instrumentation cabinets, consoles, panels • Monitors • Safety parameter display systems • Simulators, training • Switchgear • Training, operator • TV monitors and displays
Meggitt Sensing Systems	• Accelerometers • Condition monitoring, on-line surveillance, diag • Probes, eddy current • Vibration/noise measurement • Pressure Transmitters
MAN Diesel & Turbo UK	• Standby generators

Name	Products and services
Ltd	
Mirion Technologies (Canberra UK) Limited	• Health physics, equipment and supplies • Radioactive waste characterisation • Radioactive waste monitoring • Reactor protection and control
Millstock Stainless Ltd	• Special metals and alloys • Stainless steel • Steels, special • Structural steelwork • Structural supports, component
Mott MacDonald	• Analysis, seismic • Architect/engineers • Decommissioning • Design services, civil • Engineering services
Muhr GmbH	• Water intake screens • Water intake system engineering • Water treatment
MAUS ITALIA F. AGOSTINO & C. s.a.s.	• Heat exchangers • Pipe bending and cutting equipment • Welding equipment
Morgan Thermal Ceramics	• Insulation, thermal
M&M FORGINGS	• Forgings • Pumps • Spent fuel storage and transport casks • Steam turbines • Turbine generators
Mineral Insulated Cable Company (MICC) Ltd.	• Cables
MAGICS	• Cameras & CCTV Equipment • Data processing systems • Digital circuit modules • Electronic components and equipment • Electronics, radiation resistant • Instrumentation and control engineering • Maintenance • Radioactive waste monitoring • Remote vehicles • Robotics, robots and robotic equipment • Small & Advanced Reactors
Nuvia Limited	• Construction services • Consultants • Decommissioning • Decontamination services • Engineering services • Health physics & personnel radiation dose mgt • Plant life prediction and extension • Procurement • Project management
National Physical Laboratory	• Field engineering services • Instrument repair/calibration • R&D and test • Radioisotopes • Temperature measurement

Name	Products and services
Nelson® Bolzenschweiss-Technik GmbH Co & KG	• Fasteners • Process monitors, in line • Process recorders • Programmable controllers • Welding equipment
Nagra - International Services and Projects Department	• Analysis, environmental • Exploration • Geological and geotechnical services • Radioactive Waste Management • Training, general
National Nuclear Laboratory	• Decommissioning • Decontamination services • Environmental monitoring equipment and services • Fuel and fuel cycle management and services • R&D and test
Nuclear Engineering Services - NES	• Containment structures • Control rooms and control room instrumentation • Crane safety systems and services • Decommissioning • Decontamination equipment • Design services, control and instrumentation • Fuel handling equipment • Glove boxes • Instrumentation cabinets, consoles, panels • Shielding doors
NAC International Inc.	• Consultants • Fuel and fuel cycle management and services • Spent fuel storage and transport casks • Training, general • Transport of nuclear materials
Oxford Scientific Products	• Dosimeters • Health physics & personnel radiation dose mgt • Radiation monitoring
Onet Technologies SAS	• Decommissioning • Engineering services • Maintenance • Radwaste treatment, low and intermediate level • Training, general
Olympus	• Borescopes and fibrescopes • Microscopes • Non-destructive testing equipment • Ultrasonic testers and transducers • X-ray fluorescence equipment
ONET Technologies UK Ltd	• Decommissioning • Engineering services • Maintenance • Radwaste treatment, low and intermediate level • Training, general
OECD Halden Reactor Project	• Condition monitoring, on-line surveillance, diag • Control rooms and control room instrumentation • In-core monitoring and instrumentation • Research, test and training reactors • Safety parameter display systems
Ovivo UK Ltd	• Filters • Water intake screens • Water intake system engineering
Ovivo UK Ltd.	• Condensate polishing • Demineralisers

Name	Products and services
	• Ion exchange materials • Seawater desalination plant • Water treatment
Poole Process Equipment Ltd	• Heat exchangers
PHOTONIS Nuclear Instrumentation	• Connectors, electrical • Fission chambers • In-core monitoring and instrumentation • Ionisation chambers • Neutron detectors
Pompes Rütschi SAS	• Field services • Fire protection equipment • Maintenance • Pumps • Pumps, small
Power Jacks Ltd	• Actuators • Ballscrews, recirculating • Couplings • Mechanical handling equipment • Motors
PPG Architectural and Protective Coatings UK Ltd	• Coatings • Fireproofing materials • Paint systems
Procon Engineering - A Division of National Oilwell Varco UK Ltd	• Acoustic sensors • Data acquisition systems • Design services, control and instrumentation • Instrumentation and control and electrical systems • Load cells • Strain gauges, strain measurement
Prysmian Group	• Nuclear Engineering International • Cables • Electrical, cables • Fibre optics • Instrumentation and control and electrical systems • Thermocouples
Pöyry Energy Ltd	• Analysis, criticality • Analysis, environmental • Analysis, human factors • Analysis, regulatory and licensing • Analysis, shielding • Balance of plant engineering and systems • Civil works • Computer aided design and modelling • Decommissioning • Design services, civil • Design services, control and instrumentation • Design services, pipework • Design services, plant • Emergency planning services • Engineering services • Environmental and accident modelling • Fire protection services • Geological and geotechnical services • Management consulting and services • Plant life prediction and extension • Probabilistic safety and risk assessment

Name	Products and services
	• Project management • Radioactive waste characterisation • Radioactive Waste Management • Siting studies
Porvair Filtration Group Ltd	• Filter containment • Filter services • Filtered venting systems for containment • Filters • Gas absorbers • Gas purifiers • Glove box purification systems • Heating, ventilating, air conditioning equipment • Hydrogen control, ignition & recombiner equipment • Off-gas systems
Quirepace	• Blowers & fans • Materials handling equipment, air-operated • Pneumatic transfer equipment • Pumps • Vacuum equipment
Quintessa Ltd	• Analysis, ageing • Analysis, environmental • Analysis, risk • Environmental and accident modelling • Geological and geotechnical services
Reekie Machining	• Machining services • Machining services, at site • Pipe bending and cutting equipment • Tools, pneumatic and hand • Valve repair, in line
Rotork Controls Ltd	• Actuators • Control systems • Valve and valve actuator maintenance • Valve diagnostic systems • Valve position indicators
RPA Process Technologies	• Filter containment • Filters • Moisture separators/reheaters • Strainers, low pressure • Water treatment
REMTECH	• Environmental monitoring equipment and services • Security handling services • Siting studies
RPC RADICS LLC	• Control systems • Design services, control and instrumentation • Instrumentation and control and electrical systems • Instrumentation and control engineering • Integrated service and maintenance • Modernisation and upgrades • Neutron flux monitoring • Power supplies • Programmable controllers • Seismic instrumentation • Switchgear
Rolevet Ltd	• Bolting and stud tensioning services and equipment • Fasteners • Forgings • Machining services
Rolls-Royce Plc	• 3D laser scanning

Name	Products and services
	• Alarm systems • Analysers, multichannel • Analysers, single channel • Analysis, ageing • Analysis, criticality • Analysis, environmental • Analysis, failure • Analysis, maintenance • Analysis, regulatory and licensing • Analysis, seismic • Cables • Commissioning • Control rooms and control room instrumentation • Control systems • Coolant level instrumentation (reactor) • Data acquisition systems • Data processing systems • Design services, control and instrumentation • Engineering services • Field engineering services • Field services • Flow measurement • Heat exchangers • In-line sampling and analysis equipment • Inspection equipment • Inspection materials • Inspection, in-service • Inspection, pre-service • Installations, electrical • Installations, instrumentation • Installations, mechanical • Instrument repair/calibration • Instrumentation and control and electrical systems • Instrumentation and control engineering • Instrumentation cabinets, consoles, panels • Integrated service and maintenance • Inverters • Ionisation chambers • Modernisation and upgrades • Neutron detectors • Pipe inspection • Pressuriser heaters • Process information systems • Reactor instrumentation • Reactor protection and control • Resistance temperature detectors (RTDs) • Robotics, robots and robotic equipment • Safety parameter display systems • Spare parts management • Steam generator inspection • Steam generator services • Temperature measurement • Training, general • Training, maintenance • Training, operator • Pressure Transmitters • Instrumentation
Research Centre for	• Nuclear Engineering International • New reactor designs

Name	Products and services
Energy, Environment & Technology - CIEMAT	• Nuclear fuel cycle • R&D and test • Radioactive waste characterisation • Training, general
REEL	• Crane safety systems and services • Cranes & hoists • Fuel handling equipment • Fuel pool equipment • Fuelling machines • Load handling equipment • Radioactive waste handling and management analysis • Radwaste storage and transport containers
Sir Robert McAlpine Ltd	• Analysis, seismic • Ancillary buildings • Civil works • Design services, civil • Project management
STF SpA	• Condensers, steam • Feedwater heaters • Heat exchangers • Moisture separators/reheaters • Steam generators
Scandpower AB	• Analysis, human factors • Analysis, regulatory and licensing • Analysis, risk • Inspection and audit, third party • Probabilistic safety and risk assessment
Servomex Group Ltd	• Analysers • Analysis, environmental • Glove boxes • Oxygen monitoring and trace measurement
SNC-Lavalin	• Analysis, heat transfer • Design services, plant • Health physics & personnel radiation dose mgt • Hydrology • Training, health physics
SENER Ingenieria y Sistemas SA	• Analysis, seismic • Architect/engineers • Balance of plant engineering and systems • Construction services • Siting studies
SGS Qualitest - Inspection & Industrial Testing Division	• Inspection, in-service • Non-destructive testing • Non-destructive testing equipment • Pipe inspection • Training, operator
SAES Group	• Gas absorbers • Gas purifiers • Pumps • Tritium separation systems • Vacuum equipment
Sandvik Materials Technology	• Fuel cladding • Pipe fittings, flanges and union • Pipes and tubes • Stainless steel • Steam generator tubing • Steels, special • Tubing

Name	Products and services
	• Zirconium/zircaloy
Sherwood Nutec Scientific	• Analysers, multichannel • Dosimeters • Health physics & personnel radiation dose mgt • Health physics, equipment and supplies • Neutron absorbing materials • Neutron detectors
Schneider Electric - Gutor Electronic LLC	• Batteries, battery monitoring, battery testing • Battery Chargers • Inverters • Power supplies • UPS
Sarens NV	• Cranes & hoists • Engineering services • Heavy lifting services • Heavy transportation services • Hydraulic equipment
SCK CEN - Belgian Nuclear Research Centre	• Geological and geotechnical services • Reactor pressure vessels • Research, test and training reactors • Training, general • Training, health physics
Sheffield Forgemasters Engineering Ltd	• Castings • Forgings • Reactor pressure vessels • Spent fuel storage and transport casks • Steam generators
SKF France	• Bolt Tensioners • Bolting and stud tensioning services and equipment • Data acquisition systems • Fasteners • Hydraulic equipment • Robotics, robots and robotic equipment • Simulators, training • Steam generator services • Stud Tensioners • Tensioners, stud and bolt
Steag Energy Services GmbH	• Architect/engineers • Commissioning • Decommissioning • Design services, plant • Environmental and accident modelling
Strainstall Monitoring	• Data acquisition systems • Geological and geotechnical services • Strain gauges, strain measurement • Temperature measurement • Vibration/noise measurement
Strainstall UK	• Crane safety systems and services • Force sensors • Load cells • Non-destructive testing • Transducers
Studsvik AB	• Analysis, regulatory and licensing • Decommissioning • Engineering services • Fuel and fuel cycle management and services • Health physics & personnel radiation dose mgt • Hot cells & labs

Name	Products and services
	• Nuclear fuel cycle • Radwaste treatment, low and intermediate level • Stress corrosion cracking, analysis and treatment • Transport of nuclear materials
Servelec Controls	• Control systems • Data acquisition systems • Design services, control and instrumentation • Process information systems • Records management systems
Sulzer Electro Mechanical Services (UK) Limited	• Balance of plant engineering and systems • Bearings, nuclear environment • Blowers & fans • Commissioning • Compressors • Computer aided design and modelling • Engineering services • Field engineering services • Field services • Machining services • Standby generators • Steam generator services • Steam generators • Steam turbines • Transformers • Valves • Vibration/noise measurement • Welding & brazing materials
Siempelkamp Maschinen- und Anlagenbau GmbH	• Nuclear Engineering International
Sulzer Management AG	• Field services • Pumps • Pumps, small • Safeguards equipment and services
Siempelkamp NIS Ingenieurgesellschaft mbH	• Decommissioning • Decontamination services • Radioactive Waste Management • Radwaste storage and transport containers • Stud Tensioners
SNC-Lavalin - EMEA	• Computer aided design and modelling • Cores, reactor • Decommissioning • Design services, plant • Engineering services
Steve Vick International	• Decommissioning • Decontamination services • Inspection equipment • Radwaste solidification and encapsulation • Remote repair and maintenance devices
Sulzer Pompes France SASU	• Nuclear Engineering International
ŠKODA JS a.s	• Control rod drives • Fuel handling equipment • Fuel storage racks • Inspection, in-service • Pressure vessels, non-reactor

Name	Products and services
	• Reactor internals • Research, test and training reactors • Spent fuel storage and transport casks • Spent fuel storage facilities, engineering and constr. • Tensioners, stud and bolt
Thiedig, Dr. GmbH & Co KG	• Analysers • Heat exchangers • In-line sampling and analysis equipment • Oxygen monitoring and trace measurement • Water quality and chemistry, analysis & control eq
TSM Perrottet Ltd	• Concrete repair, maintenance and underwater svcs • Diving services • Spent fuel pool cleaning services • Television inspection services and equipment
TENEX	• Radioactive Waste Management • Spent fuel management and backend services • Transport of nuclear materials • Uranium conversion and uranium hexafluoride • Uranium enrichment
Teddington Engineered Solutions Ltd	• Bellows, metal • Expansion joints • Hoses and couplings • Pipe fittings, flanges and union • Pipe hangers & supports
telerob Gesellschaft für Fernhantierungstechnik GmbH	• Manipulators • Remote repair and maintenance devices • Remote vehicles • Robotic arms and manipulators • Robotics, robots and robotic equipment
Thermocoax SAS	• Instrumentation and control and electrical systems • Neutron detectors • Pressuriser heaters • Reactor instrumentation • Temperature measurement
Thermo Fisher Scientific Messtechnik GmbH	• Geiger-Mueller counters/tubes • Neutron detectors • Radiation monitoring • Radioactive waste characterisation • TLD equipment
Thompson Valves Ltd	• Valves • Valves, pressure relief • Valves, safety and relief • Valves, solenoid
TÜV SÜD Industrie Service GmbH	• Consultants • Engineering services • Inspection and audit, third party • Qualification and testing services • Radioactive waste handling and management analysis
Tecnatom - NDT	• Alarm systems • Analysis, accident and plant transient • Analysis, ageing • Analysis, failure • Analysis, fracture mechanics • Analysis, human factors • Analysis, maintenance • Analysis, piping flexibility • Analysis, regulatory and licensing • Analysis, thermal hydraulic

Name	Products and services
	• Balance of plant engineering and systems • Cables • Concrete inspection • Condenser • s, steam • Control rooms and control room instrumentation • Data acquisition systems • Design services, control and instrumentation • Electrical, cables • Emergency planning services • Emergency radiological intervention services • Emergency response info svcs, systems & facilities • Employment and recruitment services • Engineering services • Environmental and accident modelling • Field engineering services • Field services • Filter containment • Filter services • Filtered venting systems for containment • Fuel and fuel cycle management and services • Fuel element monitoring • Inspection equipment • Inspection materials • Inspection, in-service • Inspection, pre-service • Installations, instrumentation • Instrumentation and control and electrical systems • Instrumentation and control engineering • Integrated service and maintenance • Leak detection equipment and services • Leak detection systems for in-service monitoring • Modernisation and upgrades • Motors • Non-destructive testing • Non-destructive testing equipment • Nuclear fuel cycle • Outage and maintenance management services • Penetrations, electrical • Penetrations, mechanical • Pipe inspection • Plant life prediction and extension • Probes, eddy current • Probes, ultrasonic • Qualification and testing services • R&D and test • Radioactive Waste Management • Robotic arms and manipulators • Robotics, robots and robotic equipment • Simulators, training • Snubber test and reduction services • Steam generator inspection • Stress corrosion cracking, analysis and treatment • Training, filter system test and operation • Training, general • Training, maintenance • Training, operator • Training, quality management • Valve and valve actuator maintenance

Name	Products and services
	• Valve diagnostic systems • Valve position indicators • Valve repair, in line • Valve testing, on line
Technocover	• Nuclear Engineering International
Tractebel Engineering S.A.	• 3D laser scanning • Analysis, accident and plant transient • Analysis, ageing • Analysis, criticality • Analysis, environmental • Analysis, fracture mechanics • Analysis, heat transfer • Analysis, reactor physics • Analysis, regulatory and licensing • Analysis, seismic • Analysis, shielding • Analysis, stress • Analysis, thermal hydraulic • Ancillary buildings • Architect/engineers • Balance of plant engineering and systems • Commissioning • Decommissioning • Design services, civil • Design services, control and instrumentation • Design services, pipework • Design services, plant • Engineering services • Environmental and accident modelling • Field engineering services • Fire protection equipment • Fire protection services • Fuel and fuel cycle management and services • Geological and geotechnical services • Instrumentation and control engineering • Management consulting and services • Probabilistic safety and risk assessment • Project management • PWR Reactor Vessel Head Replacement • Qualification and testing services • Quality assurance • Radioactive waste characterisation • Radioactive waste handling and management analysis • Radioactive Waste Management • Reactor design, PWR • Siting studies • Steam generator replacement • Training, general • Training, quality management
TÜV SÜD Energietechnik GmbH	• Consultants • Inspection and audit, third party • Qualification and testing services • Radioactive waste handling and management analysis • Training, general
Ultra Electronics Nuclear Control Systems	• Design services, control and instrumentation • Neutron flux monitoring • Radiation monitoring • Reactor instrumentation

Name	Products and services
	• Reactor protection and control
UniTech Services GmbH	• Decontamination services • Health physics, equipment and supplies • Laundry services • Protective clothing • Respiratory protection equipment
UniTech Services Group Limited	• Decontamination services • Health physics, equipment and supplies • Laundry services • Protective clothing • Respiratory protection equipment
VacuTec Messtechnik GmbH	• Geiger-Mueller counters/tubes • Ionisation chambers • Neutron detectors • Radiation monitoring • Radioactive waste monitoring
Voestalpine Böhler Welding	• Hardfacing alloys • Welding & brazing materials
Ventx Limited	• Nuclear Engineering International
Veolia Water Technologies	• Water treatment
Valeport Limited	• Environmental monitoring equipment and services • Flow measurement • Flow meters

Walter Tosto SpA	• Design and Manufacturing of Mechanical Components:
	  ○ Heat Exchangers
	  ○ Reactor Vessels
	  ○ Steam Generators
	  ○ Pressurizers
	  ○ Pressure Vessels
	  ○ Feed Water Heaters
	  ○ Containment Vessels
	  ○ Moisture Separator Reheaters
	  ○ Feed Water Tank
	  ○ Steam Condenser Boundles
	  ○ Mixing Tanks
	  ○ Service Vessels
	  ○ Spent Fuel Casks
	• Special tailor-made components

WTI GmbH	• Analysis, criticality • Analysis, heat transfer • Analysis, shielding • Spent fuel storage facilities, engineering and constr. • Welding, waste container
W L Gore & Associates (UK) Ltd	• Cables
W. L Gore & Associates GmbH	• Cables • Electrical, cables
WorleyParsons	• Architect/engineers • Consultants • Engineering services • Modernisation and upgrades • Siting studies
Wälischmiller	• Cranes & hoists

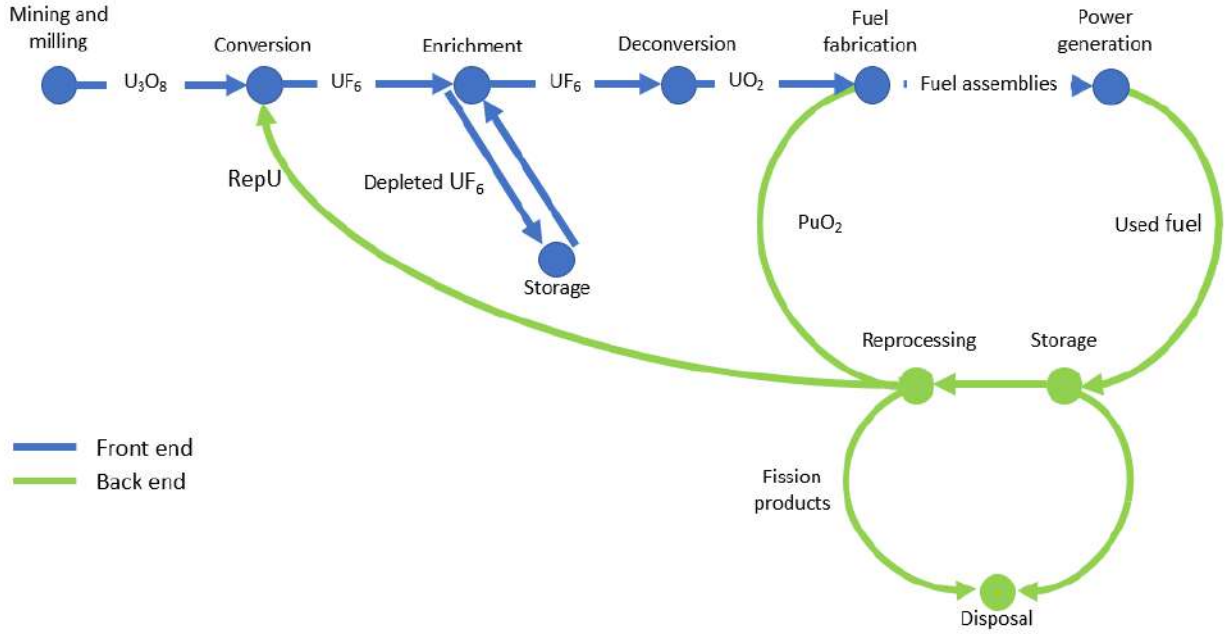
Name	Products and services
Engineering GmbH	• Decommissioning • Manipulators • Remote vehicles • Robotic arms and manipulators • Robotics, robots and robotic equipment
Wood	• Consultants • Decommissioning • Radioactive waste monitoring • Radwaste solidification and encapsulation • Spectrometers - X-ray
World Nuclear Association	• Fuel and fuel cycle management and services • Fuel market and finance services • Management consulting and services • Nuclear fuel cycle • Transport of nuclear materials

Source: Nuclear Energy Institute. 2023

Annex G Nuclear fuel cycle overview

Manufacturing nuclear fuel is a complex, technically demanding, and critical process for the operation of NPPs. The process involves a series of industrial processes, ranging from uranium mining through fuel fabrication all the way to reprocessing and disposal. The part taking place before the uranium is used as fuel in a nuclear reactor (mining, milling, conversion, enrichment, and fuel fabrication) is called the "front end". After the fuel is used, it can go through a series of further processes, that are collectively known as the "back end". "Back end" processes involve the interim storage, reprocessing, and recycling before the fuel is disposed of as waste. The nuclear fuel cycle is a global market and there are only a handful of companies that are part of it. It is therefore almost impossible to achieve a fully "re-shored supply chain" with all activities within the EU.

Figure 0.1 The nuclear fuel cycle



Source: © World Nuclear Association

Uranium mining

Uranium is a slightly radioactive, very dense (19 g/cm3, 1,67 times denser than lead)[301] material that can after several processes be used as a nuclear fuel. It is a quite abundant material, the concentration in the Earth's crust ranges from two to four parts per million, making it 500 times more abundant than gold. Uranium is therefore the 48th most abundant material on Earth[301] Natural uranium composes of two isotopes, uranium-238 (U-238) and uranium-235 (U-235) representing 99.3% and 0.7% of the total composition respectively. The significant importance for nuclear energy holds the isotope U-235, which under certain conditions can undergo fission, and release a substantial amount of energy.

301 Nuclear Fuel Facts: Uranium | Department of Energy

Since uranium is a rather abundant element, mining is happening in several countries across the world. Currently, there are three types of uranium mining depending on the nature of the orebody. The first method is open pit mining, used for deposits that are close to the surface, typically less than 120 m. With this type of mining the walls of the mine must be slopped, to prevent collapse. Therefore, the mine is much larger than the deposit itself, resulting in a vast amount of material that must be removed. Underground mining, a second method of mining uranium, is used at deposits that are more than 120 m deep. Compared to an open pit mine, the amount of material that needs to be removed to access the ore is considerably lower. On the other hand, even though the surface area of the underground mine is relatively small, there are special precautions that must be made (mine reinforcements, increased ventilation, etc.). The last currently used method of uranium mining is in-situ leach (ISL) mining. This type of mining rests on the circulation of oxygenated groundwater through a porous orebody, where it dissolves the uranium oxide and is bringing it to the surface. Weak acids or alkaline solutions are sometimes used in ISL mining to retain the uranium in the solution. Once the solution is brought back to the surface, the leached uranium oxide is extracted from the solution.

Uranium milling

Uranium milling is a process involving crushing and grinding of extracted uranium or ISL leachate to release the mineral particle. Following the grounding, the resolved slurry is leached with sulfuric acid to separate the uranium from the waste rock. The next part in the uranium milling is the process of uranium recovery from the solution and its precipitation to uranium oxide (U3O8) concentrate, that is afterwards dried and packed. The resulting concentrate is commonly called “yellowcake”. Average nuclear reactor (1 000 MW) requires approximately 200 tons of U3O8 a year for its operation.

Figure 0.2 Yellowcake



Source: © Orano

Mining and milling produce radioactive remains of the ore called tailings (solid) and raffinates (liquid). Since the remainders are radioactive and contain hazardous chemicals, they are labelled as radioactive waste. As such it must be isolated from the environment and safely stored.

Conversion and enrichment

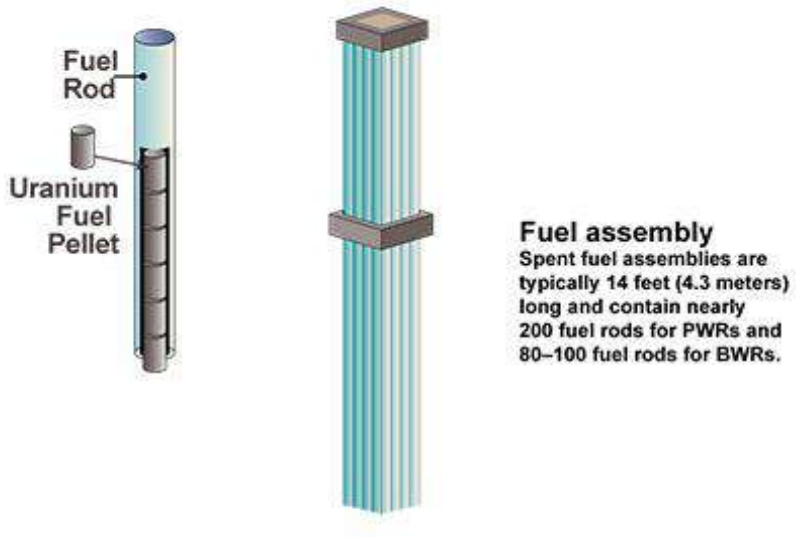
The U3O8 concentrate resulting from the milling process is not ready to be used as a fuel for nuclear reactors, additional treatment is needed. In this form the oxide has a natural composition of uranium, meaning 99.3% of U-238 and 0.7% of U-235. Most reactor types are not able to use the uranium in its natural form and the concentration of fissile U-235 must be increased. The desired concentration is typically ranging from 3.5% to 5% of U-235. The process of increasing the concentration ("enriching") of one isotope relative to the other is called isotope separation, and it requires the uranium to be in gaseous form. To transform the uranium into gaseous form, conversion must happen. During a conversion process, the uranium oxide is refined to uranium dioxide (UO2) first[302], followed by conversion to uranium hexafluoride (UF6), the gaseous form. Once the gaseous form is obtained the enrichment process takes place. The enrichment is done commercially through a series of centrifuges, where thousands of vertical tubes are spinning, causing the isotopes to separate[303]. Once the enrichment process is finished, the final product of enriched hexafluoride is obtained. The final process of conversion and enrichment is the deconversion of enriched uranium gas back to the UO2 form, in which the fuel is fabricated.

Fuel fabrication

The uranium used in a nuclear reactor typically has a form of ceramic pellets. These pellets are made by sintering, a process where the uranium dioxide is baked at a high temperature (over 1 400°C). Sintering is followed by the encasement of the pellets in metal tubes , which are then arranged in fuel assembly that is prepared to be loaded to the reactor. Fabricating a fuel assembly is a complex and very controlled process, dimension of the pellets, tubes and other elements are precisely controlled to ensure consistency in the fuel characteristics and behaviour. For the operation of a 1 000 MW reactor approximately 27 tons of fresh enriched fuel is required each year.

302 This form can be used as the fuel for reactor types that do not require enriched uranium.
303 On a basis of different physical properties, the 1% mass difference between the two isotopes.

Figure 0.3 Fuel assembly



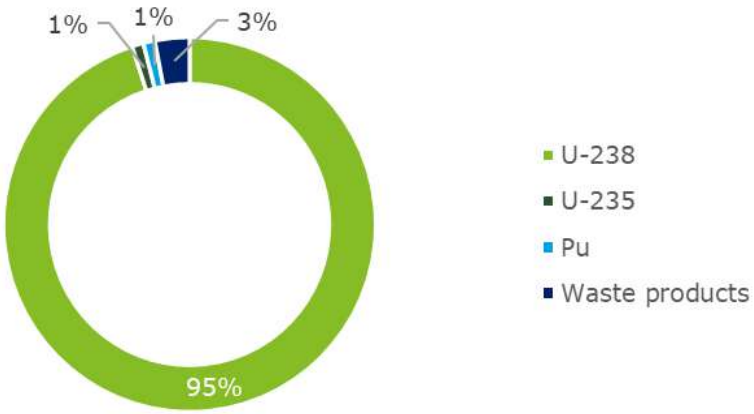
Source: © U.S. Nuclear regulatory commission

Reprocessing

The fabricated fuel is then used in the reactor to generate heat, depending on the operational campaign the fuel works in the reactor typically for 18-36 months. Once the fuel is used and withdrawn from the reactor, it can be handled in two ways, disposed or reprocessed. The final disposal is a process where the used fuel is, after its initial cooling period, put into a used nuclear fuel container (i.e., CASTOR, CONSTOR) and disposed of in the DGR (described in detail in chapter 8) where its operational lifetime ends.

The second possibility is to reprocess the used fuel, which still contains about 96% of its original uranium and the share of the fissionable U-235 has been reduced to less than 1%. For reprocessing, an important part of the used fuel is plutonium (Pu) generated while the fuel is in the reactor, the share of Pu in the used fuel is also about 1%. During the reprocessing (or recycling) of the used fuel, the uranium and plutonium are separated from the waste products, enabling the recycling of the elements to fabricate fresh fuel. Reprocessing is also significantly reducing the amount of radioactive waste. After reprocessing the uranium can be reused as fuel after undergoing conversion and enrichment. The recovered plutonium can be used directly to fabricate a mixed oxide fuel (MOX), where it substitutes the role of U-235 in normal fresh fuel.

Figure 0.4 Percentual composition of used nuclear fuel



Source: © World Nuclear Association

Annex H Economic analysis

List of indicators for the economic analysis

Indicator	Basis of the Information
General information on Nuclear Energy Plants	
Number of Nuclear Energy Plants in the EU and each Member State	• Literature & Data Review • Member State Questionnaire • EU 27
Number of Nuclear Energy Plants to be built in the next 10-20 Years in the EU and each Member State	• Literature & Data Review • Member State Questionnaire • EU 27
Number of Nuclear Energy Plants to be commissioned in the EU and each Member State	• Literature & Data Review • Member State Questionnaire • EU 27
Total Revenue of Nuclear Energy Companies in the EU and each Member State	• Member State Questionnaire • Industry Questionnaire
Total Investment Costs of Nuclear Energy Companies in the EU and each Member State	• Literature & Data Review • Case Study
Number, size, name etc. of Nuclear Energy Companies in the EU and each Member State	• Literature & Data Review • Stakeholder Questionnaire • Industry Questionnaire
Number of Employees of Nuclear Energy Companies in the EU and each Member State	• Literature and Data Review • Stakeholder Questionnaire • Industry Questionnaire
Uranium Facilities (tbd if more info needed)	
Number of Uranium Facilities in the EU and each Member State	• Literature • Member State Questionnaire
Generation/Consumption of Energy:	
Total Electricity generated in the EU and each Member State	• Literature & Data Review • Member State Questionnaire
Total Energy consumed in the EU and each Member State	• Literature & Data Review • Member State Questionnaire
Energy Export/ Import Balance in the EU and each Member State	• Literature & Data Review • Member State Questionnaire
Nuclear Energy Generation at Member State and EU level	
Total Nuclear generating capacity in the Eu and each Member State	• Literature & Data Review • Member State Questionnaire

Indicator	Basis of the Information
Average cost of producing electricity from Nuclear Plants in the EU and each Member State	• Case Study
Nuclear Fuel:	
Total Nuclear Fuel Fabrication Capacity in the EU and each Member State	• Literature Review
Total/Average Cost of purchasing and processing nuclear fuel in each Member State	• Case Study
Waste Management:	
Waste management costs and activities in each Member State / EU level	• Member State Questionnaire • Industry Questionnaire
Monitoring:	
Monitoring Plans (Which activities, how often and how many people are engaged in these activities) in each Member State / EU level	• Member State Questionnaire
Decommissioning:	
Decommissioning Plans and current activities in each Member State (Which activities, how often and how many people are engaged in these activities)	• Member State Questionnaire
Output	
GDP/GVA contribution	
GDP per capita	
Taxes/public net revenues	
Employment	
Private household income	

Definition of indicators for the nuclear ecosystem and economy

18 indicators have been defined to assess the nuclear energy ecosystem. The indicators follow the components of the ecosystem and provide general information on nuclear power plants, uranium facilities, energy production and consumption, nuclear fuel, waste management, monitoring and decommissioning. Data for the indicators comes from desk research, including existing datasets, the study's questionnaires, and specific case studies.

The combination of different sources for data allows to fill data gaps. If necessary, data gaps are closed by expert assumptions. For some of the indicators,

official/public data might not be available, e.g. financial data with regard to operating costs of nuclear power generation plants or capital expenditure related to new investment projects.

Based on the data collected for each indicator and a macroeconomic model, the economic impact of the Nuclear Energy Ecosystem as described in the following section is estimated. The outputs of the assessment that describe the total impact of the nuclear energy ecosystem are the impact/contribution to GDP (in terms of GVA), employment (job creation), taxes and household income within the EU27.

Calculation of the total economic impact of the Nuclear Energy Ecosystem

The nuclear energy ecosystem/industry is not limited to nuclear power plant operators – who, however, already contribute to the economy substantially. Furthermore, suppliers of necessary goods and services related to research and development, investments, and intermediate inputs for operations amongst others are essential. These activities are considered a part of the Nuclear Energy Ecosystem and contribute to the economy as well. Furthermore, the Nuclear Industry contributes to the economic activity in the EU in terms of its production and the demand created in supplier (upstream) industries. Inter-industry linkages allow the calculation of how many resources and workers are required in upstream industries to generate a specified value of production in the Nuclear Energy Ecosystem. Using standard input-output (I-O) multipliers, it is possible to estimate the flow-on impacts on gross output, value-added, wages, and total employment that are generated by the Nuclear Energy Industry. However, the Nuclear Energy facilities across the EU27 will serve as the basis for the estimation of the direct impact within the energy sector.

The economic activity generated by Nuclear Energy Ecosystem is accordingly the sum of direct indirect and induced components.

- The **direct** component measures economic activity directly associated with Nuclear Energy's production of goods and services – that is, the payments to the factors of production. For example, labour is a key input factor in the service provision process, with the total salaries of workers representing a direct measure of the activity generated by industry.
- The **indirect** component measures the economic activity generated by the Nuclear Energy industry through its demand for the outputs of other industries.
- The **induced** component measures economic activity arising from income being spent when employees of the nuclear energy industry and those in its supply chain spend their wages.

There are three widely used direct measures of economic activity, namely value added (consisting of labour income and the gross operating surplus), gross output and employment. By using these measures, we aim to generate insights about the economic contribution of the activity.

- **Gross output** measures the total sales value of all the goods and services that are supplied by the industry. This is a broader measure than value-added because, in addition to the value-added generated by the industry, it

also includes the value of intermediate inputs that are utilised during the production process.

- **Value added** measures the value of output (i.e. goods and services) generated by the industry's factors of production (i.e. labour and capital). The sum of value added across all entities in the economy equals GDP.
    - **Labour income** is a subcomponent of value added. It measures the value of output generated by the industry's direct labour inputs. The capital analogue to this measure is called gross operating surplus (GOS). Labour income includes payroll tax paid by companies.
    - **GOS** measures the value of output generated by the industry's direct capital inputs. In addition to profit, this includes depreciation, interest payments, and taxation, as these are all paid from returns to capital. GOS is often measured as earnings before interest, taxation, depreciation, and amortisation. GOS includes corporate tax paid by companies.
- **Employment** is a fundamentally different measure of activity from those above. It measures the number of workers who are employed by the industry, rather than the value of the worker's output. It is typically measured using headcount and/or FTE.

Moreover, the analysis provides a general overview and certain insights into the industry context, key facts on the specifics of the nuclear energy ecosystem and its supply chain. Key sectors of economic activity can be identified, and results can be analysed on Member State level as well.

Input-Output model

IO models can be used as a basis for analysing the effects of an industry's or company's activities on upstream production (supply) industries along the value chain. With the help of IO analysis, the intermediate goods incorporated in the production process can be allocated to different sectors of the economy.

In other words, the supply links among the individual sectors can be shown. This enables the input structures to be differentiated by sector. The company's purchased goods and services serve as a starting point (tier 1). On the basis of the structure of the goods and services actually required or obtained, the intermediate goods and services (tier 2 – tier n) statistically required for the production of the company's production input (tier 1) are calculated using IO analysis. As a result, the (statistically) required total input of goods and services is determined along the upstream stages of the value chain. Classical IO analysis or IO models can be used to quantify the effects of corporate activities along the upstream value chain. The analysis of the effects of business activities is based on company specific data on factor consumption as well as general statistical data compiled in the IO table. The statistical data are essentially the input-output tables.

IO tables and models are widely used in the context of classical economic impact analysis (EIA) and in environmentally extended IO analyses (EEIO). The application of IO models in these contexts has increased due to the general

availability of extensive structural data sets, especially multi-regional input-output (MRIO) tables.

A broad range of different IO models and applications based on IO tables exists. Simple static IO (quantity) models often serve as a starting point in the context of basic impact analysis. These models, which are used for comparative-static impact (scenario) analyses, allow for measurement of the economic activity of a company (or some of its activities) in terms of the demand created in supplier (upstream) industries.3 Inter-industry linkages reflected in the IO tables enable the basic calculation of the resources (e.g., workers) required in upstream industries to generate a specified value of a company's production. With the help of these IO quantity models, statements can be made about direct and indirect effects based on exogenous changes in demand as well as induced impacts generated via the additional households spendings as a result of increased income.

A primary application of the model is to assign production factors to the final demand for goods. In the context of impact analysis, the change in final demand due to a company's activities is considered. In this model, those factors employed by suppliers in all upstream stages are calculated and assigned to the change in demand generated by the company's activities. The allocation of production factors (e.g., employees) to final demand is calculated using the Leontief inverse, and gives the total production output (including upstream) involved in producing the company's output.

Deloitte has applied a model based on the Exiobase world input-output-database. The primary focus of the model is on estimating the economic contribution of the NPP ecosystem, both through construction activities, the operation of power plants and the associated fuel cycle as well as decommissioning activities. In the sense of a classic economic impact assessment, the output and the contribution to GDP are determined by multipliers using the Leontief inverse (upstream). The following assumptions and implications should be mentioned in particular:

Assumptions	Explanations / Implications
Input-Output matrix / technical coefficients	Constant technical coefficients have been used, based on the Exiobase database latest publications. It is assumed, that the technical requirements (intermediate inputs) related to e.g. the construction or the operation of NPPs remains constant over time. However, it can not be ruled out that the technical input coefficients might change over time and the impacts are under- or overestimated. E.g. , the technical inputs for production of cars might vary substantially between the production of cars with combustion engines or electrical vehicles.
Prices	For the sake of simplicity, the model assumes a price trend in line with the available long-term inflation forecasts. Individual markets, including the energy markets, are not modelled. In this respect, it cannot be ruled out that output and contributions to GDP (gross value added) may be higher or lower due to price changes.
Taxes/public net revenues	In this regard the ratio of taxes and social security contributions over GDP has been analysed for recent years. Averages for recent years were used to forecast future inflows. However, it cannot be ruled out that the contributions will vary more strongly in the future - e.g. due to demographic changes.
Imports/Exports	In this respect, the global input-output model used already takes into account a certain outflow due to supplies/contracts from foreign companies (extra-EU27), which are mapped in the inter-industry links of the model. With regard to investments in connection with new buildings, expert assumptions were made on the volume of imports (extra-EU27) based on expert estimates, industry expertise and market shares of renowned manufacturers, among other things. Nevertheless, it should be noted that there is a relatively large uncertainty factor here, as it is uncertain which companies will be awarded contracts for planned power plants, some of which are still far in the future.
Employment	It is assumed, that labour productivity/intensity changes according to the inflation rate. Thus, labour productivity is assumed to be constant (in real terms). However, it cannot be ruled out that labour productivity increased with higher rates, thus the employment impact would be overestimated. Furthermore, labour inputs in production might decrease e.g. due to automation; in this regard, employment impacts might be overestimated.

Detailed results

Figure 69: Gross Value Added (GVA) Construction EU27 (billion €)

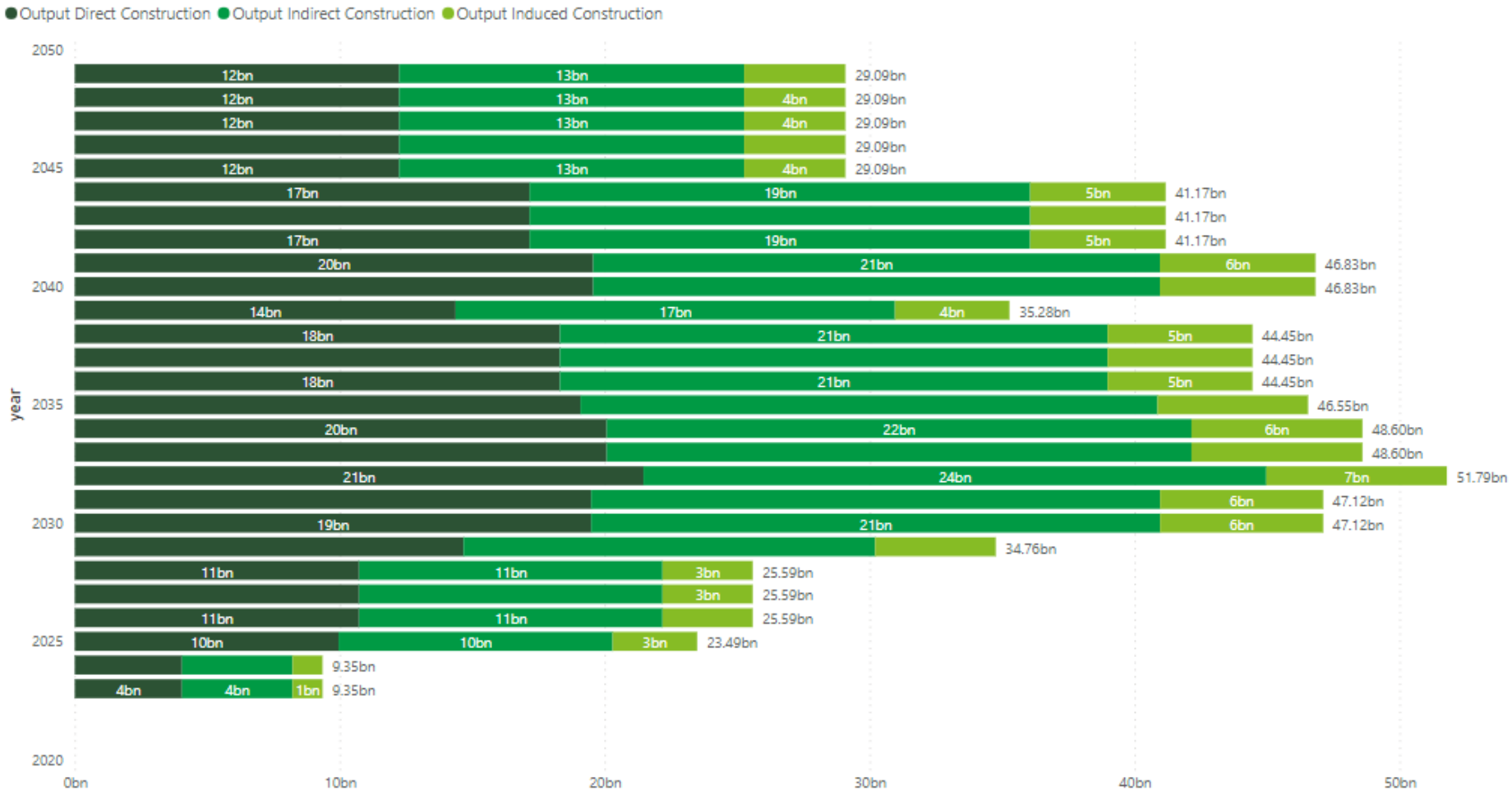


Figure 70: Employment Construction EU27 (thousand)

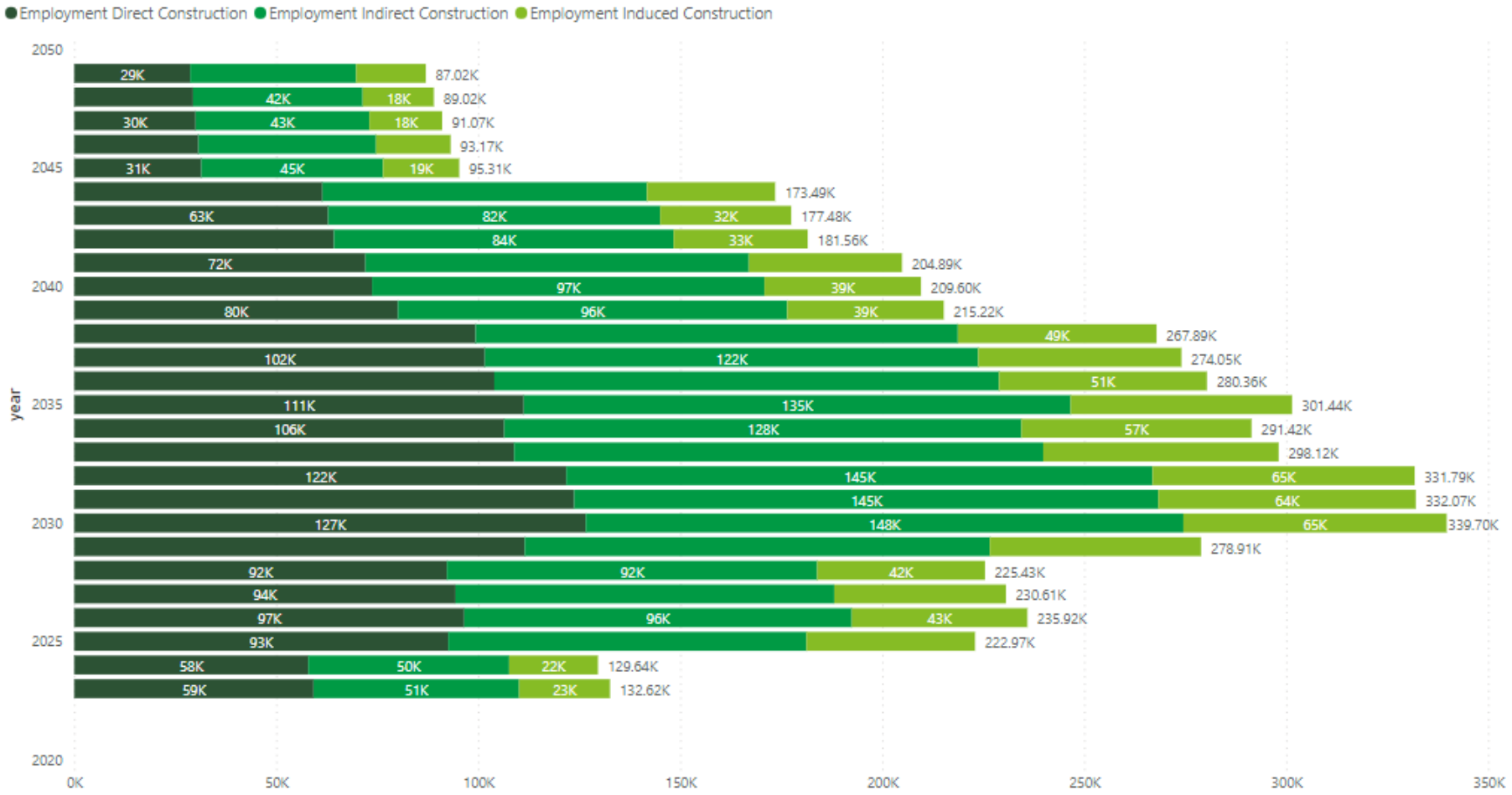


Figure 71: Gross Value Added (GVA) Operation EU27 (billion €)

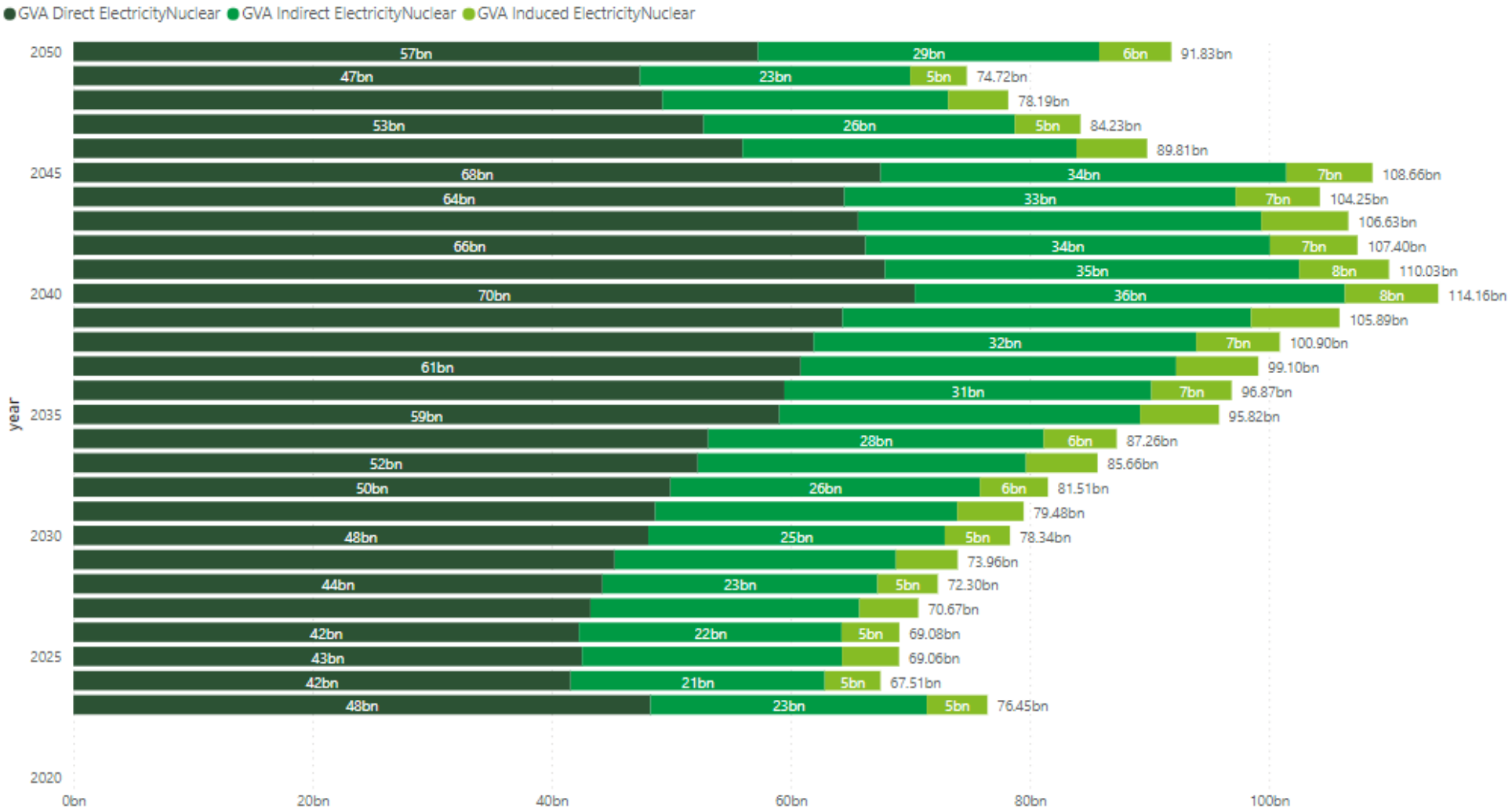


Figure 72: Employment Operation EU27 (thousand)

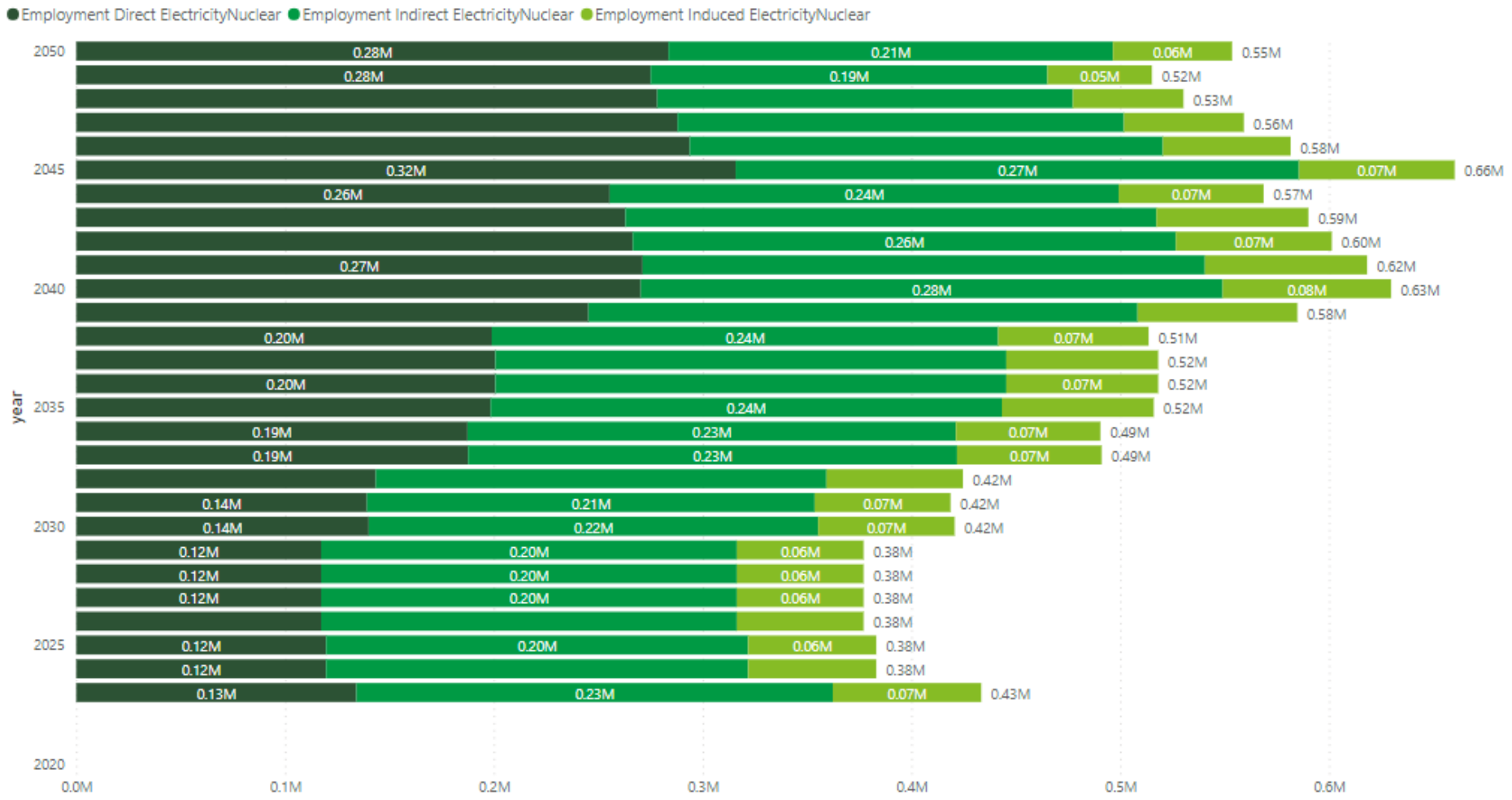


Figure 73: Gross Value Added (GVA) Nuclear Fuel EU27 (billion €)

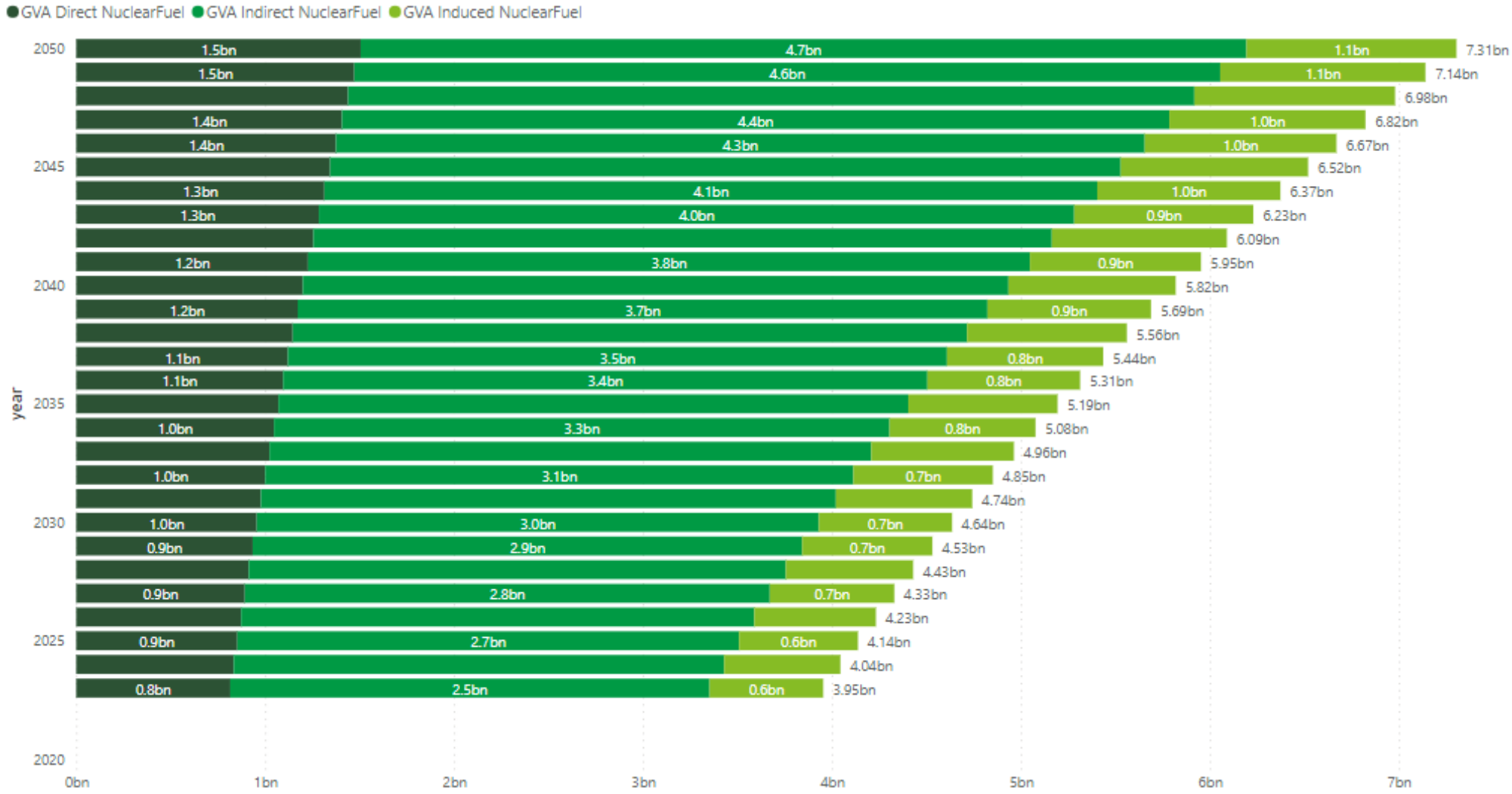


Figure 74: Gross Value Added (GVA) Decommissioning EU27 (billion €)

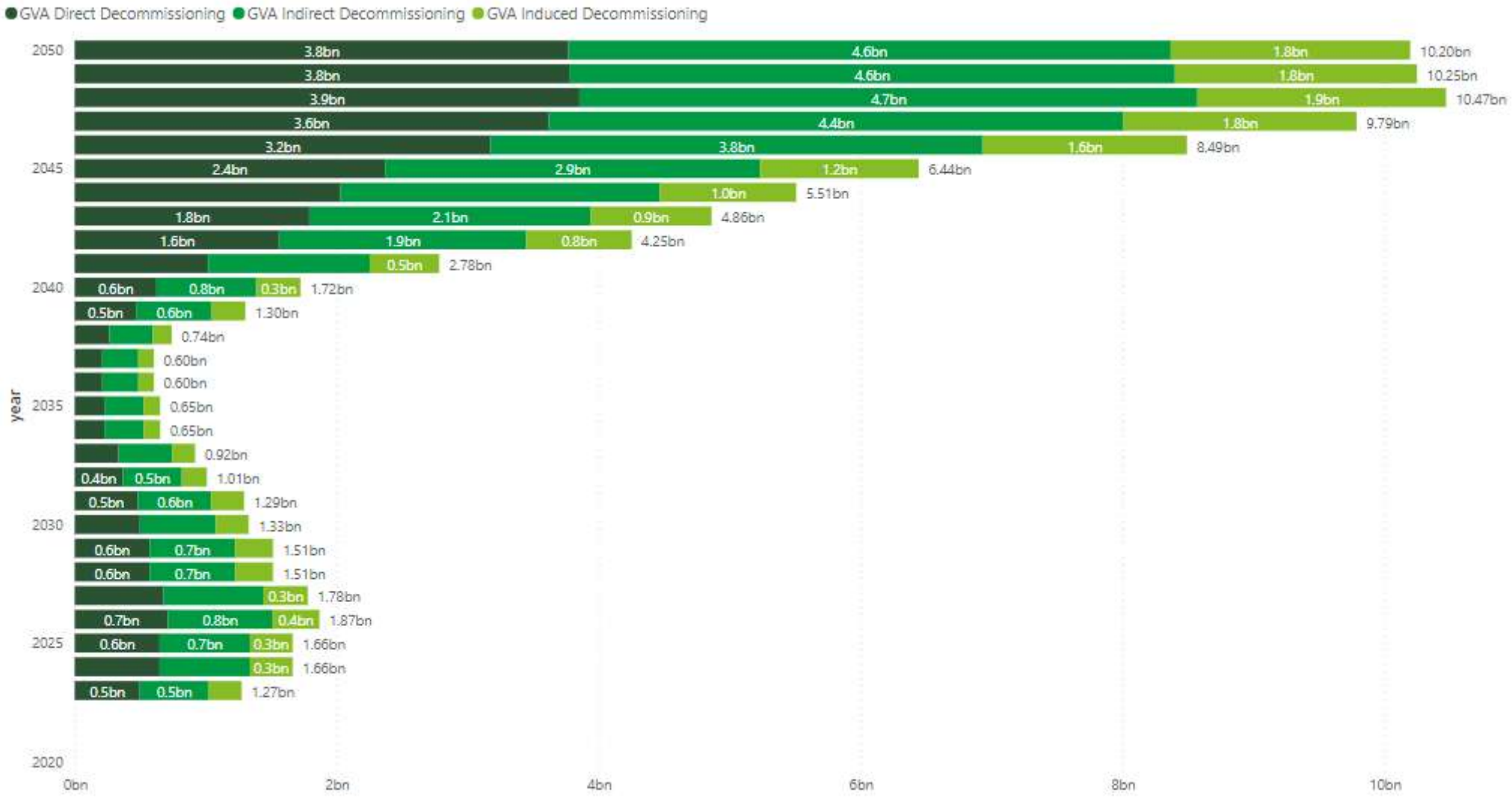


Figure 75: Employment Decommissioning EU27 (thousand)

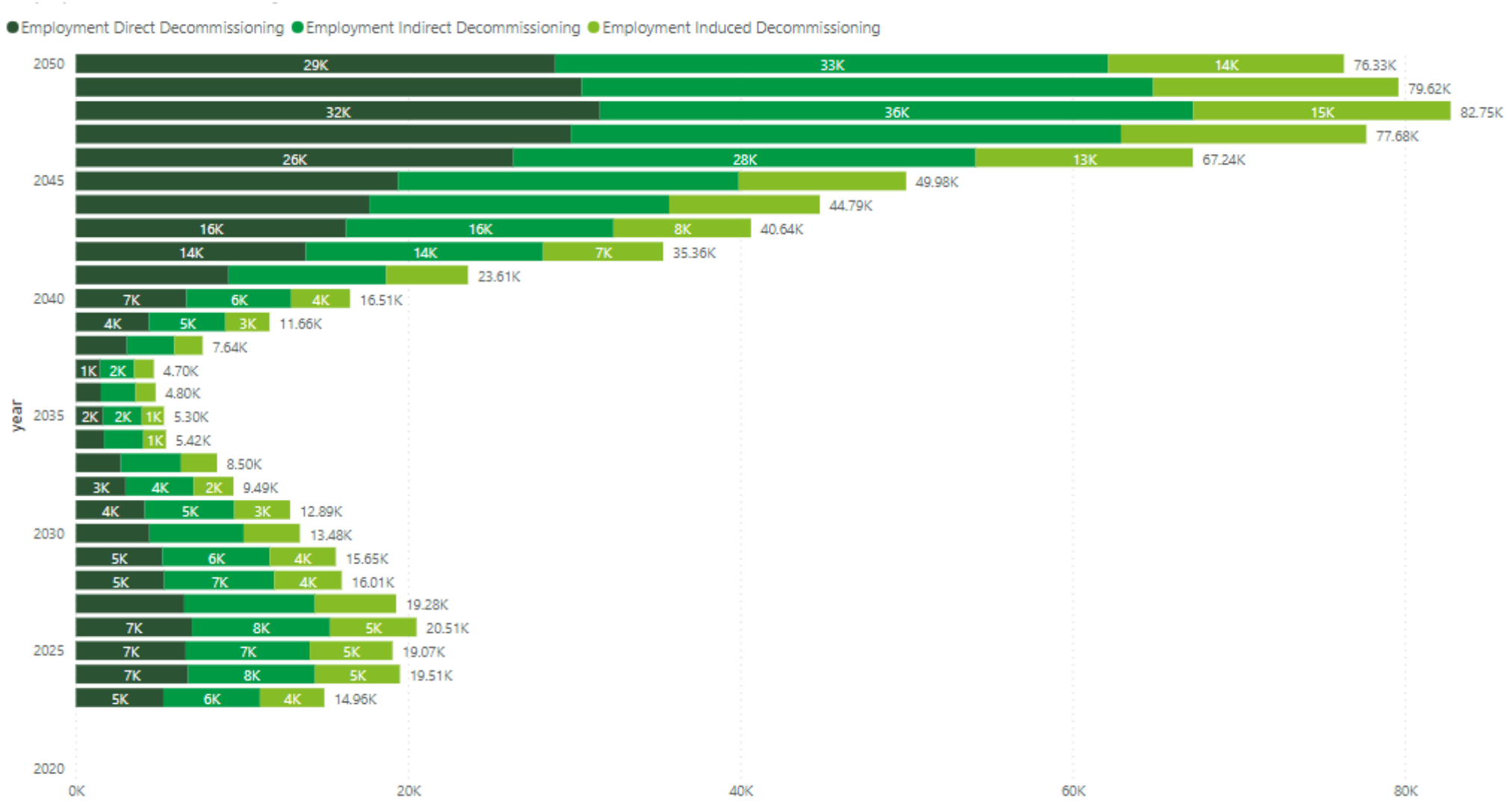
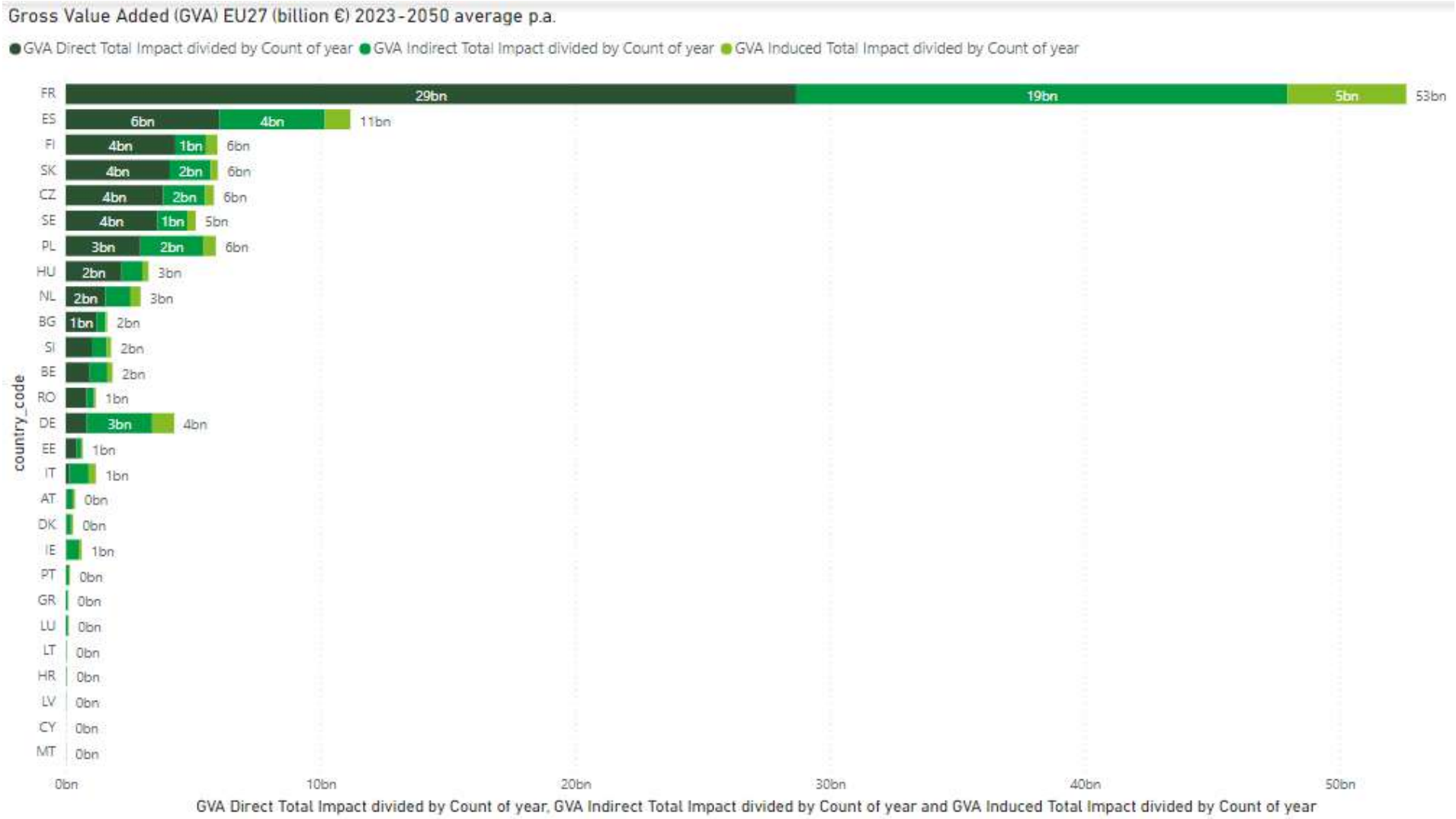


Figure 76: Gross Value Added (GVA) average 2023-2050 p.a. EU27 (billion €) by Member State


Gross Value Added (GVA) EU27 (billion €) 2023-2050 average p.a.
GVA Direct Total Impact divided by Count of year
GVA Indirect Total Impact divided by Count of year
GVA Induced Total Impact divided by Count of year
country_code
FR 29bn 19bn 5bn 53bn
ES 6bn 4bn 11bn
FI 4bn 1bn 6bn
SK 4bn 2bn 6bn
CZ 4bn 2bn 6bn
SE 4bn 1bn 5bn
PL 3bn 2bn 6bn
HU 2bn 3bn
NL 2bn 3bn
BG 1bn 2bn
SI 2bn
BE 2bn
RO 1bn
DE 3bn 4bn
EE 1bn
IT 1bn
AT 0bn
DK 0bn
IE 1bn
PT 0bn
GR 0bn
LU 0bn
LT 0bn
HR 0bn
LV 0bn
CY 0bn
MT 0bn
0bn
10bn
20bn
30bn
40bn
50bn
GVA Direct Total Impact divided by Count of year, GVA Indirect Total Impact divided by Count of year and GVA Induced Total Impact divided by Count of year

Annex I Questionnaire questions

Stakeholder questionnaire

1. The Nuclear Illustrative Programme from 2017 predicts the nuclear capacity in 2050 to be between 95-105 GW of installed capacity (in 2022 the installed capacity is 102 GW), do you think it is sufficient?
2. Is it realistic to achieve such a capacity by 2050 as much of this would need to be a new build?
3. Do you consider the intended 15 % share (approx. 100 GW installed capacity) of nuclear power in the European electricity mix in the 2050 sufficient and why? If not, please indicate how large should the share be.
4. Do you see the contribution of nuclear to net zero mainly in large reactors or in Small Modular Reactors and why?
5. What are the immediate steps that you see as crucial for the wider deployment of nuclear power in Europe in the coming years?
6. How can the European Commission better support nuclear ecosystem /safety in view of the further development of nuclear energy? Any other type of support that could be expect from the EC?
7. Do you think that the taxonomy of sustainable finance will influence the development of nuclear energy? And how?
8. The Taxonomy Regulation requires the Commission to review the technical screening criteria at least every three years and, where appropriate, amend the delegated act in line with scientific and technological developments. Are there any changes that should be implemented in the taxonomy?
9. Does your organisation plan to participate in a taxonomy aligned nuclear project? If yes, then when and how?
10. Do you think that the EU and Member States have robust and efficient licensing processes for enabling newly build Nuclear Power Plants (NPPs)?
11. Do you consider the legislation ready for licensing and operation of Small Modular Reactors?
12. Do you consider the legislation ready for licensing and operation of Generation IV reactors?
13. What steps need to be taken to prepare robust and efficient legislation for:
    a) Current reactors (Gen II & Gen III)
    b) Gen IV reactors
    c) Small Modular Reactors
14. Do you see nuclear legislation for current reactors (Gen III+) and Small Modular Reactors with Gen IV reactors as one framework?

15. Do you consider a unified European guideline for licensing process of Small Modular Reactors and Gen IV reactors a good idea?
16. Where do you see the gaps in licensing processes/ legislation? What should be revised, where and why?
17. Do you perceive the nuclear legislation environment as stable in Europe?
18. What is the estimated total revenue of all nuclear energy companies (per plant) in your country?
19. Only applicable for manufacturers/operators: What is the average cost of production of electricity in nuclear plants per TWh? What cost drivers do you expect for 2030, 2040, 2050?
20. Only applicable for operators: Please indicate the costs of purchasing nuclear fuel per generated TWh/as percentage of your total annual costs. Please also indicate the total costs of processing nuclear fuel and as percentage of your total annual costs (or per generated TWh).
21. What do you think is the maximal possible number of nuclear reactors to be built in Europe simultaneously
    a) manufacturing capacity-wise,
    b) human capacity-wise,
    c) regulatory-wise?
22. What steps are necessary for each field to ensure faster and more efficient construction of new Nuclear Power Plants:
    a) Investor steps
    b) Investment environment steps
    c) Manufacturing/Production steps
    d) Legislation/Licensing process steps
    e) Human capabilities steps
    f) Project developer / management steps
    g) Risk mitigation steps
23. How to ensure better involvement of European companies to build new Nuclear Power Plants and to provide Long Term Operation services for older plants?
24. What are the areas where European companies are less competitive? Specify by technology or from an operational perspective
25. Are there specific manufacturing companies and/or companies providing nuclear services which are currently missing in Europe?
26. Do you consider the current supply chain for delivering new nuclear units as healthy and ready for maintaining the same capacity as today?
27. Only applicable for supply chain representatives: Do you currently reach your manufacturing capacity, or do you deviate from your full capacity? What percentage would be the current capacity on average per year as compared to the full capacity? Do you see any efficiency gains to better reach full

capacity? What are the reasons for a deviation from the full capacity? Do you expect that the full capacity will be reached in 2030, 2040, 2050?

28. Only applicable for NPP operator representatives: In case the nuclear energy production in your facility deviates from the full capacity of your facility, what percentage would be the current capacity on average per year as compared to the full capacity? Do you see any efficiency gains to better reach full capacity? What are the reasons for a deviation from the full capacity? Do you expect that the full capacity will be reached in 2030, 2040, 2050?
29. How could international organisations (IAEA, OECD-NEA etc.) help the industry to be ready for manufacturing SMR components or for development of support services or competences?
30. On which topics should the communication with the EC be focused more:
    a) Operation and Long-term operation
    b) Newly build nuclear power plants
    c) Decommissioning and waste management
    d) Financing possibilities / Notification process
31. What approach do you see as the most effective for the financing of new NPPs construction and why (contract for difference [CFD], state-aid, guarantees, Mankala-structure, etc.)? Should there be any standardized framework at EU level for speeding up the notification process?
32. Do you think that the nuclear investment environment is predictable and sufficient and does not increase risks?
33. Can you see any changes to the investment environment that would speed up the development of nuclear power in Europe?
34. Should there be greater activity from the European Commission and international organization in the support of Small Modular Reactors and nuclear power in general? If yes, where should it be targeted to and how?
35. What should be the desired ownership of NPP and why?
36. What should be the desired operation framework of NPP and why?
37. Do you feel that research reactors are crucial for the successful implementation of advanced reactor systems?
38. Should the EU prepare some support programmes for research reactors, together with funding options?
39. To what extent do you deem EU support programmes for research reactors necessary for implementing advanced reactor systems?
40. Is the waste management strategy described in the Radioactive Waste Directive (RWD) sufficient?
41. Should each EU Member State be obliged to construct and operate a deep geological repository (DGR) for radioactive waste, or you would prefer shared capacities and why?

42. How will waste management change with the deployment of advanced reactors (Small Modular Reactors and Advanced Reactors) and why?
43. How many EU Member States you think will have an operational DGR in:
    a) 2030?
    b) 2040?
    c) 2050?
44. What is the estimated the number of employees per activity (e.g. operating, decommissioning, management) that work for nuclear energy companies in your country.
45. Are there enough nuclear professionals to build and operate the intended new power plants?
46. What steps should be taken to ensure there are enough skilled professionals for the construction, operation and maintenance of new power plants?
47. Do you consider that there are enough relevant skilled professionals for:
    a) Operation of the current nuclear fleet (operators, physicists etc.)
    b) Maintenance of the current nuclear fleet (technicians, welders, engineers etc.)
    c) Decommissioning of the current nuclear fleet? (decommissioning experts, dosimetry experts, technicians etc.)
    d) Increase of the capacity of the new builds (technicians, welders, construction workers etc.)?
48. On which skill set should training programmes be focused most:
    a) Design
    b) Construction
    c) Operation
    d) Decommissioning
    e) Licensing and permitting

Member States questionnaire

1. The number of reactors being currently operated in your country.
2. The share of nuclear energy in electricity production? Current state and outlook for years 2030, 2040 and 2050.
3. What is the total electricity generated from nuclear plants in terawatt-hours [TWh] in your country (current, 2030,2040,2050)?
4. Is nuclear energy incorporated into the country's energy strategy? If yes, how?
5. How many reactors and with what capacity do you plan to commission before 2025, 2030, 2035, 2040, 2045, 2050?
    a) When do you plan to commission the first and second units?
    b) What types of reactors do you plan to build?
    c) Are you considering building SMRs? When do you expect their deployment?
    d) What are the expected investment costs (and thereof, the expected funding needs)?
    e) What are the main obstacles to achieve the above objectives?
6. What type of reactors is your country operating?
7. When were these reactors commissioned?
8. Please indicate decommissioning plan for existing units.
    a) In case decommissioning already takes place in your country: What are the activities that are currently performed on a governmental and enforcement level? How many State employees are involved in these activities?
9. Do you consider the long-term operation of reactors?
    a) How important is it for your energy stability?
    b) What is the planned extension time for your reactors?
    c) What are the expected funding needs?
    d) What is the timeframe of your long-term operation programme?
    e) How many reactors will be part of the long-term operation programme?
10. How many reactors will be maintained in operation through LTO till 2030, 2040, 2050?
11. A Member State licensing process:
    a) Is it fit for newly build nuclear power plants?
    b) Is it fit for SMRs and Gen IV reactors?
    c) Do you consider a revision of your nuclear legislation?
    d) When do you plan to develop legislation that would enable licensing and operation of SMRs?
    e) What sources you will be using for the development of legislation? (IAEA, NEA, Euratom, and others)

12. To nuclear regulatory agencies/government bodies: How many staff are currently employed in your national nuclear regulatory authority (+TSOs) and how do you see this workforce evolve in the future?
13. Which type of monitoring activities take place to monitor the existing (and planned) nuclear facilities in your country?
14. Have you set final dates for the transition to advanced reactor technologies (Small modular reactors, Generation IV reactors)? (national policy level)
15. Do you have any special financial tools to finance LTO and the construction of new NPPs? (contract for difference, state guarantee, state aid, private financing, other)
16. Do you plan to use other strategies for waste management together with DGr ? (MOX recycling, actinide burning in fast reactors, others)
17. Do you have operational final disposal facilities for all very low-, low- and intermediate-level radioactive waste?
18. What is the average amount of radioactive waste in tons (very low-, low-, intermediate-level) generated per year?
19. Are your disposal facilities sufficient to store all waste generated during the operation of nuclear power plants?
20. Do you plan to build a DGR? If not, please explain your waste management strategy
    a) When do you plan to start the construction and then the operation of the repository? (Please indicate a timeline)
21. Do you have a documented plan with detailed steps to have in operation, by 2030, 2040, 2050, a disposal facility for high-level radioactive waste describing all of the following: (i) concepts or plans and technical solutions for spent fuel and radioactive waste management from generation to disposal; (ii) concepts or plans for the post-closure period of a disposal facility's lifetime, including the period during which appropriate controls are retained and the means to be employed to preserve the knowledge of that facility in the longer term ; (iii) the responsibilities for the plan implementation and the key performance indicators to monitor its progress; (iv) cost assessments and financing schemes? (Taxonomy requirement)
22. Do you have in place a radioactive waste management fund and a nuclear decommissioning fund?
    a) What is the current allocation in these funds?
23. How many research reactors are you operating?
    a) If the answer is zero, do you consider building a research reactor?
    b) What type of research reactor do you plan to build?
    c) What will be the main purpose of the research reactors? (material testing, medical isotope production, focused purely on research)
24. Is your country developing its design of a small modular reactor?

25. Please indicate the main manufacturing companies in your country that can deliver nuclear components and specialised nuclear services as well as their size (number of employees, indication about total revenue if possible).
26. What is the estimated total revenue of all nuclear energy companies (per plant) in your country?
27. Are there any specific nuclear components or services with which you are dependent on either Russia or China? Please state component/service and country.
28. During the construction of the new NPP, what share of the delivery can be done by the country's industry capacities? (percentage)
29. Does your country have a university with a programme focused on nuclear energy?
    a) Please indicate how many nuclear professionals are entering the market every year.
    b) Do you plan to establish nuclear energy-focused university programme?
30. Please describe the nuclear fuel supply chain and the path from uranium purchase to delivery of fuel assemblies.
    a) Please also indicate the number of uranium facilities in your country.
    b) If you manufacture your fuel, what is the yearly capacity of such a facility?
    c) Do you plan to build and operate nuclear fuel production facility?
31. Do you consider nuclear energy-based electricity generation an activity significantly contributing to the climate change mitigation objective?
32. What urgent steps should be taken by 2030 and 2050 to fulfil energy targets or gaps with regard to the RePowerEU scenario?
33. Do you think that the taxonomy of sustainable finance will influence the development of nuclear energy? And how?
34. The Taxonomy Regulation requires the Commission to review the technical screening criteria at least every three years and, where appropriate, amend the delegated act in line with scientific and technological developments. Are there any changes that should be implemented in the taxonomy?
35. Does your country plan to participate in a taxonomy aligned nuclear project? If yes, then how?
36. Do you find some information missing in Taxonomy? What would you like to be added?
37. If relevant, will you comply with the technical screening criteria under this Delegated Act and report based on that assessment by 1 January 2023, when the Delegated Act enters into force?
38. Will you comply with taxonomy specific requirement of using the accident-tolerant fuel for nuclear power plants from 2025?

39. Optional: What is the estimated number of employees in nuclear energy companies in your country?
40. The field for an optional comment regarding any part(s) of the questionnaire.

Industry questionnaire

1. Did you supply nuclear installation components in the past?
2. Does your company participate in the following types of projects? (construction of new technologies, nuclear technologies decommissioning, nuclear installation maintenance, nuclear fuel supply, other)
3. What is the percentage of production of your company which is for the nuclear industry?
4. Does your company plan to expand its production capacity in the future with the objective to supply components for nuclear installations?
5. Does your company collaborate on components development for new nuclear power reactors or for small modular reactors (SMR)?
6. Can your supplier of production tools assure increased deliveries of required production equipment? By what percentage is the supplier able to increase its production capacity within the next 5 years?
7. By what percentage would your company be able to increase production capacity over the next 5 years for nuclear industry?
8. What kind of support would be needed to double your production capacities in the next 5 years?
9. What type of public/private support would be required to support your company´s business objectives if one assume that 100 GW of new nuclear power will be built till 2050?
    a) If possible, please specify in specific areas (financing, material base, import etc.).
10. Have you received any form of financial support (grant, loan, etc.) for the development of your company in the field of nuclear energy in the last 5 years?
    a) If yes, what outputs were delivered with the financial support received?
11. Does your company deliver large or critical equipment for nuclear power plants (turbines, reactor coolant pumps, valves, heat exchangers, pressure vessels, I&C, containers for spent nuclear fuel etc.)?
12. If yes, how much of these equipment’s would you be able to supply to nuclear power plants in one year?
13. Do you have orders for the mentioned components for the next years?
14. Do you have a reliable supplier of a sufficient amount of raw material and semi-finished products for the production of the mentioned components? If yes, what is the usual delivery period for such materials?
15. What is your raw material base (percentage) (Europe, Asia, United States, Other)?
16. What share of production tools and machine tools for the production of large and critical equipment come from the EU market?

17. Does your company plan to actively participate in nuclear technologies construction (nuclear island)?
18. If you have not yet supplied technologies for nuclear installations, are you interested in supply of components and services for nuclear technologies?
19. What would be the estimated resources (number of employees) necessary for your company to be able to support the development of an intended 100 GW of new capacity by 2050? (Nuclear engineers, R&D engineers, Other engineers, Physicists, Technicians, Welders, Construction workers, Other)
20. How many new university graduates under the age of 30 with have you hired in the last three years? (Less than 2, 2 to 5, 5 to 10, more than 10)
21. To what extent do university graduates meet your requirements for your company´s implementation in the nuclear industry? (fully, largely, somewhat, not at all, don't know)
22. On what kind of skillset should the university/schools mainly focus on?
23. Is there a sufficient number of qualified workers to meet the requirements for your company to succeed in the nuclear industry and expand your activities?
24. Do you currently employ experts for nuclear technologies from outside the EU?
25. Does your company collaborate with the academic sector on components development?
26. Does your company implement specific quality requirements for nuclear energy (e.g. ISO 19443 standard)?
27. If no, do you plan to meet the requirements to obtain the quality certificate for nuclear safety within 3 years?
28. Can your company assure quality requirements of classified equipment for nuclear power plants?
29. By what percentage is your supply chain able to increase its production capacity within the next 5 years?
30. Do your strategic sub-suppliers have production plants in the EU?
31. What percentage of your components for your final product comes from sub-suppliers?
32. What percentage of components for your final product comes from sub-suppliers outside the European area?
33. Is it possible to ensure that your sub-suppliers of raw materials and components are only from the EU?
34. Have you encountered any difficulties to finance the supply of products and services for nuclear technologies?
35. Do financial difficulties (if experienced see previous questions), affect the supply of equipment for nuclear technologies within or outside the EU?

36. Do the difficulties of obtaining financial services for the supply of equipment for nuclear technologies limit you for the further development of the company and production capacities?
37. If possible, does your company want to invest its own funds in the development of technologies for nuclear power installations?
38. Do you consider the investment to the company´s development with the objective to supply technologies for nuclear market as risky?
39. Do you identify the EU nuclear ecosystem as stable?
40. To what extent does European legislation limit the use of sub-suppliers from outside the EU for your production capacity?
41. To what extent does the national legislation limit the use of sub-suppliers from outside the EU for your production capacity?
42. Does national legislation limit labour mobility for participation in projects for nuclear facilities (e.g., a special educational certificate is required that allows experts to work on projects for nuclear technologies)?
43. Does your national legislation limit the participation of foreign companies in projects for nuclear facilities (e.g., the requirement of a certificate or license issued by a national supervisor)

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