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Accompanying the document

Communication from the Commission

Nuclear Illustrative Programme presented under Article 40 of the Euratom Treaty – Final (after the opinion of the EESC)

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1. EXECUTIVE SUMMARY

This Staff Working Document (SWD) accompanies the Communication from the Commission on Nuclear Illustrative Programme (PINC). The SWD is structured as follows.

Section 2 presents an outlook for nuclear energy in the EU until 2050. It aggregates Member States' plans for nuclear energy as declared in their National Energy and Climate Plans (NECPs) and derives the evolution of installed generation capacity from large-scale reactors, as well as the associated investment needs. The section also discusses the role of nuclear energy in the power system, including its potential to support system integration and its ability to address flexibility needs.

Section 3 covers use cases of nuclear energy beyond power generation. Nuclear energy already supports district heating networks today and may further contribute to the decarbonisation of heat in the future. It also has an important role to play for the supply of medical radioisotopes.

Section 4 discusses two supply chains underpinning the use of nuclear energy: The supply chain for nuclear fuel, including reprocessing of spent fuel, and the supply chain for nuclear installations, including decommissioning and waste management. Rolling out Member States' plans to use nuclear energy will require investments in both supply chains.

Section 5 presents two areas of innovation in nuclear energy: small modular reactors (SMRs), including advanced modular reactors (AMRs), and microreactors on the one hand, as well as nuclear fusion on the other hand. Each area of innovation promises potential benefits for further decarbonisation, security of supply, and affordable energy in the future, but requires investments to deliver these.

Section 6 covers enabling functions of the nuclear ecosystem. Independent nuclear safety authorities, endowed with sufficient resources, are an indispensable prerequisite for the use of nuclear energy while guaranteeing the highest safety standards. Ensuring adequate transparency and participation during decision making processes around nuclear energy is key. For Member States' plans to materialise the nuclear workforce will have to replace retiring workers, and transfer skills to the next generation. Finally, international cooperation with third countries allows to foster progress in the peaceful uses of nuclear energy and reduce dependencies throughout the fuel and components value chain through diversification.

Section 7 addresses challenges in the financing of nuclear energy, arising from market incompleteness, hold-up risk, and possibly externalities relating to total system costs. The section provides a brief overview of the existing support measures to address these challenges and how they may be used to re-allocate risks affecting nuclear new-build projects. It stresses the importance of preserving incentives when fine-tuning support instruments.

2. NUCLEAR POWER OUTLOOK

This section covers the role of large-scale civilian nuclear reactors in the electricity system. Sections 2.1.1 and 2.1.2 quantify investment needs by projecting generation capacity until 2050 (1). Sections 2.2.1 and 2.2.2 discuss the role of large-scale reactors in the wider electricity system, focusing on total system costs and their potential to provide flexibility. Section 2.2.3 discusses the need for EU wide coordination.

Further below, Section 3 covers non-power uses, and Section 5.1 covers small modular reactors (SMRs) and advanced modular reactors (AMRs).

2.1. Generation capacity evolution

Analysing global trends in nuclear energy in a report from January 2025, the International Energy Agency (IEA) documented 416 Giga Watt electric capacity (GWe) of installed nuclear generation capacity at the end of 2023. It found that there were 63 nuclear reactors under construction, representing more than 70 Giga Watt (GW) of capacity, which was one of the highest levels seen since 1990. Three quarters of these were in emerging economies and half of them in China alone. Global annual investment in nuclear – encompassing both new plants and lifetime extensions of existing ones – had increased by almost 50% in the three years since 2020, exceeding USD 60 billion. Across the three scenarios the IEA considered for the global capacity evolution, it projected an increase in installed capacity to 650 GWe, 870 GWe, and more than 1,000 GWe by 2050, respectively (2). The IEA's 2050 figures include large-scale reactors and SMRs and AMRs alike.

In the EU, there were 101 nuclear power reactors operating in 12 Member States (3) at the end of 2024. Their combined net electrical generation capacity was 98 GWe. In 2023, they provided 22.8% of the EU's electricity generation. Three nuclear reactors have recently connected to the grid. Two (Olkiluoto 3 in Finland, and Flamanville 3 in France) were the first European Pressurised Water Reactors (EPR) to commence operations in Europe, while Mochovce 3 is a VVER-440 type reactor. One reactor in Slovakia (Mochovce 4) and two others in Hungary (Paks II) are under construction.

The cost of generating electricity from nuclear energy is a recurring theme in the ongoing policy debate around nuclear energy. Nuclear energy exhibits high upfront capital costs and relatively low operating costs, even after accounting for management of radioactive waste and spent fuel and eventual decommissioning of the plant. When authors quantify the levelised cost of electricity (LCOE) of nuclear energy, they generally find comparably high figures driven by the high upfront capital costs for creating a new nuclear power plant. Figure 1 shows the LCOE for various generation technologies in 2023. Nuclear new build exhibits an LCOE of around 150

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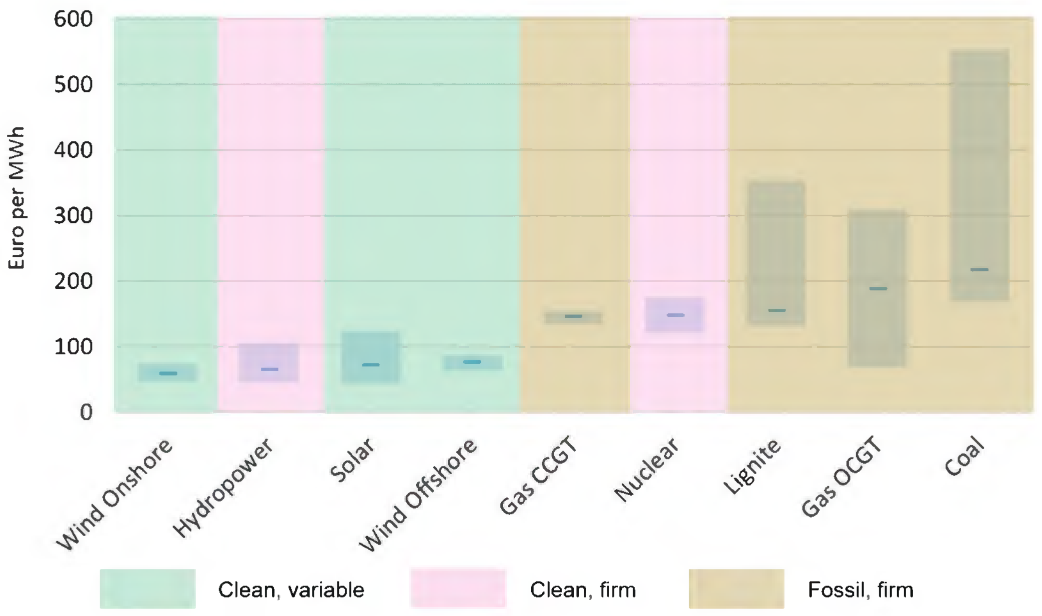
(1) The analysis focusses on the investment needs, i.e. the capital expenditures required to deliver Member States' plans. The attractiveness of the proposed investment projects for potential private project sponsors, as could be quantified through a net present value (NPV) calculation, would at least require modelling the EU's electricity market using a dispatch model. Electricity market modelling is outside of the scope of this Staff Working Document.

(2) IEA (2025), The Path to a New Era for Nuclear Energy, IEA, Paris https://www.iea.org/reports/the-path-to-a-new-era-for-nuclear-energy, Licence: CC BY 4.0.

(3) Belgium, Bulgaria, Czech Republic, Spain, France, Hungary, Netherlands, Romania, Slovenia (Croatia), Slovakia, Finland, and Sweden.

EUR/MWh (4). Out of the nine generation technologies shown, nuclear and hydropower are the only ones providing clean, firm power. Clean, variable sources exhibit lower LCOEs. The LCOE does not account for the costs to integrate a generation source with the electricity system, which may require additional investments in network and storage infrastructure not reflected in the LCOE. Section 2.2 covers power system aspects of nuclear energy.

Figure 1 – Technology-fleet specific levelised costs of electricity (LCOE) for 2023



Source: Report from the Commission to the European Parliament and the Council: Progress on competitiveness of clean energy technologies (COM/2025/74 final), Figure 1, p. 8.

Note: The solid blue lines denote the median and the light blue bars display a ±25% range across the EU, highlighting differences among Member States. Based on JRC METIS model simulation; According to: Gasparella, A., Koolen, D. and Zucker, A., The Merit Order and Price Setting Dynamics in European Electricity Markets, Publications Office of the European Union, 2023. Computation based on annualised costs for the year 2023. Capital Expenditure (Capex) and Operating Expenses (Opex) based on the 2040 climate target PRIMES reference scenario, annualised by technical lifetimes and weighted average cost of capital. Annualised costs are levelised using capacity factors derived from the METIS model. Variable costs are based on 2023 commodity prices, variable Opex and the dispatch in the METIS simulation.

Several Member States have declared plans to extend the operational lifetime of nuclear power plants or to build new ones in alignment with their National Energy and Climate Plans (NECPs) (5). This section quantifies the investment needs resulting from these plans, considering a forecast horizon until 2050. The quantification of investment needs takes two steps: section 2.1.1 projects nuclear generation capacities

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(4) Other sources report different figures for the LCOE of nuclear new build projects, which may reflect different input assumptions. For instance, the IEA reports an LCOE for new build project of 75-110 USD/MWh and significantly lower LCOEs for lifetime extensions. IEA (2025), The Path to a New Era for Nuclear Energy, IEA, Paris https://www.iea.org/reports/the-path-to-a-new-era-for-nuclear-energy, Licence: CC BY 4.0. Figure 2.7, p.53.

(5) Regulation (EU) 2018/1999 of the European Parliament and of the Council of 11 December 2018 on the Governance of the Energy Union and Climate Action, OJ L 328, 21.12.2018, p. 1–77.

for the years 2024 to 2050; section 2.1.2 derives the present value of required capital expenditures to deploy the projected capacity.

2.1.1. *Electricity generation capacities for large-scale nuclear reactors for the years 2024 to 2050*

The investment needs quantification relies on the following key data sources: the IAEA "Power Reactor Information System" (PRIS) (6), the Member States' (draft) updated NECPs (7), and investment projects notified to the Commission under Article 41 of the Euratom Treaty.

NECPs include information on national plans for lifetime extensions of existing plants, and on plans for new builds. The granularity of information varies across NECPs: some countries spell out in detail until what year they expect a given reactor to run, whereas other countries only provide high-level information. Combining (i) the information from PRIS on existing reactors, and (ii) the available information on lifetime extensions and new build plans from NECPs, complementing them with our best estimates where Member States have not yet spelled out their plans in detail, allowed to set a scenario of the evolution of nuclear generation capacities in the EU until 2050 (8).

The section takes a bottom-up approach by developing a 'base case' scenario using the information available in NECPs for each existing reactor or new build project, filling information gaps with best estimates. The 'base case' scenario starts with the existing fleet of nuclear reactors. It considers the ongoing construction projects and adds planned new-build projects as announced in Member States' NECPs. For each reactor, the scenario assumes a service life, based on information from NECPs where available, and best estimates reflecting the reactor model otherwise. Figure 2 shows the evolution of projected capacities in the 'base case' scenario.

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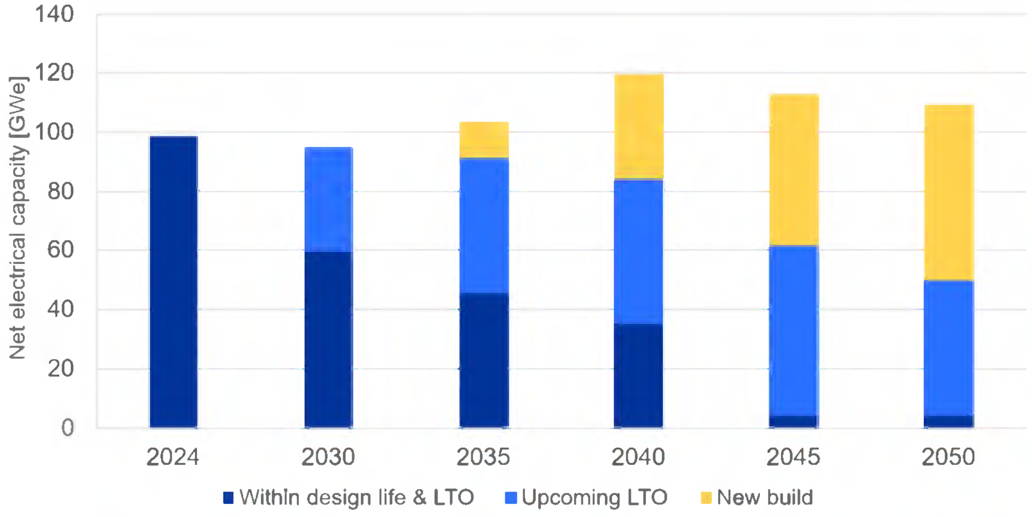
(6) The Power Reactor Information System (PRIS) - Home Page is a database compiled by the International Atomic Energy Agency (IAEA).

(7) The national energy and climate plans (NECPs) were introduced by the Regulation on the governance of the energy union and climate action (EU)2018/1999, agreed as part of the 'Clean energy for all Europeans' package which was adopted in 2019. The national plans outline how the EU countries intend to address the five dimensions of the Energy Union: (i) decarbonisation; (ii) energy efficiency; (iii) energy security; (iv) internal energy market; and (v) research, innovation and competitiveness. Member States were due to submit draft updated NECPs by 30 June 2023, and their final updated NECPs, taking account of the Commission's assessment and recommendations, by 30 June 2024. The projection of future nuclear generation capacities reflects the final updated NECPs for those Member States which have submitted them at the time of writing, and it reflects the draft updated NECPs for the other Member States.

(8) This included information and assumptions on design lives and lifespans of individual plants, the latter based on the information provided in the NECPs.

Figure 2 – 'Base case' scenario of large-scale power generation capacities in the EU, 2024 – 2050



Source: European Commission.

Notes: Section 5.1 treats SMRs separately.

In Figure 2 capacities are broken down into three categories. The first category (in dark blue) shows reactors that exist today and are either within their design life or where the owners have already invested in a LTO programme in the past. The second category (in light blue) shows reactors that exist today, but where new LTO programmes are assumed to come up in 2025 or later. The third category (in yellow) shows planned new build capacities. Without lifetime extensions, all but the most recently added reactors would retire before 2050. Taking the assumed lifetime extensions into account, the installed capacity of existing reactors will decline from c. 98 GWe today to c. 50 GWe in 2050. New build capacity will add c. 60 GWe, leading to c. 109 GWe in 2050. This is an increase by 11% from today's capacity. The installed capacity may reach higher levels in between, if new builds can commence operations early enough. These reactors would provide about 12% of all electricity produced in the EU in 2050.

A sensitivity analysis is here below presented as there is uncertainty around the capacity evolution, arising mainly from two factors: (i) actual achievement of plants' lifetime extension; and (ii) time of delivery of new build projects.

Sensitivity to actual achievement of LTOs

A sensitivity analysis to the 'base case' scenario shows that LTOs have a significant effect on the installed capacity in 2050. Operating plants undergo Periodic Safety Reviews at least every ten years (9). At each review, the Nuclear Safety Regulator decides whether the plant is suitable to continue safe operations or not. For some existing plants, the Nuclear Safety Regulator has already approved a longer license, or the operators have announced plans to request permission to operate beyond 60

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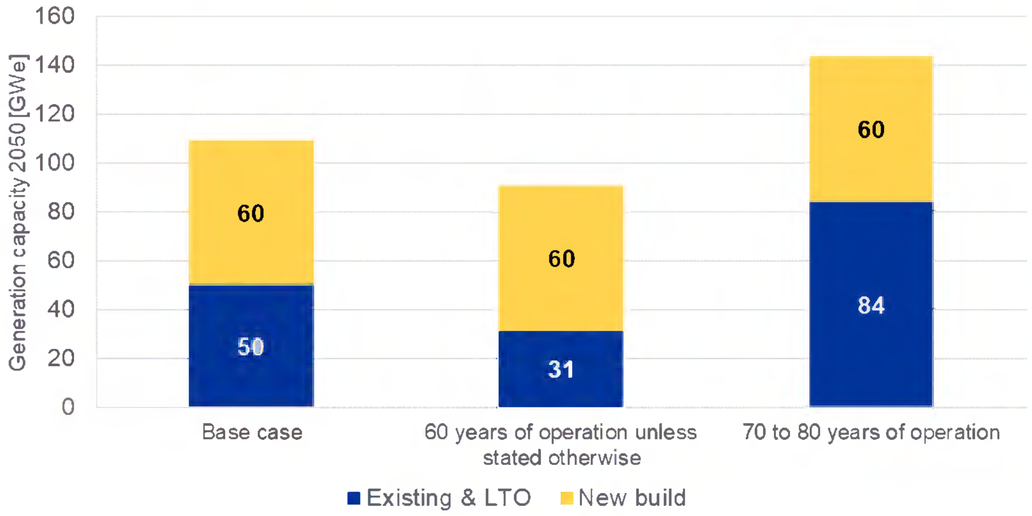
(9) Council Directive 2009/71/Euratom of 25 June 2009 establishing a Community framework for the nuclear safety of nuclear installations, OJ L 172, 2.7.2009, p. 18–22, Article 8c.

years (10). If all other plants stopped their operations after reaching 60 years, Member States' plans for new builds would not suffice to maintain the existing capacity by 2050. Instead, the installed capacity would drop to around 91 GWe, with approximately 31 GWe from existing plants. Alternatively, if all existing plants managed to achieve 70 or even 80 years of operation, the installed capacity could reach up to 144 GWe by 2050, with around 84 GWe from existing plants. Thus, actual achievement of LTOs could shift the 2050 installed capacity by more than 50 GWe. Figure 3 shows sensitivity of the installed capacity by 2050 to the operating life of existing plants. It illustrates that successful LTO programmes are essential to maintaining today's capacity by 2050.

Figure 3 – Sensitivity of 2050 installed large-scale reactor capacity to LTOs



Source: European Commission.

Notes: Section 5.1 treats SMRs separately.

Sensitivity to actual construction time for new builds

The 'base case' scenario considers new build projects to commence commercial operations as announced in Member States' NECPs. A sensitivity analysis to reflect potential delay in new build projects shows that delays can have a significant impact on the installed capacity in 2050. If all announced new build projects experienced a delay of 10 years (11), installed capacity by 2050 could drop to c. 85 GWe, with c. 35 GWe from new build plants. Thus, delays could shift the installed capacity in 2050 by more than 20 GWe. Figure 4 illustrates sensitivity of the installed capacity to a delay in all new build projects. The installed capacity from large-scale reactors by 2050 decreases as the assumed delay to new build projects increases. This underscores the importance of the nuclear industry delivering projects on time.

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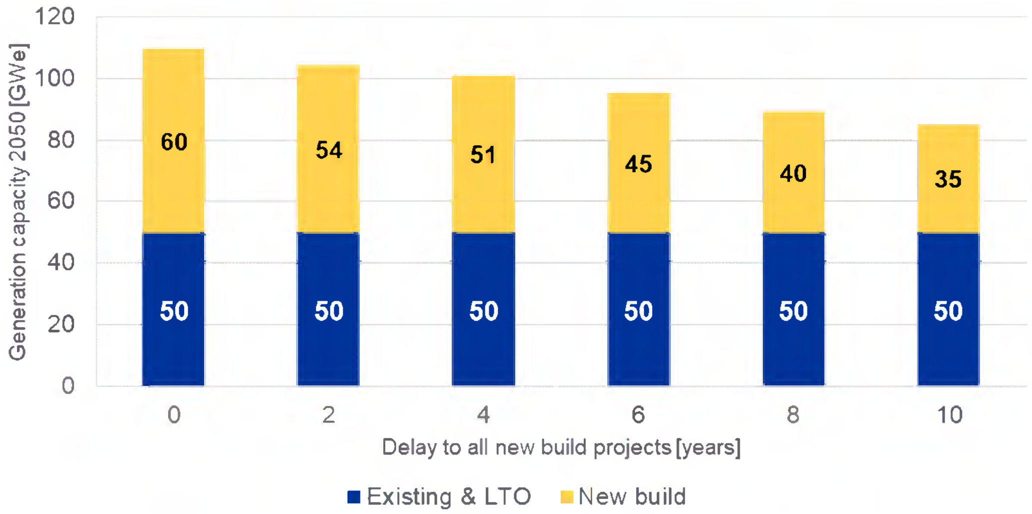
(10) In the 'base case' scenario, 36 out of the 101 existing nuclear power plants operate for more than 60 years.

(11) Two recently completed new build projects in the EU, Flamanville 3 and Olkiluoto 3, experienced delays of more than 10 years. The recently completed Vogtle 3 project in the US experienced 7 years of delay. Since the analysis shows the effect of a delay to all new build projects announced in Member States' NECPs, 10 years may suffice as upper limit for the sensitivity.

Figure 4 – Sensitivity of 2050 installed large-scale reactor capacity to delayed new build

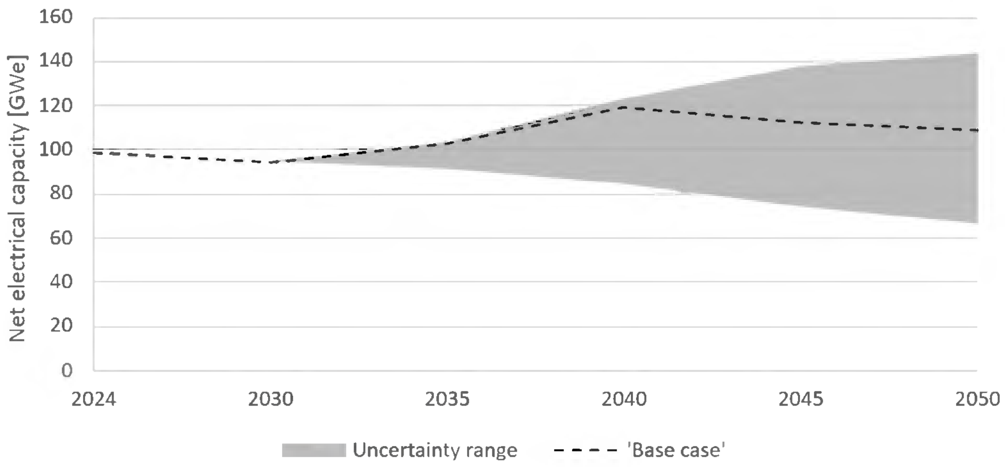


Source: European Commission.

Notes: The 'base case' scenario coincides with no delay. Section 5.1 treats SMRs separately.

In a scenario, where most plants discontinue operations after 60 years of service and where new build projects experience a 10-year delay, the installed capacity could drop to less than 70 GWe by 2050. Thus, the range of uncertainty around the 'base case' scenario covers c. 77 GWe, as Figure 5 illustrates.

Figure 5 – 'Base case' capacity evolution and uncertainty range



Source: European Commission.

Executing Member States' plans requires simultaneously extending plants' operating life beyond 60 years and delivering new build projects on time.

2.1.2. *Present value of required capital expenditures*

The analysis focusses on the investment needs, i.e. the capital expenditures required to deliver the installed capacity in accordance with Member States' plans. Converting the stream of LTOs and new build capacities into a flow of capital expenditures requires assumptions on the unit investment costs for LTOs and for new build plants. The unit investment cost includes two parts:

- The “overnight cost”, which refers to the cost of constructing the plant, including equipment, construction materials, and labour, but excluding interest during construction.

- Interest during construction (IDC), i.e. investors’ opportunity cost of providing capital during the construction period. It depends on the time to build the plant and the discount rate.

The construction period for a new build project stretches over several years. Project developers incur capital expenditures during the entire construction period already. To accommodate this, the ‘base case’ scenario takes assumptions on the overnight costs, the construction period, and the appropriate discount rate to calculate the “present value equivalent” cost figure combining overnight cost and IDC. Present value equivalent means that if project developers incur this one-off cost at the end of the construction period, the present value of this one-off cost is identical to the present value of spreading the overnight costs uniformly over the construction period (12).

Table 1 below summaries the assumptions on the discount rate, construction period and overnight cost for a new build project, and construction period and overnight cost for a lifetime extension in the ‘base case’ scenario.

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(12) Let r denote the discount rate, t the start year of construction, T the construction period in years, and O the overnight construction cost. Then $c = O/T$ is the annual construction cost, assuming a uniform profile. Assuming construction costs occur in the middle of a calendar year, the present value of construction costs is given by $c\sum_{k=t}^{t+T}\left(\frac{1}{1+r}\right)^{k-0.5}$. The analysis considers the ‘present value equivalent costs’, i.e. the hypothetical one-off construction cost X with identical present value: $X\left(\frac{1}{1+r}\right)^{t+T-0.5} = c\sum_{k=t}^{t+T}\left(\frac{1}{1+r}\right)^{k-0.5}$. For $r > 0$, as can be assumed, there is an analytical solution to X. The assumption of uniformly distributed construction costs may overstate the present value costs, as project developers have an incentive to back-load construction capital expenditures where possible within engineering constraints, as this shortens the gap between expenditures and earnings from operations, which in turn increases the value of the project.

Table 1 – Key assumptions for 'base case' scenario

Item	value	unit
Discount rate (weighted average cost of capital)	7.5	% p.a.
Construction period for new build	9	years
Overnight construction cost for new build	8,000	EUR/kWe
Present value equivalent for new build	10,871	EUR/kWe
Construction period for LTO	2	years
Overnight construction cost for LTO	790	EUR/kWe
Present value equivalent for LTO	820	EUR/kWe

Source: Discount rate: European Commission: Directorate-General for Climate Action, Directorate-General for Energy, Directorate-General for Mobility and Transport, De Vita, A., Capros, P. et al., EU reference scenario 2020 – Energy, transport and GHG emissions – Trends to 2050, Publications Office, 2021, https://data.europa.eu/doi/10.2833/35750 , Table 12, p. 169.

Construction periods for new build and LTO, overnight construction cost for new build and LTO: Investment notifications submitted to the Commission pursuant to Art. 41 of the Euratom Treaty and IEA (2020), Projected Costs of Generating Electricity 2020, IEA, Paris https://www.iea.org/reports/projected-costs-of-generating-electricity-2020, Licence: CC BY 4.0.

Notes: Present value equivalents are mathematical functions of the discount rate, construction period, and overnight costs, see footnote (12).
"p.a." means per annum.

The discount rate reflects the weighted average cost of capital (WACC) of the project. The base case assumption of 7.5 % p.a. reflects the EU Reference Scenario 2020 assumption for energy supply investments under contracts for differences. The analysis considers constant construction costs in real terms and the discount rate is also a real discount rate. Pursuant to Article 41 of the Euratom Treaty, investors in the nuclear sector are obliged to notify the Commission of their investment plans under certain conditions (13). The Commission uses the information gathered through these notifications, together with other sources, to inform its cost assumptions. The 'base case' assumptions for the construction period of 9 years and the overnight construction costs for new build of 8,000 EUR/kWe reflect the expectations project developers expressed in recent investment notifications.

For LTOs, the 'base case' assumptions for the construction period of 2 years and for the overnight construction costs of 790 EUR/kWe reflect expectations project developers expressed in recent investment notifications pursuant to Article 41 of the Euratom Treaty (14).

Multiplying the flow of LTOs and new build capacities with the present value equivalents for construction costs generates the cash flow of capital expenditures.

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(13) The Commission received a total 44 investment notifications between January 2018 and February 2025.

(14) The analysis considers a uniform LTO overnight cost case independent of the LTO duration, i.e. whether it is a life-extension for 10 or for 20 years. This reflects that the key cost driver for life extensions are the components that need replacement, not the duration of the life extension. This also becomes evident from investment notifications pursuant to Article 41 of the Euratom Treaty, where the Commission has observed notifications for a life extension for 20 years with a lower unit construction cost than seen in other notifications for a life extension for only 10 years.

Applying the discount rate gives the present value of capital expenditures, i.e. the investment needs. Nuclear capacities anticipated in the 'base case' scenario will require investments of around EUR 241 billion in present value terms ([15]). Lifetime extensions account for EUR 36 billion of those investments. Thus, while the actual achievement of LTOs can have a large impact on the installed capacity by 2050 (see Figure 3 above), they account only for a minor share of investment needs ([16]). New-build large-scale reactors account for EUR 205 billion ([17]).

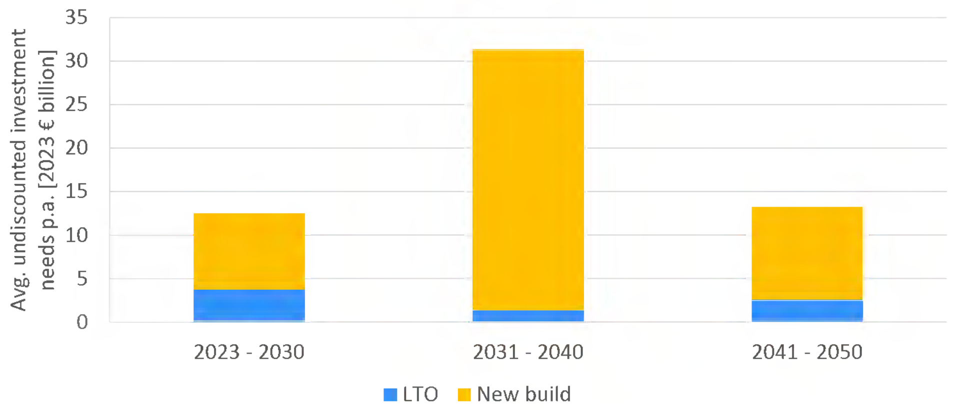
To ease comparison with studies which may report undiscounted investment needs, Figure 6 shows the undiscounted average annual investment needs to deliver the capacities in the 'base case' scenario until 2050. Average annual investment needs peak in the 2030s at more than EUR 30 billion per year. In the 2020s and 2040s, they will be more than EUR 12 billion per year. Investment needs for new-builds dominate throughout. Investment needs for LTOs are highest in the 2020s, at more than EUR 3 billion per year.

([15]) The Commission Staff Working Document accompanying the PINC adopted in 2017 reported a range of EUR 349 to 455 billion for new build and EUR 47 billion for LTOs until 2050. This is significantly higher than the present figures of EUR 205 billion for new build and EUR 36 billion for LTOs. There are multiple factors accounting for this difference: (i) the 2017 figures included new build and LTOs in the UK, which has a significant nuclear programme, but has since left the Union – this reduces investment needs all else equal; (ii) compared to the 2017 projection, the current projection reflects less new build and more LTOs – this reduces investment needs all else equal; (iii) the forecast window shortened from 2015 – 2050 to 2024 – 2050 – this reduces reported investment needs all else equal; (iv) the 2017 figures recognised interest during construction, but they did not reflect a present value, whereas the currently reported figures reflect a present value – this reduces the reported investment needs all else equal; and finally (v) unit cost assumptions increased significantly between 2017 and today – this increases investment needs all else equal. A cross-check of figures addressing (i) and (iv), i.e. correcting for the UK's exit from the Union, and disregarding discounting leads to current figures that are significantly higher than 2017 figures. This result is likely driven by the significant increase in unit costs for new build and LTOs.

([16]) The Commission supports several research projects on extending the operating life of nuclear power plants, possibly up to 100 years. Examples include, but are not necessarily limited to: STRUMAT-LTO (Structural Materials for LTO), DELISA- LTO (LTO VVER Ageing components), FIND (LTO ISIR AGE Structural Health piping).

([17]) An attempt to quantify the monetary investment needs for the deployment of SMRs, AMRs, and microreactors is outside the scope of this Staff Working Document, because there is more uncertainty around the costs for these innovative reactor types than there is for large-scale reactors.

Figure 6 – Undiscounted annual investment needs, 2023 – 2050



Source: European Commission

As for the capacity scenario, there is also uncertainty around the key assumptions for investments. A sensitivity analysis to discount rates, actual construction time for new builds, and overnight costs follows.

Sensitivity to discount rates

If the discount rate increases, future capital expenditures get discounted stronger and the investment needs decrease in present value terms. However, it is important to keep in mind the analysis of investment needs in this section considers capital expenditures in isolation, whereas project developers consider and discount all cash flows associated with a candidate investment project. This includes capital expenditures for construction, but also earnings from operations, and decommissioning costs. As earnings necessarily arrive after construction expenditures, a lower discount rate increases the value of a candidate project to the investor, all else equal. Policymakers aiming to stimulate private sector investments in nuclear energy should aim at improving the risk allocation between stakeholders with a view to reduce the appropriate discount rate (see Section 7). Figure 7 shows sensitivity of investment needs to the discount rate (18).

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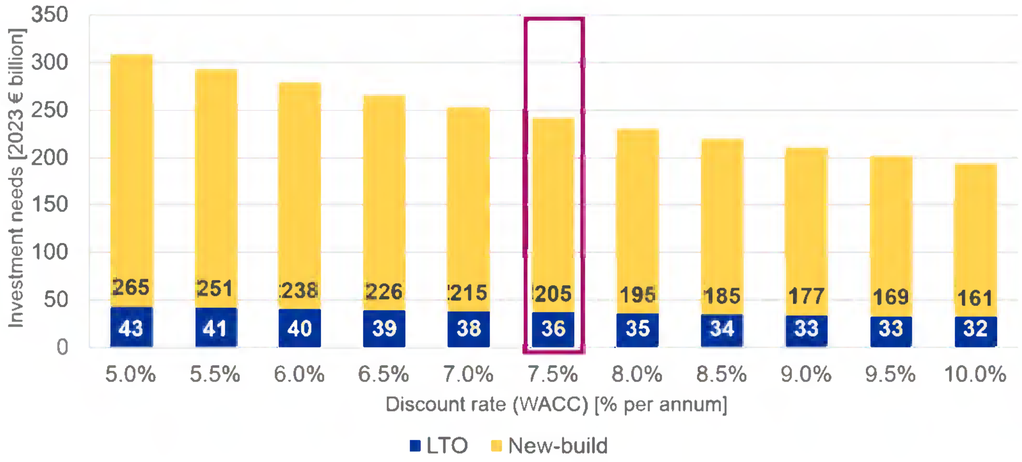
(18) The analysis assumes constant overnight construction costs in real terms until 2050. The sensitivity to the discount rate can simultaneously be interpreted as a sensitivity to the assumption of constant real overnight construction costs: The 'base case' discount rate r is 7.5%. If one wanted to assume that real construction costs decrease by a rate of $g = 0.5\%$ per annum, the annual discount factor would be $\frac{1-g}{1+r} = \frac{0.995}{1.075} \approx 0.926 \approx \frac{1}{1+8\%}$ Thus, the 8.0% discount rate sensitivity can also be interpreted as the 'base case' discount rate of 7.5% and an annual reduction of real overnight construction costs of 0.5%. Generally, higher discount rate sensitivities can be interpreted as 'base case' discount rate and decreasing real overnight construction costs, and lower discount rate sensitivities as 'base case' discount rate and increasing real overnight construction costs.

Figure 7 – Investment needs for large-scale reactors until 2050 for a range of discount rates between 5% and 10%



Source: European Commission.

Notes: 'Base case' scenario highlighted in red rectangle.
Investment needs cover capital expenditures only and therefore decrease with the discount rate. However, project developers consider all subsequent cash flows, including earnings from operations and decommissioning costs. When incentivising private sector investment in nuclear energy, policymakers should aim at lowering discount rates through improving the risk allocation between stakeholders.

Sensitivity to actual construction time for new builds

The success of new-build construction projects is an important driver for investment needs. If new-build projects get delayed by 5 years, and constructions costs increase proportionally with construction time, installed capacity in 2050 decreases by almost 9 GWe, while the required investments increase by more than EUR 45 billion, i.e. society has to spend more for less capacity. The sensitivity analysis to delays shows that capacity added until 2050 can decrease significantly, while investment needs until 2050 stay in the same ballpark range and may even increase. This underlines again the importance for the nuclear industry to deliver new build projects on time and within budget. Figure 8 below shows sensitivity of investment needs to the construction period for new build projects (19).

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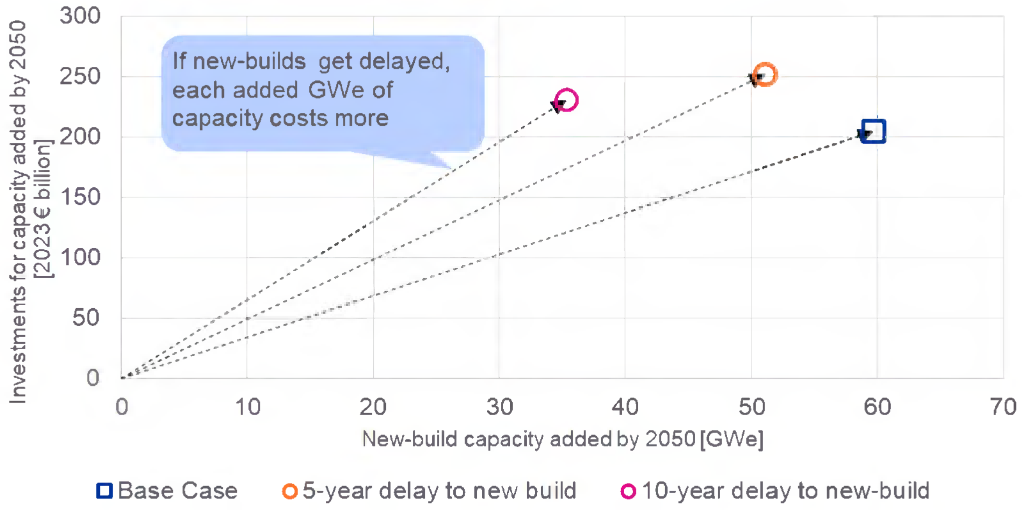
(19) The analysis does not consider a sensitivity to the construction time for LTOs, as their construction time is generally short relative to the construction time for new builds, and reasonable sensitivities to LTO construction time would only have a minor impact on investment needs.

Figure 8 – Investment needs for new build capacity until 2050 for delayed new-build deployment scenarios

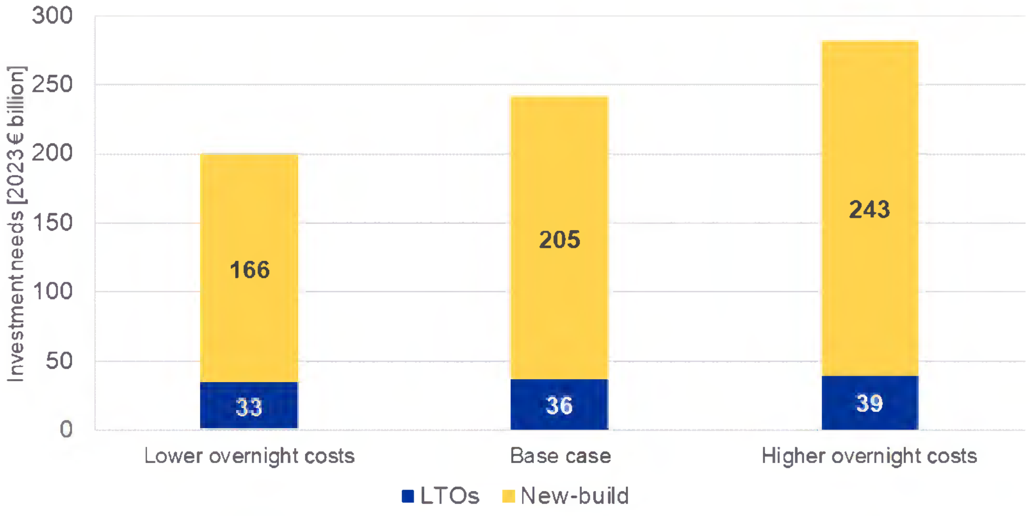


Source: European Commission.

Sensitivity to overnight cost assumptions

Next to the 'base case' scenario, the figure presents two alternative cost scenarios, one with lower overnight constructions costs for LTOs and new build, one with higher costs. These alternative cost assumptions reflect the lower and higher parts of the cost range investors have reported to the Commission in recent years pursuant to Article 41 of the Euratom Treaty. Investment needs range between EUR 199 billion to EUR 282 billion. This wide range further reinforces the importance for the industry to strive for cost reductions and to avoid overruns. Figure 9 shows sensitivity to overnight cost assumptions.

Figure 9 – Investment needs for new build capacity until 2050 across different overnight cost scenarios



Source: European Commission.

Notes: In the 'lower overnight costs' scenario, new builds cost 6,500 €/kWe and LTOs cost 720 €/kWe, in the 'base case' scenario they cost 8,000 €/kWe and 790 €/kWe, and in the 'higher overnight costs' scenario, they cost 9,500 €/kWe and 850 €/kWe, respectively.

2.2. Power system effects

Nuclear energy provides clean, reliable and flexible power. It is flexible in the sense that a nuclear power plant's output can respond to market signals.

Section 2.2.1 covers nuclear energy from a total system perspective. When considering the cost-optimal energy mix for reaching decarbonisation, security and stability of supply, and industrial policy objectives while ensuring affordable energy for households and industry, Member States must consider market uncertainty and total costs. Member States with an existing nuclear fleet may conclude that lifetime extension of current nuclear reactors can be economically attractive, as part of the overall power generation portfolio. The cost-effectiveness of new build nuclear power is more uncertain and depends on the Member State's and EU power portfolio, its interconnectivity, and available flexibility.

Section 2.2.2 considers nuclear energy's potential to provide flexibility to the electricity system. As a dispatchable power source, nuclear energy contributes to balancing demand and supply, in particular at longer timescales such as weekly and monthly. This way, nuclear energy may facilitate further deployment of renewables, the phase-out of fossil generation assets, and it may contribute to dampening short-term price volatility ([20]).

In addition, section 2.2.3 reflects on needs for EU-wide coordination.

2.2.1. System integration

A common set of challenges arises linked to the rapid decarbonisation and electrification of the economy, economy combined with an increased decentralisation of production, such as grid and system integration, flexibility, storage, and congestion management. These issues will impact the overall system associated with the decarbonisation, and significant investments are needed in networks and flexibility to accommodate an efficient integration in power systems.

Nuclear energy comes at high upfront capital costs. However, deploying nuclear energy may allow for savings in the system elsewhere, i.e. through lower investment needs for transmission, distribution, and storage infrastructure. Integrating nuclear energy may provide complementary means for flexible and decarbonised generation, enabling system integration, as studies have shown for the EU ([21]) and for France specifically ([22]). Power system integration, technological progress, speed of deployment, and costs improvements along the deployment of different clean technologies will determine the relative competitiveness of nuclear energy.

An illustration is shown in Figure 10, from a study on the Polish case of power system expansion ([23]). The study's base scenario considers introducing nuclear energy to the Polish power system. The study compares the resulting total system costs in the base

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([20]) Nuclear energy may contribute to frequency control. However, this aspect is outside of the scope of this section's analysis.

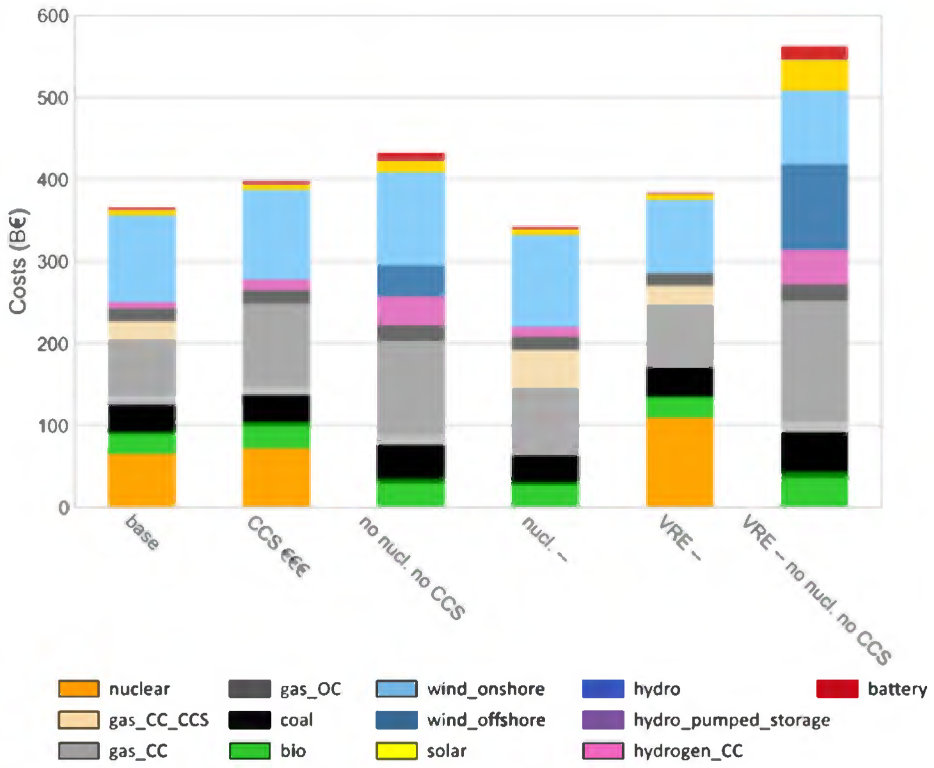
([21]) Compass Lexecon Report, 2024. Pathways to 2050 - the role of nuclear in a low-carbon Europe.

([22]) RTE, 2021. Futurs énergétiques 2050 – Energy Pathways to 2050.

([23]) Quantified Carbon for Clean Air Task Force, 2023. Power System Expansion Poland.

scenario with several alternative scenarios (24). Scenarios including nuclear deployment are generally at the lower end of the total system cost distribution. However, the least-cost scenario is one without nuclear deployment. In this scenario, the Polish energy system relies more on imports and experiences higher electricity prices than in the base scenario (25).

Figure 10 – Total cumulative system costs for 2030 to 2050 in selected scenarios in Poland, by technology



Source: Quantified Carbon for Clean Air Task Force, 2023. Power System Expansion Poland, Figure 26, p. 64, cf. footnote (20)

Notes: CC = combined cycle; CCS = carbon capture and storage; OC = open cycle; VRE = variable renewable energy.

Figure 11 shows findings from a study by the French electricity transmission system operator RTE of the potential evolution of the French electricity system until 2060. RTE's "*study concludes with a fair degree of confidence that the scenarios that include a nuclear fleet of at least 40 GW (N2 and N03) may, over the long term, result in lower costs for society than one based on 100% renewables and large energy farms. This is true even if "gross" production costs are higher on average for new nuclear plants than for large renewable energy farms. Indeed, the integration of large quantities of wind turbines or solar panels creates a very significant need for flexible resources (storage, demand side management and new backup plants) to offset their variability, as well as for grid strengthening (connection, transmission and*

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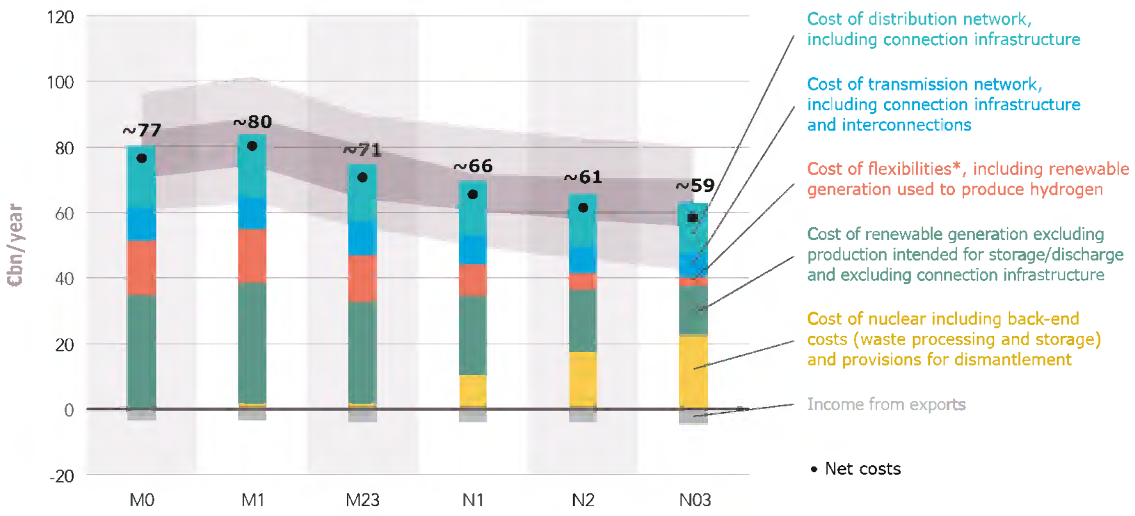
(24) See Quantified Carbon for Clean Air Task Force, 2023. Power System Expansion Poland, pp.15-16 for scenario descriptions.

(25) Quantified Carbon for Clean Air Task Force, 2023. Power System Expansion Poland, pp.64-65

distribution). Once all these costs are factored in, the scenarios that include new nuclear reactors appear more competitive.” (26)

Figure 11 – Annualised full costs in France per scenario in 2060



Source: RTE, 2021. Futurs énergétiques 2050 – Energy Pathways to 2050, p. 31.

Notes: The scenarios N2 and N03 include a nuclear fleet of at least 40 GW.

2.2.2. *Flexibility*

One important factor contributing to lower power system costs is the increase of flexibility and storage solutions. In the EU, flexibility requirements are expected to increase across all timescales (daily, weekly, and seasonal), with flexibility needs estimated to equal 30% of total electrical EU demand in 2050, up from 24% in 2030 and 11% in 2021 (27). A range of solutions, such as interconnectors, storage (mostly batteries), dispatchable generation, and demand-side flexibility may supply flexibility.

In principle, the economics of nuclear power investments favour the use for baseload generation. Nevertheless, in the EU, nuclear power plants often allow for load following (28) (29). Indeed, according to the current version of the European Utility Requirements (EUR) (30) nuclear power plants must be capable of daily load cycling operation, from 100% nominal power (Pr) down to the minimum operating level of

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(26) RTE, 2021. Futurs énergétiques 2050 – Energy Pathways to 2050, p. 30.

(27) Koolen, D., De Felice, M. and Busch, S., 2023. Flexibility requirements and the role of storage in future European power systems, JRC130519.

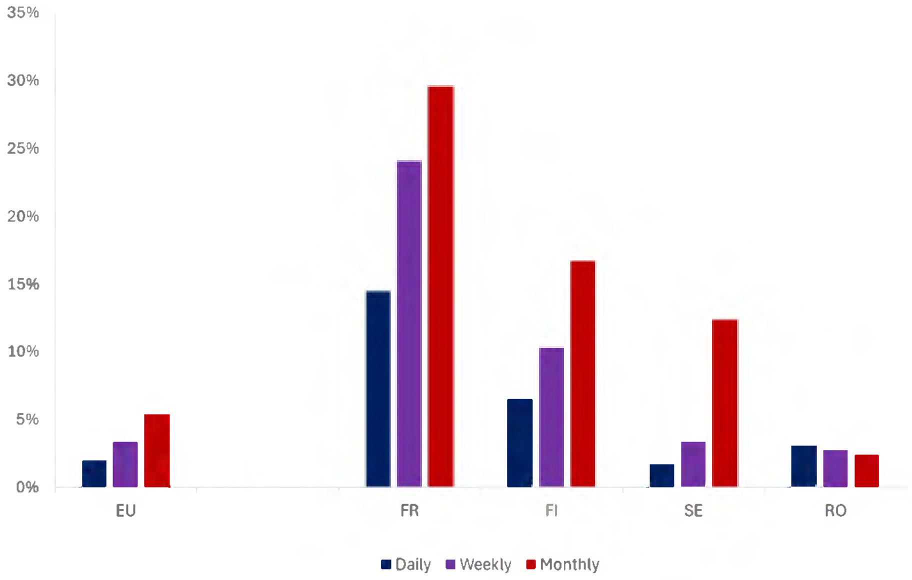
(28) Non-Baseload Operation in Nuclear Power Plants, IAEA Nuclear Energy Series No. NP-T-3.23, © IAEA, 2018.

(29) Grünwald et Caviezel, 2017. Lastfolgefähigkeit Deutscher Kernkraftwerke, Büro für Technikfolgen-Abschätzung des deutschen Bundestags (TAB).

(30) European Utility Requirements, Document REV E Volume 2 – Chapter 2 – performance requirement section 2.2.

the Unit (31), with a rate of change of electric output of 3-5 % of Pr/min (32). Moreover, they provide frequency control services to the transmission grid operator (33). To quantify the potential flexibility contribution of nuclear, the METIS power system model is applied here, modelling flexibility needs in energy volume in the year 2030. Figure 12 indicates that in Member States with a significant amount of nuclear capacity installed, nuclear energy will play a considerable role in providing flexibility. While the exact importance of nuclear depends on the availability and cost of other flexibility solutions in the system, nuclear may primarily address the weekly flexibility needs, for instance in view of adapting to meteorological forecasts and longer-term monthly flexibility needs, as these are costly to address by current clean storage and flexibility solutions such as batteries and demand side response.

Figure 12 – Contribution of nuclear energy to daily, weekly and monthly flexibility needs in energy volume in the EU and selected Member States in 2030



Source: Commission analysis based on METIS energy model.

Notes: The methodology is further explained in Koolen, D., De Felice, M. and Busch, S., 2023. Flexibility requirements and the role of storage in future European power systems, JRC130519. It follows a generalised approach of the proposed methodology for estimating "RES integration needs", as submitted by the European Network of Transmission System Operators for Electricity (ENTSO-E) and the European Distribution System Operators Entity (EU DSO Entity) to ACER, looking at both positive and negative needs.

Already today, nuclear reactors provide considerable flexible capacity. As shown in Figure 13, the French nuclear electricity generation fleet provides for modulation on

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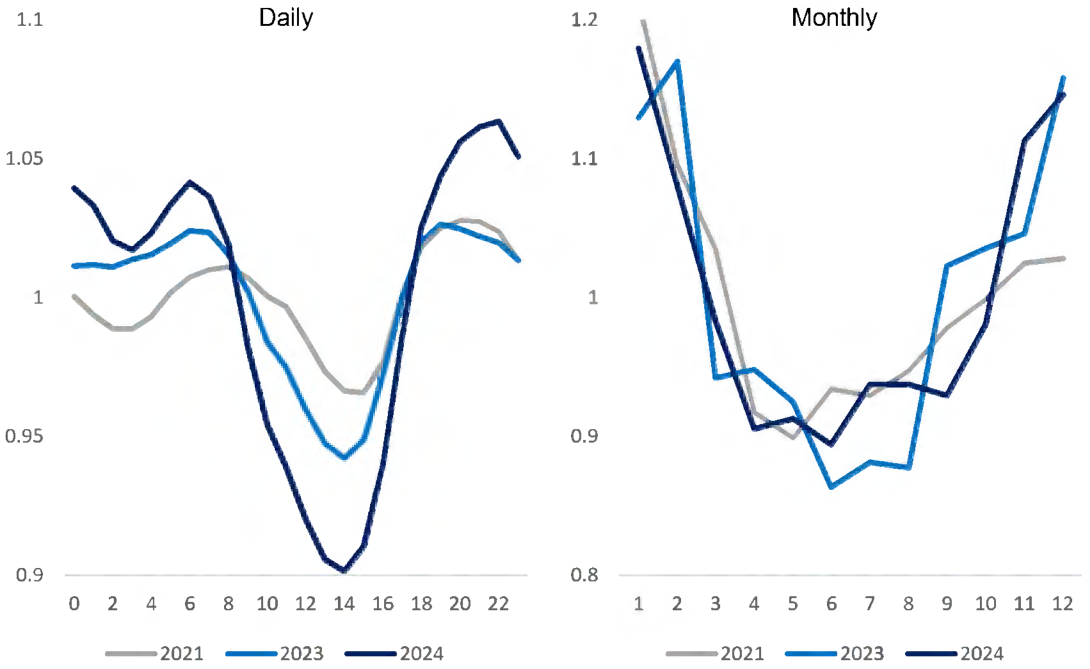
(31) Light water reactors are capable of continuous operation between 50% and 100% of their rated power Pr. Some designs can be operated at a lower ratio of the rated power (typically down to 20%) during certain phases of the fuel irradiation cycle.

(32) The Unit* should be capable to go through the following number of load scheduled variations, each variation being defined as a transient from full power to minimum load and back to full power: (a) 2 per day; (b) 5 per week; and (c) cumulatively 200 per year.

(33) Sustainable Nuclear Energy Technology Platform, 2020. Load following capabilities of Nuclear Power Plants. Nuclear Energy Factsheets.

the short and long-term timescale (34). The French nuclear fleet's contribution to flexibility at the daily timescale has increased in recent years. Factors such as relatively low demand, strong hydro and ample solar generation (incl. from neighbouring countries) caused a strong modulation of the nuclear fleet in 2024 (35). The French transmission system operator RTE estimates that there is a clear inverse correlation between the degree to which France will need additional flexible capacity in the future and the share of nuclear energy generation in the system (36).

Figure 13 – Normalised nuclear electricity generation in France, daily (left) and monthly (right) timescale



Source: Commission analysis based on ENTSO-E.

Notes: 2022 excluded due to exceptional outages.

Finally, the integration of nuclear capacity may provide benefits in terms of price volatility. While the effect of nuclear power on energy spot prices may be relatively limited, as nuclear energy is seldom the marginal producer setting the price, there is a correlation between decreased supply and increased demand pushing up energy prices.

2.2.3. *Need for EU-wide coordination*

Deploying nuclear energy can reduce total system costs domestically, as RTE's analyses show for France (section 2.2.1), but there can also be cross-border effects. Figure 14 below groups EU Member States into four categories: nuclear versus non-

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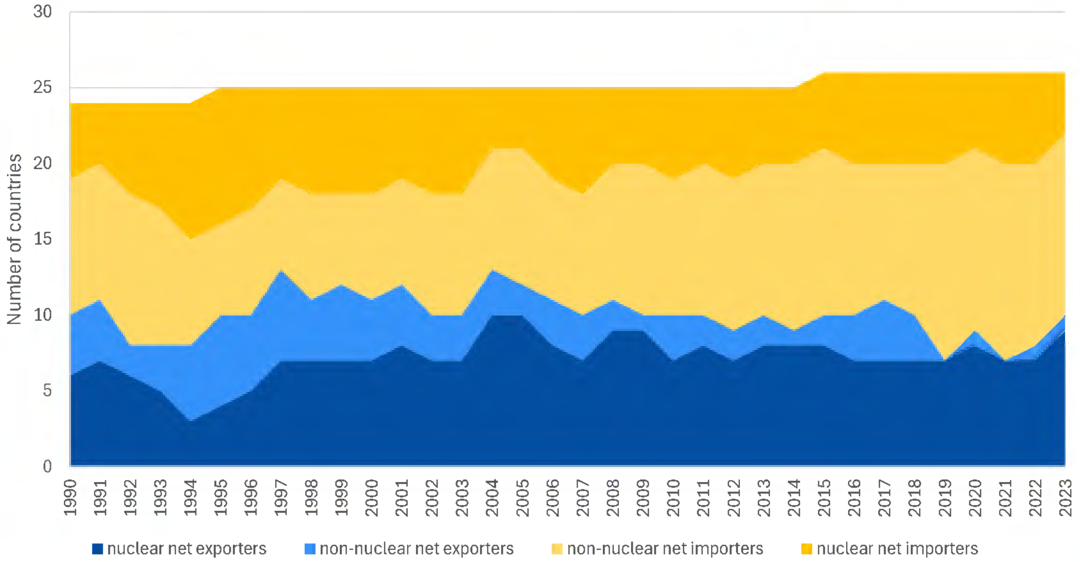
(34) P. Morilhat et al., 2019. Nuclear Power Plant flexibility at EDF, HAL open science. The study notes that French nuclear power plants (PWR 900 and 1,300) use "grey" control rods, which are specially adapted for plant flexibility. Whereas most nuclear reactors are still fitted with standard "black" control rods, "grey" control rods are designed to have lower neutron absorption, allowing adjustment to local power patterns.

(35) For example, average daily ramping capacity of the nuclear French fleet was around 4 GW in July 2024, mainly corresponding to an increase in solar generation (based on ENTSO-E).

(36) RTE, 2021. Futurs énergétiques 2050 – Energy Pathways to 2050.

nuclear Member States and net exporters versus net importers. Among the net exporters the nuclear countries outnumber the non-nuclear ones almost consistently, in particular in recent years. Among the net importers, the non-nuclear countries outnumber the nuclear ones. While a more granular analysis of electricity trade flows may provide further insights, the fact that net exporters are predominantly nuclear countries suggests that deploying nuclear energy may contribute to system integration in adjacent countries, and possibly yield further system benefits there, too.

Figure 14 – Net exporters and importers of electricity, 1990 – 2023



Source: European Commission analysis based on Eurostat data.

Notes: The figure considers all 27 EU Member States; however, Ireland was not trading electricity before 1995, and Malta not before 2015. Cyprus is not yet connected to the European mainland. The figure considers the electricity trade balance with all interconnected markets, including non-EU Member States. In a given calendar year, a country is classified as “nuclear” if there is installed nuclear power generation capacity. The net exporters are blue, the net importers yellow. The nuclear countries are the darker shades at the edges (top and bottom), the non-nuclear countries are the lighter shades in the middle.

Cross-border effects on total system costs call for EU-wide coordination of the further development of the European energy system with a view to keep total system costs as low as possible, while achieving decarbonisation and energy security.

3. BEYOND ELECTRICITY GENERATION

The role of nuclear technology extends beyond pure electricity generation, both for energy supply and non-energy day-to-day applications. In the energy system, nuclear energy plays a role in providing heat to households and to the industry – this is developed in section 3.1. In the medical field, nuclear technology is indispensable for diagnostics and treatments – this is developed in section 3.2 with a focus on radioisotopes.

Furthermore, there exist concepts for innovative spacecraft propulsion systems using nuclear energy. The European Space Agency (ESA) commissioned a project, which aims to harness the potential of Nuclear Electric Propulsion for space missions with a view to strengthen European autonomy in this sector (37). The anticipated benefits of nuclear propulsion systems include a much faster travel speed, which will allow humanity to explore deeper into space.

3.1. Heat supply

3.1.1. Present and future role of nuclear in the energy system

The transition to a green-house gas (GHG) neutral economy by 2050 is characterised by a shift away from carbon-intensive technologies and a significant electrification of key demand sectors (38). In the EU, the share of electricity in final energy demand is projected to increase from currently 22% to 57% in 2050 (39). The total electricity generation is projected to more than double over the same time (40). The existing nuclear fleet as well as new projected investments, both on EU level and globally aim predominantly at supplying electricity (41). Yet, nuclear energy-based solutions providing heat to end users in the industry and household sectors already exist today (42) (43).

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(37) Concepts for nuclear energy-based spacecraft propulsion systems may include fission or fusion technology (cf. Section 5.2). As part of the ESA-commissioned “RocketRoll”-project, a consortium led by Tractebel that includes the French Alternative Energies and Atomic Energy Commission (CEA), ArianeGroup, Airbus and Frazer Nash defined a comprehensive technology roadmap to equip Europe with advanced propulsion systems capable of undertaking long-duration missions, including manned expeditions to Mars. Several start-ups explore the spacecraft propulsion use case for fusion energy, see CNN (April 3, 2025): Nuclear-powered rocket concept could cut journey time to Mars in half.

(38) Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: Securing our future. Europe’s 2040 climate target and path to climate neutrality by 2050 building a sustainable, just and prosperous society, COM(2024) 63 final.

(39) SWD(2024) 63, Figure 32

(40) SWD(2024) 61, Figure 19

(41) IEA (2024), World Energy Outlook 2024, IEA, Paris, World Energy Outlook 2024.

(42) NEA (2022). Beyond Electricity: The Economics of Nuclear Cogeneration, NEA Report No. 7363, Paris.

(43) Leurent et al. 2017. Driving forces and obstacles to nuclear cogeneration in Europe: Lessons learnt from Finland, Energy Policy, Vol. 107, pp. 138–150.

3.1.2. Nuclear heat use cases

The European Industrial Alliance on SMRs aims at decarbonising sectors with hard-to-abate emissions ([44]). This includes heat for industry and households, delivered though heat networks or in the form of hydrogen, cf. also section 5.1.

Many industrial processes rely on the availability of high temperature heat which today is largely generated from fossil fuels. The demand for industrial process heat in the EU is around 1900 TWh (see Figure 15), of which 960 TWh on temperature levels of 500°C – 1000°C ([45]) ([46]) ([47]). Options exist to directly electrify most industrial heat applications except for steel production from iron ore, which could make use of hydrogen as a chemical reduction agent. In line with the projected electrification of demand sectors, studies see the demand of high temperature heat dropping by 40% to about 620 TWh in 2050. Hydrogen will be key for decarbonising this remaining demand for high temperature heat and feedstock in industry with a total production projected to reach 2000 TWh in 2050 ([48]). In the considered scenario, about 40% of the hydrogen produced in 2050 will be further transformed into renewable fuels of non-biological origin. About 11% (213 TWh) of the hydrogen produced would be used in industry.

([44]) European Industrial Alliance on Small Modular Reactors – European Commission.

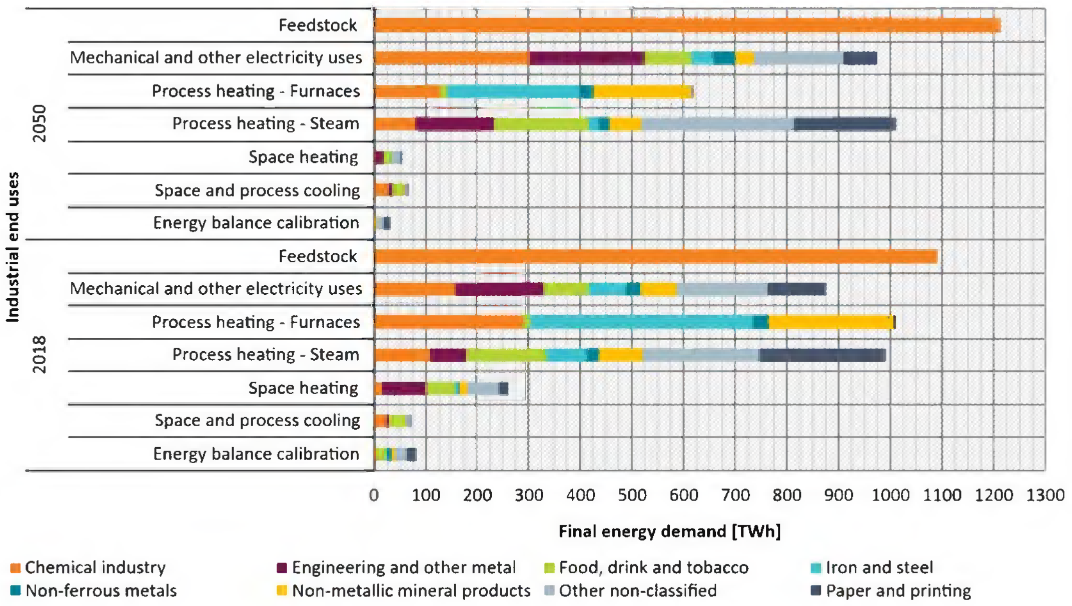
([45]) Agora, 2024. Direct electrification of industrial process heat.

([46]) Rehfeldt et al., 2018. A bottom-up estimation of the heating and cooling demand in European industry, Energy Efficiency 11, pp. 1057–1082.

([47]) European Commission, 2023. METIS 3, Study S5, The impact of industry transition on a CO_2-neutral European energy system.

([48]) SWD (2024) 63, Figure 31.

Figure 15 – Projected total energy demand in industry in 2018 and 2050 by end-use (EU27+UK, 2018 and 2050)



Source: METIS 3 project description.

Notes: Feedstock = energy carriers used as raw materials in the chemical industry.

Use cases for nuclear heat can be categorised by the temperature level of the heat provided. Heat from nuclear power plants has already been used or considered for district heating, the chemical industry or water desalination (49) (50). Nuclear designs capable of producing high temperature heat could be deployed in the chemical industry or to produce hydrogen via high-temperature electrolysis (51), reducing both the electricity and the overall energy requirements of the process as compared to low-temperature electrolysis of water. Specifically designed nuclear cogeneration plants could provide both heat and electricity for industrial sites. Optimising the utilisation of both electricity and heat to produce different shares of hydrogen and electricity or by storing high temperature heat in molten salt could allow running a fleet of high temperature reactors at high load factors in a system largely based on renewable sources (52).

Reactor concepts capable of providing high temperature heat already exist (53) and have been demonstrated. The potential rollout of a fleet of advanced reactors to supply high temperature heat for certain industrial sectors or low temperature heat for industry or district heating is addressed in section 5.1. How much of this potential could materialise will depend on the relative competitiveness, government support,

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(49) Nuclear-Renewable Hybrid Energy Systems, Nuclear Energy Series, NR-T-1.24, © IAEA, 2023.

(50) Small Modular Reactors, Advances in SMR Developments, IAEA International Conference on Small Modular Reactors and their Applications, 21-25 October 2024, IAEA, Vienna, Austria.

(51) Industrial Applications of Nuclear Energy, Nuclear Energy Series No. NP-T-4.3, © IAEA, 2017.

(52) Matthews et al. 2024, The Road to Net Zero, Renewables and Nuclear Working Together, Manchester University Dalton Institute

(53) HTGR development in JAEA: HTTR, accessed on 16 March 2025.

location of heat supply and demand, and the availability of other competing technologies to generate electricity and hydrogen. In this context, several research projects on nuclear heating and cogeneration have been supported through the Euratom Research and Training Programme (54).

3.2. Radioisotopes

Radioisotopes, as well as stable isotopes (55), play an important role in various industrial applications and in healthcare.

3.2.1. The use of medical radioisotopes

Radioisotopes are indispensable for diagnosis of cancer, cardiac, pulmonary, neurological and other diseases, and are increasingly important for cancer therapy. It is therefore important to strategically secure long-term supply of medical radioisotopes in the EU, maintaining the sectoral EU competitiveness and ensuring patients' access to vital medical procedures.

In 2021, cancer was the second leading cause of death in the EU, with 1.1 million deaths, which equated to 21.6 % of the total number of deaths in the EU (56). In Europe, the economic burden of cancer is estimated at EUR 100 billion, and without decisive action cancer cases are expected to increase by 19% until 2040 and cancer deaths by 27% (57).

In the EU, more than 1,500 nuclear medicine centers perform about 10 million procedures each year, with about 100 different radioisotopes (58). Diagnostic imaging is most of these procedures (59). However, the strong increase in the therapeutic procedures observed in the past few years is expected to continue in the coming years (60). Moreover, modern targeted therapies (also known as 'radioligand therapy') are particularly intended for refractory cancer where patients do not respond to other treatments and can be combined with a nuclear diagnostic test in a novel 'theranostics' approach. Figure 16 shows that the number of eligible patients for radiopharmaceutical/radioligand therapies in the EU-27 trends to triple in the next decade (around 130,000 in 2025 against 400,000 in 2035).

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(54) TANDEM (Small Modular ReacTor for a European sAfe aNd Decarbonized Energy Mix), SANE (Safety Assessment of Non-Electric Uses of Nuclear Energy), and EASI-SMR (Ensuring Assessment of Safety Innovations for Small Modular Reactors).

(55) A radioisotope is an unstable form of a chemical element which emits radiation until it reaches a stable status (stable isotope).

(56) A cancer plan for Europe; Cancer statistics - Statistics Explained - Eurostat

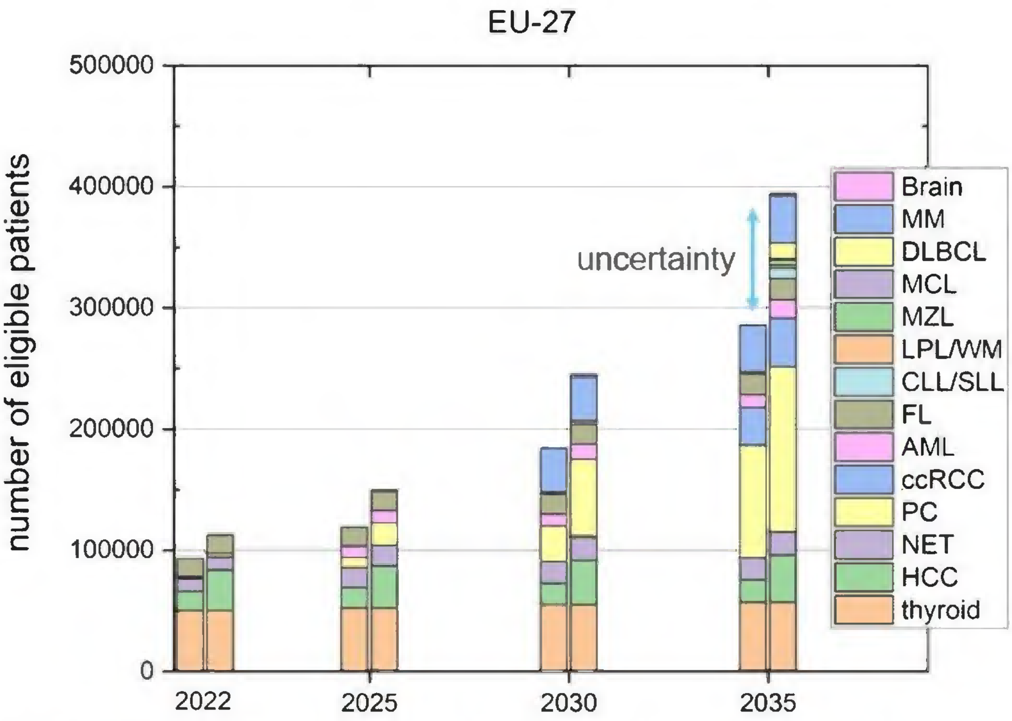
(57) ECIS - European Cancer Information System

(58) European Commission: Joint Research Centre, Mario, N., Kolmayer, A., Turquet, G., Goulart De Medeiros, M. et al., Study on sustainable and resilient supply of medical radioisotopes in the EU, Goulart De Medeiros, M.(editor) and Joerger, A.(editor), Publications Office of the European Union, 2022, https://data.europa.eu/doi/10.2760/911131

(59) MedRaysIntell, Nuclear Medicine Report & Directory Edition 2024

(60) As shown in Figure 16, the number of patients eligible for radioligand therapy is expected to triple from 2022 to 2035. Source: JRC own research (not published), reproduced with permission of the author

Figure 16 – Estimated evolution of the number of eligible patients for radiopharmaceutical / radioligand therapies in the EU-27 until 2035 by cancer type



HCC = hepatocellular carcinoma, NET = neuroendocrine tumours, PC = prostate cancer, ccRCC = clear cell renal cell carcinoma, AML = Acute Myeloid Leukaemia, FL = follicular lymphoma, CLL/SLL = Chronic lymphocytic leukaemia/Small lymphocytic lymphoma, LPL/WM =Lymphoplasmacytic lymphoma/ Waldenström Macroglobulinemia, MZL =Marginal zone lymphoma, MCL =Mantle cell lymphoma, DLBCL = Diffuse large B-cell lymphoma, MM = Multiple myeloma

Source: JRC own research (not published), reproduced with permission of the author.

Notes: For each year, the left columns present the lower and the right columns the upper estimate.

3.2.2. The global radioisotopes market and supply chain

Radioisotopes are mainly produced by irradiation in research reactors, where target material is bombarded with particles such as neutrons or protons, then chemically processed into the required chemical form. As shown in Figure 17 below, Europe is a global leader in that market, consistently providing more than 65% of the global irradiation services (61), with strong export position. The main European producers of radioisotopes for the global market are research reactors and associated facilities located in the Netherlands, Belgium, Poland, and Czechia.

Radioisotopes are also produced for local use – utilising smaller research reactors, particle accelerators and medical cyclotrons – in most EU Member States. Production in nuclear power reactors has started in Canada and is also being considered in the EU (62).

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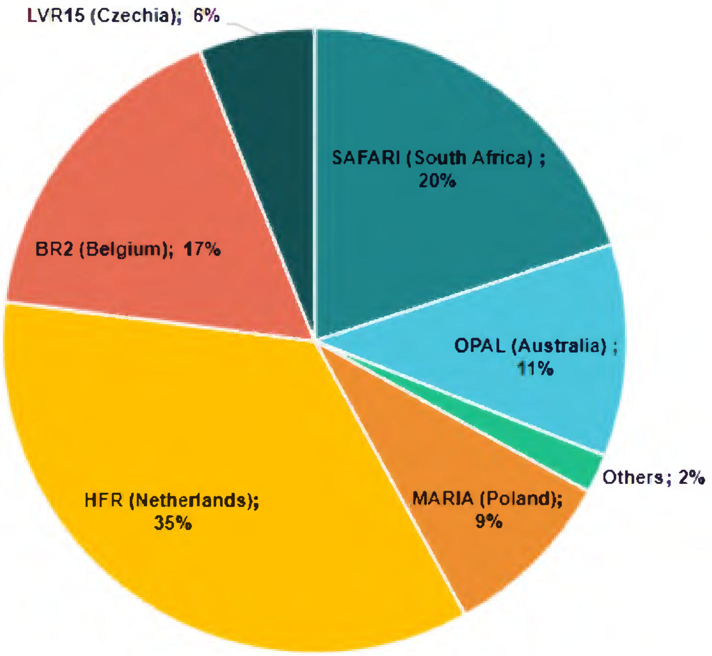
(61) JRC, "Study on sustainable and resilient supply of medical radioisotopes in the EU – Diagnostic Radionuclides" (2021), updated by NucAdvisor (2024).

(62) The future production of Lutetium-177 in a Romanian reactor has been recently announced: [Framatome and Nuclearelectrica take the next step in producing cancer-fighting Lutetium-177 in Romania - Framatome]

Figure 17 – Share of the global market for irradiation services for radioisotope production



Source: JRC, "Study on sustainable and resilient supply of medical radioisotopes in the EU – Diagnostic Radionuclides" (2021), updated by NucAdvisor (2024).

The transport of medical radioisotopes is a key element within the supply chain. Their production is concentrated in few Member States and their short half-lives impose tight schedules that may be impacted by disruptions and delays. Despite a well-established regulatory framework at international level, its practical implementation often poses challenges, in particular for the mutual recognition of shipment containers and licensed carriers among countries. The transport sector should also adapt to the increasing demand for these specialised services in the coming years.

Despite its leadership position in production and supply of medical radioisotopes, the EU is dependent on foreign supply of source materials and suffers from supply chain fragility due to ageing of its indigenous irradiation facilities.

Russia is the sole supplier of certain stable isotopes, which are indispensable as source material to produce key radioisotopes for cancer therapy ([63]). Existing stocks held by radioisotope producers have so far averted severe supply disruptions, and recently announced projects in the US, Canada, South Africa and elsewhere are expected to improve the global security of supply of these isotopes. However, there is a significant potential to leverage existing (pre-production) technology and experience ([64]) to develop indigenous production in the EU.

High-assay low-enriched uranium (HALEU) is used in research reactors as fuel and/or as irradiation targets for production of the most significant radioisotopes in use

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([63]) This mostly concerns Yterbium-176 used to produce Lutetium-177, but other needs that cannot be met by the current European industrial technology and capacity may arise in the future.

([64]) The main player is Orano, France.

today ([65]). Without homegrown production, HALEU is obtained from existing stocks in the US which should run out by mid/late-2030s ([66]). The US and the UK have important projects for HALEU production underway ([67]) (see box on HALEU in section 4.2.4), with first deliveries expected before 2030. In the EU, the sole needs of research reactors and radioisotopes production make it hard to justify an investment in a full HALEU fuel supply chain. Nevertheless, a limited investment in part of the supply chain – such as a small-scale metallisation facility of about 1 ton/year – could be economically viable and supportive to increasing the EU strategic economy.

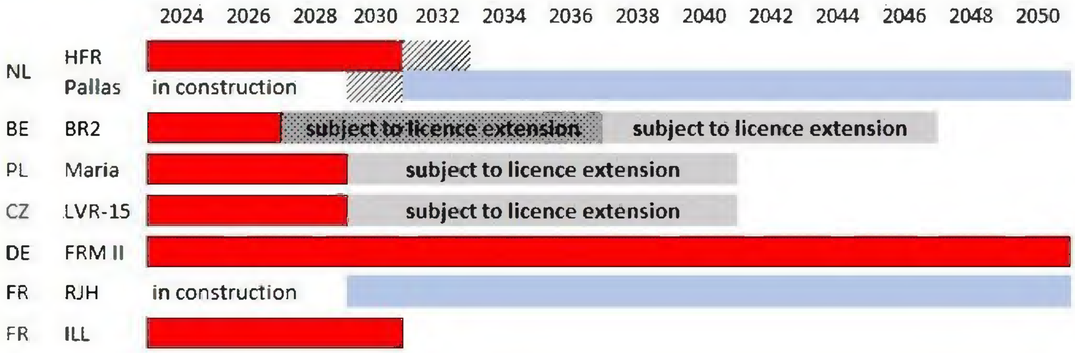
Moreover, the EU research reactors are ageing and will need major refurbishments to be gradually upgraded and partially replaced by about 2030.

Production capabilities and new production technologies should be developed and put in place to diversify production means and increase the system resilience.

3.2.3. Changes in the European Union nuclear infrastructures supporting the supply of medical radioisotopes

Since the last PINC in 2017, the construction of new research reactors has started or continued as shown in Figure 18 ([68]).

Figure 18 – Estimated landscape of EU research reactors for medical radioisotopes production



Source: JRC, "Study on sustainable and resilient supply of medical radioisotopes in the EU – Therapeutic radionuclides" (2022), updated by NucAdvisor (2024)

The European fleet of research reactors for radioisotopes production remains largely unchanged. At the time of the previous PINC, research reactors in the Netherlands (HFR), Poland (Maria), and Czechia (LVR-15) had already switched to HALEU fuels. Research reactors in Belgium (BR2), France (ILL), and Germany (FRM II) are yet undergoing the process of conversion to HALEU fuel. Several of these reactors

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(65) Sections 4.3 on the Supply chain for nuclear installations life-cycle and 5.1 on SMRs address further this topic.

(66) ESA report on "Securing the European Supply of 19.75% Enriched Uranium Fuel", May 2022.

(67) As part of the US and UK respective programmes to develop advanced nuclear power reactors and (re)develop their fuel cycle supply chains.

(68) JRC, "Study on sustainable and resilient supply of medical radioisotopes in the EU – Therapeutic radionuclides" (2022), updated by NucAdvisor (2024)

also underwent, or are undergoing or preparing for, Periodic Safety Reviews, modernisation and lifetime extension projects, and license extensions.

Several new installations are under construction. The PALLAS reactor in the Netherlands, which is estimated to be operational around 2030, is a complete infrastructure for production of medical radioisotopes with a capacity to supply to more than 30,000 patients per day. ([69]) The Jules Horowitz Reactor (RJH) in France is expected to bring additional radioisotope supply capacity on the market, although it is a multi-functional facility with no precise date for market entry.

The MYRRHA (Multi-purpose hYbrid Research Reactor for High-tech Applications) facility in Belgium has launched the construction of its 'Phase 1 / MINERVA' particle accelerator. MYRRHA is intended for the production of "theranostic" radioisotopes. The Accelerator Driven System (ADS) consists in a subcritical nuclear reactor and a high-power linear accelerator, which is expected to deliver radioisotopes for medical applications as of 2027.

3.2.4. Findings and recommendations

The security of supply of radioisotopes for medical applications is key to maintain and protect our European social model. Therefore, it requires that the EU strategic independence is pursued.

Member States and, potentially, EU investment is needed to secure source materials and develop new industrial capacity reducing foreign dependencies. The diversification and renewal of the radioisotopes production facilities would further increase the resilience of the supply chain. Dedicated support for research, development and innovation is key for developing innovative treatments for cancer and bolstering the EU competitiveness in this area. A broader monitoring system on the demand and supply of medical radioisotopes is also deemed important to better inform the market and foster investments ([70]).

In 2021, the Commission published the SAMIRA Action Plan ([71]) as part of the outcomes of Europe's Beating Cancer Plan. This plan set in motion actions to support the safe and high-quality use of radiological and nuclear technology in healthcare, with the security of supply of radioisotopes being one of its priority areas. Under SAMIRA, the Commission started a process towards establishing the "European Radioisotope Valley Initiative" (ERVI), for implementation in the next EU Multiannual Financial Framework.

By mid-2026, the Commission plans to adopt a Communication on ERVI as an EU initiative aiming to increase the EU's domestic production of medical radioisotopes, reduce EU dependency on foreign suppliers, in particular Russia, and improve the resilience of the European supply chain, taking into account different needs of Member States. The Commission will evaluate the infrastructure and financial needs

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([69]) PALLAS

([70]) Building upon the European Observatory on the Supply of Medical Radioisotopes, which is co-chaired by the Euratom Supply Agency (ESA) and industry.

([71]) Commission Staff Working Document on a Strategic Agenda for Medical Ionising Radiation Applications (SAMIRA), SWD(2021) 14 final.

of the European supply chain and make specific proposals on how to ensure better co-ordination and secure investment in this area ([72]).

Member States have continuously supported and guided the Commission efforts to address radioisotopes supply issues. The Council of the European Union issued several sets of conclusions on this subject, most recently in June 2024 ([73]). Likewise, in May 2024, the European Economic and Social Committee issued their opinion ([74]).

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[72] Roadmap towards ending Russian energy imports, COM/2025/440 final/2, supports also these objectives.

[73] The security of supply of radioisotopes for medical use, Council conclusions, 17 June 2024.

[74] Europe's Beating Cancer Plan: Driving forces for the security of medical radioisotopes supply, Opinion of the European Economic and Social Committee, C/2024/4661.

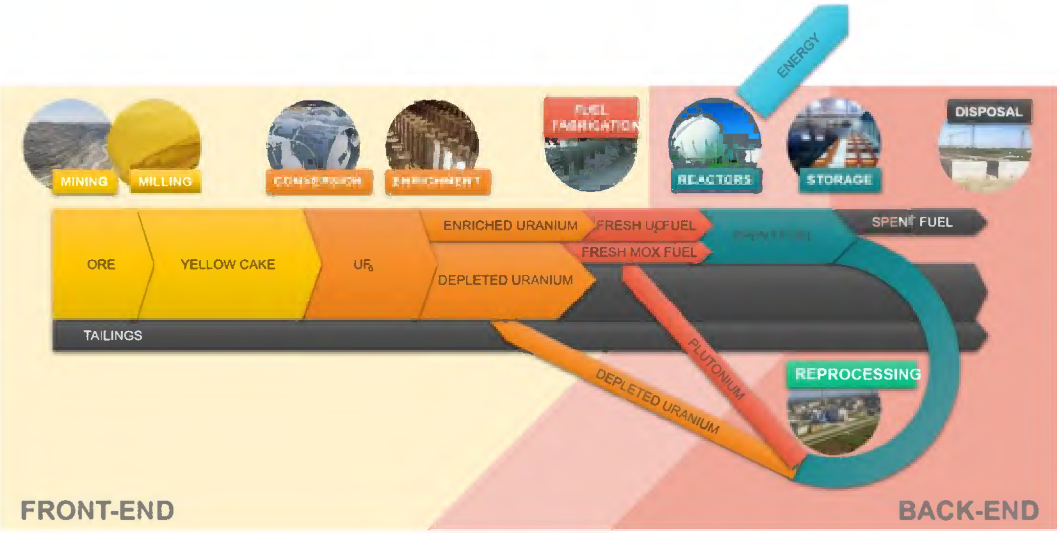
4. ANALYSIS OF THE SUPPLY CHAIN

To fulfil its potential, nuclear energy requires a robust and reliable supply chain that covers its entire life cycle. This section presents an analysis of the supply chain over the whole nuclear energy life cycle. The analysis focuses on two main areas: the ‘nuclear fuel cycle’ (discussed in Section 4.2), and the ‘nuclear installation life cycle’ (covered in Section 4.3). Both sections aim at providing an overview of the necessary components for an effective nuclear energy supply chain.

4.1. Overview

The ‘nuclear fuel cycle’ is the series of industrial processes that involve the production of energy from uranium in nuclear power reactors, see Figure 19.

Figure 19 – Nuclear fuel cycle

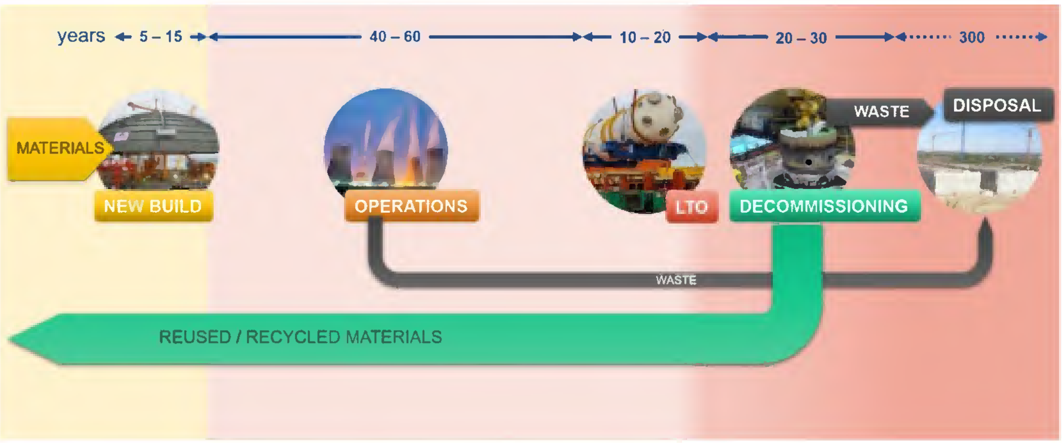


Source: European Commission.

Uranium is a relatively common element which is mined in a number of countries. Uranium must be processed (i.e. converted and enriched) before it can be used for manufacturing nuclear fuel assemblies to be exploited in a nuclear reactor. Fuel assemblies removed from a reactor, after they have reached the end of their useful life, can be either reprocessed and recycled for new fuel or disposed of as nuclear waste, possibly after transmutation. These two options are commonly referred to as closed and open nuclear fuel cycle, respectively.

The ‘nuclear installation life-cycle’ is the series of industrial processes that involve the design, manufacturing, construction, operation, maintenance, and decommissioning of any nuclear installations (i.e. power reactors as well as other nuclear fuel cycle facilities) or associated equipment, see Figure 20.

Figure 20 – Nuclear installation life-cycle



Source: European Commission.

The nuclear industry in the EU covers to varying extents all stages of both the ‘nuclear fuel cycle’ and the ‘nuclear installation life-cycle’. The EU industrial capacity in the nuclear energy sector has a crucial role to play in security of supply provided that adequate diversification of supplies is guaranteed.

The extent to which scenarios described in section 2.1 will realise, eventually, is essentially bound to a robust, reliable and interlinked EU supply chain. This has to be achieved in a context when the EU nuclear industry faces a complex landscape of risks. Politically, acceptance of nuclear power remains mixed, with some Member States opposing nuclear expansion. Geopolitical risks also affect the supply chain industry, particularly in relation to dependencies on non-EU suppliers for critical materials or components.

The analysis in sections 4.2 and 4.3 aims at identifying gaps and areas to focus on and where Member States should consider further investments to accomplish their plans (75).

4.2. Supply chain for the nuclear fuel cycle

This section analyses the several steps of the ‘nuclear fuel cycle’ with a view on the status quo (compared to the status quo at the time of the previous PINC) and future projections of the nuclear fuel market. Information and data underpinning the analysis are mainly derived from the Euratom Supply Agency (ESA) (76). Other sources of data are specifically indicated when used.

ESA performed analyses of conversion and enrichment markets based on information Euratom utilities reported directly to the agency in 2023 as part of ESA’s annual survey, and based on the generation capacity forecast presented in section 2.1. ESA also relied on data published by the World Nuclear Association (WNA) and industry data.

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(75) Addressing investment needs will require further discussion and alignment with several Member States.

(76) Euratom Supply Agency - European Commission

Demand projections for EU Member States are based on generation capacity projections, which include currently operating reactors, LTO plans, and new builds indicated by Member States in their National Energy and Climate Plans (NECPs), see section 2.1. Other region's projections are based on industry reports.

Current capacity of service providers is based on data available in industry reports and industry consultations, as well as public announcements concerning the investments plans in capacity extension (77).

Most nuclear reactors use fuel made from low-enriched uranium (LEU), where the share of the fissile U-235 isotope has been enriched to between 3% to 5% (78). Fuel for some advanced reactor designs (see Section 5.1) or the production of some medical radioisotopes (see Section 3.2) requires a higher concentration of U-235. In high-assay low-enriched uranium (HALEU), the U-235 isotope has been enriched to greater than 5% and less than 20% (79). Some other new reactor designs in particular Advanced Modular Reactors (AMRs) which are based on fast reactor technologies e.g. Sodium Fast Reactors (SFR) or Lead Fast Reactors (LFR) also use different types of higher enriched fuel such as Mixed Oxide (MOX) which is composed of uranium oxide (UO□) and plutonium oxide (PuO□). Some AMRs based on Molten Salt Technology (MSR) can use low-enriched uranium (U-235 or U-233) fuels dissolved in the molten salt mixture or can incorporate plutonium as fissile material, either alone or in combination with uranium. Some MSR designs propose using Thorium as a fuel source. This section focusses on the supply chain for the LEU fuel cycle and provides information on HALEU in a dedicated box.

4.2.1. Mining and milling

Uranium is mined and milled across the globe in several regions and countries, such as Australia, Canada, Africa, and Asia. Kazakhstan accounts for more than 40% of the world's uranium production, see Table 2. Uranium mining within the European Union has significantly declined over the past few decades (80), leading to a heavy reliance on imports to meet the regional demand.

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(77) This analysis does not reflect investment notifications submitted to the Commission pursuant to Art. 41 of the Euratom Treaty.

(78) Uranium found in nature consists largely of two isotopes, U-235 and U-238. The production of energy in nuclear reactors is from the 'fission' or splitting of the U-235 atoms, a process which releases energy in the form of heat. U-235 is the main fissile isotope of uranium. Natural uranium contains 0.7% of the U-235 isotope. The remaining 99.3% is mostly the U-238 isotope, which does not contribute directly to the fission process (though it does so indirectly by the formation of fissile isotopes of plutonium). Isotope separation is a physical process to concentrate ('enrich') one isotope relative to others. Most reactors require uranium to be enriched from 0.7% to between 3% to 5% U-235 in their fuel. This is normal low-enriched uranium (LEU). Source: Uranium Enrichment - World Nuclear Association

(79) High-Assay Low-Enriched Uranium (HALEU) - World Nuclear Association

(80) Whenever uranium mining and milling is pursued it "[…] produces large amounts of very low-level waste due to formation of waste rock dumps and/or tailings. These dumps and tailings are located close to the uranium mines and the related ore processing plants and their environmentally safe management can be ensured by the application of standard tailings and waste rock handling measures.", cf, the related JRC study. Another aspect of this challenge is ensuring adequate working conditions for uranium mine and mill workers, including compensation, safety, and responsible management of radiological exposure.

Table 2 – Production of natural uranium (in tonnes of uranium equivalent)

Country	2016	2017	2021	2022
Kazakhstan	24,689	23,321	21,819	21,227
Canada	14,039	13,116	4,693	7,351
Namibia	3,654	4,224	5,753	5,613
Australia	6,315	5,882	4,192	4,553
Uzbekistan	3,325	3,400	3,520	3,300
Russia	3,004	2,917	2,635	2,508
Niger	3,479	3,449	2,248	2,020
China	1,616	1,692	1,600	1,700
Others	662	506	695	708
South Africa	490	308	192	200
Ukraine	808	707	455	100
USA	1,125	940	8	75
Total	**63,206**	**60,462**	**47,810**	**49,355**
% of world demand	96%	93%	76%	74%

Source: Data from the WNA and specialised publications.

Notes: Because of rounding, totals may not add up.
2023 data not available at the date of publication of the report.

Global primary uranium production, i.e. uranium sourced through mining instead of e.g. recycling, accounted for about 49,355 tU in 2022. The 2023 production estimate is at the same level. This figure satisfies approximately 75%-80% of global demand. The remainer is satisfied from secondary sources, e.g. inventory drawdowns ([81]).

A joint report by the OECD's NEA and the IAEA estimates global uranium production capacities from existing and committed production centres at 69,675 tU for 2025 ([82]). Uranium output has remained significantly below full capacity due to temporary mining suspensions in key producing countries, and higher production rates in the near term appear unlikely.

ESA reported that in 2023, demand for natural uranium in the EU accounted for approximately 22% of global uranium requirements. In 2023, EU utilities purchased a total of 14,578 tU. 93% of these purchases took place under multiannual contracts, while spot contracts accounted for the remaining part.

([81]) As with other energy minerals, imbalances between demand for uranium and primary production are traditionally bridged through inventory drawdowns, which can include commercial or government-held inventories. In the case of uranium, such secondary sources may – depending on economic factors – also include depleted uranium upgrades, or natural uranium saved by uranium enrichers by means of underfeeding.

([82]) NEA (2023), Uranium 2022: Resources, Production and Demand, OECD Publishing, Paris. https://www.oecd-nea.org/jcms/pl_79960/uranium-2022-resources-production-and-demand

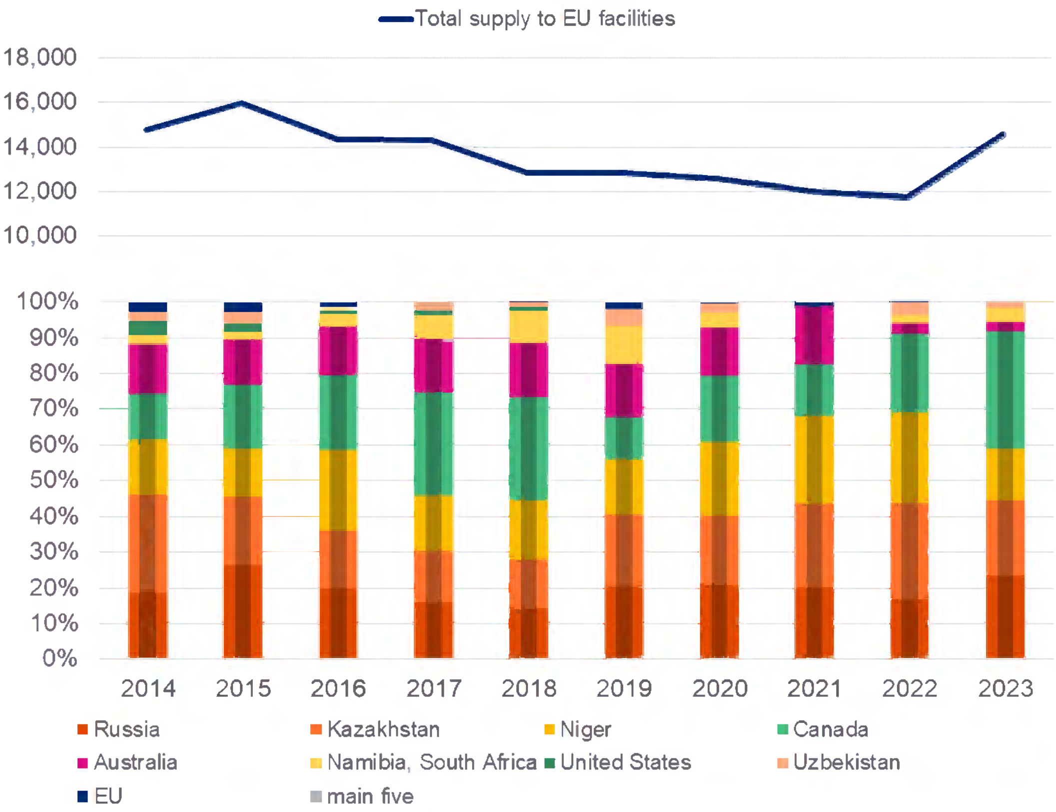
Table 3 – Origins of uranium delivered to EU utilities (in tonnes of uranium)

Country	2022	2023
Canada	2,578	4,802
Russia	1,980	3,419
Kazakhstan	3,145	3,061
Niger	2,975	2,089
South Africa, Namibia	262	562
Australia	327	372
Uzbekistan	441	271
United States	0	4
EU	17	0
Total	**11,724**	**14,578**

Source: Euratom Supply Agency, Annual Report 2023.

Notes: Because of rounding, totals may not add up.

Figure 21 – Supply of uranium to EU utilities by origin (tU)



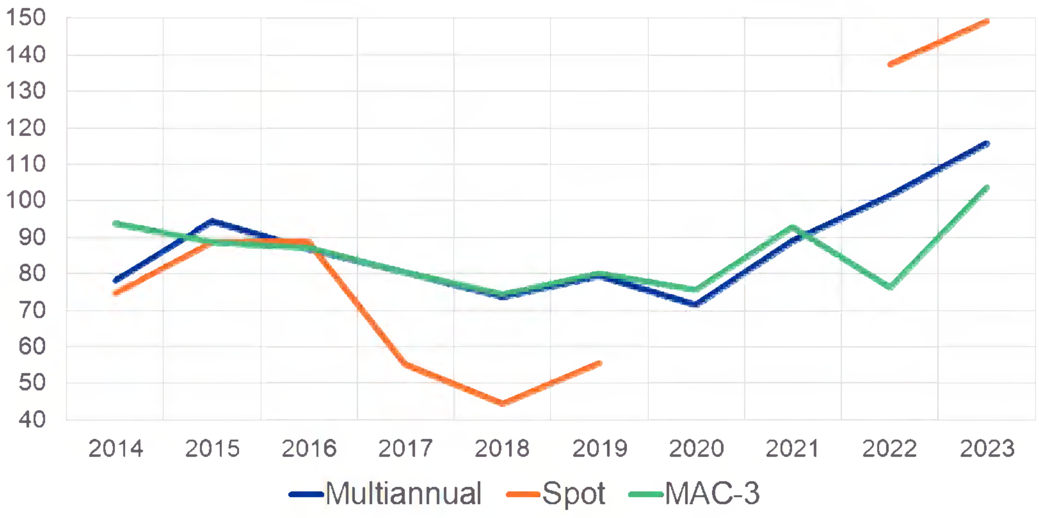
Source: Euratom Supply Agency, Annual Report 2023.

In the past decade, until 2021, EU utilities received natural uranium supplies mainly from five countries: Canada, Russia, Kazakhstan, Niger, and Australia. In 2022 and 2023, supplies from Australia decreased, and the other four countries supplied more than 94% of uranium to the EU, see Table 3 and Figure 21. A preliminary analysis of available data indicates that in 2024, supply from Niger and Russia decreased substantially, while supplies from Australia went back to 2020 levels and supplies from China appeared for the first time (83).

Only a portion of the recoverable uranium resource base can be extracted economically, as resources with mining costs above current market prices cannot be mined profitably. ESA monitors the market under its market observatory role (84).

In 2023, the global uranium market continued to face challenges due to Russia's unjustified military aggression against Ukraine, the coup d'état in Niger, production issues, difficulties in transportation, and stronger demand, which influenced supply and demand and put upwards pressure on uranium prices, see Figure 22.

Figure 22 – ESA average prices for natural uranium (EUR/kgU)



Source: Euratom Supply Agency - Annual Report 2023.

Significant portions of identified resources have historically remained unextracted due to governments not granting licenses (for example in Sweden). The rise in uranium prices in the past four years spurred exploration and the reopening of several mines worldwide, increasing production capacity. In its forward-looking analysis of the uranium market, the World Nuclear Association considers several factors, including decisions to extend the life of nuclear power plants, revisions of previous retirements, and non-power applications, as drivers to open new mines and to make new investments (85).

The EU's future demand for uranium will depend on the evolution of reactor capacity. If Member States' plans materialise and the installed generation capacity increases until 2050, demand for uranium is likely to increase as well. This trend may be further reinforced by the potential deployment by SMRs and AMRs in the EU. The global demand for uranium may increase more steeply until 2050, given the nuclear programmes in emerging economies, e.g. China and India. All else equal, these developments will put upwards pressure on uranium prices, and thereby create an

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(83) Source: Euratom Supply Agency.

(84) Market Observatory - European Commission

(85) WNA, Global Scenarios for Demand and Supply Availability 2023-2040

incentive to further draw down inventories, increase production rates at existing mines, and possibly explore further resources. Given that existing mines produced below capacity in recent years, a potential supply inadequacy seems unlikely in the near term. As outlined in the REPowerEU Roadmap (86), the Commission envisages to restrict new supply contracts co-signed by the Euratom Supply Agency for uranium as well as enriched uranium and other nuclear materials with Russian suppliers, as of a certain date. Deliveries based on existing contracts will continue but prolongations as well as new supply contracts would no longer be approved by the Euratom Supply Agency.

In addition, the Roadmap puts forward measures aiming to establish specific targets for Member States to: (i) replace Russian nuclear fuels with alternative fuels by accelerating the contracting and licensing of such fuels and developing further fully European alternatives; (ii) phase out reliance on Russia for uranium, enriched uranium and other nuclear materials; and (iii) increase transparency on dependencies and encourage diversification of Russian supplies of spare parts and maintenance services. As part of this effort, Member States will also be required to develop and implement national plans that outline their specific actions and timelines.

4.2.2. Conversion

Uranium conversion is a crucial step in the nuclear fuel cycle, which transforms processed uranium ore (uranium oxide, U□O□, commonly known as “yellowcake”) into a chemical form (most prominently UF_6) suitable for enrichment and eventual use in nuclear reactors.

There is a small number of uranium conversion facilities worldwide, see Table 4. While the uranium conversion market underwent significant changes in the past, there was no previous case as striking as the recent surge in prices. In the period from February 2022 until December 2023, the long-term unit price almost doubled, and the spot unit price tripled. This trend reflected increasing demand from western suppliers. (87)

Table 4 – Commercial facilities for uranium conversion to UF_6 (tonnes of Uranium as UF_6)

Company	Country	Nameplate capacity	Planned additional capacity
Orano	France	15,000	
CNNC	China	15,000	21,000 *(2025-2040)*
ConverDyn	USA	15,000	
Rosatom	Russia	12,500	
Cameco	Canada	12,500	
Cameco	UK	0	5,000 *(2032-2034)*
Total		**70,000**	**26,000**

Source: Euratom Supply Agency, https://converdyn.com/facility/.

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(86) Roadmap towards ending Russian energy imports, COM/2025/440 final/2.

(87) ESA - ESA Annual Report 2023

Notes: Information on conversion capacity in China is uncertain. ConverDyn suspended activities in 2017 and restarted in July 2023.

The only conversion plant in the EU – Orano's "Philippe Coste" – has a nameplate capacity of 15,000 tU as UF_6 annually. The actual production rate is not yet at the nameplate capacity; however, the production rate was ramped up over the past years and the current output estimate is at around 75% of the nameplate capacity. The company plans to ramp up the production to 90% of the nameplate capacity by 2029.

The US-based firm ConverDyn current production estimates are at 9,000 tU per year at its Metropolis plant. ConverDyn's declared a nameplate capacity of 15,000 tU in 2007, however they were in temporary shutdown from 2017 to 2023 due to poor market conditions.

Based on available information, conversion capacity in China may have reached a total of 10,500 tU (evidence is limited as to actual output). It is sound to assume that China will develop indigenous conversion capacity to support an ambitious nuclear power development plan in the next decade and beyond. According to the Nuclear Fuel Report (2023), uranium demand is projected to reach almost 50,000 tU by 2050 (62). This leads to the conclusion that conversion capacity will need to nearly triple by that time.

Russian (Rosatom) capacity has varied in recent years due to upgrades and refurbishments at Seversk, but capacity is supplemented by upgrading tails and underfeeding in order to generate UF_6 (see the Box in Section 4.2.3 on underfeeding). Existing nameplate capacity could be 16,000 tU per year, but a more conservative estimate (based on limited refinement capacity) is 12,500 tU per year.

Table 5 – Provision of conversion services to EU utilities in 2023 (tonnes of Uranium as UF_6)

Converter	Quantity	Share
Orano	3,834	29%
Rosatom	3,543	27%
Cameco	2,525	19%
ConverDyn	2,448	18%
Unspecified	1,013	8%
Total	**13,364**	

Source: Euratom Supply Agency Annual Report 2023.

Notes: Because of rounding, totals may not add up.

The backward analysis and the assessment of the present state of the global market of conversion services highlight the need for higher strategic independency at EU level to support the competitiveness of EU industry, see Table 5. A preliminary analysis of available data indicates that in 2024 the share of conversion services provided to EU utilities from Russia decreased from 27% to 23%, and the equivalent share was covered from Chinese supply. The forward analysis presented here below (see Figure 23) provides an assessment of potential vulnerabilities in the supply vs demand balance until 2050 on a global scale.

Based on current plans, the domestic conversion capacity will be barely sufficient to meet EU demand through to 2050, with no margin against the 'base case' scenario presented in Section 2.1. Moreover, there are two main elements to consider which may importantly reduce the domestic supply actually available to EU utilities: (i) realisation of the 'high-capacity' scenario whereby the EU conversion capacity will be definitely insufficient; and (ii) commercial commitments undertaken by the EU producers with customers outside the EU.

Extending the analysis to Western Europe, Ukraine, North America, Japan and South Korea the gap analysis shows that missing supply capacity exceeds 10,000 tU as UF_6 annually. Taking planned expansions of conversion capacity into account, the gap may decrease to a bit more than 1,500 tU annually by 2034. However, in absence of further investments in expanding conversion capacity in the 'West', the gap will increase again and may reach more than 10,000 tU annually by 2050.

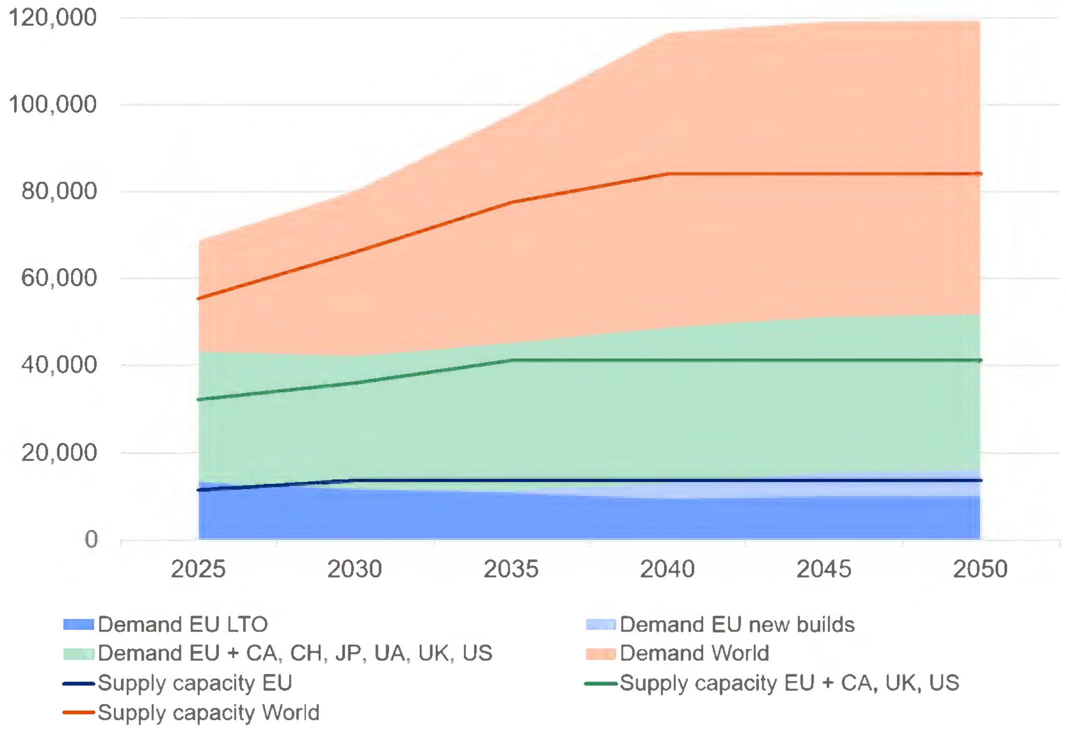
The capacity gap can be mitigated by secondary sources of UF_6, particularly inventories held by utilities. Nevertheless, in the long run, there will be insufficient capacity to convert enough uranium to meet the demand from Western reactors. Inventories held by EU utilities — primarily in the form of already converted uranium (UF_6), enriched UF_6, and fresh fuel — can sustain EU reactors for approximately two years.

The remaining demand is currently satisfied by other suppliers, such as those from Russia, and by secondary sources. It is important to underline that if there was a sudden supply interruption, alternative sources such as reprocessing and MOX fuel would be insufficient to cover the gap, given the limited inventories. This underscores the need to expand further conversion capacity in the West and in the EU, also with a view to achieve the REPowerEU objective of diversifying energy supplies.

The gap analysis on the global scale shows a strong deficit to supply all existing nuclear reactors. That deficit is set to increase, if no further investments in conversion capacities are pursued at global level.

Investments for expansion of existing conversion facilities ranges around EUR 600 million per additional capacity of 1,000 tU as UF_6 annually. Beside the critical need for strategic autonomy, there are also market opportunities for EU industrial operators to seize justifying further investments.

Figure 23 – Global demand for conversion services vs supply capacity projections. (tU as UF_6 per year)



Source: Euratom Supply Agency.

Notes: The stacked areas representing demand are additive, i.e. global demand is given by the blue, green, and red areas

4.2.3. Enrichment

Uranium enrichment is a vital step in the nuclear fuel cycle. The enrichment process separates a uranium gaseous flow into two streams, one being enriched in ‘fissile’ isotope uranium-235 (U-235) to the required level; the other being progressively depleted of ‘fissile’ isotope and called ‘tails’, or simply depleted uranium. This is essential because natural uranium contains only about 0.7% U-235, which is not enough for most nuclear reactors in the EU ([88]).

Being proliferation-sensitive, enrichment technology is available only to a limited number of governments, who entrust it to an even smaller number of commercial operators, see Table 6. Amid the current geopolitical tensions and other shocks to global energy markets, it is therefore noteworthy that such a sensitive market segment seems to have embarked on significant change due to governmental steers towards higher strategic independency and market opportunities for commercial operators.

([88]) With few exceptions, such as CANDU type reactors in Romania, the fleet of light water reactors in the EU requires low-enriched uranium (LEU) to operate.

Since 2016, prices of enrichment were relatively stable until February 2022. Afterwards, both spot and long-term prices increased substantially and in December 2023 they had multiplied by 2.5 times both. (89)

Table 6 – Commercial and domestic facilities for uranium enrichment (million SWU per year)

Company	Country	Nameplate capacity	Planned additional capacity	
CNNC	China	10.0	21.0	*(2025-40)*
Global Laser	United States	0	6.0	*(2030)*
Orano	France	7.5	2.9	*(2030)*
Orano	United States	0	Unspecified	*(2031-35)*
Rosatom	Russia	27.1		
Urenco	United States	4.3	0.7	*(2025)*
Urenco	Netherlands	5.0	0.8	*(2028)*
Urenco	United Kingdom	4.5		
Urenco	Germany	3.5	0.3	
Other	Brazil/ Japan	0.2		
Total		**62.1**	**31.4**	

Source: European Commission, Euratom Supply Agency, WNA, https://www.orano.group/en, https://www.urenco.com/, https://www.nrc.gov/materials/fuel-cycle-fac/laser.html.

Notes: Separative work unit, abbreviated as SWU, is the standard measure of the effort required to separate isotopes of uranium (U235 and U238) during an enrichment process in nuclear facilities. 1 SWU is equivalent to 1 kg of separative work.

Urenco has two enrichment plants operating in the EU (NL, DE). The Urenco Group announced expansion of enrichment capacity at LES/Eunice (US) and in Almelo (NL) by adding centrifuge technology to meet greater customer demands. (90)

Orano reported that its facility 'Georges Besse 2' in southern France reached full production capacity of 7,500 tSWU per year in 2016. Recently Orano approved an investment of EUR 1.7 billion to increase the facility's capacity by 30% or more. In the US, Orano has embarked in a multibillion project (project IKE) to realise an enrichment facility at Oak Ridge, TN with an ambition to cope with increasing demand from US facilities. (91)

Global Laser Enrichment (US) reported that it is considering advancing construction at the Paducah Laser Enrichment Facility from 2030 in order to meet LEU and HALEU requirements. (92)

CNEIC (China) enrichment capacity reached a nameplate figure of 6,500-7,000 tSWU per year in 2018 and consecutively ramped up its production capacities, which is estimated to reach the level of 10,500 tSWU per year now. Similarly to the

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(89) ESA, Annual report 2023

(90) https://www.urenco.com/

(91) https://www.orano.group/en

(92) https://www.nrc.gov/materials/fuel-cycle-fac/laser.html

anticipated development scenario of the conversion capacity it is anticipated that the enrichment capacity should achieve approximately 31,500 tSWU per year after 2040.

Rosatom/TVEL (Russia) is the largest global enricher with an overall capacity of 27,100 tSWU per year at four sites. (93)

INB (Brazil) and JNFL (Japan) have capacity of less than 200 tSWU per year combined. The plant at Rokkasho-mura (Japan) is currently at a standstill. Both countries have plans for modest capacity increase before 2030.

In 2023, enrichment service deliveries to EU utilities (see Table 7) were 12% higher than in 2022. Over the period since 2016 enrichment service deliveries to EU utilities ranged between 10,290 and 12,912 tSWU per year, and there were no clear trends of increasing demand. As in the past, the enrichment services were acquired from three global service providers: Orano (FR), Urenco (DE, NL, UK, US) and TVEL (RU). (94)

Table 7 – Origin of enrichment services to EU utilities in 2023 (million SWU)

Origin	Quantity	Share
EU	6.728	55%
Russia	4.647	38%
Other	0.885	7%
Total	**12.260**	

Source: Euratom Supply Agency Annual Report 2023.

Notes: Because of rounding, totals may not add up.

The backward analysis and the assessment of the present state of global market of enrichment services highlight the need for higher strategic independency at EU level to support the competitiveness of EU industry. A preliminary analysis of available data indicates that in 2024 the share of enrichment services provided to EU utilities from Russia decreased from 38% to 30%. The forward analysis presented here below (see Figure 24) provides an assessment of potential vulnerabilities in the supply vs demand balance until 2050 in a global scale.

Based on current plans, the domestic enrichment plants' aggregated capacity will be sufficient to meet EU demand through to 2050, with a surplus of supply capacity around 80% against the 'base case' scenario presented in section 2.1. However, there are two main elements to consider which may importantly reduce the domestic supply actually available to EU utilities: (i) realisation of the 'high-capacity' scenario whereby the surplus would be reduced to less than 30%; and (ii) commercial commitments undertaken by the EU producers with customers outside the EU.

Extending the analysis to Western Europe, Ukraine, North America, Japan and South Korea the gap analysis shows that missing supply capacity exceeds 9,000 tSWU per year. The gap will possibly decrease towards the end of the decade and be at around

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(93) World Nuclear Association, https://world-nuclear.org/information-library/nuclear-fuel-cycle/conversion-enrichment-and-fabrication/uranium-enrichment#enrichment-capacity

(94) Euratom Supply Agency - Annual Report 2023, Annual Report 2021. Annual Report 2019. Annual Report 2017.

1,100 tSWU in 2034, based on announced investments in France, the Netherlands, the United Kingdom and in the US. However, even when accounting for emerging technologies, e.g. the planned 'Global Laser' project, the available capacity will barely suffice to satisfy demand from Western reactors. Such gap will be wider if ambitious LTOs and new builds plan will materialise (for example in the US). An upward pressure to the demand will be also given by the market uptake of HALEU related to modular reactors and research reactors.

Similarly to the conversion services market, secondary sources of UF_6 can partially bridge the enrichment services gap in the short-term. Inventories held by utilities may contribute to serving the demand, too. Nevertheless, in the long run, new capacity is needed.

Currently, other suppliers, such as those from Russia, and secondary sources satisfy the remaining demand. It is important to underline that if there was a sudden supply interruption, other secondary sources like reprocessing and MOX fuel would be insufficient to cover the gap, given the limited inventories.

The gap analysis on the global scale shows that while presently the supply capacity is abundant compared to the demand, development scenarios indicate that plans for new enrichment capacity do not match plans for new power production which will lead the demand. Also in this case, the analysis provides likely an under-estimate of the gap due to the uptake of HALEU.

Investments for expansion of existing enrichment facilities ranges around EUR 600 million per additional capacity of 1,000 tSWU/y (95).

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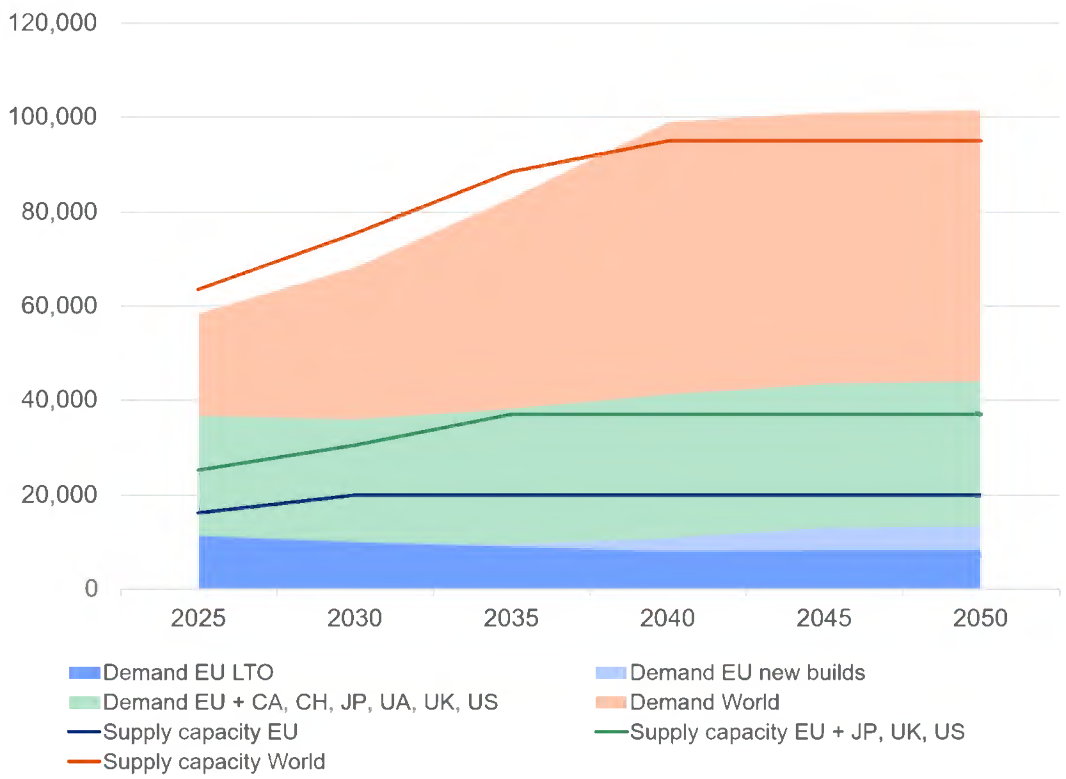
(95) France: EIB and Orano sign a loan agreement for €400 million relating to the project to extend the Georges Besse 2 uranium enrichment plant, accessed on 23 May 2025.

Figure 24 – Demand for enrichment services vs supply capacity projections. (tSWU per year)



Source: Euratom Supply Agency.

Notes: Separative work unit, abbreviated as SWU, is the standard measure of the effort required to separate isotopes of uranium (U235 and U238) during an enrichment process in nuclear facilities. 1 SWU is equivalent to 1 kg of separative work. As a larger unit, 1 tonne of separative work units or tSWU equals 1,000 kg of separative work. The stacked areas representing demand are additive, i.e. global demand is given by the blue, green, and red areas.

4.2.4. Fuel fabrication

Fuel fabrication is a manufacturing service that requires preparing fuel assemblies to the exact requirements of the customer reactor unit ([96]). While some degree of competition is theoretically possible, vendors consolidation over the years has led to a high degree of concentration. Moreover, for vendors to develop new designs and supply fuel assemblies to reactor operators, long lead times are necessary due to safety implications and licensing processes. As a consequence, utilities should secure supplies by maintaining at least two alternative suppliers.

Most EU utilities can purchase fuel from at least two alternative suppliers. As an exception, dependence on a single design and supplier of fuel was the case for water-water energy reactors (VVER) and became a vulnerability for the security of supply ([97]). Fuel to those reactors has been originally delivered from TVEL (RU), a

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([96]) Reactor fuel typically consists of ceramic pellets made from uranium dioxide, pressed and heated at high temperatures. These pellets are sealed in metal tubes, usually a zirconium alloy, to create fuel rods. The rods are grouped into a fuel assembly for use in the reactor.

([97]) Euratom Supply Agency, Annual Report 2023.

subsidiary of Rosatom, within bundled contracts offering uranium and all related services including production of fuel assemblies.

VVER reactors, a type of pressurized water reactor developed in Russia, play a significant role in the nuclear energy landscapes in some eastern EU Member States. VVER-440 reactors are generally used in smaller power plants in the Czech Republic, Finland, Hungary and Slovakia. VVER-1000 reactors are found in larger, more recent facilities in the Czech Republic and Bulgaria.

At the end of 2025, all concerned EU operators have taken action to diversify nuclear fuel supply. Some are already well advanced in licensing alternative supplies. Besides, some utilities rose fresh fuel stocks to cover the period until alternative fuels – including related plant adaptations – will be completed and licensed.

As part of VVER fuel diversification, two projects ([98]) were established following a call by the European Commission and co-funded by the EU. Those projects involve fuel fabricators Westinghouse (US/CAN) and Framatome (FR). In addition, Framatome is going to manufacture fuel for VVER reactors under a joint venture with TVEL (RU) ([99]).

Alternative VVER fuel supplies are expected to become fully available by 2027, pending regulatory approval. Framatome's independently developed European design for VVER fuel is anticipated to be ready not earlier than 2030.

([98]) The three-year Accelerated Programme for Implementation of Secure Nuclear Fuel Supply (APIS), launched in January 2023 and coordinated by Westinghouse, aims at developing and delivering safe, fully European nuclear fuel for nuclear power reactors without involving Russian capital, technology, or expertise. https://apis-project.eu/

The second project (SAVE) is led by Framatome and brings together 17 partners from seven EU Member States as well as Ukraine, to contribute to the swift and secure development and deployment of a European fuel solution for VVER reactors. It is important to note that for the Framatome-TVEL collaboration, only the final stage of fuel fabrication will occur in Germany or France, while all components required for production will be sourced from Russia.

([99]) The components required for production will be sourced from Russia while the fuel fabrication will occur in Germany or France.

Box - Supply of High-assay low-enriched uranium (HALEU)

Traditionally, fuels for the EU research reactors and radioisotope production targets used highly enriched uranium (HEU), supplied mainly from the US and Russia (up to 25%). Under global nuclear security commitments, EU Member States engaged in converting to use of HALEU for research reactors and radioisotope production targets.

European research reactors with low to medium power density cores and medical radioisotopes producers transitioned to HALEU. The remaining European high performance research reactors are going to use HALEU as soon as technically and economically feasible (2026 onwards).

Currently, metallic HALEU is obtained either by down-blending US HEU stocks or from Russia. There is a very limited enrichment capacity for HALEU and no civil facilities for production of metal HALEU in the Western world.

Domestic commercial HALEU production, required mainly by many advanced reactor designs, has become a strategic objective for security of supply.

The US Department of Energy (DoE) estimates that the US will require more than 40 tonnes of HALEU before 2030, deemed to continue to increase afterwards. Accordingly, DoE established the HALEU Availability Program under the Energy Act of 2020, and the Inflation Reduction Act included a USD 700 million support package. Additional USD 500 million was earmarked for HALEU in the Emergency National Security Supplemental Appropriations Act providing USD 2.72 billion to support domestic uranium enrichment.

In 2024, the UK government announced investments up to GBP 300 million to launch a HALEU programme, under which the UK government awarded already GBP 196 million to Urenco to build a uranium enrichment facility in Capenhurst, with the capacity to produce up to 10 tonnes of HALEU per year by 2031. In addition, the UK government set out the Nuclear Fuel Fund (GBP 50 million) to support the UK's nuclear fuel supply chain in the UK and globally. Eight projects have so far been awarded a total of GBP 22.3 million, including: (i) GBP 10.5 million to Westinghouse to enable its Springfields plant in Preston, Lancashire, to manufacture a broader range of nuclear fuel types for large reactors, SMRs and AMRs in the UK and overseas; and (ii) GBP 9.5 million to Urenco to develop LEU+ and HALEU enrichment capability at its Capenhurst site in Cheshire.

Besides production, uptake of HALEU will require developing dedicated transport solutions, because there is no licensed transportation method for HALEU aside from using existing HEU casks, allowing only small shipments in a costly way. US DoE earmarked up to USD 16 million to develop licensed transportation packages for HALEU. In the UK the Nuclear Decommissioning Authority's subsidiary Nuclear Transport Solutions (NTS) has been awarded funding up to GBP 11.5 million to spearhead the development of transport capabilities for the UK's future use of HALEU.

4.2.5. Reprocessing

Spent nuclear fuel retains about 96% of its original uranium, 3% waste products, and 1% plutonium generated in the reactor but not consumed during operation. Reprocessing is a process to separate uranium and plutonium from waste products, so that they can be recycled into fresh fuel, such as Mixed Oxides (MOX). This process significantly reduces the overall volume of long-lived, high-level radioactive waste.

Strategies to ensure a safe and cost-effective overall management of spent fuel differ from one country to another and can be described as follows: (i) the 'open cycle' or 'once through' or 'direct disposal' strategy in which spent fuel is considered as waste; (ii) the 'closed cycle' (including the 'partially closed cycle') strategy, in which spent fuel is considered as a potential future energy resource and reprocessed to recycle uranium and plutonium in new fuel assemblies. During the reprocessing high-level waste is produced. An overview is provided in Table 8.

Table 8 – Nuclear power fuel cycle strategies

MS	Commercial scale reprocessing facility	Spent fuel currently in another country for reprocessing	Earlier reprocessing, but practice currently ceased	Planning direct placement of spent fuel in a repository	Keeping options open
BE (•)			✓	✓	✓
BG (•)		✓			
CZ (•)			✓	✓	
FI			✓	✓	
FR	✓				
DE			✓	✓	
HU (•)(†)			✓	✓	
IT		✓			
LT				✓	
NL		✓			
RO				✓	
SK			✓	✓	✓
SI				✓	✓
ES			✓	✓	
SE (‡)			✓	✓	

Source: Status and Trends in Spent Fuel and Radioactive Waste Management, IAEA Nuclear Energy Series No. NW-T-1.14 (Rev. 1).

Notes: (•) Mixed policy: some fuel has been or will be reprocessed other fuel will or may be direct disposed.
(†) Earlier fuel returns to the Russian Federation, but no requirement to return waste from reprocessing to Hungary.
(‡) Earlier reprocessing was done abroad.

The EU's approach to spent fuel management is guided by the Radioactive Waste and Spent Fuel Management Directive (2011/70/Euratom) (100), which requires all EU countries to have national policies and programmes for the management of these materials. Currently, the majority of Member States have chosen direct disposal of spent fuel in deep geological repositories as the preferred long-term solution for

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(100) 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, OJ L 199, 2.8.2011 p. 48–56.

managing high-level radioactive waste. France and the Netherlands currently continue to perform reprocessing. France uses its reprocessed fuel as MOX in several of its operating nuclear power plants. Research in transmutation is relevant with a view to reduce storage needs for high-level radioactive waste.

4.2.6. Findings and conclusions on nuclear fuel supply chain

The geopolitical developments, having impacted our continent, affected profoundly the functioning of the nuclear market. Russia's unjustified military aggression against Ukraine has, inter alia, disrupted the global supply system for all sources of energy. It has jeopardised the trust to a major nuclear energy partner until then, undermining the Community's security of supply of nuclear materials and services and aggravating dependence issues.

In response, the EU adopted far-reaching restrictive measures ([101]), targeting legal entities, natural persons, and a number of activities, but also affecting transport and trade. In the follow-up to the REPowerEU Plan ([102]), the Commission has published on 6 May 2025 the Roadmap towards ending Russian energy imports where several security of supply related measures were announced. ([103]). This includes trade measures on the import of enriched uranium, and restrictions on contracts co-signed by the Euratom Supply Agency for uranium, enriched uranium and other nuclear materials with Russian suppliers as of a certain date. The roadmap also envisages measures establishing specific targets for Member States to replace Russian nuclear fuels with alternative fuels, phase out reliance on Russia for uranium, enriched uranium and other nuclear materials, and increase transparency on dependencies and encourage diversification of Russian supplies of spare parts and maintenance services.

Meanwhile, various challenges emerged to transportation routes from Russia and via Ukraine, and to the logistics of nuclear fuels. Also, the air transportation route - that some countries opted for as replacement of the railway route through Ukraine – may be unavailable and exceptional. Fuel delivery through the Black Sea needs additional risk assessment as it is affected by Russia's war of aggression against Ukraine. Planned deliveries of Russian nuclear material and fuel may be further hindered in the evolving situation and due to emerging concerns of carriers refusing to transport, refusal to harbour or to deal with Russian goods amid public sensitivity and/or reputational risks.

Looking to future scenarios, demand in nuclear fuel cycle supplies and services is set to grow globally. At EU level, the 'high-capacity' scenario set out on the basis of Member States plans will also lead to increase demand in such supplies and services. Therefore, ensuring strategic autonomy and security of supply from ore to nuclear fuel should remain a critical objective of Member States with nuclear energy programmes. Moreover, all Member States should also consider the strategic importance of security of supply for nuclear technologies related to supply of

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([101]) Council Regulation (EU) No 833/2014 of 31 July 2014 concerning restrictive measures in view of Russia's actions destabilising the situation in Ukraine, as amended many times (the current consolidated version as of 13.4.2022).

([102]) REPowerEU Plan: Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of Regions, adopted on 18.5.2022 – COM(2022) 230 final.

([103]) Roadmap towards ending Russian energy imports, COM/2025/440 final/2.

radioisotopes. ESA provides support in monitoring developments in the nuclear fuel market and in relevant technological fields in order to identify market trends that could affect security of the European Union’s supply of nuclear materials and services (104).

The EU industry has sufficient access to supplies today and, in the short term, can tactically satisfy possible supply gaps via existing inventories. Yet only investments into new capacities, in particular for conversion services, will strategically resolve the issue. The market is already sensing the possible scarcity of low-risk supplies and prices have seen extraordinary increases in a short time.

As a first line of action, to ensure that uranium resources are available when needed on the global market, future supply would benefit from timely research and innovation aimed at enhancing uranium exploration and developing new, more cost-effective extraction techniques.

Most importantly, in the medium and long term, EU utilities’ demand for conversion and enrichment services face a starkened risk of shortages which Member States need to address with stimulus to adequate investments, bearing in mind that to make up for the additional conversion and enrichment capacity will take several years. Such investments may also be driven by increasing market opportunities.

Phasing out supplies from unreliable partners is a necessity. Against this background, increased cooperation between the EU and reliable international partners (see section 6.4) as regards uranium supply and nuclear fuel services will be beneficial to all parties. Recognising the need to find long term solutions, the EU and several states should coordinate to ensure genuine security of supply.

4.3. Supply chain for nuclear installations life cycle

In this section an analysis is provided of the supply chain for the ‘nuclear installation life cycle’. The supply chain network must ensure delivery of materials, components, and services essential for constructing, operating, maintaining, and dismantling nuclear installations within the EU. With a focus on installations such as reactors, this section covers front-end (new builds), operation and maintenance (including LTOs), and backend (decommissioning and waste management).

Over the past two decades, the EU’s nuclear supply chain reoriented towards maintenance and safety upgrades in the frame of plant outages and periodic safety reviews rather than new constructions. Moreover, an important number of installations shifted to decommissioning, with a consequent ramping up of waste production.

As a matter of fact, in this century, the rate of newly commissioned nuclear power plants was starkly lower than before. Since 2000 new nuclear power plants commissioned in Europe have been three European Pressurised Reactor (EPR), which were built or are still under construction in Finland, France, and the UK, two VVER-440, which had been in construction since the 1980’s in Slovakia, and one CANDU reactor in Romania.

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(104) https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32008D0114&from=EN

In the same period, the EU's supply chain has continuously and adequately provided services to operating plants, as demonstrated by implementation of 10-year Periodic Safety Reviews, of long-term operations, and of post-Fukushima safety upgrades at all nuclear power plants in Europe ([105]).

4.3.1. Supply of key materials for construction and operation

Nuclear industry makes use of a wide range of materials from those that are relatively common in other industries too (e.g. concrete, steel, copper) to specialty ones that enable functionality within a nuclear project (e.g. certain rare earth elements, boron, zirconium, and particular alloys). Concrete and steel account for the bulk of material requirements for a nuclear plant, see Table 9. ([106]) The table below provides an example of the range of materials need for a Pressurized Water Reactor.

Table 9 – Materials input requirements per kW for a Pressurised Water Reactor

Material	kg / kW
Concrete	180 – 560
Carbon steel	10 – 65
Wood	4,7 – 5,6
Stainless steel	1.56 – 2.10
Galvanised iron	1.26
Polyvinyl chloride (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, ISBN 978-0-12-385971-6.

Rare earth elements are used in nuclear reactor applications, predominantly in reactor control rods, for example: (i) Samarium-149 as strong neutron absorber in control rods; (ii) Europium due to its very low melting point and neutron absorption features;

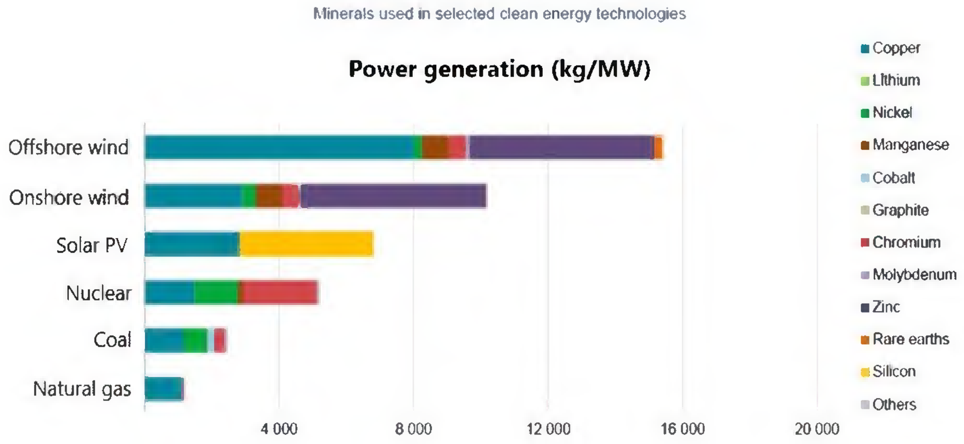
([105]) See PINC 2017 SWD pages 21-22 Box 4 and Follow-up of the peer review of the stress tests performed on European nuclear power plants | ENSREG

([106]) WNA report "The World Nuclear Supply Chain 2023 report" page 75-78

(iii) Gadolinium being very effective for use with neutron radiography and in shielding of nuclear reactors, providing greater durability of alloys. However, the dependency of nuclear reactors on rare earth is considered limited compared to other clean energy technologies, see Figure 25. ([107])

There are no clear signals that key materials used within the nuclear supply chain would not be accessible in the near-term. Nonetheless challenges may rise to access some materials in a cost-competitive and timely manner at the volumes required due to geopolitical and other factors, especially in case of stark demand for other types of clean energy technologies.

Figure 25 – Minerals used in selected energy technologies



Source: The Role of Critical Minerals in Clean Energy Transitions, World Energy Outlook Special Report, International Energy Agency, March 2022 (revised version), page 6.

4.3.2. Construction of new nuclear power plants

According to the WNA ([108]) there are currently 12 vendors of large-scale reactors ([109]) among which one is from the EU (Framatome).

The analysis of the relevant supply chain may be split into two segments: (i) primary circuit including the reactor, steam generator, main coolant pumps and pressuriser; and (ii) secondary circuit including the turbine, generator, condenser and in general the balancing of plant, see Figure 26.

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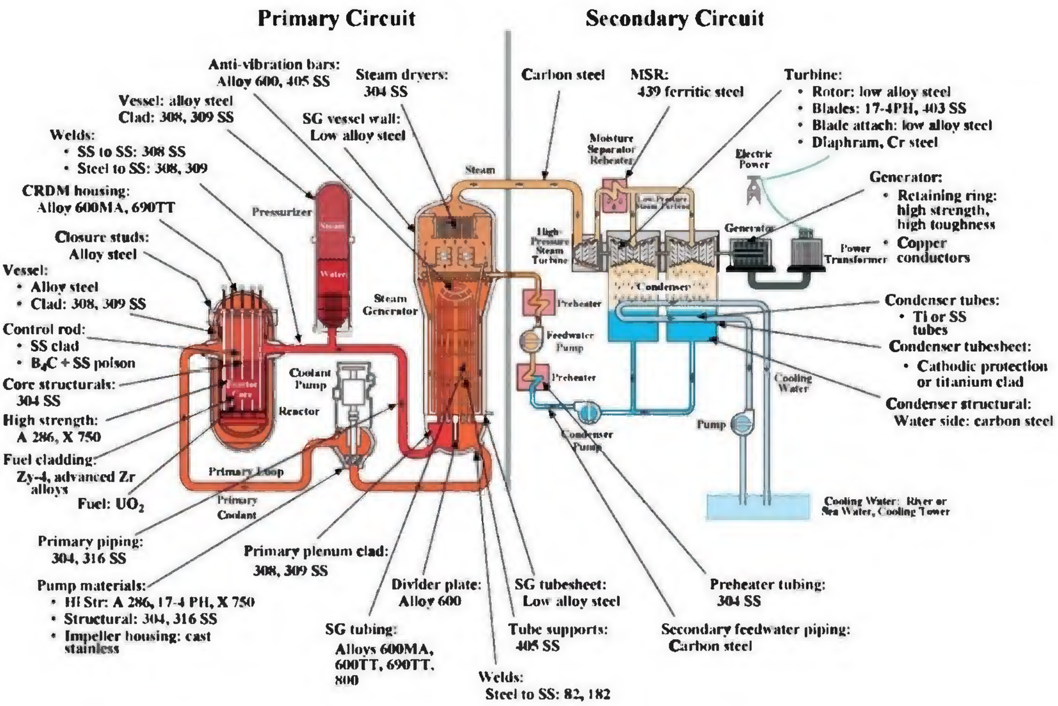
[107] Report on the European nuclear ecosystem, prepared by Deloitte for DG ENER, 2023 [yet unpublished].

[108] The World Nuclear Supply Chain, 2023 Edition, World Nuclear Association, 2023.

[109] SNC-Lavalin, China National Nuclear Corporation (CNNC), China General Nuclear Power Group (CGN), Framatome, GE Hitachi, Korea Electric Power Corporation (KEPCO), Mitsubishi Heavy Industries (MHI), Nuclear Power Corporation of India Ltd (NPCIL), Rosatom, State Power Investment Corporation (SPIC), Toshiba and Westinghouse Electric Company

Figure 26 – Main components of a Pressurised Water Reactor (PWR)



Source: Todd Allen et al., Materials challenges for nuclear systems, Materials Today, Volume 13, Issue 12, December 2010.

A representative "overnight" cost breakdown for nuclear new build is presented in the following Figure 27. 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% (110) of the overall overnight costs.

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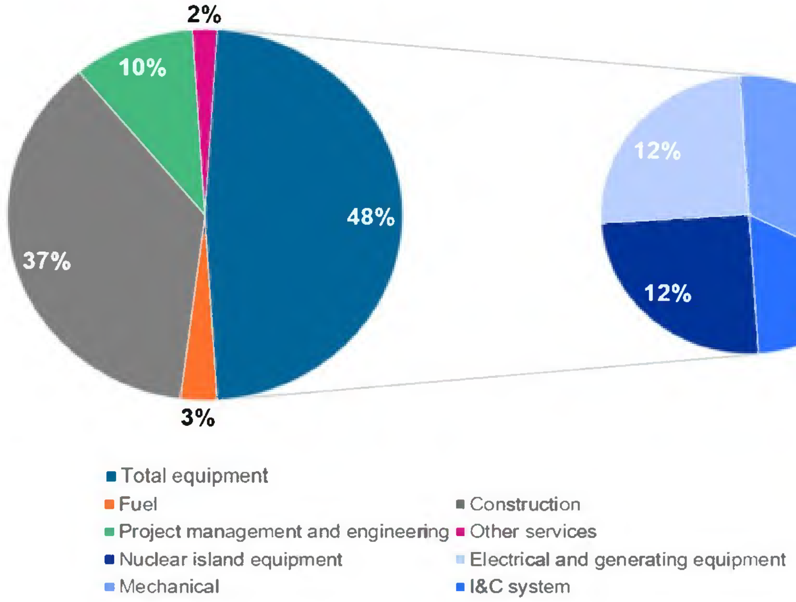
(110) Nuclear island equipment – 12%, Electrical and generating equipment – 12%, Mechanical – 16%, I&C system – 8%.

Figure 27 – "Overnight" cost breakdown for nuclear new-build



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

Notes: I&C = Instrumentation and Control.

The projected scenarios of new builds in the EU (see section 2.1) imply that the nuclear supply chain will have to ramp up to larger capacities and widen their scope of work to produce all needed components for a nuclear power plant (not only the replaceable ones). **To achieve constructing 60 GWe** of new nuclear power capacity by 2050, Member States and industry may need to **start building approximately 20 GWe of nuclear capacity simultaneously** (if constructions begin today, assuming an average construction time of about nine years). This would necessitate that about **15 large nuclear reactors are built concurrently in the EU over the next 25 years**. However, the analysis of Member States' NECP in Section 2 shows that the anticipated investment in large reactors is concentrated in the 2030s. In that decade, an even greater number of large-scale reactors will have to be built simultaneously to meet Member States' plans.

Notwithstanding the work and initiatives taken by the EU industry to maintain manufacturing capacities over the last two decades, there are still areas where capabilities have declined or disappeared in the EU, and which would need to be redeveloped to allow swift development of new units and regain EU sovereignty. This is in particular the case for the forging of heavy components (see Box below).

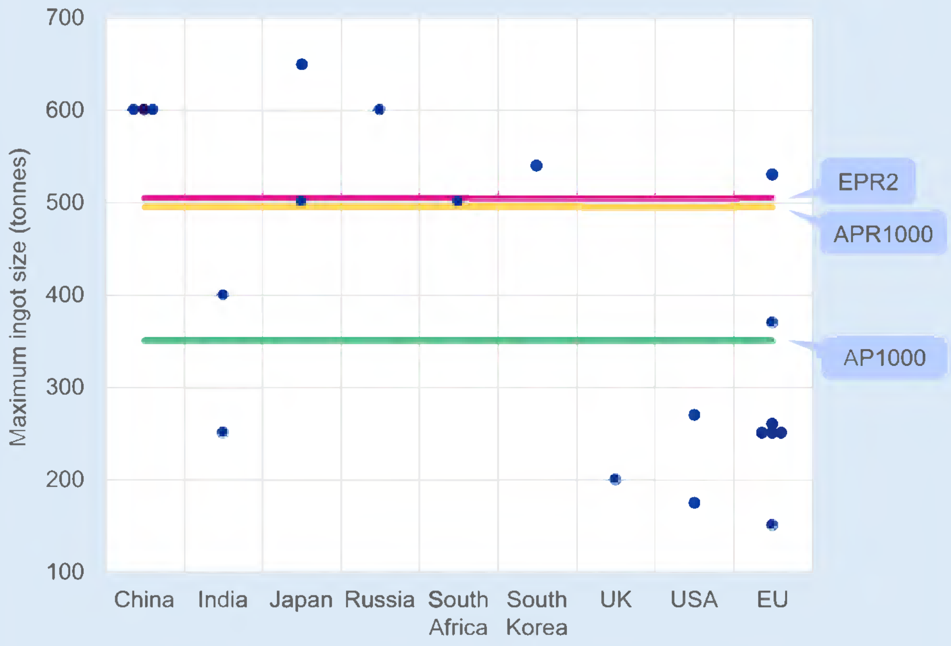
Box - Needs for heavy forging

Heavy forging is a critical component of the supply chain for new reactors building. Some reactor components are manufactured specifically for a particular reactor design, and there is accordingly a dedicated supply chain associated with each reactor vendor. Heavy forging capacity may become a limiting factor to the roll-out of plans for large scale nuclear power plants.

As reported by WNA (•), complemented by other sources of information (**), main large components of Generation III/III+ plants, such as reactor pressure vessels, are made from nearly 200 forgings, amounting to over 4000 tonnes of steel, some weighing around 500 tonnes each.

Member States with plans for new large nuclear reactors (e.g. Czechia, France, Poland) target currently the following models: EDF EPR2, Westinghouse AP1000, and KHNP APR1000. For these models, single ingot weight may well exceed 350 tonnes up to 500 tonnes.

The chart below shows how existing heavy forging companies are located geographically and what kind of reactors they may serve in particular for reactor pressure vessels forging. It appears that capacity for homegrown large reactors' components requires attention to sustain Member States plans, especially in relation to France.



(•) The World Nuclear Supply Chain, 2023 Edition, World Nuclear Association, 2023.

(**) Le Creusot - Framatome

4.3.3. *Long term operations*

As indicated by the WNA (111), long term operations involve the maintenance or replacement of a number of systems and components, such as:

- mechanical equipment for reactor vessel heads, steam generators, turbines, pumps, motors, valves;
- fluid systems piping replacement with corrosion-resistant materials, independent core cooling system, large diameter piping, buried piping replacement with high density polyethylene;
- electrical equipment alternators, transformers, high voltage posts, electrical boards;
- instrumentation and control (I&C) control room, cables, sensors;
- civil works cooling towers;
- post-Fukushima safety measures filter vents, emergency diesel generators, additional ultimate cooling systems;
- fire protection.

Consequently, many EU businesses thrived in the market of LTOs on EU nuclear power plants. This helped maintaining knowledge and activities. For example, in France the "*Grand Carénage*" (112) plan for the whole EDF fleet has been budgeted around EUR 65 billion (113) for the period 2014-2028, providing scope for work on most items mentioned above.

Another important element driving the availability of the supply chain is that not all components used in nuclear facilities must proceed from a unique "nuclear design". High quality components used in other industrial sectors (such as chemical, or oil & gas) can often be procured for use in safety-classified applications in nuclear power plants. These products are referred to as "commercial grade products". The nuclear industry made an effort to use such kind of products and to adapt them to nuclear requirements to compensate some shortage of specific nuclear components on the market. This evolutionary change started 40 years ago by the Electric Power Research Institute (EPRI) in the US, and later spread to international nuclear fleets in South Korea and Spain. In 2020, the European Commission Joint Research Centre published a comprehensive report about the current challenges of the European nuclear supply chain (114). This report highlighted the effort ongoing to address the concern of nuclear component obsolescence by replacing them with commercial grade products. Since then, utilities in Finland and Sweden also progressed in the frame of the KELPO project (115). In 2022, nucleareurope published an international guideline on this

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(111) The World Nuclear Supply Chain, 2023 Edition, World Nuclear Association, 2023.

(112) La R&D et le Grand Carénage - 28/05/2020 | EDF FR

(113) Éclairer l'avenir : l'électricité aux horizons 2035 et 2050 - Rapport - Sénat

(114) JRC Publications Repository - Current Challenges of the European Nuclear Supply Chain 2020.

(115) KELPO – Development of the licensing and qualification processes for the systems and equipment of nuclear facilities in Finland - Finnish Energy

topic (116). In 2023 the IAEA published detailed report about the "Suitability Evaluation of Commercial Grade Products for Use in Nuclear Power Plant Safety Systems" (117). All these elements show the challenges that the nuclear industry is facing with its supply chain and the replacement on certain components on its existing fleet.

With an ageing reactor fleet, over 80% of existing reactors will require extended maintenance, specialised component replacement, and regular upgrades to ensure safety and functionality. This will require large production capacities just to cope with replacements.

4.3.4. Distinctive features of Small Modular Reactors (SMRs)

SMRs (118) present both opportunities and challenges for the EU nuclear supply chain. In the framework of the European SMR pre-partnership (119), data were collected on the European supply chain via a questionnaire distributed to nucleareurope's member associations and through the analysis of publicly available information. Altogether the data originated from 200 companies.

The questionnaire was answered by 91 suppliers located in 10 European countries. Despite the non-comprehensive geographical coverage (120), gathered information provide a sample picture of the availability of suppliers in several EU countries and product sectors (see Figures 28–29).

The analysis showed that more than 60% of suppliers have pertinent know-how for more than one reactor technology, and about 30% of them have worked on more than two different reactor technologies. This is important in relation to the variety of technologies under development for SMRs and advanced modular reactors (AMRs). The analysis highlighted as well that many companies have track-records in working with different code & standards, including international standards (such as

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(116) Quality Assurance Guideline for Procuring High-Quality Industrial Grade Items Aimed at Supporting Safety Functions in Nuclear Facilities, Volume 1: Methodology and Volume 2: User's Guide, Foratom, March 2022

(117) Suitability Evaluation of Commercial Grade Products for Use in Nuclear Power Plant Safety Systems | IAEA 2023.

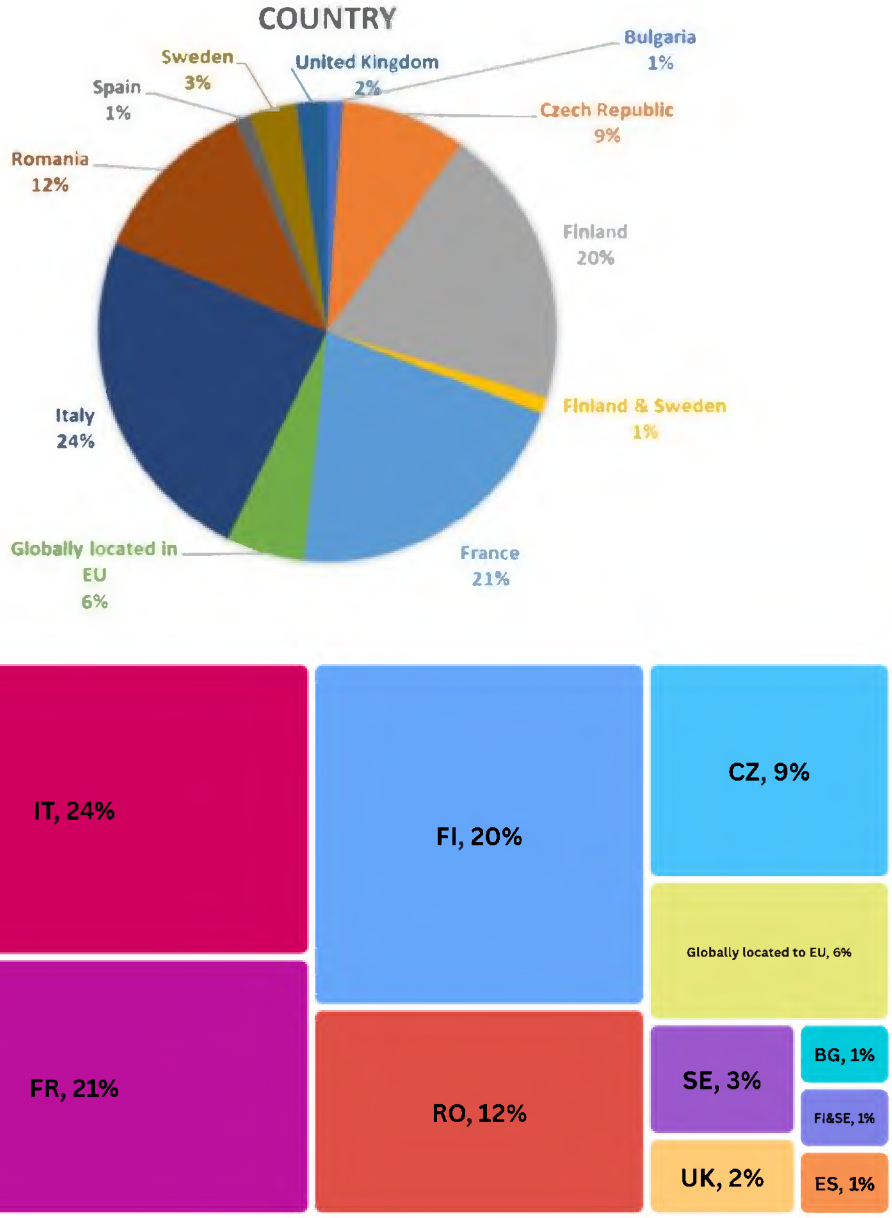
(118) Advanced Modular Reactors (AMRs) are a sub-category of SMRs. They typically use novel coolants (e.g., gas, liquid metal, molten salt) and advanced fuels. They often aim to achieve higher temperatures and efficiencies than current technologies.

(119) European SMR pre-Partnership, Workstream 4 – Supply Chain Adaptation, Technical Report, 2023. European SMR pre-Partnership - nucleareurope

(120) Among these 10 countries there was potential to gather more responses, particularly from Spain, the UK, and the Czech Republic. Additionally, no responses were obtained from certain countries with potential companies for the SMR supply chain, such as Germany and Belgium.

IEC (121)/IEEE (122)/ISO (123)), and for nuclear pressure vessel codes (such as AFCEN (124) or ASME (125)).

Figure 28 – Suppliers by country of origin (based on questionnaires)



Source: European SMR pre-Partnership, Workstream 4 – Supply Chain Adaptation, Technical Report, 2023.

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(121) International Electrotechnical Commission

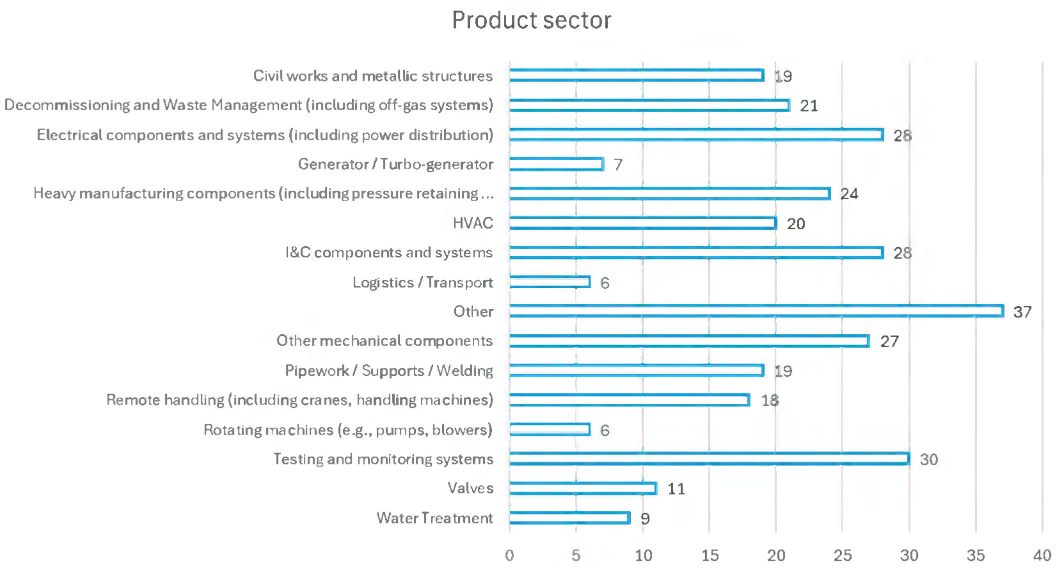
(122) IEEE SA - Standards

(123) ISO - Standards

(124) Association française pour les règles de conception, de construction et de surveillance en exploitation des matériels des chaudières électro-nucléaires Shaping the Rules for a Sustainable Nuclear Technology

(125) The American Society of Mechanical Engineers - ASME

Figure 29 – Company product sectors indicated by the respondents



Source: European SMR pre-Partnership, Workstream 4 – Supply Chain Adaptation, Technical Report, 2023.

4.3.5. *Decommissioning and waste management*

The back-end of the nuclear energy life cycle involves the safe management of spent fuel and radioactive waste (including disposal), as well as the safe decommissioning of the nuclear facilities.

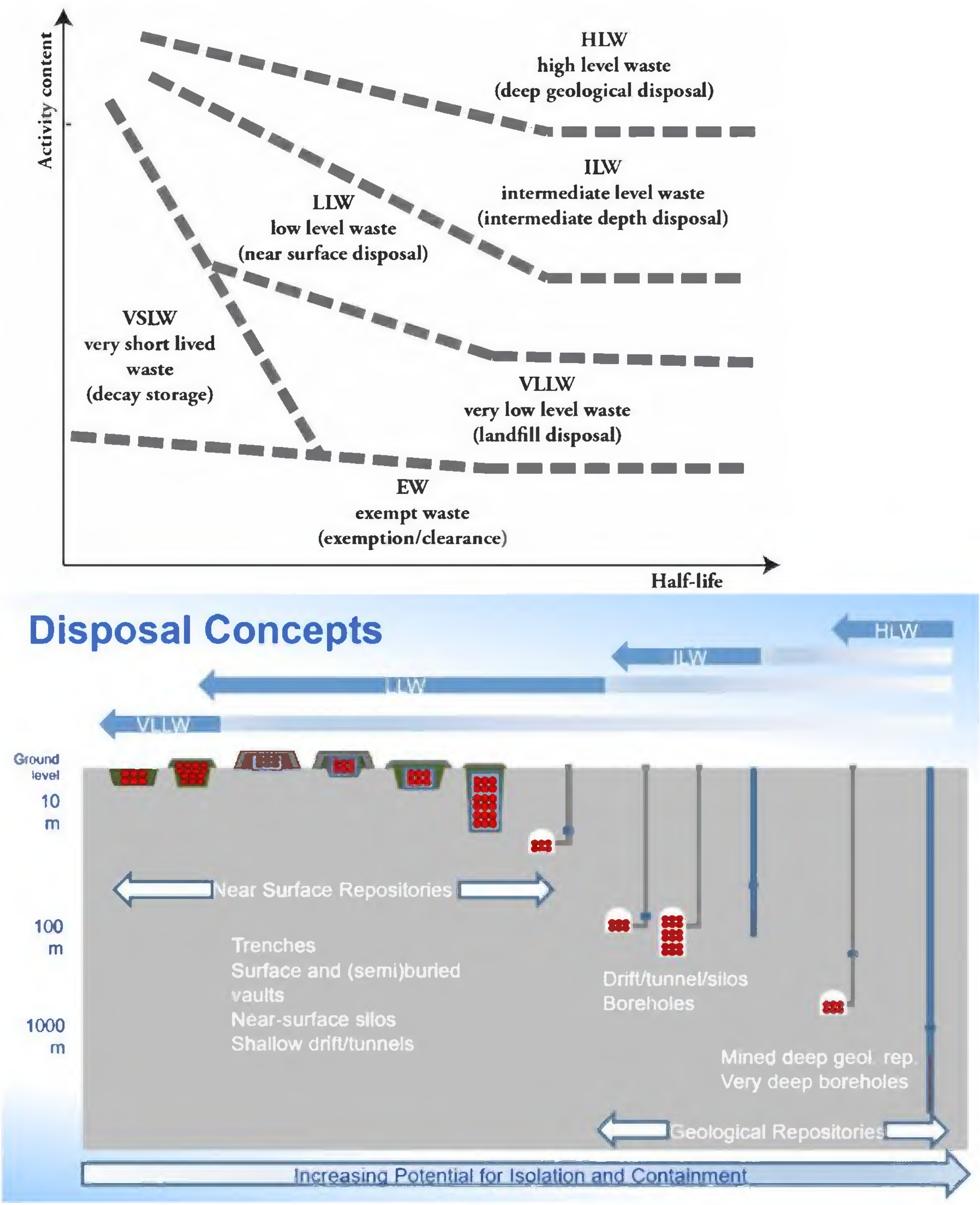
In lay terms, decommissioning ([126]) means all activities to be carried out after the final shut-down of a nuclear installation to remove and dismantle equipment and to demolish the buildings, if need be, until the release of its site for other uses or re-use for a new nuclear installation. Decommissioning is highly interconnected to the spent fuel and radioactive waste management.

Radioactive waste ([127]) is classified under national programmes according to its hazards and the available or planned management routes. In general, radioactive waste can be classified as high-level (HLW), intermediate-level (ILW), low-level (LLW) and very-low-level waste (VLLW). This classification together with the suitable disposal concepts are presented in Figure 30.

([126]) 'Decommissioning' refers to "administrative and technical actions taken to allow the removal of some or all of the regulatory controls from a facility" - IAEA Nuclear Safety and Security Glossary.

([127]) 'Radioactive waste' means radioactive material in gaseous, liquid or solid form for which no further use is foreseen or considered by the Member State or by a legal or natural person whose decision is accepted by the Member State, and which is regulated as radioactive waste by a competent regulatory authority under the legislative and regulatory framework of the Member State – Council Directive 2011/70/Euratom.

Figure 30 – Waste classification and disposal concepts



Source: Classification of Radioactive Waste, IAEA Safety Standards Series No. GSG-1, General Safety Guide.
Status and Trends in Spent Fuel and Radioactive Waste Management, IAEA Nuclear Energy Series No. NW-T-1.14 (Rev. 1).

The vast majority of radioactive waste is classified as low-level waste or very-low-level waste and originates from day-to-day activities at nuclear power plants and other nuclear installations, as well as during their decommissioning. This kind of waste is also the main waste stream from the use of radioisotopes, including in medical applications.

Council Directive 2011/70/Euratom provides the requirements for the management of spent fuel and radioactive waste from generation to disposal. The Directive states that radioactive waste shall be disposed of in the Member State in which it was generated, unless there are appropriate agreements with other countries. Each Member State has their national programme for management of radioactive waste and spent fuel. The Directive requires that Member States ensure the implementation of their respective national programmes, covering all types of spent fuel and radioactive waste under their jurisdiction and all stages of spent fuel and radioactive waste management from generation to disposal. National policies shall ensure that the costs for the management of spent fuel and radioactive waste, from their generation through the final disposal, are borne by those who generated the materials (128).

The Commission publishes periodically the radioactive waste and spent fuel inventory in the EU (129) under the Community framework for the responsible and safe management of spent fuel and radioactive waste (130). In the EU, about 40,000 m^3 of radioactive waste and around 1,000 tonnes of heavy metal (131) of spent nuclear fuel are generated each year against a supply of 620 TWh of electricity taking year 2023 as reference (132). More than 90% of radioactive waste is classified either as very-low-level or as low-level, while high-level waste accounts for 0.2%, the rest being intermediate-level waste.

Looking at the geographical distribution of radioactive waste in the countries with past or present nuclear power programmes, most of waste was produced in the Member States with larger fleets of nuclear power plants (see Figure 31).

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(128) Council Directive 2011/70/EURATOM

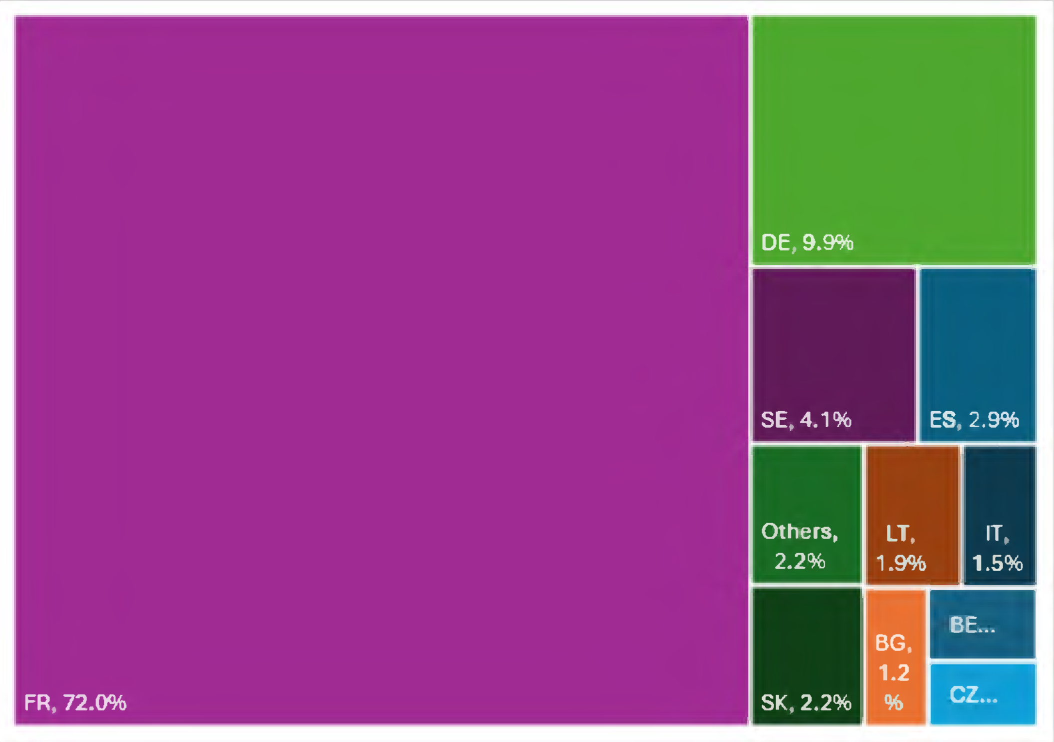
(129) COM(2024) 197 final - Report from the Commission to the Council and the European Parliament on progress of implementation of Council Directive 2011/70/EURATOM and an inventory of radioactive waste and spent fuel present in the Community's territory and the future prospects - THIRD REPORT

(130) Council Directive 2011/70/Euratom.

(131) Tonnes of heavy metal, abbreviated as tHM, is a unit of mass used to quantify uranium, plutonium, thorium and mixtures of these elements.

(132) Shedding light on energy in Europe – 2025 edition, ESTAT, ISBN 978-92-68-22424-3

Figure 31 – Distribution of total volumes of radioactive waste in Member States with nuclear power programme (end of 2019)



Source: 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 - THIRD REPORT.

In the EU, generally there has been significant progress in the disposing of very-low-level or low-level waste. Further efforts are required for intermediate-level waste.

In relation to high-level waste, concerned Member States need to put in place the infrastructure to dispose of it. There is an international consensus that the safest option is to dispose of high-level waste in stable geological formations usually several hundred metres or more below the surface. Finland is close to operating the national deep geological repository for spent fuel; this is a first-of-a-kind facility worldwide. The construction licence for a similar facility in Sweden was issued lately. France is advancing with the underground preparations and the authorisations. These examples demonstrate EU leadership in the sector; that leadership needs be followed by other concerned Member States that should possibly accelerate their plans (see Figure 32). Effective decommissioning and responsible management of radioactive waste and spent fuel are key to continued public support to the use of nuclear energy in Member States (133), and a fundamental pre-requisite for classifying certain nuclear activities

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(133) The responsible management of radioactive waste and spent fuel continues to attract interest from a broad range of civil society stakeholders. A recent example is an art installation addressing the longevity of deep geological repositories, which was presented at the Luxembourgish centre for contemporary art, Casino Luxembourg, in the summer of 2024.

as sustainable, as established by the Commission under the Taxonomy regulation (134).

Figure 32 – Planned start-up of operation of deep geological repositories

Source: Adapted from 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 - THIRD REPORT

Directive 2011/70/Euratom requires each Member State to estimate national programme costs and put in place financing schemes for the safe and responsible management of radioactive waste. Member States' estimates vary widely in terms of methodology, assumptions, completeness of data, scope and time frames. In the latest report published by the Commission (135), the overall EU cost estimate for the management of all radioactive waste, i.e. including waste generated from past activities, all waste expected from ongoing and future activities, and decommissioning of operational activities, was around EUR 300 billion (136). Preliminary analysis of national updates provided in 2024 shows that, while Member States have somewhat improved the quality of assessments, the overall cost estimate is relatively stable. The Commission will publish such updates as per the requirements of the Radioactive Waste Directive.

Decommissioning of nuclear reactors and management of decommissioning waste is becoming more and more important, as a large number of nuclear power reactors were shut down, and the current global fleet of operating power reactors is ageing.

On the one hand, as of end 2023, 74 nuclear power reactors were at different stages of decommissioning in the EU and plans were reported for those installations which are still operating. In the last decade, decommissioning activities progressed significantly on several sites, supported by the EU supply chain which proved to be capable and knowledgeable. Yet only 3 reactors were declared fully decommissioned to date, and the time lapse from shut-down date is steadily increasing (see Figure 33).

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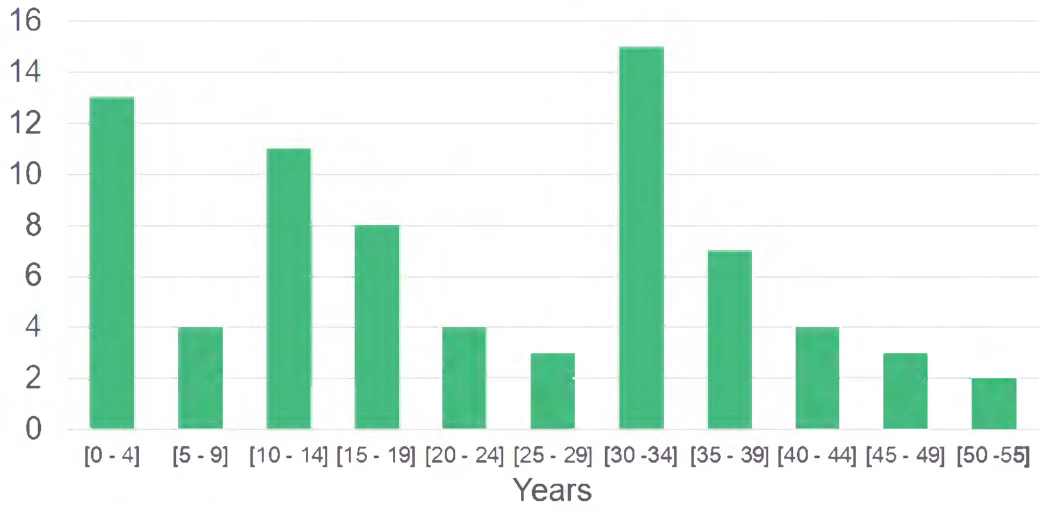
(134) Regulation (EU) 2020/852, OJ L 198, 22.6.2020, p. 13–43; Commission Delegated Regulation (EU) 2022/1214, OJ L 188, 15.7.2022, p. 1–45, EU taxonomy for sustainable activities - European Commission

(135) COM(2024) 197 final - 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 - THIRD REPORT

(136) This figure represents the sum of Member States' individual estimates. Member States' estimates vary widely in terms of methodology, assumptions, completeness of data, scope and time frames. Individual Member States' figures may or may not represent a present value figure.

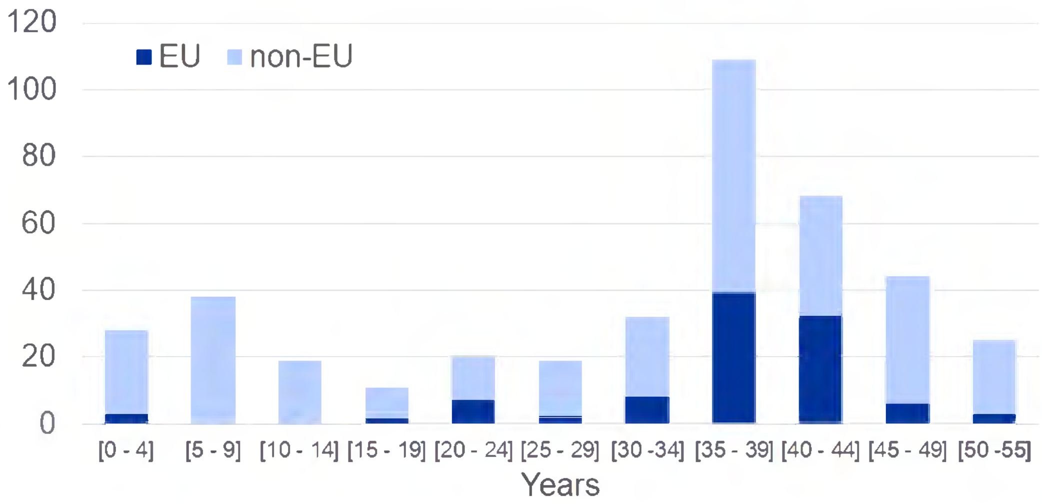
Figure 33 – Number of power reactors in decommissioning by time elapsed since shut-down (as of 31 December 2023)



Source: European Commission's analysis of IAEA PRIS and IAEA RDS-2.

On the other hand, as of end 2023, more than one third of power reactors had been in operation for longer than 40 years worldwide; in the EU that amount rises beyond 40% (see Figure 34).

Figure 34 – Number of operational reactors by age (as of 31 December 2023)



Source: European Commission's analysis of IAEA PRIS and IAEA RDS-2.

Decommissioning of shutdown nuclear power plants generates large amounts of materials, and this means that in the next decades, the amounts of waste from decommissioning will grow. A very large share of those materials is typically released from regulatory control as non-radioactive and recycled or reused in line with circular economy principles. However, the rest is managed as radioactive waste and mostly belongs to the categories very-low-level and low-level waste (see box for a concrete case).

A topical study on the market for decommissioning nuclear facilities in the EU (137) provided an estimate of the budgets for decommissioning and dismantling activities of nuclear power plants over the coming century: about EUR_{2016} 80 billion (138). That study provided also a projection over time of expenditures over time: between EUR 1.4 billion and EUR 2.2 billion per year until 2035; up to about EUR 3.0 billion per year in 2045. Besides several other factors, actual expenditures will clearly depend on lifetime extensions (see section 2), however those figures represent valid proxies of the order of magnitude of the decommissioning market value (139).

The Commission set up the Nuclear Backend Financial Aspects expert group (NuBaFA) in April 2021 to help analyse financial aspects of nuclear decommissioning, spent fuel and radioactive waste management, such as cost estimations, financing mechanisms, securing of required funds and their management. NuBaFA took over from the former Decommissioning Funding Group (DFG), which was introduced by Commission Recommendation 2006/851/Euratom (140) and is composed of representatives appointed by EU countries, with a high level of expertise in the financial aspects of nuclear decommissioning and spent fuel and radioactive waste management.

To further support Member States, the Commission published studies on the risk profile of the funds allocated to finance the back-end activities of the nuclear fuel cycle in the EU (141) and on methodologies of cost assessment for radioactive waste and spent fuel management (142).

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(137) European Commission: Directorate-General for Energy, *Study on market for decommissioning nuclear facilities in the European Union*, Publications Office, 2019, https://data.europa.eu/doi/10.2833/20237.

(138) The budgets needed for decommissioning and dismantling may evolve over time if Member States change nuclear provision requirements.

(139) Euratom decommissioning assistance programmes are distinct from forward-looking nuclear investment planning.

(140) Commission Recommendation on the management of financial resources for the decommissioning of nuclear installations, spent fuel and radioactive waste, OJ L 330, 28.11.2006, p. 31–35, EUR-Lex - 32006H0851 - EN - EUR-Lex

(141) European Commission: Directorate-General for Energy, Briedyte, A., Lau, J., Bauer, G., Koenig, R. W. et al., Study on the risk profile of the funds allocated to finance the back-end activities of the nuclear fuel cycle in the EU, Publications Office, 2019, https://data.europa.eu/doi/10.2833/882170

(142) European Commission: Directorate-General for Energy, Deloitte, NucAdvisor and VVA, Methodologies of cost assessment for radioactive waste and spent fuel management – An overview of the practices adopted in the EU, Publications Office of the European Union, 2020, https://data.europa.eu/doi/10.2833/476584

Box - Decommissioning Bohunice V1 nuclear power plant in Slovakia

The European Union has co-financed the decommissioning programme of the Bohunice V1 nuclear power plant in Slovakia. This is a meaningful case for a brief technoeconomic evaluation, as the programme is close to completion.

The Bohunice V1 nuclear power plant consisted of two VVER-440 reactors which operated from 1980 until 2006 and from 1981 until 2008, respectively, generating 148.53 TWh of electricity altogether. These reactors were shut down prior to their design lifetime.

The decommissioning programme set a budget of EUR 1.237 billion to carry out all decommissioning and waste management activities including disposal of very-low-level and low-level waste, and interim storage of intermediate-level waste and spent fuel. Accordingly, the budget covered all the back end for this installation, except the geological disposal facility.

As of end 2024, the reactors had been fully dismantled, and the clean-up of reactors' building was close to completion. At the same time the contract was kicked-off for the execution of the last stage of decommissioning, consisting of demolishing of the reactors' building. Therefore, the level of maturity of the programme is high and the set budget will eventually differ marginally from incurred final costs.

On this basis, the unit cost for decommissioning of Bohunice V1 nuclear power plant may be estimated at EUR 8.33 per supplied MWh. While it is not possible to generalise the estimate for other decommissioning projects, it is a valid approximation of the relative magnitude of decommissioning costs to be compared with LCOE (•) for new large-scale reactors (†). It is expected that decommissioning unit costs per supplied MWh will be sensibly lower for reactors that operated for the whole design lifetime or beyond that.

The Bohunice V1 decommissioning programme has been also a concrete case of application of circular economy principles. Up to 99% of the total amount of materials (metals, concrete) resulting from dismantling/demolishing operations, including the actual reactors' components, were decontaminated for release and recycling. (‡)

(•) Levelised Cost Of Electricity (LCOE) = average cost of electricity generation over the economic lifetime of a production asset, including capital, operation and maintenance, fuel, and decommissioning.

(†) For new large-scale nuclear reactors, the projected LCOE in 2040 in the European Union ranges between EUR 69/MWh (USD 75/MWh) and EUR 101/MWh (USD 110/MWh). Source: IEA - The Path to a New Era for Nuclear Energy, January 2025.

(‡) COM(2024) 181 final - Report from the Commission to the European Parliament and the Council on the implementation of the work under the nuclear decommissioning assistance programme to Bulgaria, Slovakia and Lithuania and JRC programme in 2022 and previous years.

4.3.6. *Findings and conclusions on nuclear installations supply chain*

The EU's nuclear industry is facing significant challenges in responding to current and future nuclear development trends across the segments including new builds and lifetime extensions, (as well as decommissioning and waste management). Therefore, the industry has to undergo a substantial transformation to increase its capacity, effectiveness, and competitiveness. At the same time, the supply chain must make efforts to become sufficiently resilient and agile to be prepared for potential future disruptions that might arise from geopolitical shocks, (un)availability of raw materials, or climate change. At the same time, the supply chain must make efforts to address the diversification of nuclear technologies: a new generation of large-scale power plants, SMRs and AMRs, which need different technologies and components.

To address current and future needs, the EU nuclear supply chain will have to adapt via avenues such as standardisation and enhanced cooperation, as there are challenges such as reattracting suppliers who have left the sector, modernising existing infrastructure, and enhancing efficiencies to meet increased demand. The main prerequisite to drive supply chain capacities at scale is that Member States planning to use nuclear energy hold long-term policy commitments, for market conditions to stabilise under consistent plans for construction of new reactors.

While there are efforts to standardisation and harmonisation in technical codes and safety practices, varying requirements which continue to exist between EU countries can delay construction and add to costs. Socio-economically, the EU nuclear sector needs substantial investment to revitalise its workforce, infrastructure, and manufacturing capabilities. The sector's competitiveness could also be enhanced through coordinated policies and public engagement to address concerns about safety, environmental impact, and long-term waste management.

Specifically, the challenges associated with supply chain development for SMRs remain substantial, because the supply chain has to flexibly cope with many different designs and manufacturing requirements. SMR production emphasises standardisation at all levels, from system design to component fabrication, calling for a higher degree of standardisation and regulatory harmonisation across the EU to avoid design modifications when deploying SMRs in various countries. Additionally, AMRs, which incorporate innovative designs, pose challenges in terms of development of supply chain for new components using advanced materials, requiring also specialised workforce training (143).

The Net-Zero Industry Act (NZIA) aims to enhance European manufacturing capacity for net-zero technologies and their key components, addressing barriers to scaling up production in Europe. The Regulation aims at increasing the competitiveness of the net-zero technology sector, attracting investments, and improving market access for clean tech in the EU. Following the adoption of NZIA, secondary legislation and a Communication address which components qualify as primarily used for net-zero technologies under the NZIA, rules on non-price criteria in renewable energy auctions, main specific components relevant for the NZIA access to markets chapter, information on where the EU's supply of net-zero technologies comes from, and common criteria on strategic project selection.

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(143) Proceedings of the EDF European Supplier Workshop, Paris, 4 June 2024.

5. INNOVATION

The competitiveness of the nuclear industry will also depend on its ability to introduce innovations. Within the EU, there is sufficient experience, know-how, technology, and resources to make progress in this area.

This chapter discusses two major subjects for innovation where EU industry is involved, and expectations are high: Small Modular Reactors (covered in Section 5.1) and Fusion (discussed in Section 5.2).

5.1. Small Modular Reactors

Small Modular Reactors (SMRs) ([144]) present both opportunities and challenges for the EU nuclear sector. These reactors, which are smaller and could be built in modular units, are set to offer flexibility in addressing diverse energy needs, including district heating, industrial power, and hydrogen production. The scalability of these reactors, both, Generation III+ and Generation IV designs, aligns well with EU decarbonisation goals and could serve as a complement to renewable energy, addressing gaps in power supply due to renewables' variability.

Besides small reactors (with power output up to 300 MW), the development of microreactors holds an important market potential. Microreactors could fit into shipping containers and can be delivered in remote sites to provide up to 20 MW, so to compete with electric batteries as a source of zero-carbon energy, and to replace diesel and gas generators.

These innovative reactors promise to offer shorter construction times and potential for cost efficiencies through modularisation and series effect.

Several EU Member States consider the use of nuclear energy in combination with renewable and other low-carbon sources. Most envisage the technology of SMRs as a complement to large scale nuclear reactors, contributing to delivering at least 90% carbon emission reduction by 2040, while increasing the strategic autonomy and resilience of the European economy.

In line with the EU's climate neutrality objective strategy, the Commission has considered the role of low-carbon energy sources in the context of the Communication "Securing our future. Europe's 2040 climate target and path to climate neutrality by 2050 building a sustainable, just and prosperous society" which was adopted in February 2024 ([145]). In parallel, the Commission launched "*an Industrial Alliance to facilitate stakeholder's cooperation at EU level and to accelerate the deployment of Small Modular Reactors (SMRs)*" (see section 5.1.5).

5.1.1. Technology of modular reactors

Modular reactors may bring notable innovation to the nuclear industry, offering several advantages over traditional large scale nuclear power plants. As per the

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([144]) Advanced Modular Reactors (AMRs) are a sub-category of SMRs. They typically use novel coolants (e.g., gas, liquid metal, molten salt) and advanced fuels. They often aim to achieve higher temperatures and efficiencies than current technologies.

([145]) COM(2024) 63 final

definition set by IAEA "*SMRs are advanced reactors with a power capacity of typically up to 300 MW(e) per unit*" ([146]), i.e. significantly smaller than current large size operating nuclear reactors which normally have power outputs between 900 MWe and 1,700 MWe. The front runner SMRs are based on Light Water Reactor (LWR) technology, like most large reactors currently operating around the world. SMRs comprise also the so-called Advanced Modular Reactors (AMRs), whose designs are comparable to Generation IV reactors (such as High Temperature Reactors – HTRs, Molten Salt Reactors – MSRs, and Liquid Metal Fast Reactors – LMFRs) ([147]), see Table 10.

Table 10 – Examples of SMRs (non-exhaustive list)

Reactor type	Description	Examples
Light Water Reactors (LWRs)	LWRs are similar to most existing nuclear power plants but on a smaller scale. They use water as both a coolant and a neutron moderator.	• Nuward (EDF) • NuScale VOYGR™ SMR • GE-Hitachi BWRX-300 • Rolls-Royce SMR • CityHeat project (Calogena, Steady Energy)
High-Temperature Gas Reactors (HTRs)	These reactors typically use helium as coolant and graphite as a moderator. They can achieve higher temperatures than LWRs, allowing for more efficient power generation and for high-temperature heat use in industrial applications.	• Jimmy Energy • Blue Capsule
Molten Salt Reactors (MSRs)	MSRs use a mixture of salts, typically as both the coolant and fuel, allowing for operation at higher temperatures and near to atmospheric pressure.	• Thorizon • NAAREA • STELLARIA
Liquid Metal Fast Reactors (LMFR)	These reactors use a metal or metal alloy (such as sodium or lead) as coolant and can operate at high temperatures without high pressure. They are targeting to close the nuclear fuel cycle, burning high level radioactive waste and plutonium originating from other reactors, producing, at the same time, electricity and/or heat.	• EU-SMR-LFR project (Ansaldo Nucleare, SCK•CEN, ENEA, RATEN) • European LFR AS Project (newcleo) • HEXANA, OTRERA

Source: European Commission.

In the field of AMRs several companies are now also developing microreactors, which are typically based on the Generation-IV technology and a power output up to 20 MW. Microreactors are conceived to operate like large batteries with no control rooms or workers on-site. A recent technoeconomic analysis performed by Idaho

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([146]) Advances in Small Modular Reactor Technology Developments, A Supplement to: IAEA Advanced Reactors Information System (ARIS), 2022 Edition, © IAEA, 2022.

([147]) Generation IV International Forum | GIF Portal

National Laboratory in the frame of US Department of Energy – Microreactor Program (148) indicated that a levelised cost of energy around 140 USD/MWh is achievable. Such cost level would make microreactors not competitive to serve the electricity grid, however their use in difficult to access markets, where energy costs are high, such as remote mining sites, oil and gas industry both on and offshore. Several companies are also currently envisaging such type of designs to power ships for maritime transport. Moreover, the defence industry has showed interest for transportable nuclear reactors (including via air).

Several companies are also currently envisaging such type of designs to power ships for maritime transport. From a technological point of view, SMRs could significantly reduce the environmental footprint of shipping by replacing heavy fuel oil and marine diesel with nuclear fission-based energy. However, apart from specific technical challenges linked to having a nuclear propelled ship, there are several regulatory barriers which would need to be overcome, the economic viability would need to be demonstrated, and attaining public acceptance could be even more difficult than for a land-based SMR.

Envisaged advantages of modular reactors are production as factory-built modules (enabling efficiency of production through the scale effects of in-series manufacturing), a smaller land footprint and reduced cooling water usage, as well as reduced construction and operational costs, potentially making them a more appealing choice for private investors.

SMR have the potential to supply electricity and can serve as a reliable source of heat for specific industries and urban districts as well as for low-carbon hydrogen production. Additional potential applications include power generation for grid balancing or for power supply of data centres, mining operations currently using diesel generators, and desalination. Ongoing feasibility studies like the Euratom Research and Training Programme project TANDEM (149) are investigating the utilisation of SMRs for integration into hybrid energy systems, generation of off-the-grid electricity for industrial clusters and as power sources for hydrogen production hubs (150). The Sustainable Nuclear Energy Technology Platform (SNETP) works on the European Nuclear Cogeneration Industrial Initiative (NC2I), which aims at demonstrating innovative and competitive energy solutions for the low-carbon cogeneration of heat and electricity, and hydrogen production based on nuclear energy (151). The Generation IV International Forum (GIF) was created in 2001 as a co-operative international endeavour seeking to develop the research necessary to test the feasibility and performance of fourth generation nuclear systems (Gen-IV

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(148) Botros N. Hanna et al. Technoeconomic Evaluation of Microreactor Using Detailed Bottom-up Estimate, INL/RPT-24-80433, Revision 1, 2024.

(149) TANDEM

(150) The Euratom Research and Training Programme addressed the growing interest in SMRs by funding research with a particular focus on their safety features and passive safety systems. Five research projects, as well as research at the JRC, aim to verify potential advantages of SMRs in terms of design simplification and inherent safety features. They also address new challenges with regard to safety, security and safeguards. By supporting design improvements, Euratom funded research facilitates the work of the European Industrial Alliance on SMRs, see Interim evaluation of the 2021-2025 Euratom research and training programme.

(151) SNETP, NC2I

systems), and to make them available for industrial deployment by 2030 (152). Thus, some of GIF's work may also support the development and deployment of AMRs.

5.1.2. Hybrid energy systems

Numerous analyses (153) consistently substantiate that SMRs will complement, rather than compete with large-scale nuclear plants and renewable energy sources. Instead, SMRs may help achieve an integrated, secure, stable, high-efficient and resilient energy system. SMRs could be instrumental in future hybrid energy systems, contributing to clean hydrogen production, and to significant reductions in greenhouse gas emissions.

For instance, SMRs could provide power supply that can quickly adjust balancing energy needs of the grid, thus contributing to overall grid resilience.

Furthermore, SMRs can be deployed in a wider variety of locations than large-size nuclear power plants for efficient utilisation of existing infrastructure and integration of diverse and complementary energy sources within a given region.

Modular reactors could also play a dual role in low-carbon hydrogen production. Besides directly supplying electricity for conventional electrolysers, AMRs could also serve as providers of heat for high-temperature steam electrolysers, yielding a significant reduction in electricity consumption per kilogram of hydrogen produced. If these dual advantages turn out implementable and scalable, SMRs could emerge as potential catalysts for supporting the expansion of the clean hydrogen market in Europe.

5.1.3. Potential development of modular reactors in the EU

There is a potential market for modular reactors in the EU, yet no SMRs have so far been put in operation in Europe. It is anticipated that the first SMRs will be operating in Europe in the early 2030s. As part of the European SMRs pre-Partnership (see section 5.1.5), a group of European experts from sector organisations conducted a detailed analysis of the potential development of SMRs and AMRs in the EU, exploring their various applications such as electricity generation, industrial heat, district heating, and hydrogen production. These studies led to the creation of three scenarios and projections for SMR development between 2030 and 2050, which were published in a report in July 2023. The projections for the two main scenarios (a "current projection" scenario (154) and a "boosted development" scenario (155) estimate SMR capacity to range from 17 GW to 53 GW by 2050, with half of this capacity dedicated to heat and hydrogen production, see Figure 35. Additionally, all three scenarios project a significant acceleration in development by 2040, aligned with the larger-scale deployment of AMRs.

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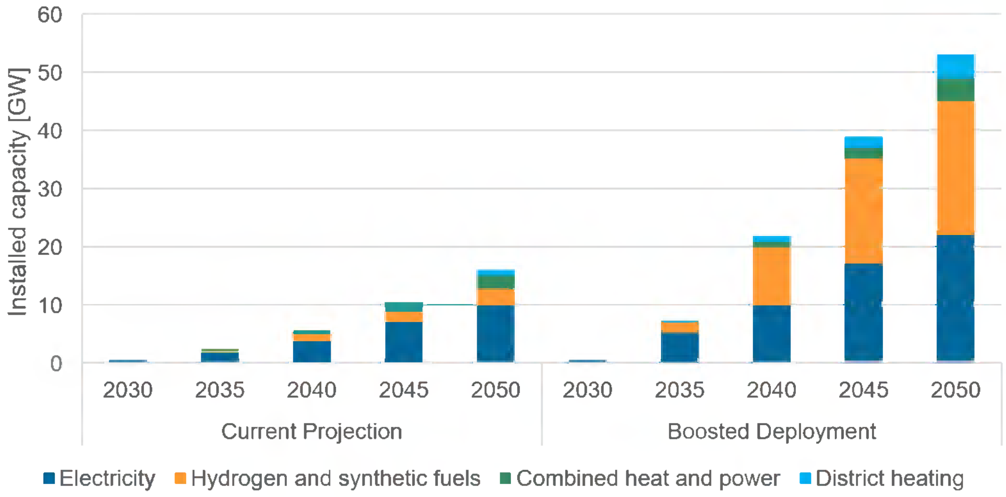
(152) GIF

(153) IEA (2025), The Path to a New Era for Nuclear Energy, IEA, Paris; NEA (2021), Small Modular Reactors: Challenges and Opportunities.

(154) Scenario based on the SMRs/AMRs projects announced in 2023 with an assumption that half of these projects would reach completion.

(155) Scenario including in addition: successful deployment of the necessary supply chain in the EU, success in licensing harmonisation and new projects starting following success of the first ones.

Figure 35 – SMR deployment scenarios



Source: European SMR pre-Partnership Report, Workstream 1 – Market Analysis, 2023.

Notes: In GWe for electricity and hydrogen; in GWth for industrial heat and district heat.

Recently, several other reports were published on the subject. While some of them like the IAEA “Energy, Electricity and Nuclear Power Estimates for the Period up to 2050” (156) or the NEA “Small Modular reactor Dashboard, 2nd edition” (157) do not detail precisely the capacity of SMRs development in Europe, they still emphasise the high potential for SMRs development in the World.

Other reports like the IEA “Path to a new era for nuclear energy” (158) or the Compass Lexecon for nucleareurope “Pathways to 2050: the role of nuclear in a low-carbon Europe” (159) provide more detailed information about potential scenarios for SMRs development in Europe. These different projections confirmed the projections made in the frame of the European SMRs pre-Partnership and range from 10 GWe to round 50 GWe of SMRs capacity installed by 2050 in Europe. This development is conditioned by the existence of a well-functioning nuclear supply chain in Europe, a highly skilled workforce, large-scale investments of public and private resources and broad research capabilities.

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(156) Energy, Electricity and Nuclear Power Estimates for the Period up to 2050, Reference Data Series No. 1, 2024 Edition, © IAEA, 2024.

(157) NEA (2024), The NEA Small Modular Reactor Dashboard: Second Edition.

(158) IEA (2025), The Path to a New Era for Nuclear Energy, IEA, Paris https://www.iea.org/reports/the-path-to-a-new-era-for-nuclear-energy, Licence: CC BY 4.0

(159) Pathways to 2050 - nucleareurope

Box – Data centres and Artificial Intelligence may drive the SMRs' roll out

Data centres have become a major electricity consumer and are set to increase their energy demand with Artificial Intelligence (AI) steadily ramping up the digitalisation of the global economy.

Based on US Energy Information Administration database, in 2020 only 22 countries worldwide had a bigger annual electricity demand than the global portfolio of Data Centres. The total global energy demand for data centres now exceeds the consumption of most economies, and they account for around 2% to 4% of global greenhouse gas emissions. In 2020, the global portfolio of Data Centres consumed 250 TWh of electricity (†); for comparison, in the same year the EU consumed 2,463 TWh, with Italy at 283 TWh and Spain at 223 TWh (‡).

The "2024 United States Data Center Energy Usage Report" (*) revealed that from 2016 to 2023 electricity consumption from data centres tripled in the US and projected a possible further triplication in 2028. As a result the report also estimated a total power demand for data centres between 74 GW and 132 GW.

In response to environmental regulations the industry is facing increasing demands for sustainability reporting, with existing policies already directly targeting data centre sector. Nuclear technology as a solution to access a low-emission, abundant, dense and continuous energy source fit well the growing need to reduce data centres carbon footprint combined with their 24/7 high energy demand (•).

Several 'Big Tech' companies have made moves to support development of small reactors or even revive shut-down reactors. In Autumn 2024 several announcements confirmed this new dynamism.

- Microsoft announced a 20-year power purchase agreement with Constellation that will see Three Mile Island unit 1 restarted.
- Google announced a deal to purchase energy from Kairos Power supporting the first commercial deployment of its fluoride salt-cooled high-temperature AMRs by 2030 and a subsequent fleet totalling 500 MW by 2035.
- Amazon announced a series of agreements to take a stake in advanced nuclear reactor developer X-energy and rolling out its Xe-100 advanced small modular reactor. For this project Amazon will fund the initial feasibility phase at a site near 'Energy Northwest' Columbia Generating Station.

(†) Powering data centres with advanced nuclear technologies, White paper on Data centres, Tractebel, 2024.

(‡) ESTAT, Energy statistics.

(*) 2024 United States Data Center Energy Usage Report, LBNL-2001637, Lawrence Berkeley National Laboratory, December 2024.

(•) Small Modular Nuclear Reactors Suitability for Data Centers | Schneider Electric White Paper 186 – Schneider Electric – September 2024.
Revitalising Nuclear: The UK Can Power AI and Lead the Clean-Energy Transition - Tony Blair Institute for global change - December 2024.

The development and deployment of modular reactors will not be without challenges, as most technologies are at a low technological readiness level. While first projects were completed in Russia and China (160) and some more reactors are under construction, in the EU the technology still has to demonstrate that it will meet expectations in terms of cost, time to market, nuclear safety, and water usage. Moreover, the supply chain needs to ramp up should a large number of SMRs be built, and key components for Gen IV AMRs would require specific manufacturing capabilities and capacities in the EU.

Although SMR projects are expected to attract private investors due to the lower upfront capital required their operating costs per MWh produced are foreseen to be higher than the ones for large nuclear plant (161). It is expected that public intervention could continue to play a role, particularly in the context of the decarbonisation agenda of national and regional governments, by incentivising and crowding in private investments in SMRs and AMRs.

Despite aiming to be cheaper than traditional reactors, SMRs still require hundreds of millions of euros to build, which, combined especially with the fact that these are new technologies, could hinder their financing. The modular design of SMRs promises to simplify and shorten the construction phase, potentially reducing the magnitude of risk for lenders. Some governments are providing incentives to lower financial risks and encourage SMR development (see Table 11).

As an example, the European Commission has approved, under EU State aid rules, a EUR 300 million French measure to support Electricité de France's (EDF) subsidiary Nuward for research and development of SMRs (162). Under the measure, the aid takes the form of a direct grant of up to EUR 300 million that will cover the R&D project until early 2027. This EUR 300 million grant follows a previous EUR 50 million French measure approved by the Commission in December 2022 to support an earlier phase of the Nuward project, cf. also further discussion on costs and benefits market participants do not fully take into account for SMRs/AMRs in section 7.1.4.

A number of countries are already engaged in developing and deploying SMRs in the next decade, allocating significant funding to support projects or industry on their territories, see Table 11.

Table 11 – Public funding for SMRs (non-exhaustive list)

EU Member States	
France (•)	Allocated EUR 500 million for the development of light water SMR technologies (2021-2030) and additional EUR 500 million for AMRs (2023-2030)
Netherlands (†)	Foresees EUR 65 million in 2024 for the preparation of SMR deployment and the province of Noord-Brabant announced it will invest

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(160) Small Modular Reactors Catalogue 2024, IAEA, 2024. Of the two operational SMRs, the Russian KLT-40S is a floating pressurised water reactor, while the Chinese HTR-10 is a high-temperature gas cooled reactor, which may be considered as an advanced modular reactor and a prototype towards the development of Generation-IV reactors.

(161) Small Modular Reactors: Nuclear Energy Market Potential for Near-term Deployment – NEA.

(162) EUR 300 million French State aid

	EUR 4 million in further development of molten salt reactors in March 2025
Belgium (‡)	Announced financial support of EUR 25 million annually (2023-2030)
Sweden (*)	Plans around EUR 9 million for construction of lead-cooled fast reactor (AMR demonstrator)
Third countries	
USA (••)	On 16 October 2024, the U.S. Department of Energy (DOE) opened applications for up to USD 900 million to support the initial US deployments of Generation III+ SMR technologies. DOE has already granted regular funding to many US SMR projects, e.g. TerraPower's Natrium, X-Energy's Xe-100, NuScale, etc.
UK (**)	Established Advanced Nuclear Fund of GBP 385 million (GBP 215 million for SMRs and GBP 170 for AMRs)
Canada (††)	Launched Enabling Small Modular Reactors Program funded with CAD 29.6 million over four years to fund research on safe SMR waste management solutions and to develop supply chain for SMR manufacturing and fuel supply to support the crucial elements necessary for Canada's SMR industry

Source: (•) Nucléaire de demain : 6 nouveaux lauréats du dispositif « Réacteurs nucléaires innovants » de France 2030 | info.gouv.fr
(•) France 2030 : un plan ambitieux sur le nucléaire de demain | Ministère de l'Économie des Finances et de la Souveraineté industrielle et numérique
(†) Dutch government allocates funding for nuclear programme - World Nuclear News
(†) Dutch province provides funding for MSR development - World Nuclear News
(‡) Belgium government allocates funding for SMR research - World Nuclear News
(*) Blykalla starts work on non-nuclear prototype SMR - World Nuclear News
(••) Funding Notice: Generation III+ Small Modular Reactor Program | Department of Energy
(••) Industry FOA Awardees | Department of Energy
(**) Advanced Nuclear Technologies - GOV.UK
(††) Canada Launches New Small Modular Reactor Funding Program - Canada.ca

5.1.4. *Safety and licensing*

All SMR designs under development will have to ensure the highest standards of safety, environmental protection as well as radiation protection for workers and citizens, responsible management of radioactive waste and spent fuel, and a reliable non-proliferation regime, which ensures that nuclear material is not diverted from its intended use. An important driver for their deployment will also be transparency and public acceptance. SMRs have advanced engineered features, are deployable either as a single or multi-module plant and are designed to be built in factories and shipped to utilities for installation. Their industrial standardisation could contribute to lower construction cost, but this is highly dependent on scale effect (deployment of fleet). Therefore, licensing will be a key issue for the rollout of SMRs.

SMRs using LWR technology are likely to have a shorter licensing process, as the technology is already proven, and existing regulatory requirements are applicable. However, several SMR designs are novel with features that have not been deployed before, even in the case of LWR-designs.

Licensing will be more complex for AMRs with other Gen IV technologies, such as MSR and LMFR, where much more development work, testing and demonstration of safety systems will be needed.

In the EU, licensing is a national responsibility. The deployment of advanced reactors incorporating emerging technologies needs a predictable regulatory framework and regulatory authorities that have the capabilities to independently analyse the safety implications of the new technologies. In other words, regulators "need to be flexible, accessible, enabling, and willing to work in a collaborative manner both domestically and internationally." ([163]).

As explained in an OECD/NEA publication, those "countries with a technology-neutral licensing framework, performance-based regulatory systems and a widely used graded approach will likely find their system easier to adapt to SMRs than those countries with a technology-specific licensing framework or a prescriptive regulatory system." ([164]).

As part of the workstream on SMR safety within the European SMRs pre-Partnership, 20 experts from 15 EU nuclear safety regulators collaborated for two years on SMR pre-licensing. The conclusions of this work clearly highlight:

- the need to engage in early dialogues between designers-licensees and regulators on main elements of the SMR design options;
- the willingness to promote cooperation of interested regulators to carry out a joint safety pre-assessment on a mature design and its dissemination with other regulators; and
- the importance to identify in an early phase potential blocking points in the safety requirements or licensing processes and arrangements for convergence. ([165])

At the level of the cooperation among several regulatory authorities on a SMR specific design, the main example in the EU is the Joint Early Review (JER) ([166]) which started in June 2022 originally by three EU regulators: the French Authorité de Sûreté Nucléaire et de Radioprotection (ASNR) with the participation of the Czech Republic's State Office for Nuclear Safety (SÚJB), and Finland's Radiation and Nuclear Safety Authority (STUK) on the NUWARD SMR design. This cooperation now also includes three additional nuclear safety regulators from Sweden (SSM), Poland (PAA) and the Netherlands (ANVS).

In this context many aspects are under examination in the EU, but primarily the development of harmonised standards and regulatory approaches for SMR licensing in order to enable a more streamlined deployment of SMRs in different EU countries. The Commission's role is to support a harmonisation of the processes among interested regulators in the frame of the European Nuclear Safety Regulators Group

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([163]) NEA (2022), Harmonising the Nuclear Licensing Process for Emerging Technologies: A Global Path Forward, OECD Publishing, Paris.

([164]) NEA (2021), Small Modular Reactors: Challenges and Opportunities, OECD Publishing, Paris.

([165]) European SMR pre-Partnership report, WS2 - licensing - revision June 2024 | ENSREG

([166]) Joint Early Review (JER) | Nuward

(ENSREG) to ensure the safest possible development of SMRs in the next decade and beyond. In that frame an SMR Task Force has been created in the beginning of 2025 within ENSREG to continue the work started in the frame of the European SMRs pre-Partnership and to interact closely with the Technical Working Group on nuclear safety and safeguards created in the frame of the European SMR Industrial Alliance.

5.1.5. The European SMRs pre-Partnership and Industrial Alliance

In 2021, the Commission initiated the process toward a European SMR initiative by hosting a workshop on SMRs which brought together policymakers, industry leaders, regulatory bodies, and financial stakeholders. In early 2022, building on the outcomes of this event, European stakeholders formed of a European pre-Partnership with the primary objective of identifying the enabling conditions for the operation of the first SMRs in Europe by the early 2030s. The pre-Partnership work that was conducted by more than 120 EU experts was divided in five workstreams: market analysis, licensing, financing, supply chain adaptation, and research & innovation. The work resulted in five reports published in July 2023 ([167]) and it was followed by a stakeholders' consultation from 17 July to 29 September 2023.

Then building on the work of the European SMR pre-Partnership, the support expressed by several Member States and by industry stakeholders at the occasion of the European Nuclear Energy Forum of October 2023, as well as on the report adopted ([168]) by the European Parliament in December 2023, the European Commission established in February 2024 the European Industrial Alliance in Small Modular Reactors.

The general objective of the European Industrial Alliance on SMRs is to facilitate and accelerate the development, demonstration, and deployment of the first SMRs projects in Europe in the early 2030s, by assisting emerging SMRs projects to reach the demonstration and deployment phase.

In this perspective, the Alliance pursues the following specific objectives according to its Terms of References ([169]):

1) Facilitate and accelerate the safe and cost-effective development and deployment of SMRs projects through supporting relevant stakeholders' (including established and emerging European companies) collaboration to structure, advance and deploy their products in the European market and beyond.

2) Strengthen the enabling conditions for SMR development by mapping and assessing, the performance and completeness of the European nuclear supply chain, including raw materials availability, fuel cycle supply, waste management, research & innovation, skills development as well as identifying relevant regulatory and non-regulatory solutions, in full respect of the EU acquis.

3) Provide feedback and recommendations to the Commission and Member States on relevant policies to ensure the highest safety and environmental standards for the development and deployment of SMRs, including through collaboration with

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([167]) European SMR pre-Partnership - nucleareurope

([168]) REPORT on small modular reactors | A9-0408/2023 | European Parliament

([169]) Terms of Reference - European Industrial Alliance on SMRs nuclear regulatory authorities, the European Nuclear Safety Regulators Group (ENSREG) and other public authorities.

4) Provide guidance and recommendations on relevant policies to raise public awareness about SMRs' benefits and challenges and launch an open, transparent, and inclusive debate with social partners, stakeholders and the civil society, particularly on topics such as siting process, social acceptance, public engagement, radioactive waste management and decommissioning of SMRs.

5) Identify and prioritise the future needs for qualified and trained workforce and of training provision, building on the already existing programmes and instruments.

6) Foster nuclear research and development activities with a special focus on developing and deploying innovative nuclear fuels required for AMRs operation.

7) Promote collaboration with trusted international partners and expand the EU potential to export SMRs technologies to global markets.

Following the establishment of the Alliance, the initial membership call elicited responses from over 300 stakeholders, encompassing SMR technology designers, utilities, energy-intensive users, supply chain companies, research institutes, financial institutions, and civil society organisations. The Alliance members and its Governing Board were formally confirmed at the inaugural General Assembly in Brussels on 29-30 May 2024.

So far, the Alliance has already launched 8 Technical Working Groups which will allow to address in details key topics like supply chain, skills and industrial competence, licensing, financing, management of spent fuel and radioactive waste, public acceptance which are key towards the development of SMRs in Europe.

In pursuit of tangible project outcomes, the Alliance launched in June 2024 a call for SMR projects wishing to be considered for the Alliance's Project Working Groups. Following the 2nd Governing Board meeting, held on 7 October 2024 the first batch of SMR projects that would constitute the Project-Working Groups (PWGs) under the Alliance have been identified (170). Building on this, the Alliance the European Industrial Alliance on Small Modular Reactors (SMRs) adopted its first Strategic Action Plan at their second General Assembly in September 2025. As announced in the Action Plan for Affordable Energy, the Commission will adopt an SMR strategy in 2026.

To support these activities the Commission, on top of being directly engaged in the European SMR Industrial Alliance as a facilitator, is also supporting research on SMRs' safety via research projects co-funded under the Euratom Research and Training Programme, with focus on safety and licencing aspects. Moreover, the Joint Research Centre contributes since many years with research and policy support to the operation of nuclear power plants in accordance with the highest safety principles and safeguards. The safety, security and safeguards related research activities of JRC address also innovative and new reactors, fuels and fuel cycles with a special focus on SMRs and AMRs. The work includes research on new fuel types, new waste forms, and innovative materials, also in support to licensing and standardisation.

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(170) European SMRs Industrial Alliance - PWGs

5.2. Nuclear fusion

Nuclear fusion involves combining light atomic nuclei to form a heavier nucleus, releasing energy. Unlike nuclear fission, which splits atoms and generates long-lived radioactive waste, fusion does not produce long-lived radioactive waste and is inherently safer than nuclear fission due to the absence of chain reactions. The primary fuel for fusion — deuterium and tritium — can be sourced from water and lithium, ensuring security of supply. As for nuclear fission, fusion reactions do not produce greenhouse gases, making it a promising solution for addressing climate change in the long term ([171]) ([172]). The energy yield from fusion is significantly higher than chemical/combustion reactions, and continuous progress in plasma confinement methods (magnetic or inertial) contribute to bring commercial fusion energy nearer.

On 21 January 2025, Commission President von der Leyen stated at the World Economic Forum in Davos the need to invest in "next-generation clean energy technologies, like fusion". A recommendation for further support into nuclear fusion as a future source of energy is included in the Draghi report ([173]).

The momentum is also favourable outside the EU, with a general recognition of the potential of fusion energy in future energy mixes, and an acceleration of research and demonstration, with increased support for the development of innovative private companies. The creation of the world fusion energy group in November 2024 ([174]), following the 28th Conference of the Parties to the UN Framework Convention on Climate Change (COP 28) was a clear sign in this sense.

This trend is also clear, e.g., in the US, the UK, China, Japan, and South-Korea – countries which have all unveiled ambitious roadmaps and commitments for the development and commercialisation of fusion energy ([175]). These countries show good technological progresses and significant contributions to lift the fusion challenges ([176]). While approaches for achieving this goal vary from one country to another, a stronger cooperation between publicly funded science and the private sector (notably, innovative start-ups), is generally considered as a key enabler.

Several approaches to achieve controlled nuclear fusion exist, each with its own advantages and challenges and different level of maturity. The most widely studied methods include.

- **Magnetic Confinement Fusion (MCF):** Utilised in devices like tokamaks (ITER, Joint European Torus or JET) and stellarators (Wendelstein 7-X), where powerful

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([171]) IAEA World Fusion Outlook 2024, Non-serial Publications, © IAEA, 2024.

([172]) Fusion - Frequently asked questions | IAEA

([173]) "Develop an overarching EU innovation strategy for nuclear fusion energy and support the creation of a public-private partnership to promote its rapid, economically viable commercialisation. […]. The deployment of fusion energy will require public and private investment to act in synergy."

([174]) Inaugural Ministerial Meeting of the IAEA World Fusion Energy Group, 6 November 2024, Rome, Italy

([175]) As illustrated, for instance, by the US Department of Energy's 2024 Fusion Energy Strategy, or recent announcements (GPB 410 million investment to accelerate development of fusion energy) from the UK government

([176]) IAEA World Fusion Outlook 2024, Non-serial Publications, © IAEA, 2024.

magnetic fields confine hot plasma to achieve fusion conditions. Superconducting magnets permit to improve efficiency.

- **Inertial Confinement Fusion (ICF):** Uses high-energy lasers or ion beams to compress fuel pellets, as demonstrated in the National Ignition Facility (NIF) in the US, which achieved net energy gain in 2022.

- **Hybrid and Alternative Concepts:** Including magnetised target fusion, field-reversed configurations, and stellarator-tokamak hybrids, aiming to optimise plasma stability and energy efficiency.

Despite recent advancements, several key challenges must still be solved before fusion energy can become a commercially viable power source, cf. notably ([177]).

- **Energy Break-even:** Achieving and sustaining net energy gain remains a fundamental hurdle, requiring more efficient plasma confinement and advanced reactor designs.

- **Material Durability:** Developing materials capable of withstanding extreme temperatures, radiation, and neutron irradiation over extended periods is crucial for the longevity and safety of fusion reactors.

- **Tritium Breeding and Handling:** Establishing a sustainable, closed-loop tritium breeding cycle to fuel reactors while ensuring safe storage and handling of tritium remains a significant engineering challenge.

- **Regulatory and Public Acceptance:** Developing clear, fusion-specific regulatory frameworks and fostering public trust through transparent safety standards and environmental impact assessments is essential for widespread adoption.

- **Economic Viability:** Reducing the costs of reactor construction, maintenance, and fuel production to make fusion energy competitive with other energy sources remains a priority.

- **Scalability and Grid Integration:** Addressing how fusion plants can be integrated into existing energy grids and scaled up for widespread electricity production.

- **Technology Transfer:** Seizing opportunities in the short-term for developing fusion and non-fusion applications of research and raise interest in the field.

- **Knowledge Management:** Ensuring that the tacit knowledge generated in many years is not lost to foster risk mitigation, better exploitation, efficiency and issue prevention.

Those challenges are addressed through research: the European Co-funded Partnership EUROfusion, specific projects like the International Fusion Materials Irradiation FacilityDEMO Oriented NEutron Source (IFMIF-DONES) and the

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([177]) Fusion Energy: Potentially Transformative Technology Still Faces Fundamental Challenges | U.S. GAO; Stakeholders' projections of the timeline to reach commercially viable power source range from 10 years to several decades.

Broader Approach activities (178), IAEA's work on safety framework for fusion, economics studies, and policy developments.

5.2.1. ITER: The EU's Flagship Project to demonstrate the scientific and technological feasibility of fusion

The **International Thermonuclear Experimental Reactor (ITER)**, based in France, is the world's largest fusion experiment aimed at demonstrating net energy gain at a power plant scale. It represents one of the most ambitious international scientific collaborations, with the European Union being the primary contributor (45%) alongside China, India, Japan, Korea, Russia, and the US. The project is designed to validate the feasibility of large-scale fusion energy production and serve as a prototype for future commercial reactors.

Economic and technological impacts of ITER

ITER has generated substantial employment across Europe, particularly in France and Spain, which are the largest beneficiaries in terms of job creation. Between 2008 and 2017, the project created approximately 34,000 job-years within the EU-28. The direct employment impact includes construction jobs (2,300 at the ITER site in France), industrial manufacturing (1,400 jobs), and business services (2,100 jobs).

ITER has played a crucial role in establishing a global fusion supply chain, engaging companies across multiple sectors, including superconducting magnet production, cryogenic systems, and advanced materials. The project catalysed the development of a network of suppliers, many of which secured contracts beyond ITER, supporting both public and private fusion initiatives worldwide. In a worldwide perspective, the fusion energy supply chain is expected to expand significantly, with private fusion initiatives estimated to extend the market to reach EUR 500 million annually (179).

Economic models indicate that ITER provides a nearly 1:1 return on investment in gross value added (GVA) (180). Between 2008 and 2017, the cumulative GVA impact was approximately EUR 4.8 billion, almost equivalent to the amount spent on the project. Projections suggest that by 2030, ITER could generate an additional EUR 15.9 billion in GVA and create 72,400 job-years.

Spin-off effects further enhance ITER's economic impact. For example, firms that have worked on ITER have gained a competitive edge, allowing them to win contracts in other industries (181). This "ITER effect" mirrors the benefits experienced by companies involved in CERN's Large Hadron Collider, where high-tech suppliers saw long-term profitability improvements.

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(178) For more details see IFMIF-DONES, International materials facility IFMIF-DONES starts construction phase - EUROfusion, and BROADER APPROACH

(179) Analysis on a strategic public-private partnership approach to foster innovation in fusion energy. Trinomics, p. 48

(180) Study on the impact of the ITER project activities in the EU, ENER/D4/2017-458, Trinomics, p. 23

(181) The giant EB welding machine (K6000) finds further application in pro-beams aerospace business and has helped the company to develop a competitive edge for welding assignments in this market, in Study on the impact of the ITER project activities in the EU, ENER/D4/2017-458, Trinomics, p. 112.

ITER has been a major driver of scientific and technological innovation, fostering advancements in materials science, superconducting magnet technology, and plasma physics. European research institutions have leveraged ITER funding to develop intellectual property and enhance technological capabilities, with researchers obtaining PhD degrees through their work on ITER (182).

Furthermore, ITER's research has contributed to the development of high-performance computing, remote handling systems, and diagnostics, which have applications in industries such as aerospace, medical imaging, and robotics.

Challenges and future prospects

While ITER marks a significant step towards fusion commercialisation, it faces several challenges.

- **Engineering Complexities of a First-of-a-Kind (FOAK) installation:** The unprecedented scale and complexity of components such as the vacuum vessel and superconducting coils require innovative manufacturing and assembly techniques.
- **Rising Costs and Delays:** The extensive research and construction efforts have led to budget overruns and project timeline extensions, necessitating additional funding and international support. A new baseline 2024 was presented to the ITER members in June 2024 and was subject to independent assessment. In June 2025, the ITER Council adopted a phase-gate approval of the baseline allowing better project control and securing budget of phase 1 (ending in 2028) within the current MMF. With the adoption of the new baseline, the ITER project is back on track and performance index indicate the project is ahead of schedule and slighly under budget.
- **Tritium Fuel Supply and Handling:** Ensuring a sustainable and efficient tritium cycle is essential for long-term operation, involving both breeding technologies and regulatory compliance.

Despite these hurdles, ITER remains the cornerstone of global fusion research and of the EU fusion strategy, with lessons learned expected to directly inform the design and construction of future commercial fusion power plants (within several decades).

The knowledge and industrial base built through ITER will be essential for the development of the EU's first demonstration fusion power plant (DEMO), able to produce large quantities of energy on the grid. The DEMO project, developed by the European partnership EUROfusion (183), is tentatively scheduled in 2050 and is expected to be financed through several sources of investment for an amount of several billions of Euros. The DEMO project will further strengthen Europe's position in the global fusion industry. Eurofusion will represent European fusion industries and research organisations. The project also seeks to develop a Strategic Research and Innovation Agenda (SRIA) to guide R&D in fusion.

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(182) Study on the impact of the ITER project activities in the EU, ENER/D4/2017-458, Trinomics, pp. 104-105.

(183) DEMO - EUROfusion

5.2.2. *The EURATOM Research & Training Programme*

The Euratom Research & Training Programme is a five-year (plus two) initiative dedicated to advancing nuclear research and innovation. In addition to supporting innovative fusion research, the programme also addresses nuclear safety, radiation protection, and waste management within the realm of fission ([184]). These global efforts are executed through grants awarded to research and industry beneficiaries.

The current iteration, running from 2021 to 2027, has a total budget of EUR 1.98 billion, with EUR 836 million specifically allocated for fusion research and innovation innovation.

EUROfusion serves as the fusion flagship of the Euratom Programme, operating as a co-funded European partnership that unites leading research centres specialised in fusion research. ([185]) Established by the European Commission in 2014, EUROfusion comprises 30 member organisations and collaborates with 167 affiliated entities, including nearly all EU Member States, as well as Ukraine, Norway, and Switzerland.

EUROfusion's primary aim is to harmonise fusion research and development priorities with the ultimate objective of generating electricity from fusion energy. Its strategic roadmap is built on three pillars.

- Preparing for ITER experiments;
- Developing a concept for DEMO, a future commercial demonstration fusion power plant and ITER's successor, which aims to connect fusion energy to the grid;
- Supporting the IFMIF DONES project focused on fusion materials.

EUROfusion's research is wide-ranging, moving from strategies for particle and power exhaust to safety, maintenance and design activities.

Organisationally, EUROfusion is a European partnership and encompasses Work Packages on fusion science, fusion technology but also on communication, education, and public engagement. To support these objectives, EUROfusion employs a team of approximately 5,000 researchers, technicians, and administrators.

Technology transfer

A key aspect of EUROfusion is the focus on technology transfer with the goal of disseminating research results and fostering collaboration with industry. The partnership has engaged with industry in several ways. From 2014 to 2021, it subcontracted and partnered with companies as affiliated entities, allocating EUR 35.5 million. Additionally, a framework contract valued at EUR 10.14 million,

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([184]) In particular, research and development (R&D) in nuclear fission is crucial for enhancing safety, including waste management, improving efficiency, and ensuring sustainability. In terms of safety, R&D focuses on advancing reactor safety measures, developing sophisticated waste management solutions, and optimising fuel cycles. Efforts to improve efficiency aim to boost reactor performance and extend operational lifespans while considering economic viability. Achievements in these key areas of nuclear fission are a pre-requisite for public acceptance.

([185]) For more details, see EUROfusion - Realising Fusion Energy spanning from 2020 to 2024, was awarded by large industrial group to provide expertise.

As the new Fusion for Energy (F4E) ([186]) leadership has placed the development and consolidation of a European fusion supply chain at the heart of the revised industrial policy, F4E continues its efforts to map all relevant actors and their respective capabilities and encourage the development of clusters, as this is the case in other sectors such as the aerospace and the microelectronics. In particular, as part of its Technology Development programme (TDP), F4E aims to develop a comprehensive view of all the key enabling technologies needed before moving towards commercial fusion (e.g., tritium breeding, materials qualification). To this end, F4E collects and organises input from its competent experts and key external stakeholders to prepare its annual action plans, prioritising technology development activities in order to support the competitiveness of European industry. The Technology Transfer Programme implemented by F4E seeks to lay the foundations for a structured and sustainable innovation ecosystem by promoting the creation of new businesses based on the commercial exploitation of fusion breakthroughs in new markets.

The alignment of technology transfer activities between F4E and EUROfusion has recently led to the creation of a common platform ([187]) listing concrete applications, resulting from the participation of the European companies in ITER. The aim of this list prepared by F4E and EUROfusion is to promote the portfolio of technologies developed by F4E by making them widely available and commercially viable.

5.2.3. Recent developments in private innovative projects

Private Sector Growth and Funding

Fusion is no longer a "public affair only". An increasing number of startups and ventures have emerged with the aim of privately developing this energy source. The industry had attracted more than EUR 8.2 billion in 2025, compared to EUR 1.6 billion in 2021 ([188]). In the same period, the number of fusion entities worldwide has more than doubled, reaching a total of 53. The United States hosts the largest concentration, with 29 entities. The EU hosts 7 startups, but the interest of numerous companies (from France, Germany, Italy, and Spain) highlights the Union's dedication to advancing this innovative field of energy production.

Table 12 shows the amount of public investment by national authorities.

([186]) F4E is a Joint Undertaking implementing ITER and related fusion activities.

([187]) Fusion Technology portfolio - Fusion Technology Transfer

([188]) 2025-Global-Fusion-Industry-Report.pdf

Table 12 – Public investment on fusion by national authorities (non-exhaustive list)

Countries	Amount invested by national authorities
China	USD 1,000 – 1,500 million annually
United States	USD 763 million in 2023
Japan	Not available
United Kingdom	GBP 650 million over 2023–2027
Germany	EUR 1,370 million over 2024–2029
Italy	EUR 500 million over 30 years

Source: Different press articles. Figures not fully comparable. For Italy, amount above mentioned include the participation of a private investor (ENI, the energy company), which have joined the consortium led by ENEA, the Italian national advanced energy agency to build the Divertor Tokamak Test (DTT).

The overview given in Table 12 does not include the contributions to ITER, which represent a budget of approximatively EUR 651 million annually ([189]).

The EU is the host of seven Fusion start-ups.

- **Proxima Fusion (Germany):** developing quasi-isodynamic stellarators (magnetic confinement) for fusion power plants, leveraging high-temperature superconductors and computational optimisation.

- **Gauss Fusion (Germany):** developing high-field magnetic confinement fusion for fusion power plants.

- **Novatron (Sweden):** developing an open-field line (magnetic) confinement solution for fusion power plants.

- **Marvel Fusion (Germany):** developing a laser-driven fusion solution (inertial confinement).

- **Focused Energy (Germany):** developing a laser-driven fusion solution (inertial confinement), focusing on optimising the fuel and laser systems, and integration.

- **Renaissance Fusion (France):** developing stellarator solutions (magnetic confinement), working e.g. on high-temperature superconductor coils design and neutron shielding and heat extraction.

- **Deutelio (Italy):** developing a magnetic confinement solution (“Polomac”) for fusion power plants.

At the international level, the following companies are illustrative of the fast development of the sector.

- **Commonwealth Fusion Systems (CFS):** Developing a compact high-field tokamak leveraging high-temperature superconductors to achieve net energy gain.

([189]) ITER - Performance - European Commission

- **Helion Energy:** Pursuing magnetised target fusion with direct electricity conversion, targeting electricity production within a decade.

- **TAE Technologies:** Working on field-reversed configurations with an emphasis on using hydrogen-boron fuel cycles to reduce neutron production.

- **Tokamak Energy (UK):** Focused on spherical tokamaks, aiming to develop commercial fusion power plants by the late 2030s.

- **General Fusion (Canada):** Developing magnetised target fusion with liquid metal walls to improve plasma stability and energy efficiency.

- **ENN (China):** Upgrade of a spherical tokamak, aiming to develop a pilot plant by 2038.

Public-Private Partnerships (PPP)

Public-private partnerships can play a crucial role in accelerating the commercialisation of fusion energy by leveraging the strengths of both sectors. Governments provide funding stability, regulatory support, and large-scale research facilities, while private enterprises bring innovation, agility, and commercial expertise.

The fusion PPP aims at supporting EU innovation on key enabling technologies for fusion with the goal to contribute to future DEMO design and development, to maintain EU industrial know-how and competitiveness, and to leverage EU scientific leadership and the ITER project.

The benefits of PPPs can be summarised as follows.

- **Risk Mitigation:** Reducing financial and technological uncertainties by sharing costs and expertise between governments and private investors.

- **Accelerated Innovation:** Enabling faster prototype development through collaborative research and shared technological advancements.

- **Infrastructure Sharing:** Providing access to cutting-edge facilities and specialised equipment that may be too costly for private entities to develop independently.

- **Regulatory Support:** Aligning policy frameworks to create a predictable and conducive environment for fusion energy commercialisation.

- **Long-Term Investment Stability:** Ensuring sustained financial backing and market confidence through government participation.

In 2023, the Commission launched a study to examine best PPP arrangements options at EU level. In particular, three instruments (a Co-Programmed European Partnership, F4E Innovation Partnerships and the EIT-KIC InnoEnergy) were identified, each addressing different needs and is complementary towards achieving the proposed benefits.

In an effort to connect the public and private sectors, the European Commission is in a process of creating a European Fusion Stakeholder Platform which will bring together industry (including supply chain, startups, energy providers and investors), technology centres, academia and research organisations. This platform will be engaged in the definition of an Industry-led European association with legal personality and will sign the Memorandum of Understanding with the European Commission for the creation of the PPP (Public–private partnership) based on SRIA (Strategic Research and Innovation Agenda) developed by the Platform. In the framework of the Partnership, the Platform is prepared to engage the EU fusion industry, support innovation in alternative fusion concepts, and address critical technology bottlenecks. This will be done through calls issued in 2026 and 2027, where the gap identified by the platform will be taggle by jointed effort of industry and public bodies.

The recently endorsed Important Project of Common European Interest (IPCEI) candidate on innovative nuclear technologies includes fusion technologies among its five workstreams. This initiative aims to complement the current fusion efforts and to foster a cohesive approach across the full innovation-to-commercialization pipeline, including through PPPs.

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On PPP initiatives and timeline, it is worth to mention **EU Fusion for Energy (F4E) (2007-Present),** which facilitates collaboration between public institutions and private companies, including start-ups, providing grants and infrastructure to support fusion startups. Key partnerships include contributions to ITER and emerging private-sector projects.

Also, the **US Department of Energy's Milestone-Based Fusion Program (2022-Present)** offers financial incentives tied to performance milestones, encouraging private sector advancements in fusion technology. The program has accelerated prototype development efforts, with multiple companies targeting net energy gain by the 2030s.

The **UK's STEP Program (2021-2040)** is a national initiative focusing on commercial fusion power plant development, with the goal of delivering a fully operational demonstration plant by 2040. Industry partnerships and public funding play a central role in advancing STEP's milestones.

By fostering these partnerships, governments and private firms can create a pathway to achieving commercially viable fusion energy within the coming decades.

5.2.4. Development of regulatory frameworks

The development of regulatory frameworks for fusion energy is essential to facilitate its commercialisation while ensuring safety, efficiency, and public trust. Unlike

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(190) Approved integrated Important Projects of Common European Interest, IPCEI - European Commission

fission-based nuclear energy, fusion presents different safety challenges, requiring a tailored regulatory approach that balances innovation with precautionary measures.

At present, no country has a dedicated comprehensive fusion-specific regulatory framework although a number of experimental fusion facilities such as JET (Joint European Torus) and ITER have been subject to safety regulations.

While there is no international consensus on regulatory approach for fusion facilities, the opinion that the nuclear safety framework for fission power reactors is not appropriate for fusion reactors is rather spread within the fusion community and regulators, who share the view that the fusion specificities should be addressed with a proportionate approach, taking the potential hazards in full consideration.

The need for a differentiated, and proportionate, approach is also one conclusion of a EUROfusion working group established to deliver recommendations on the regulatory framework for the safety and licensing of fusion power plants (191) (192).

At EU level, the question is focused on whether and how the existing nuclear safety, waste management and the radioprotection framework should be adapted to fusion needs. In this sense, the Commission is consulting interested stakeholders and notably the ENSREG (193).

The Commission objectives are:

- To ensure safety for both the workers and the public, together with the protection of the environment for each fusion installation.
- To provide industry and research organisations with a regulatory framework aiming at ensuring a common approach and at optimising the time and cost of the licensing process.

The Commission also participates in international efforts on the topic:

International Atomic Energy Agency (IAEA): The IAEA is leading global efforts to create harmonised regulatory approaches. At this stage, it collects “Experiences for Consideration in Fusion Power Plant Design Safety and Safety Assessment” (TecDoc 2076) that will be followed by specific safety reports.

ITER and International Collaboration: The ITER project has established precedent-setting regulatory procedures that serve as a model for future fusion facilities worldwide. As the largest international fusion experiment, ITER has brought together scientists, engineers, and policymakers from 35 countries to develop a comprehensive regulatory approach. This collaboration has helped refine best practices in safety, licensing, and operational procedures, influencing national regulatory frameworks.

National approaches

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(191) J. Elbez-Uzan et al., Recommendations for the future regulation of fusion power plants, Nucl. Fusion 64 (2024), https://iopscience.iop.org/article/10.1088/1741-4326/ad13ad/pdf

(192) Considerations for the future regulation of fusion power plants by Joelle Elbez-Uzan, © IAEA, 2024.

(193) European Nuclear Safety Regulators Group, ENSREG

- **United States:** The 2024 ADVANCE Act classifies fusion under by-product material regulations, significantly easing regulatory burdens compared to traditional nuclear fission plants. The US Nuclear Regulatory Commission (NRC) is also working on dedicated fusion-specific regulations to streamline licensing.

- **United Kingdom:** The UK government is developing a proportionate regulatory framework tailored to fusion energy, focusing on risk-based licensing that reflects the inherently safer nature of fusion compared to fission.

- **Other Countries:** China, Japan, and Canada are also actively shaping their regulatory policies, drawing insights from international research programs and ongoing fusion experiments.

A well-structured regulatory framework could play a pivotal role bringing a high level of safety and predictability on licensing time and cost and enabling the successful transition of fusion energy from experimental research to large-scale commercial deployment.

5.2.5. Need for an EU Strategy on Fusion

It is very important to link further investments in fusion research to a broader European action, aimed at mastering fusion not just as a research topic but as a tool for long-term energy independence, sustained decarbonisation in the long term, as well as European industrial competitiveness. This '*momentum*' (please see section 5.2) shows the strong support to the development of such EU Energy Strategy within a large worldwide context.

International developments show rapid and massive investments both public and private in conjunction with national fusion strategies developments such as the publication of the UK Fusion Strategy in 2021 (and its update in 2023), the Japan's Fusion Energy Innovation Strategy published in 2023, and the Fusion Energy Strategy 2024 published by the US DoE. There is a clear identified risk for the EU to lose its leadership (194).

The Commission's March 2024 study (195), the Draghi (196) report and the recent European Parliament (197) debate on Fusion energy highlight the need for an overarching EU fusion innovation strategy and a public-private partnership to fast-track fusion commercialisation. Moreover, this would give a strong message to private investors and mitigate the above-mentioned risk.

The adoption of a comprehensive EU fusion strategy, as announced in the Action Plan for Affordable Energy and foreseen for the beginning of 2026, with EU's leading

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(194) Most of the private investment goes to the US (source FIA)
The EU has progressively lost its share in nuclear fusion patents while China has increased it significantly.

(195) New Commission report on potential public-private partnership approach to foster innovation in fusion energy

(196) The Draghi report on EU competitiveness

(197) European Parliament plenary session in Strasbourg, Sitting of 20-01-2025 | Plenary | European Parliament

participation in ITER confirmed as its cornerstone, would pave the fastest possible way to the fusion energy commercialisation.

The proposed strategy will aim at establishing a comprehensive EU-wide approach. It will cover several topics, including advancing the construction of ITER, addressing critical technological gaps, supporting supply chain, mobilizing private investments, promoting stakeholder dialogue, international collaborations with trusted partners, and an effective EU-level decision-making process. The strategy will aim at setting the stage for the developing a future pilot fusion power plant capable of producing net electricity, a pivotal milestone for the industrial growth and commercialization of fusion energy.

DG RTD and DG ENER have set up an informal Commission Expert Group known as the Fusion Expert Group (FEG) comprising representatives from Member States and chaired by the EC, with EUROfusion and F4E participating as observers. This advisory group aims to streamline governance of all research and innovation activities related to fusion and provide advice to the Commission on fusion energy policy. An opinion paper ([198]) from the FEG '*Towards the EU Fusion Strategy*' was published in April 2025.

In addition, relevant stakeholders were consulted also through recently organised events ([199]).

Innovation pillar & European Innovation Council (EIC) funding

The European Innovation Council, the main element of the innovation pillar of Horizon Europe, supports game changing innovations throughout the entire innovation lifecycle from early-stage research to proof of concept, technology transfer, and the financing and scale up of startups and SMEs.

([198]) Fusion Expert Group opinion paper - Publications Office of the EU.

([199]) Fostering Fusion Innovation: High-Level European Roundtable (14 March 2024, Brussels), the EU Blueprint for Fusion Energy Conference (23 April 2024, Strasbourg), the EU Fusion Business Forum (3-4 July 2024, Berlin).

6. ENABLERS

In this chapter, the document delves into the EU's regulatory capacity (Section 6.1), explores how trust is built through transparency measures (Section 6.2), discusses the development of skills and human resources within the industry (Section 6.3), and examines international partnerships (Section 6.4).

Nuclear liability in case of an accident is another important element related to nuclear safety, public perception but also to legal certainty for investors. In the EU, nuclear third-party liability is governed by national law and shaped by two international conventions, the 1960 Paris Convention or the 1963 Vienna Convention (200).

6.1. Regulatory capacity

6.1.1. High-level qualitative requirements on the regulatory resources in the international and Euratom legislation on nuclear safety, spent fuel and radioactive waste management and decommissioning

Having a **strong and independent regulatory authority** is instrumental to achieve a high level of nuclear safety. Endowing the national regulators with sufficient resources – both human and financial – to carry out their tasks of regulating, monitoring, and enforcing nuclear safety rules, as well as securing the safety of the spent fuel and radioactive waste management is an essential component of regulatory independence (201). This principle has been laid down in various **international** and **Euratom** legal instruments, as exemplified in Table 13 (202). EU Member States incorporate relevant requirements into their nuclear safety-related legislative, regulatory, and administrative measures, taking into account national specificities.

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(200) Most of the Member States which joined the EU before 2004 are Parties to the Paris Convention and to its Supplementary Convention, the Brussels Convention, adopted under the auspices of the Organisation for Economic Co-operation and Development (OECD). Most of the EU Member States which joined the EU in 2004 and 2007 as well as Croatia, are Parties to the Vienna Convention adopted under the auspices of the International Atomic Energy Agency (IAEA).

(201) A further challenge for nuclear safety regulators may arise from evolving requirements for nuclear safety, for instance through the necessity to adapt to climate change. Existing (and planned) installations may need to anticipate that cooling with river water may not be possible all year due to lower water levels, and additional efforts may be required to achieve resilience against more severe extreme weather events (including downfalls leading to local flooding). In the context of placing small modular reactors, extreme weather events may expose them to the risk of damage or sudden lack of access to maintenance. The JRC has analysed these aspects as part of its "Technical assessment of nuclear energy with respect to the 'do no significant harm' criteria of Regulation (EU) 2020/852 ('Taxonomy Regulation')".

(202) At the same time, the environmental acquis must be strictly implemented, through assessments such as those stemming from Directive 2011/92/EU on the assessment of the effects of certain public and private projects on the environment, Directive 2001/42/EC on the assessment of the effects of certain plans and programmes on the environment, Directive 92/43/EEC on the conservation of natural habitats and of wild fauna and flora, and Directive 2000/60/EC establishing a framework for Community action in the field of water policy.

Table 13 – Requirements on the adequacy of the regulatory resources

Level	Legally binding and non-legally binding instruments	
International level	Convention on Nuclear Safety (•)	Article 8, paragraph (1)
	Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management (†)	Article 20
	IAEA safety standards (‡)	Examples: – Fundamental Safety Principles, IAEA Safety Standards Series No. SF-1, 2006 – Governmental, Legal and Regulatory Framework for Safety, IAEA Safety Standards Series No. GSR Part 1 (Rev. 1), 2016 – Management and Staffing of the Regulatory Body for Safety, IAEA Safety Standards Series No. GSG-12, 2018 – Functions and Processes of the Regulatory Body for Safety, IAEA Safety Standards Series No. GSG-13, 2018 – Managing Regulatory Body Competence, Safety Reports Series No. 79, 2013
Euratom level	Nuclear Safety Directive (*)	Article 5 paragraph 2, letter (c) Article 5 paragraph 2, letter (d)
	Radioactive Waste Directive (§)	Article 6

Source: (•) INFCIRC/449 of 5 July 1994
(†) INFCIRC/546 of 24 December 1997
(‡) See IAEA website, www.iaea.org/resources/safety-standards
(*) Council Directive 2009/71/Euratom
(§) Council Directive 2011/70/Euratom

Focusing on the **Euratom legislation**, the Nuclear Safety Directive addresses explicitly the regulatory resources aspect. First, with respect to the **financial resources**, the Directive requires that the national competent regulatory authority must be provided with 'dedicated and appropriate budget allocations to allow for the delivery of its regulatory tasks as defined in the national framework' and should be 'responsible for the implementation of the allocated budget.' (203) Second, as regards the **human resources**, the regulator should employ 'an appropriate number of staff with qualifications, experience and expertise necessary to fulfil its obligations.' The Directive also acknowledges the possibility of using 'external scientific and technical resources and expertise in support of [the competent regulatory authorities'] regulatory functions,' (204) while encouraging the enactment of rules to prevent and resolve potential conflicts of interest. (205)

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(203) Article 5 paragraph 2, letter (c), Nuclear Safety Directive.

(204) Article 5, paragraph 2, letter (d), Nuclear Safety Directive.

(205) Recital 9, Preamble of Council Directive 2014/87/Euratom.

The Radioactive Waste Directive also contains separate provisions on regulatory authorities. First, it requires the Member States to 'establish and maintain a competent regulatory authority' that is 'functionally separate from any other body or organisation concerned with the promotion or utilisation of nuclear energy or radioactive material'. Second, the Member States must ensure that the regulatory authority has 'the legal powers and human and financial resources necessary to fulfil its obligations'.

The Directives, therefore, set out high-level provisions to ensure that the competent regulatory authorities are provided with adequate resources to properly carry out their assigned responsibilities ([206]). Insofar as they comply with the Directives' obligations, the Member States have the flexibility to choose the appropriate transposition instruments and to put in place implementation tools and mechanisms. It is essential that providing sufficient resources to the regulatory authorities remains a top priority – both for the regulators and for the other relevant Member States' authorities, particularly those responsible for approving the state budget.

6.1.2. Diversity of national approaches to ensure the adequacy of the regulators' financial and human resources

At the Member State level, **national circumstances** ([207]) play an important role in developing the domestic approaches on regulatory resources. General considerations include the national policy in respect to the use of nuclear energy for generating electricity, the characteristics of the national legislative, regulatory, and organisational framework, and the types and number of nuclear installations in operation or planned (as well as under decommissioning). Specific considerations are linked to the legal status and structure of the regulatory body ([208]), its concrete tasks, or the use of in-house and outsourced competences. Without prejudice to these national variables, regulators typically use a **systematic approach** to estimate their resources needs. ([209])

It should be noted that the regulatory activities pertinent to new nuclear build and the lifetime extension of existing plants in the EU cover a wide variety of aspects, such as nuclear safety, nuclear safeguards, nuclear security, radiation protection, emergency preparedness and response. However, this section of the PINC discusses regulatory capacity in respect to nuclear safety only, since regulatory capacity for nuclear safety is a fundamental feature for informing other regulatory tasks, focusing further on the regulatory activities related to licensing. From a nuclear safety angle,

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([206]) Regulatory capacity and resources must be maintained and further enhanced to ensure robust safeguards and security. However, assessing these specific needs falls outside the scope of the current PINC Staff Working Document.

([207]) Organization, Management and Staffing of the Regulatory Body for Safety, General Safety Guide No. GSG-12, © IAEA, 2018.

([208]) In the EU, three organisational schemes can be identified: (i) regulatory authorities as self-standing administrative authorities; (ii) regulatory authorities as administrative authorities, which are not organisationally part of a specific Ministry, but fall under its supervision; (iii) regulatory authorities are Directorates/Departments or Units/Services of Ministries that are not concerned with the promotion or utilisation of nuclear energy.

([209]) ENSREG Guidelines regarding Member States Reports as required under Article 9.1 of Council Directive 2009/71/EURATOM of 25 June 2009 establishing a Community framework for the nuclear safety of nuclear installations, HLG_p(2012-21)_108.

the Commission's second report on the implementation of the Nuclear Safety Directive, (210) hereinafter referred to as the '2022 NSD Progress Report' addressed the issue of regulatory resources, (211) based, primarily, on information drawn from the Member States' national reports. (212) While more details are available in the 2022 NSD Progress Report, Table 14 provides a summary of the domestic approaches on the topic of regulatory resources, as identified in this progress report.

Table 14 – Common trends on resources of regulatory authorities in Member States

Topic	Summary
National framework	
Type of requirements	– General and/or specific legal requirements, general budgetary provisions – Specific regulatory procedures (in some cases)
Financial resources	
Financing models	– State budget allocations or – Combination of budgetary funds and recovery of incurred costs from licence holders or service charges
Role of the regulators	– Planning of financing needs (notably as regards State budget financing) → annual plans (typically) / multiannual plans (e.g. 3-year perspective) – Autonomous implementation of the allocated funds → annual plans
Additional resources	– Various mechanisms: o special fees from the licensees o state mechanisms in the budgetary procedures o rebalancing funds among activities o recourse to the state reserve – non-limited credits for exceptional situations etc.
Transparency of expenditure	– Various mechanisms: o key performance indicators, o publication of annual reports – publication of audit conclusions etc.
Areas for further work (some instances)	– Ensuring adequate financing of regulatory activities
Human resources (numbers and qualifications)	
Role of the regulators	– Evaluation of staffing needs (usually feeding into the financial planning) → annual plans (typically) / multiannual plans (3-year perspective), complemented by operational plans / other types of evaluations – Recruitment of new staff – Staff allocation – Training (for new and existing staff)
Additional resources	– Possibility to request additional resources / flexibility clauses (in some cases)
Staff qualification	– Various mechanisms: o education and expertise conditions upon recruitment o initial training for newcomers

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(210) Report from the Commission to the Council and the European Parliament on the progress made with the implementation of Directive 2009/71/Euratom establishing a Community framework for the safety of nuclear installations amended by Directive 2014/87/Euratom (COM/2022/173 final), accompanied by a Staff Working Document (SWD/2022/107 final).

(211) COM/2022/173 final (section 2.2), and SWD/2022/107 final (sections 2.2.1.3 and 2.2.1.4).

(212) Nuclear safety

	– continuous training (recourse to a combination of in-house and external sources) etc.
External expertise	– Commonly used to support regulatory decisions – Various types of external expertise: o scientific councils or committees o institutes or technical support organisations (TSOs) specifically established – outside experts / consultants (specific projects)
Areas for further work (some instances)	– Maintaining appropriate staffing – Attracting and keeping sufficient and/or qualified staff (in some cases, this shortage is covered by resorting to external expertise).

Source: European Commission

The Commission made several observations addressed to the Member States in the 2022 NSD Progress Report, and, on this basis, highlighted areas where there is scope for future action at EU level to continuously improve nuclear safety in the EU. Specifically on the topic of regulatory resources, in its observations, the Commission stressed the need to enact **specific legal provisions** requiring that adequate and dedicated financial and human resources (for the latter, both in terms of numbers and qualifications) are available to regulators, supported by mechanisms, criteria and procedures, including flexibility mechanisms allowing the regulators to receive additional resources. (213)

Furthermore, regulatory independence – including the components of the 'dedicated and appropriate budget allocations' and 'appropriate number of staff with qualifications, experience and expertise, and preservation of knowledge' – was highlighted as a key topic where a **common approach at EU level** could be beneficial. (214) In line with the 2022 NSD Progress Report and considering the outcomes of a workshop held in November 2022 to discuss the report's findings with relevant stakeholders (including regulators), **regulatory independence** (together with the nuclear safety objective, and safety culture) were confirmed as **priority nuclear safety areas**.

The Commission's activities related to the implementation of the Directive focus on these priority areas and are conducted in close coordination with the stakeholders, particularly the regulatory authorities within ENSREG. A series of annual workshops will commence in 2026. Regarding regulatory independence – with an emphasis on regulatory resources – the Commission plans to facilitate an exchange of views and experiences among Member States in 2026. This initiative aims to identify and share examples of effective national approaches for ensuring adequate regulatory resources.

In the third Waste Report (215) it is concluded that Member States had at least one competent regulatory authority. In a few cases, the arrangements are such that local/regional competent authorities work together with national authorities when they deal with radioactive waste management; the related national reports did not

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(213) COM/2022/173 final., section II, sub-section 2.2.

(214) COM/2022/173 final, section IV.

(215) 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 - THIRD REPORT {COM(2024) 197 final} - {SWD(2024) 127 final}

provide information on their roles and responsibilities, or on how they interact with each other.

While most Member States devised mechanisms to retain skilled staff within the regulatory authorities, some faced challenges in maintaining adequate human resources in the long term. Outcomes of recent international peer review missions confirmed this trend. Most national reports provide information on measures for ensuring technical and financial independence of the competent regulatory authorities. A total of 19 Member States provided actual staff numbers; therefore, the information in Table 3 of the accompanying staff document to the Waste Report (216) does not cover the full EU-27.

6.1.3. Regulators play a strategic role in ensuring the safe completion of nuclear new build investment projects

The EU Member States have a rather diverse energy mix. For nuclear energy, the situation varies from those that have one or more nuclear power plants, to those without any. Some Member States plan to continue or even increase nuclear energy generation, while others have decided to discontinue operations after a certain date or have prohibited the construction of new plants. In the current global context, marked by an increasing support of nuclear energy to meet both climate objectives and the challenge of ensuring secure and affordable energy, (217) several Member States intend to expand their electricity generation portfolio with new nuclear power reactors, as indicated in section 2.1.

The nuclear energy projects typically face 'complex project planning period, long construction timelines, regulatory complexities, long payback periods and lengthy debt tenors.' (218) involving a wide variety of stakeholders (governments, regulators, industry, public). In light of their complexity, such projects generate an additional workload for the regulatory authorities; the issue of sufficient financing and staffing comes, therefore, into the spotlight. As an illustration, one of the actions included in the Summary Report of the 8th and 9th Review Meeting under the Convention on Nuclear Safety was that 'Contracting Parties should establish durable capacity building programmes to align regulatory capabilities with future needs.' (219) In addition, several IAEA Integrated Regulatory Review Service (IRRS) mission results (220) stress the importance of ensuring adequate staffing and financing of regulatory activities, highlighting instances when additional work is needed.

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(216) Commission Staff Working Document Accompanying the 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 - THIRD REPORT {COM(2024) 197 final} - {SWD(2024) 127 final}

(217) Nuclear Technology Review 2024, Report by the Director General, GC(68)/INF/4, © IAEA, 2024.

(218) Climate Change and Nuclear Power 2024: Financing Nuclear Energy in Low Carbon Transitions, Non-serial Publications, © IAEA, 2024.

(219) CNS/8&9RM/2023/08 – Final of 31 March 2023.

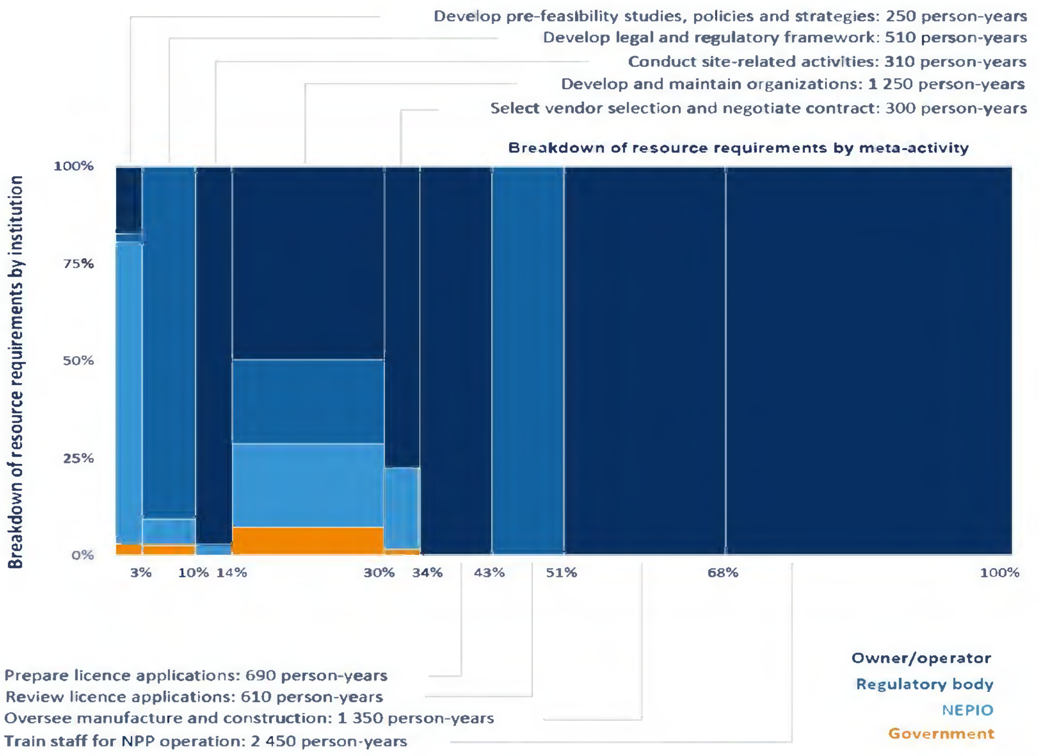
(220) See the IRRS mission reports available at https://www.iaea.org/services/review-missions/integrated-regulatory-review-service-irrs

In the context of the nuclear energy projects, the **regulators'** role is instrumental, notably for the following activities. (221)

- Developing regulations for the licensing process of nuclear installations and providing guidance to the applicants to provide clarity in the licensing process and assessing licence applications.
- Conducting reviews, assessments, and inspections to evaluate the applicants' compliance with the regulatory requirements.
- Taking regulatory decisions and granting (whenever this task belongs to the regulator), amending, suspending or revoking licences, conditions or authorisations, as appropriate.

In the framework of the Milestones Approach, the IAEA estimated the resources (including of regulators) for the development of a new nuclear power programme, as illustrated in Figure 36.

Figure 36 – IAEA breakdown of resource requirements



Source: Resource Requirements for Nuclear Power Infrastructure Development, Nuclear Energy Series No. NG-T-3.21, © IAEA, 2022, 10.

Notes: For the purposes of the IAEA referenced publication, the IAEA resource estimation is made against the Nuclear Infrastructure Competency Framework for nuclear power programmes, based on the Milestones approach and a number of other publications addressing specific aspects of nuclear infrastructure. The resource estimates are based on the development of a nuclear power programme of two units, in a country that already has some experience of and capability for managing large infrastructure projects.

This figure is pertinent as it reveals that, while the regulator is involved, to a different extent, in various activities, the most resource-intensive activity that falls exclusively

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(221) Licensing Process for Nuclear Installations, Safety Standards Series No. SSG-12, © IAEA, 2010.

under the regulator's remit is **reviewing licence applications**. In the EU, there is a significant variety of licensing approaches and systems, and different types of licences and authorisations are issued at various stages. Member States choose either to issue licences corresponding to each step of the licensing process (siting, design, construction, commissioning, operation, decommissioning) or to divide these steps into several sub-steps or merge several steps (e.g. combined licences for construction and operation). Conditions may be attached to the licences granted, requiring that the licensee obtains further, more specific, authorisations or approvals before carrying out particular activities. While the regulatory authorities are generally empowered to make regulatory decisions and to grant, amend, suspend or revoke licences, conditions or authorisations, in a few cases, the licences are granted by the Government based on a prior evaluation of the licence application (including nuclear safety aspects) by the competent regulatory authority.

Regardless of the licensing model adopted in the Member State engaged in a nuclear investment project, the national regulators will have to analyse substantial and complex documentation, as well as to conduct reviews, assessments and inspections. Already as part of the pre-application process the regulators will be involved in early engagement with the applicant to discuss the proposed project, its design and potential licensing challenges. This is, evidently, a highly resource-intensive process.

Box below provides an example showing, on the one hand, planned increases in the staff numbers through recruitment or mobility solutions, but also, on the other hand, the need to further secure supplementary personnel.

Box – EU regulators human resources in Member States planning to develop nuclear energy

A survey carried out by the European Commission in 2025 amongst the regulatory authorities reunited in the European Nuclear Safety Regulators Group (ENSREG) revealed that several regulators, notably from Member States planning or implementing new reactor projects, envisage increasing resources (including those dedicated to nuclear safety). Examples include the regulators from Czechia, Hungary, the Netherlands, Poland, Slovenia, and Finland.

Evolution of new build projects and need of retaining existing regulatory competence are important factors coming into play when planning human resources uptake. Projections indicate both annual increases and increases with a multiannual perspective. As compared to the 2024 baseline figures, **planned additional positions ranges from 10% to 50% percent staff increase up to doubling the number of staff**, depending on the national circumstances.

In addition to own staff, regulatory authorities of some Member States are supported by external expertise, some having a permanent status (scientific councils, committees, institutes, or Technical Support Organisations specifically established with the aim of advising the regulators). Examples include Belgium, Bulgaria, Czechia, Germany, France, Slovenia, and Finland.

Considering the specificities of each licensing system, the precise quantification of the resources involved in the licensing is made by each domestic authority. Whenever additional resources are needed, besides relying on the available national mechanisms mentioned in Table 14, the cooperation between the regulatory authorities of various countries, notably those licensing a similar reactor technology, is an opportunity for sharing regulatory knowledge and experience.

6.1.4. Regulatory cooperation as a solution to optimise the use of resources

The Nuclear Safety Directive requires that the Member States' safety frameworks provide for a system of licensing and prohibits the operation of nuclear installations without a licence. The Waste Directive requires that the national framework provides a system of licensing of spent fuel and radioactive waste management activities, facilities or both, including the prohibition of spent fuel or radioactive waste management activities, of the operation of a spent fuel or radioactive waste management facility without a licence or both and, if appropriate, prescribing conditions for further management of the activity, facility or both.

The Directives are not prescriptive as regards the licensing process, its steps, or the national authorities responsible for issuing licenses. Ultimately, the decision on how to structure the licensing system remains a national responsibility. In the EU, the licensing approaches are diverse, with the regulators being typically responsible for granting licences, as well as amending, suspending or revoking licences. According to the OECD NEA, current reactor licensing frameworks typically rely 'on an extensive experience base with large single-unit LWRs that use uranium oxide fuel with enrichment below 5%.' (222) Therefore, acquiring or transferring the requisite expertise to assess alternative reactor technologies is not straightforward. It is even more complicated in relation to wide range of spent fuel and radioactive waste management facilities.

The 2022 NSD Progress Report acknowledges this variety and encourages strengthened collaboration amongst regulatory authorities on licensing practices, regarded as bringing benefits 'by identifying potential commonalities to promote consistency and best use of resources.' (223) As a nuclear installation built in a country is likely to be similar to installations being proposed or built in many countries around the world, taking account of international good practice, international standards, and the assessments undertaken by other regulators is beneficial. Besides offering a platform for effectively exchanging experience, regulatory cooperation can also contribute to the resource optimisation.

Such cooperation (224) can be achieved by working with the nuclear regulators of other countries (bilateral collaboration) or under the auspices of international organisations (multilateral collaboration). An example of bilateral cooperation is the exchange between Sweden, Denmark, Finland and Norway, that include licensing aspects. (225)

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(222) NEA (2021), Small Modular Reactors: Challenges and Opportunities, OECD Publishing, Paris.

(223) COM/2022/173 final., section II, sub-section 2.1.

(224) For an overview of the cooperation activities in nuclear, see the WNA website Cooperation in Nuclear Power - World Nuclear Association

(225) As indicated in the National Report of Sweden of 2020 under the Nuclear Safety Directive 'Notifications according to the agreement have been made, among other things, in connection with

Bilateral agreements are also commonly in place between neighbouring countries. Examples of multilateral cooperation fora include the IAEA Nuclear Harmonisation and Standardisation Initiative (NHSI), ([226]) the OECD NEA Multinational Design Evaluation Programme (MDEP), ([227]) and the World Nuclear Association Cooperation in Reactor Design Evaluation and Licensing (CORDEL). ([228])

Safety and licensing aspects for SMRs and AMRs are covered in section 5.1.4.

In conclusion, the regulatory cooperation at a European level may support the regulatory infrastructure development, optimise resources, improve coordination and complementarity, as well as identify any barriers and limitations at an early stage, seeking convergence solutions.

On a general level, when selecting locations, Member States should perform a screening for climate risks next to the general risk assessment for the planned infrastructure and take into account which areas are more conducive to reduce the identified risks to acceptable levels.

At all levels – the EU, national, regional and local – authorities must make a major effort to accelerate the permitting procedures for clean energy projects, as outlined in the Draghi report. A large part of the time taken by the permitting processes for clean energy investments is dedicated to environmental assessments. Targeted updates to the legislative framework on environmental assessments could support faster permitting procedures for such projects, while maintaining same level of environmental safeguards and protecting human health. Against this background, the Commission will assess the possibility streamlining of licencing practices for new innovative nuclear energy technologies such as SMRs.

6.2. Transparency

6.2.1. The importance of public information and public participation in the decision making on nuclear installations is globally recognised

Nuclear programmes and activities typically involve a wide variety of stakeholders to engage with, building trust, demonstrating accountability, exhibiting open and transparent communication, practising early and frequent consultation and communicating benefits and risks. ([229])

While the term ‘stakeholder’ can be interpreted in different ways, a broad definition encompasses ‘any group or individual who feels affected by an activity, whether physically or emotionally.’ ([230]) Distinctions can also be drawn between organisations and groups that are statutory stakeholders (those required by law to be involved in

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applications for increasing the thermal power in nuclear reactors, planned decommissioning and ongoing licensing preparation of new final repositories.’

([226]) Nuclear Harmonization and Standardization Initiative (NHSI), © IAEA, 2025.

([227]) NEA Multinational Design Evaluation Programme (MDEP)

([228]) Working Groups - World Nuclear Association

([229]) Stakeholder Engagement in Nuclear Programmes, Nuclear Energy Series No. NG-G-5.1, © IAEA, 2021.

([230]) ibid.

any planning, development or operation of a nuclear project) and non-statutory stakeholders (those who have an interest in or will be directly or indirectly impacted). (231) This section will focus on the latter category, by looking at ways to ensure effective public communication and consultation on nuclear safety matters.

Public information about nuclear activities in general, and on the development of nuclear programmes/projects in particular, and active public engagement contribute to enhancing awareness, understanding, and confidence, thereby supporting nuclear safety. In this respect, it was noted that, ‘intensive public scrutiny may in a certain way contribute to nuclear safety by challenging the experts to do their analyses as transparently, comprehensively and soundly as possible, and to present a generally understandable and compelling justification.’ (232) While the responsibility for decision making lies with national authorities, public involvement enhances the component of confidence and trust, essential for the successful completion of nuclear investment projects. However, for the engagement with the public to be effective, some challenges that should be considered include ensuring the participation of informed members of the public who can question the experts, (233) as well as for the public to respond positively and actively participate every time consultation opportunities are presented.

From a regulatory perspective, involving the public in a new nuclear project has the potential to reinforce public awareness on the role and responsibility of the regulatory authority, strengthen the legitimacy of the regulatory decisions by considering a broader pool of views, and ensure the external scrutiny that enhances the ability of the regulator to make independent regulatory judgement and decisions. Indeed, openness (operating in a way which does not conceal thoughts or information and supports ongoing communication) and transparency (proactively disclosing relevant, accessible and accurate information about the regulatory process and decisions) are regarded as essential characteristics of a trusted nuclear regulator. (234)

Transparency requirements relevant for the nuclear domain are laid down in instruments with varying legal force, pertaining to nuclear law and environmental law, at international and Euratom levels (see Table 15).

Table 15 – Requirements on transparency

Level	Legally binding and non-legally binding instruments	
International level	Treaties – environment	– Convention on Access to Information, Public Participation in Decision-Making and Access to Justice in Environmental Matters (Aarhus Convention) (i) – Convention on Environmental Impact Assessment in a Transboundary Context (Espoo Convention), (ii) as amended; Protocol on Strategic Environmental Assessment to the Convention on

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(231) Handbook on Nuclear Law, © IAEA, 2003.

(232) Raetzke, C. (2014), Nuclear law and environmental law in the licensing of nuclear installations, Nuclear Law Bulletin, vol. 2013/2.

(233) An example is the establishment of the local information committees (in France, CLI) that include in their composition also persons appointed for their expertise in the nuclear field.

(234) NEA (2024), Characteristics of a Trusted Nuclear Regulator, OECD Publishing, Paris.

		Environmental Impact Assessment in a Transboundary Context (iii)
	Treaties – nuclear	– Convention on Nuclear Safety (iv) – Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management (Joint Convention) (v)
	IAEA safety standards (vi)	Examples: – Fundamental Safety Principles, IAEA Safety Standards Series No. SF-1, 2006 – Licensing Process for Nuclear Installations, IAEA Safety Standards Series No. SSG-12, 2010 – Communication and Consultation with Interested Parties by the Regulatory Body, IAEA Safety Standards Series No. GSG-6, 2017 – Arrangements for Public Communication in Preparedness and Response for a Nuclear or Radiological Emergency, IAEA Safety Standards Series No. GSG-14, 2020 – Stakeholder Involvement Throughout the Life Cycle of Nuclear Facilities, IAEA Nuclear Energy Series No. NG-T-1.4, 2011 – Stakeholder Engagement in Nuclear Programmes, IAEA Nuclear Energy Series No. NG-G-5.1, 2021
EU level	Legislation – environment	– Public Access to Environmental Information Directive (vii) – Environmental Impact Assessment (EIA) Directive (viii) – Regulation (EC) N° 1367/2006, as amended (ix)
Euratom level	Legislation – nuclear	– Nuclear Safety Directive, as amended (x) – Spent Fuel and Radioactive Waste Directive (xi) – Basic Safety Standards Directive (xii)

Source: (i) UNTS 447, 38 ILM 517 (1999).
(ii) 1989 UNTS 309, 30 ILM 800 (1991).
(iii) 2685 UNTS 140.
(iv) INFCIRC/449 of 5 July 1994.
(v) INFCIRC/546 of 24 December 1997.
(vi) See IAEA website, www.iaea.org/resources/safety-standards.
(vii) Directive 2003/4/EC of the European Parliament and of the Council.
(viii) Directive 2011/92/EU of the European Parliament and of the Council.
(ix) Regulation (EC) No 1367/2006 of the European Parliament and of the Council.
(x) Council Directive 2009/71/Euratom.
(xi) Council Directive 2011/70/Euratom.
(xii) Council Directive 2013/59/Euratom.

At national level, while the domestic legal and regulatory framework sets out the key requirements on both informing and allowing the public to be heard, it is important to complement this framework with dedicated communication strategies and plans, as well as practical communication mechanisms and channels (both national and cross-border). Focusing on public participation as an enabler for investment projects, several key parameters should be clearly spelled out, notably the place where the documentation can be consulted, the consultation modalities (e.g. submitting written comments or appearing at public hearings), the time schedule, and the way the input is taken into account.

More detailed guidance on the communication and consultation with the public and other interested parties by the regulatory body can be found in several IAEA safety standards series publications. In particular, the IAEA Safety Standard Series GSG-6, Communication and Consultation with Interested Parties by the Regulatory Body,

(235) focuses on the role of the regulatory body in communicating and consulting the public for all facilities and activities, and for all stages during their lifetime. These activities are seen as 'strategic instruments that support the regulatory body in performing its regulatory functions;' enabling the regulators to 'make informed decisions and to develop awareness of safety among interested parties, thereby promoting safety culture.' (236)

While, as indicated in section 6.1, licensing arrangements vary, they typically include specific milestones that present opportunities for the public to be consulted and have a say. While the siting phase is identified as potentially being 'extremely contentious,' even when it had been completed, it is advisable that, building on the lessons learned, to continue to engage with in the public during the other licensing phases. The end of the installation's lifecycle should not be overlooked, with 'local oversight of decommissioning and cleanup activities' being a feature of stakeholder involvement.

In practical terms, the public participation can be organised in several ways, such as. (237)

- Consultations initiated by national regulators.
- Hearings and debates coordinated by public entities other than regulators (such as local planning authorities, environmental authorities or government departments), which include.
    - National debates – organised in the context of a draft law, major new policy or a nation-wide project such as the construction of a new nuclear power plant.
    - Local hearings – organised locally in the context of a specific project, such as the extension of the operating life of a nuclear installation, or a change in its operating licence.
- Standing bodies, that are often set up in the vicinity of a nuclear power plant. Examples exist at national level, particularly the Local Information Committee (CLI) in France. There is also a tendency towards establishing groupings of affected communities, such as the Group of European Municipalities with Nuclear Facilities (GMF) (238), seeking to represent the views of its member local authorities at European level.

As an illustration of the public's views, the World Nuclear Association report "Licensing and Project Development of New Nuclear Plants" (239) reveals that almost all respondents stress that early and adequate public involvement is essential, indicating that fairness in the process of public consultation is certainly a vital factor for acceptance of nuclear projects. It was recommended that public participation should be coordinated with the steps of the licensing process, concentrating on the

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(235) Communication and Consultation with Interested Parties by the Regulatory Body, Safety Standards Series No. GSG-6, © IAEA, 2017.

(236) Handbook on Nuclear Law, © IAEA, 2003.

(237) See ENSREG website: Public participation | ENSREG

(238) GMF EUROPE – Group of European Municipalities with Nuclear Facilities

(239) WNA_REPORT_Nuclear_Licensing.pdf

early phases when the basic decisions are taken, and that discussions, once they are resolved, should not be re-opened later.

In experience of the several companies, the continuous, transparent interaction with stakeholders is essential for building and maintaining acceptance and trust throughout the projects. For example, stakeholder engagement and public acceptance are linked to all of Posiva's activities. Posiva Oy is an expert organisation in environmental technology, which is tasked with handling the final disposal of the spent nuclear fuel. The aim of Posiva is also to increase knowledge about nuclear and its back end, as well as to support open and constructive interaction in the company's neighbourhood, Finnish society and industry world. In their lessons learned, Posiva concluded that trust is built slowly and maintaining it must be taken care of from the very beginning throughout the long lifetime of any project, including the final disposal project.

Box – Public consultation on the continued operation of the 900 MWe reactors in France

As reported in the National Report of France for the 8th and 9th Review Meeting under the Convention on Nuclear Safety (August 2022), the High Committee for Transparency and Information on Nuclear Safety (HCTISN), acting on a proposal of the French nuclear safety authority, and with the support of a number of players, including the National Association of Local Information Committees and Commissions (ANCCLI) and the Local Information Committee (CLI), held a public consultation (for which no provision was made in the regulations) from 6 September 2018 to 31 March 2019 on the generic phase of the 4th periodic safety review of the 900 MWe reactors in the French NPP fleet (32 reactors operated by EDF on eight sites), coinciding with their 40th year of operation.

The public consultation, consisting in both on-line and at local public inquiry meetings, was related to the conditions for continued operation of these 900 MWe reactors. The public was asked to help determine the priority themes for the safety improvement debates, on the basis of 15 topics. The public was able to hold discussions with experts from the Électricité de France (EDF), the ASN and the French Institute for Radiation Protection and Nuclear Safety (IRSN) during the public meetings, to ask questions and obtain information from the on-line platform created for this public inquiry.

The public was informed and its questions and opinions collected at both regional and national levels, via a digital platform. A total of 16 meetings attracting 1,300 participants was held around each of the eight sites concerned, as well as within a number of higher education facilities.

The stakeholder involvement is continuous process and there is also value to be open, proactive and understandable in communications.

From these general considerations, the ensuing text will look at the EU situation.

6.2.2. *Variety of EU arrangements aiming to ensure that the public is properly informed and involved*

Focusing on the **Euratom nuclear safety-related legislation addressing transparency**, the Nuclear Safety Directive addresses it both from the perspectives of providing information and offering participation opportunities. First, in respect to **public information**, the Directive lays down the general obligation to make available "necessary information in relation to the nuclear safety of nuclear installations and its regulation" to "the general public, with specific consideration to local authorities, population and stakeholders in the vicinity of a nuclear installation." (240) The Directive further specifies this obligation by referring to information on normal operating conditions of nuclear installations, and in case of incidents and accidents, incumbent on both the regulatory authority and on the licence holder in the framework of their communication policy. Second, concerning **public participation**, the Directive calls for the general public to be given appropriate opportunities to participate effectively in the decision-making process related to the licensing of nuclear installations. (241) The link to the environmental legislation is made in the Directive's Preamble that refers to the use of nuclear safety assessments for the assessment of the risk of a major accident, as covered by the EIA Directive.

The Radioactive Waste Directive contains similar requirements. In respect to **public information**, it requires Member States to ensure that necessary information on the management of spent fuel and radioactive waste be made available to workers and the general public", including the competent regulatory authority to inform the public in the fields of its competence. Concerning **public participation**, it obliges Member States to ensure that "the public be given the necessary opportunities to participate effectively in the decision-making process regarding spent fuel and radioactive waste management in accordance with national legislation and international obligations". The Directive also requires the Member State to set out how they intent to implement these obligations in their national programmes under the Directive and to report on their implementation of these programmes every three years.

In light of the above, the Euratom directives enshrine fundamental, high-level requirements on public information and public participation. The Member States have the flexibility of choosing the appropriate transposing instruments and, importantly when it comes to transparency, putting in place the adequate toolbox, taking due account of the national specificities. In this vein, based on the Euratom legal requirements, the European Nuclear Safety Regulators Group (ENSREG) identified several good practices for the regulatory authorities (see Box below), indicating, however, that these are "generic in nature and may need to be adapted to the organisational structures in individual Member States." (242)

Good practices for regulatory authorities identified by ENSREG.

1) **Promote a culture of openness and transparency within the Regulators** so that all staff understand the importance of being transparent and of engagement

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(240) Article 8, paragraph 1, Nuclear Safety Directive.

(241) Article 8, paragraph 1, Nuclear Safety Directive.

(242) European Nuclear Safety Regulators Group, "Guidance on Openness and Transparency for European Nuclear Safety Regulators", HLG-p(2019-39)_165.

with interested parties. Openness and transparency shall be included in the core of the organisational values and behaviours.

2) **Develop a policy/strategy on communication** which clearly sets out the organisation's commitment to open communication and the way in which transparency is implemented. Underpin this with, if applicable, regularly updated plans detailing the activities that the Regulators will undertake to ensure effective communication with interested parties.

3) **Develop an appropriate toolkit for effective communication with the public and other interested parties.** For example, an accessible website where the general public and specific interested parties can find in-depth and understandable information on aspects of the Regulator's work and, in particular, on regulatory decisions and opinions. The website should, for example, include access to on-line radioactivity monitoring data, to the relevant guidelines and legislation, to information on specific events and incidents, to research and other reports and to press releases. It should also support interactive consultation with interested parties and collection of feedback from website visitors. It is recommended to use online communication, including social media, as appropriate.

4) **Produce an annual report** on the Regulator's activities with the aim to demonstrate key achievements of the previous year. The annual report should be accessible to the public.

5) **Communicate effectively and proactively with interested parties in a timely manner** using appropriate means that enhance their participation, in accordance with the requirements included in national, European and international law. Establishing relations in a more informal manner could help to build trust. The Regulators may consider the organisation of public meetings on a regular basis, as a way of promoting dialogue and interaction with interested parties.

6) **Communicate effectively with the media** and become the main point of reference for traditional and new media for information related to nuclear safety, radioactive waste management or safety-significant nuclear and radiological events to the public. Efforts for coordinated information should be applied. Doing this will help to establish the Regulators as a credible source of information and will ensure that there is coordinated regular interaction.

7) **Produce information in plain language**. The information may need to be adapted for different target audiences. For example, some audiences will require more technical and complex information. Provide translated information where deemed necessary.

8) **When developing documents, consider in advance which information might be sensitive**, and organise the content so as to ensure that the public version contains as much useful information as possible. For pre-existing documents being made public, delete only those parts of the document where commercial, national defence, public safety, security, proprietary, privacy issues or other restrictions within the framework of national legislation apply. This promotes a high degree of transparency. When balancing transparency against sensitivity/security it is important to justify why some information cannot be disclosed.

9) **Evaluate the effectiveness of the Regulator´s communication** in terms of openness and transparency. Share the results, as appropriate.

At the EU level, from a nuclear safety perspective, the Commission’s 2022 NSD Progress Report addressed in detail, inter alia, the issue of transparency, (243) based, primarily, on information drawn from the Member States’ national reports. (244) While more details are available in the 2022 NSD Progress Report, Table 16 provides a summary of the typical domestic approaches on transparency, identified in this progress report.

Table 16 – Common trends on transparency in Member States

Topic	Summary
National framework	
Type of requirements	– General legislation – right of free access to information – Specific legal provisions – nuclear-related transparency (dissemination of information, public participation)
Provision of information	
Information dissemination mechanisms	– National arrangements o Regulatory authorities: ▪ annual reports ▪ results of regular inspection reports ▪ information on the website available in more than one language ▪ social media ▪ contacts with the press ▪ special websites following major events ▪ opportunities to provide feedback and ask questions ▪ bodies for information, consultation and debate on the risk associated with nuclear activities etc. o Licence holders: ▪ visitor centres ▪ printed information magazines and brochures ▪ consultative bodies to reinforce the relations with local residents ▪ meetings at schools and universities ▪ site visits ▪ thematic events and open days etc. – International, regional and bilateral cooperation agreements
Public participation	
Consultation framework	– Consultations in the frame of the EU environmental legislation on Environmental Impact Assessments or international “environmental” treaties, such as the Espoo and Aarhus conventions – Specific nuclear-related consultations (in some cases)
Public consultation mechanisms	– Various mechanisms: o announcements in the press inviting replies within clear deadlines o non-technical summaries o public hearings o independent expert panels

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(243) COM/2022/173 final (section 2.4), and SWD/2022/107 final (section 2.4).

(244) Nuclear safety

	– dedicated organisations to provide information to the public and reports on how the public's comments were taken into account.

Source: European Commission.

Overall, in its observations to the Member States, the Commission supported a self-standing public consultation process on the licensing of nuclear installations from the perspective of nuclear safety. (245) In support of this observation, the Report noted that the Member States generally link their consultation processes with the information and consultation obligations laid down in the international and the EU environmental legislation mentioned in Table 15, and that only a few Member States conduct specific nuclear safety-related public consultations, including in relation to major operational changes or LTO decisions. Furthermore, the Commission also highlighted the topic of strengthening transparency as a key topic of common interest at EU level (246), and has consistently engaged in dialogue with the involved stakeholders, including the civil society.

6.2.3. *Nuclear safety is of high interest for the citizens calling for a continuous dialogue and exchange*

Since the previous Nuclear Illustrative Programme, the 2019 Eurobarometer on 'Europeans attitudes on EU Energy Policy' (247) revealed that, in response to the question 'What does EU energy policy mean to you?', for 18% of the respondents, EU policy means ensuring that nuclear energy is safe and secure, with the highest percentages being registered in Slovakia (36%) and Lithuania (36%). In addition, 85% of respondents say it is necessary to ensure that nuclear energy is safe and secure in the EU.

A more recent international survey of the OECD NEA in the framework of the Global Forum on Nuclear Education, Science, Technology and Policy, (248) whose results were released in 2024, confirmed this general interest. This survey sought to explore the links between an individual's core values and their perception of science, risk and nuclear matters. In relation to the topic of nuclear energy (questions whether new nuclear power plants should be built, whether building nuclear power plants in their country was a good thing, and whether the existing nuclear power plants in their country should be shut down), the replies show an opinion which is overall favourable to nuclear energy. A total of 74% declare that building nuclear power plants was a good thing, 71% are in favour of building new nuclear power plants and only 10% believe that 'existing nuclear power plants must be closed.'

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(245) Report from the Commission to the Council and the European Parliament on the progress made with the implementation of Directive 2009/71/Euratom establishing a Community framework for the safety of nuclear installations amended by Directive 2014/87/Euratom, COM/2022/173 final, section II / 2.4.

(246) Report from the Commission to the Council and the European Parliament on the progress made with the implementation of Directive 2009/71/Euratom establishing a Community framework for the safety of nuclear installations amended by Directive 2014/87/Euratom, COM/2022/173 final, section IV.

(247) Europeans attitudes on EU Energy Policy - September 2019 - - Eurobarometer survey

(248) NEA (2024), The Perception of Science, Risk and Nuclear Energy: An International Survey, NEA Working Papers, OECD Publishing, Paris, https://www.oecd-nea.org/jcms/pl_90306/the-perception-of-science-risk-and-nuclear-energy-an-international-survey?details=tru

In addition, it should be acknowledged that a major preoccupation for the public relates to the risk of accidents and the emergency preparedness and response (EP&R) arrangements. This is a key finding stemming from the 'Study on good practices in implementing the requirements on public information in the event of an emergency, under the Euratom Basic Safety Standards Directive and Nuclear Safety Directive' (249) commissioned by the Commission. This study covers the topics of information and transparency requirements; the role of media in nuclear and radiological emergencies; communication in exercises; stakeholder engagement before and during an emergency and cross-border arrangements. It also highlights good practices in each of these areas, which could be considered by the Member States. Examples of good practices include paying attention to recognising challenges concerning transparency during a nuclear or radiological emergency in advance and developing approaches to deal with these challenges during an emergency; monitoring and reviewing regulatory processes related to emergency preparedness and response to ensure openness and transparency; including informed civil society and citizen scientists (i.e. volunteers in the scientific process) in emergency management, including in conducting independent measurements.

Taking into account these views from the public (exemplified in the above examples), the Commission considers that the dialogue with an active and engaged civil society promotes a better understanding of the concerns and can positively contribute to strengthening nuclear safety. In the nuclear field, the Commission has been systematically engaging in a dialogue with the civil society, with several roundtables having been organised in cooperation with the civil society, (250) addressing important safety topics like emergency preparedness and response, and transparency. These events reunited a broad spectrum of stakeholders (civil society, nuclear regulators, nuclear industry, Aarhus Compliance Committee), and provided a forum to discuss national and transboundary experiences, identify challenges, and best practices to address them. The European Cluster Collaboration Platforms could serve as an instrument for raising awareness at regional level and to promote cooperation between nuclear-relevant clusters across the EU (251).

Transparency and stakeholder engagement/involvement **are critical to achieving public acceptance and thereby enhancing the efficiency and cost-effectiveness of**

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(249) Study on good practices in implementing the requirements on public information in the event of an emergency, under the Euratom Basic Safety Standards Directive and Nuclear Safety Directive - Publications Office of the EU

(250) Aarhus Convention and Nuclear Roundtable "Emergency Preparedness and Response to nuclear accidental and post-accidental situations" (29-30 November 2016) organised by the European Commission (DG ENER), and the French Federation of Local Commission of Information (ANCCLI); Aarhus Convention and Nuclear Roundtable "On information and public participation in the field of Radioactive Waste Management (RWM)" (13-15 January 2021) organised by the Nuclear Transparency Watch (NTW) network and the European Commission (DG ENER); Aarhus Convention and Nuclear Roundtable "Cross-border Emergency Preparedness and Response to nuclear accidental and post-accidental situations (EP&R)" (12-19-26 January 2022) organised by the Nuclear Transparency Watch (NTW) network and the European Commission (DG ENER); Aarhus Convention and Nuclear Round Table "Implementation of the Nuclear Safety Directive: transparency, public participation, and the role of civil society in independent nuclear regulation" (21-22 January 2025) organised by the Nuclear Transparency Watch network and the European Commission (DG ENER).

(251) Homepage | European Cluster Collaboration Platform

the licensing process for new nuclear facilities. This may reduce the time required for licencing and the cost of the licensing process overall:

Foremost, transparent communication and stakeholder involvement are fundamental in building trust among stakeholders, which is essential for streamlining the siting and licensing processes of nuclear facilities and facilitating public acceptance throughout the lifecycle of such nuclear facilities. When stakeholders, including the general public, are continuously informed and included in the decision-making process, it fosters trust (252) and reduces opposition (253).

Moreover, engaging stakeholders early and continuously throughout the licensing process leads to better understanding and cooperation (254). This involvement allows stakeholders to express their concerns and influence decisions, which can pre-emptively address potential issues, thereby facilitating smoother and faster approval processes.

Furthermore, by gaining public acceptance through transparency and engagement, the likelihood of delays caused by public opposition decreases (255). This can result in a more efficient licensing process, ultimately saving time and reducing associated costs.

Finaly, by involving the public and stakeholders, regulatory bodies can make more practical, relevant, and coordinated decisions (256). This level of scrutiny ensures that decisions are better informed and more widely accepted, contributing to a faster and more economical licensing process.

6.3. Skills and human resources

6.3.1. Skills shortage affects nuclear investments

Now that investments in new nuclear capacity appear to be increasing, either based on existing technologies or new technologies like SMRs or AMRs, renewed emphasis needs to be placed on securing the necessary skills and workforce to accompany those investments.

Similar conclusions have been drawn by the IAEA, NEA, the US, Canada, the UK and several EU Member States, and numerous initiatives have been launched to respond to these challenges (257).

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(252) T. Perko, H. Monken-Fernandes, M. Martell, N. Zeleznik, P. O'Sullivan. Societal constraints related to environmental remediation and decommissioning programmes. Journal of Environmental Radioactivity 196 (2019) 171-180.

(253) T. Perko, M. Martell and C. Turcanu. Transparency and stakeholder engagement in nuclear or radiological emergency management. Radioprotection, Volume 55, May 2020.

(254) Communication and Stakeholder Involvement in Radioactive Waste Disposal. IAEA Nuclear Energy Series No. NW-T-1.16.

(255) Communication and Stakeholder Involvement in Radioactive Waste Disposal. IAEA Nuclear Energy Series No. NW-T-1.16. P. 12, 14 and 59.

(256) NEA (2022), Stakeholder Confidence in Radioactive Waste Management. An annotated Glossary of Key Terms – 2022 Update. Nuclear Energy Agency No. 7606.

(257) Managing human resources in the field of nuclear energy, Nuclear Energy Series No. NG-G-2.1 (Rev. 1), © IAEA, 2023.
IAEA: https://www.iaea.org/topics/human-resource-development

There is increasing demand for workers at all levels and in all sub-sectors of the nuclear ecosystem – construction workers, technicians, nuclear engineers and scientists, skilled power plant operators, nuclear-aware generalists and regulatory staff to assess and license new projects (258).

Many regulatory bodies in the EU have concentrated on long-term operation, but the assessment of advanced reactors will demand different expertise, which needs to be built up.

Another challenge is the lack of quantified data on the current nuclear workforce and future needs for the whole EU. Some Member States have carried out their own assessments, but not all have disclosed this information. In France, which has the largest nuclear sector in Europe with around 220,000 workers, the trade association of the French nuclear industry GIFEN has estimated the recruitment needs in the period 2023–2033 to be in the order of 60,000 full time jobs in the 20 key activities studied and around 100,000 jobs for the whole nuclear sector, with up to 10,000 recruits needed per year (259).

There is a need for comprehensive workforce assessments at the national level also in other Member States to provide data for a sound formulation of a clear skills strategy.

According to different estimates (260), the EU nuclear sector provided around 500,000 direct and indirect jobs in 2022–2023. It is estimated that each gigawatt of nuclear power generates 50,000 labour years of direct employment during its lifetime. (261)

In addition, it is estimated that the ecosystem generates 2.2 indirect jobs per 1 job in the nuclear sector (e.g. subcontractors, secondary technology suppliers, steel manufacturers). (262) Consequently, this economic activity creates several hundred thousand additional induced jobs, and according to some estimates the sector sustains more than 1.1 million jobs in total (263).

NEA: https://www.oecd-nea.org/jcms/pl_21786/nuclear-education-skills-and-technology-nest-framework
UK: https://nuclearskillsdeliverygroup.com/
Canada: https://cna.ca/2024/11/19/building-a-skilled-nuclear-workforce-for-canadas-energy-future/
US: https://www.energy.gov/ne/articles/5-workforce-trends-nuclear-energy
Finland: Survey of Competence in the Nuclear Energy Sector 2017–2018 in Finland, http://urn.fi/URN:ISBN:978-952-327-410-5
France: GIFEN, Programme Match, April 2023

(258) The workforce can be categorised in the following groups: (i) nuclear experts (those with formal higher education in nuclear fields: nuclear engineers and scientists, power plant operators); (ii) nuclearised professionals (non-nuclear engineers and technical staff: construction workers, technicians); and (iii) nuclear-aware support staff (e.g. regulatory staff to access and license new projects).

(259) GIFEN, Programme Match, April 2023

(260) GIFEN, Programme Match, April 2023; ENEN2plus Euratom Research and Training Programme Project.

(261) NEA (2018), Measuring Employment Generated by the Nuclear Power Sector.

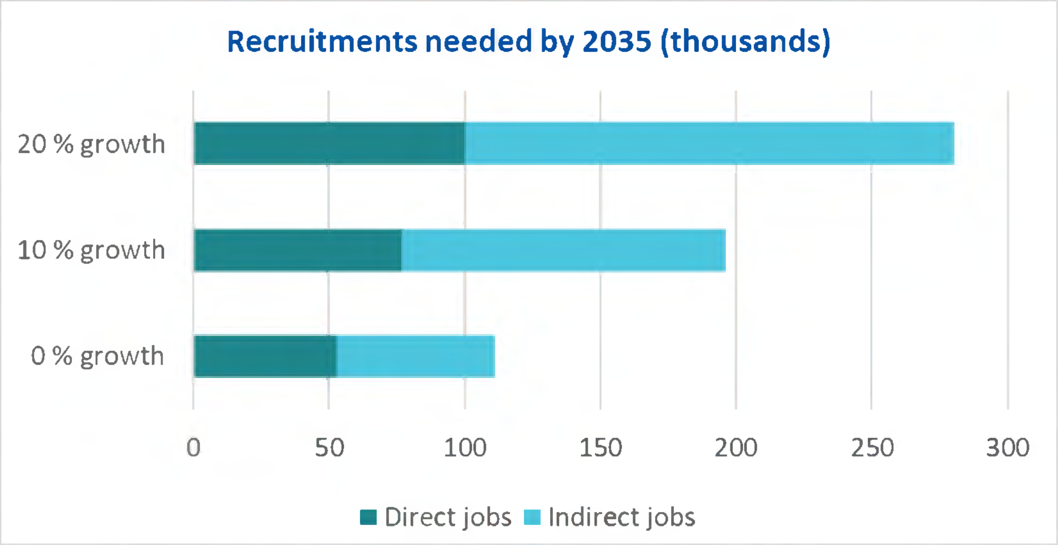
(262) Report on the European nuclear ecosystem, prepared by Deloitte for DG ENER, 2023 [yet unpublished].

(263) Impact Report – Vision to 2050, prepared by Deloitte for Foratom, April 2019.

According to a recent study sponsored by the Commission (264), the EU nuclear sector may need an additional 180,000 – 250,000 new professionals until 2050, in addition to replacing retiring employees. 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 sector may require a further 40,000 professionals.

Figure 37 presents an overview of the expected recruitment needs in the nuclear sector until 2035, depending on the growth in the sector. Even under a no-growth scenario (nuclear generation capacity stays stable), around 100,000 people would still need to be recruited to replace retiring workers.

Figure 37 – Recruitment needs under different nuclear growth scenarios by 2035 (thousands)



Source: ENEN2plus Euratom Research and Training Programme Project.

6.3.2. *Main challenges*

- **Ageing** workforce

Many of the skilled professionals were recruited in the 1970s and 1980s, during a period of rapid growth of the nuclear industry. These workers are now approaching retirement age.

The ageing workforce and the decline in the number of nuclear professionals under the age of 35 presents a risk for the future construction and operation of nuclear power plants and decommissioning of old ones.

- Nuclear sector has an **image problem** and is not attractive to young people, often not even considered as an option.

Like many traditional industries, the nuclear industry has experienced a decline in popularity, with many young people opting for careers in other industries, such as

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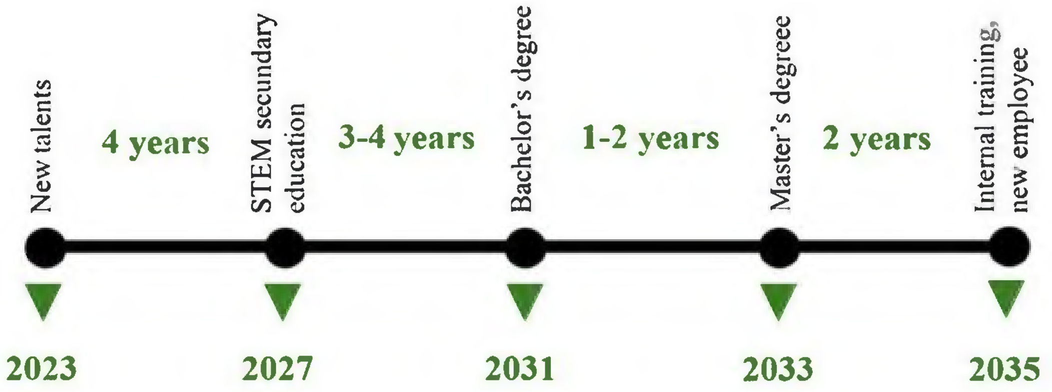
(264) Report on the European nuclear ecosystem, prepared by Deloitte for DG ENER, 2023 [yet unpublished].

renewable energy or information technology, leading to a lack of human capital to replace the existing workforce.

The ageing workforce and lack of sufficient newcomers creates a bottleneck for new nuclear projects and leads to a situation where many companies are competing for a limited number of professionals.

- **Insufficient education** in science, technology, engineering, and mathematics (STEM subjects), in particular when compared with Asian countries ([265]). This topic is addressed in more detail in the recent Commission Communication "A STEM Education Strategic Plan: skills for competitiveness and innovation" ([266]). Even with good educational programmes, there are no quick fixes, since becoming a skilled nuclear worker takes many years. Figure 38 shows that depending on the starting point, it takes 4–14 years to achieve a basic high level STEM education, which then needs to be further developed by on-the-job training.

Figure 38 – Timeline for becoming a skilled nuclear worker



Source: Report on the European nuclear ecosystem, prepared by Deloitte for DG ENER, 2023 [yet unpublished].

Improving the availability of skilled personnel for the nuclear industry requires a structured, targeted and multifaceted approach that involves education and training programmes, increased university programmes, apprenticeships and internships, and partnerships between public organizations and industry ([267]).

This will require a clear EU vision for nuclear energy, availability of quantified data from national workforce assessments and better funding and financing options. Engaging national/regional and local authorities, as well as improving the gender balance and youth engagement through scholarship opportunities, are also critical for ensuring the long-term sustainability of the sector.

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[265] The Global Distribution of STEM Graduates: Which Countries Lead the Way? | Center for Security and Emerging Technology

[266] Commission Communication to the European Parliament, the Council, the European Economic and Social Commitee and the Commitee of Regions "A STEM Education Strategic Plan: skills for competitiveness and innovation", COM(2025) 89 final

[267] Euratom-supported education, training and and access to research infrastructure, including to facilities of the Commission's Joint Reseaerch Centre, contribute to nuclear safety, regulatory capacity, and rolling out long-term operation and decommissioning needs.

Focusing on the low-carbon benefits of nuclear energy and the promising new technologies – SMRs and AMRs – could help to improve the attractiveness of the nuclear sector. SMRs can also help maintain highly skilled and well-paid jobs in places where they would otherwise disappear (for example due to the closure of coal fired plants), and they can help to attract workers if they are sited closer to major cities than conventional nuclear power plants. At the same time, insufficient human resources may also become an important bottleneck for SMR deployment. In the context of the European Industrial Alliance on SMRs, a dedicated Technical Working Group on skills has been set up, see section 5.1.5.

The elevation of skills to the Executive Vice President level within the new Commission and the recent Commission Communication *Union of Skills* (268) underscore the growing recognition of their importance in different policy areas. The Draghi report highlights the necessity for a Nuclear Skills Academy for attracting and retaining talent, particularly in light of the emergence of new technologies (SMRs and AMRs) (269). Such an Academy could serve as an EU umbrella-initiative that encompasses all ongoing EU activities, develops complementary training actions, and offers strategic advice for the support of future initiatives. In this context, Net Zero Industry Act (270) also establishes Net Zero Industry Academies to develop learning content for education and training providers in EU countries.

Member States play a vital role in formulating policies and providing funding to facilitate the development and functioning of the nuclear industry and academia. However, budgets would need to be increased to ensure a sufficient number of professionals for the nuclear sector.

The Commission can play a pivotal role as a catalyst and network facilitator, including through coordinating research and innovation needs under the Euratom Research and Training Programme (271). Currently the Horizon Europe, a Research & Innovation funding programme that runs until 2027 is providing support for education and training activities, albeit not specifically in the nuclear sector. It is also crucial to have sufficient up-to-date high-level nuclear research, testing and training infrastructures available in Europe, and to maintain access to the facilities of the Commission's Joint Research Centre.

The need for robust European nuclear research infrastructure has an important significance as it supports cutting-edge research, fosters innovation, and enhances collaborative efforts among Member States. This includes the development and maintenance of experimental facilities, data-sharing platforms, and integrated research networks that enable scientists and engineers to conduct comprehensive studies in nuclear safety, waste management, fusion energy, and the development of next-generation reactor technologies. It also ensures that Europe remains at the forefront of nuclear science and technology, maintaining Europe's competitive edge

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(268) COM(2025) final.

(269) The Draghi Report, The future of European competitiveness, Part B | In-depth analysis and recommendations, p. 37.

(270) Regulation (EU) 2024/1735 of the European Parliament and of the Council of 13 June 2024 on establishing a framework of measures for strengthening Europe's net-zero technology manufacturing ecosystem and amending Regulation (EU) 2018/1724, OJ L, 2024/1735, 28.6.2024

(271) The Euratom Research and Training Programme supports nuclear research, innovation and skills development, including safety, waste management and fusion research, without extending to deployment or investment decision-making.

in the global research landscape and in meeting future energy and environmental challenges.

Box – EHRO-N

The European Human Resources Observatory for the Nuclear Sector (EHRO-N) is driven by organisations representing major stakeholders in the European Civil Nuclear Sector and managed by the European Commission's Joint Research Centre (JRC).

EHRO-N mission is built on the strong mandate of the Council of the European Union in 2008: "It is essential to maintain in the European Union a high level of education and training in the nuclear field and, at the same time, preserve the skills that we already have."

EHRO-N is collaborating with "EURATOM Coordination and Support Actions" on education and training such as ENEN2Plus.

Finally, students and graduates must know that they are needed, and that there is work for them. This can be done by more frequent exchanges between industry and academia (hosting lectures, workshops, industry apprenticeship, mentoring). The industry could also support independent scientific centres outside their companies.

Above all, close cooperation between industry, universities and governments is needed.

Box – Cooperation on skills between different stakeholders

In the **Netherlands**, a declaration of intent was signed in January 2024 by industry participants COVRA, EPZ, NRG-Pallas and Urenco, and educational institutions Scalda, Horizon College/Regio College, Vonk, ROC van Twente and TU Delft.

The aim was to jointly develop a new nuclear curriculum to attract students for careers in the nuclear sector. The organisations will develop a multi-year plan for cooperation and will jointly explore funding opportunities.

NRG-Pallas and TU Delft are already cooperating on the Nuclear Academy programme, which is funded by the Ministry of Economic Affairs and Climate. The programme focuses on strengthening nuclear knowledge and skills in the Netherlands on various levels.

Moreover, Urenco is supporting the Delft Excellent Laboratory Facilities for Innovation and Nuclear Education (DELFINE) programme for three years to increase the pool of nuclear talent. The collaboration between TU Delft and Urenco annually supports at least 60 students and researchers in their research work, both in the field of energy and medical isotopes.

In **France**, the French nuclear industry, the *Union des Industries et Métiers de la Métallurgie* (UIMM), the *Union Française de l'Electricité* (UFE), *France Industrie and Pôle Emploi* have created a *"Université des Métiers du Nucléaire"* (University of Nuclear Professions) to boost the nuclear sector's training systems at regional, interregional and national levels.

EDF is also involved at all levels of education, from high schools to higher education institutions. It collaborates with the Training Centre for Apprentices in Energy Professions (*Centre de Formation des Apprentis des Métiers de l'Energie* – CFA) to increase the number of technician trainees, as well as of apprentices and interns.

The **Euratom project Skills4Nuclear** started in March 2025 to address shortages in nuclear skills for current and future technologies, such as SMRs and fusion energy. The initiative gathered 19 European partners: universities, research centres, nuclear and other industrial sectors, as well as education and human resources specialists. Skills4Nuclear will lay the groundwork for a nuclear skills strategy for Europe. It aims at promoting cross-sector collaboration and mobility, including upskilling and reskilling. Additionally, it seeks to improve diversity and digitalisation in the sector. Skills4Nuclear complements the existing efforts carried out under the Euratom Research and Training Programme to support nuclear education and ease access to nuclear research infrastructures with projects such as ENEN2Plus and OFFERR.

6.4. International cooperation

6.4.1. International partnerships

Euratom external relations with third countries and international organisations allow to foster progress in the peaceful uses of nuclear energy.

According to article 101 of the Euratom Treaty, the Community may conclude agreements with a third-State or an international organisation.

Furthermore, Euratom, its 26 non-nuclear weapon Member States, and the International Atomic Energy Agency (IAEA) signed agreements (272) to implement safeguards in connection with the Treaty on the Non-Proliferation of Nuclear Weapons (NPT).

In 2022 Euratom also signed a Memorandum of Understanding (MoU) with the IAEA on nuclear safety cooperation, covering, in addition to developing R&D cooperation, the safety of SMRs and fusion devices.

Euratom, while not a member of the OECD Nuclear Energy Agency (NEA), attends as an invited guest its Steering Committee for Nuclear Energy. Euratom's goal in participating in these meetings is to help align the positions of its Member States.

Switzerland (from 1 January 2025) and Ukraine are associated with the Euratom Research and Training Programmes 2021-2025 and 2026-2027. Switzerland is also a member of the Fusion for Energy Joint Undertaking from 1 January 2026.

6.4.2. Nuclear cooperation agreements as facilitators and enablers for investments

Euratom has so far signed nuclear cooperation agreements (NCAs) with 10 third countries, see Table 17. The NCAs provide for cooperation with key partner countries on issues of mutual interest, including on nuclear safety and security of supply. They also govern, for example, the transfer of nuclear materials, equipment and technologies. As the NCAs provide an overall framework for cooperation in compliance with international norms, they can be seen as enablers and facilitators for investments.

NCAs establish a legal framework that facilitates a wide range of cooperation in the peaceful uses of nuclear energy.

- Some extended scope NCAs aim specifically to facilitate nuclear trade and commercial cooperation (e.g. Euratom – US, UK (273) or JP). In the US or Canada (274), for example, a NCA is a legal pre-condition for cooperation with Euratom Member States as regards bilateral transfers of nuclear materials.

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(272) INFCIRC/193, 5 April 1973; INFCIRC/290, 27 July 1978.

(273) As evidence for the enabling nature of NCAs, in addition to the 2021 NCA with UK, a 2018 UK Euratom Exit factsheet explicitly noted that: "[…] *The UK currently utilises Euratom's NCAs to enable trade with Australia, Canada and the US (trade with Japan is facilitated by an existing Euratom-Japan NCA in addition to the UK-Japan NCA).*" – Euratom Exit Factsheet: Nuclear Cooperation Agreement

(274) International agreements

- Other NCAs have a narrower scope and are mostly limited to nuclear safeguards and non-proliferation provisions (Uzbekistan, Kazakhstan, Ukraine).

Table 17 – Euratom Nuclear Cooperation Agreements (with a narrow and extended scope)

Scope	**Extended scope** **CA**	 **US**	 **JP**	 **ZA**	 **UK**
Year of signature	*1959*	*1996*	*2007*	*2013*	*2021*
Facilitating trade		✓		✓	✓
Supply of nuclear material	✓	✓	✓	✓	✓
Supply of non-nuclear material	✓	✓	✓	✓	✓
Supply of equipment	✓	✓	✓	✓	✓
Technology transfer	✓				✓
Procurement & equipment of devices	✓				✓
Waste management	✓	✓	✓	✓	✓
Nuclear safety	✓	✓	✓	✓	✓
Nuclear security and physical protection	✓		✓	✓	✓
Nuclear safeguards	✓	✓	✓	✓	✓
Non-power uses				✓	✓
Mining					✓
Research and development	✓	✓	✓	✓	✓
Fusion		✓		✓	✓
Tritium	✓				
	Narrow scope **AR**	 **UZ**	 **UA**	 **KZ**	 **AU**
Year of signature	*1997*	*2003*	*2006*	*2009*	*2012*
Facilitating trade		✓	✓	✓	
Supply of nuclear material					✓
Supply of non-nuclear material					✓
Supply of equipment					✓
Technology transfer					✓
Procurement & equipment of devices					✓
Waste management	✓	✓			✓
Nuclear safety	✓	✓	✓	✓	✓
Nuclear security and physical protection		✓	✓	✓	✓
Nuclear safeguards	✓	✓	✓	✓	✓
Non-power uses	✓	✓	✓	✓	✓
Mining					✓
Research and development		✓	✓		✓
Fusion	✓		✓	✓	
Tritium					

Source: European Commission.

Notes: Dates refer to the publication year in the Official Journal of the EU.
EURATOM also concluded R&D NCAs with India and China; as such they are however less likely to trigger important investments.

In conjunction with other non-proliferation tools, particularly the NPT, the NCAs help to advance broader non-proliferation and safeguards principles. They include assurances that transfers of nuclear items in the scope of an agreement are properly protected, securely handled and used exclusively for peaceful purposes.

6.4.3. *Bilateral agreements as enablers for investments*

Some Members States prefer the use of bilateral agreements. They are complementing the Euratom level NCAs and cover elements which are not within the scope of such NCAs (e.g. transfer of technologies).

Such agreements need to be notified to the Commission under Article 103 of the Euratom Treaty so that the European Commission can carry out an assessment on the compatibility of any draft agreement or contract concluded by a Member State with a third State, an international organisation or a national of a third State with the provisions of the Euratom Treaty and the secondary legislation adopted on its basis.

Such agreements may be enablers for future investments decisions. This is for example the case for the Canada-Romania cooperation agreement of 1977 as amended in 2015:

Box – Nuclear cooperation agreements, the case of Romania and Canada

The Canada-Romania nuclear cooperation agreement was signed in 1977 and amended in 2015. The agreement has had effects as facilitated investments in Romania's nuclear sector, especially in recent developments.

In September 2023, significant financial support enabled by the agreement was announced: Canada committed CAD 3 billion (c. EUR 1.9 billion) in export financing to support the construction of two new CANDU-6 reactors at the Cernavoda Nuclear Power Plant. The investment is expected to create jobs both in Canada and Romania.

The agreement has also effects on strategic security of supply as it allowed Romania to develop a stable and independent energy infrastructure, reducing dependency from Russia.

6.4.4. *Conclusion*

The Euratom external relations framework plays a crucial role in advancing peaceful nuclear energy initiatives by fostering international cooperation and investment. Through strategic agreements, such as NCAs and Member States' bilateral agreements, Euratom may enhance compliance with safety standards, align Member States' positions, and adapt to emerging technologies, ensuring robust, forward-looking nuclear partnerships in accordance with the Euratom Treaty (275).

The Commission will reflect on how to further enhance these agreements so as to capture new realities such as cooperation on the development of new technologies for example (SMRs/AMRs) not yet addressed in existing NCAs.

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(275) In addition. the European Instrument for International Nuclear Safety Cooperation (INSC) is a key tool for strengthening the adoption of the highest international nuclear safety standards globally.

7. FINANCIAL MODELS

A frictionless market allows the financing of all economically efficient activities. In the context of power generation, a frictionless market would facilitate the deployment of the economically efficient mix of power generation technologies without a need for state intervention. However, in the presence of costs and benefits market participants do not fully take into account (276), non-intervention from the government may lead to unacceptable outcomes, such as insufficient availability of generation capacity, a generation mix that would be costlier than necessary, or the failure to decarbonise. Section 7.1 describes such costs and benefits the Commission has identified in the context of nuclear energy. Section 7.2 provides a brief overview of available instruments governments have used. In this context, the (re-)allocation of risks plays a crucial role. Section 7.3 summarises main risks affecting nuclear new build projects. Section 7.4 addresses the impact state support mechanisms may have on beneficiaries' incentives in the context of nuclear energy. Section 7.5 summarises policy actions. It should be noted that this section is without prejudice to the case-by-case assessment on necessity, appropriateness and proportionality of State support required to ensure State aid can be found compatible under Article 107 TFEU. Member States considering the support of nuclear generation assets via State aid are invited to contact the Commission early on, and in any case considerably in advance of any formal State aid notification, to avoid delays and ensure a legally and economically sound decision is taken.

7.1. Costs and benefits market participants do not fully take into account in nuclear energy and public intervention

The Commission has identified certain costs and benefits market participants may not fully take into account relating to nuclear power development that could be considered as a basis for public intervention.

7.1.1. Lack of market-based instruments for risk allocation

The Commission identified a lack of market-based instruments enabling stakeholders of a nuclear new build project to efficiently allocate the project risks among them (277). The relevant stakeholders include project developer, technology vendor, electricity consumers, lenders, state entities, however there are possibly more to consider on a case-by-case basis. Nuclear new build projects exhibit longer construction times as well as longer operating lifetimes than other large-scale infrastructure and energy projects, see the Box below. An absence of market-based instruments that cover such long periods reduces the ability of private stakeholders to implement the optimal (or their desired) risk allocation among them. A suboptimal risk allocation results in one or more stakeholders assuming risks for which they demand higher compensation in the form of return on investment than another stakeholder would under the optimal allocation. Thus, suboptimal risk allocation increases the project's cost of capital, i.e. the rate of return the project must generate

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(276) See Communication from the Commission – Guidelines on State aid for climate, environmental protection and energy 2022 (2022/C 80/01) for more details.

(277) Commission Decision (EU) 2015/658 of 8 October 2014 on the aid measure SA.34947 (2013/C) (ex 2013/N) which the United Kingdom is planning to implement for support to the Hinkley Point C nuclear power station, (recitals 381 – 383).

for investors to sponsor the project (278). Changes in the required rate of return have a significant impact on the earnings the plant needs to generate during operations to recoup the initial investment. If the required rate of return goes too high, the project may not go ahead at all. This is consistent with industry players confirming at recent stakeholder events that the next nuclear new build projects will in their view require state support (279). It should be noted that some investors realise projects in nuclear installations without state intervention. Examples include lifetime extensions of existing plants in the EU, Microsoft's investment in the restart of the previously shutdown plant at Three Miles Island in the US, and recently announced projects on investments in SMRs (see the box on data centres in section 5.1.3).

Well-designed public interventions improve the risk allocation beyond what private parties could achieve by themselves. This reduces the project's cost of capital (280). It enables contributions from private investors who would otherwise provide less funding or stay away altogether. Thus, improving the risk allocation beyond what private stakeholders can achieve on their own is part of minimising the public support required for the project to go ahead (281). Public intervention must respect State aid requirements and avoid overcompensating project sponsors (282). Thus, the lower the project's remaining risk-exposure post-intervention, the lower is the return project sponsors need and may expect, and vice versa.

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(278) The lack of market-based instruments to implement the desired risk allocation may also affect the capital structure, i.e. the debt-to-equity ratio. Project developers may not be able to implement the capital structure they would desire in a complete market. For instance, the lack of a liquid market for long-term power purchase agreements could limit the amount of debt project developers can take on relative to a situation where such a market existed.

(279) Industry representatives have repeatedly confirmed this view, for instance at the 17th European Nuclear Energy Forum held from 30 September to 1 October 2024 in Prague, Czech Republic. 17th European Nuclear Energy Forum.

(280) The OECD's Nuclear Energy Agency shares the view that a nuclear new build project's risk allocation affects its cost of capital: "*It is useful to think of financing as a project output, rather than a project input. Financing conditions are primarily the outcome of decisions regarding the management of the different risks affecting the project.*" OECD Nuclear Energy Agency (2024), Effective Frameworks and Strategies for Financing Nuclear New Build, https://www.oecd-nea.org/jcms/pl_96124/effective-frameworks-and-strategies-for-financing-nuclear-new-build, p. 11.

(281) This is consistent with the Commission's practice to assess the proportionality of a proposed measure when assessing State aid notifications.

(282) Art 19d, para. 2 (c), Regulation (EU) 2019/943 of the European Parliament and of the Council of 5 June 2019 on the internal market for electricity, as amended by Regulation (EU) 2024/1747 of the European Parliament and of the Council of 13 June 2024.

Box – Long project life cycle contributes to uncertainty

Nuclear power plants and other clean energy generation technologies, e.g. solar and wind, have in common that the upfront capital costs account for a relatively large share of lifecycle costs. In contrast, operating costs account for a larger share of lifecycle costs for fossil-fuelled generation assets. This makes clean technologies “capital intensive”. Nuclear power plants differ from most other clean generation technologies in that their construction periods are longer. The average commissioning time (i.e. time for planning and construction) for solar photovoltaic (PV) and onshore wind projects commissioned in the OECD countries after 2011 was 2.3 and 2.7 years, respectively (•). By comparison, four nuclear new build projects began construction in the OECD countries after 2011, the Vogtle 3 and 4 plants in the US, and the Shin-Hanul 1 and 2 plants in South Korea. The average construction time (i.e. excluding planning time) for these four plants was 10.5 years (†). There are more extreme examples, e.g. Olkiluoto 3 in Finland and Flamanville 3 in France, where construction took more than 17 years.

The long construction period contributes to uncertainty of construction costs. For projects with relatively short construction periods, e.g. solar PV, project developers may be able to contract all required input materials and services for a fixed price in advance. At the time of the final investment decision, there is only little uncertainty around construction costs, because all or a large part of the construction costs are locked in. For projects with a longer construction period, e.g. nuclear or offshore wind, suppliers and service providers may not be able or may not be willing to agree to fixed prices several years in advance (‡). Therefore, prices of the required goods and services may change as construction is already underway. This leads to higher uncertainty around construction costs at the time the project developer takes the final investment decision. The long operating period also poses a challenge. The design life of the EPR2 reactor model is 60 years, older reactor models have design lives of 30 or 40 years. Available market-based instruments to trade electricity, e.g. power futures or power purchase agreements, do not cover such long periods. Likewise, commercial banks typically do not offer loans for such long horizons and typically only sovereign entities can emit bonds with such long maturities. Therefore, project developers remain exposed to uncertainty on market price of electricity, which limits their ability to fund the project with debt.

(•) Anurag Gumber, Riccardo Zana, Bjarne Steffen, A global analysis of renewable energy project commissioning timelines, Applied Energy, Volume 358, 2024, 122563, Figure 2.

(†) Analysis based on IAEA PRIS database.

(‡) The lead contractor for engineering, procurement, and construction (EPC) at the Olkiluoto 3 new build project agreed to a fixed price ‘turnkey’ contract. However, the EPC contractor itself relies on numerous suppliers and subcontractors during the construction project, and the EPC contractor may not be able to enter fixed-price contracts with all of them for all required inputs to the construction project at the time of the final investment decision.

7.1.2. Hold-up risk

The Commission also recognised the challenge of (predominantly political) “hold-up” risk in the context of nuclear new build projects ([283]). Laws and regulations may change during the lifetime of the project and thereby make the project less profitable than planned. Once private parties have sunk capital in the project, they are locked in and may not be able to recover their investment if the state intervenes afterwards. In principle, all investments face this risk, i.e. it is not specific to infrastructure or nuclear. However, for projects with long lifetimes and with more applicable regulations, such as nuclear, potential investors may perceive the risk to be more pronounced. This risk of ex-post intervention may lead private investors to require a higher return on investment than they would otherwise, or it may deter potential private investors from participating in a project altogether. The lack of market-based risk allocation instruments may further compound this challenge. The state can alleviate hold-up risk by providing specific change-of-law or policy protections, or by participating in the project, e.g. through derisking instruments like loans or guarantees, which are in general less distortive than an equity contribution. State funding may serve as a commitment device by which the state reassures private investors that it will not harm the project ex post.

7.1.3. Externalities relating to investment needs in other infrastructure

In addition, there may be a further rationale for state intervention arising from a possible externality: the continued efforts to decarbonise the economy will require an expansion of electricity generation capacity in the EU. Every newly deployed generator must be connected to the existing electricity grid except for special cases where a generator has a direct connection to a consumer. Distributed generation assets may require higher investments in the build-out of electricity transmission and distribution networks than centralised assets. However, under the current electricity market design in the EU, wholesale power prices do not fully reflect network capacities, or the costs associated with expanding the network ([284]). Studies carried out by the French electricity transmission system operator RTE ([285]) and by the US Department of Energy ([286]) have demonstrated that the deployment of new large-scale nuclear reactors may contribute to reduce the electricity system integration costs (see section 2.1). Depending on the electricity system under consideration, the lower investment needs for transmission and distribution infrastructure and storage can outweigh the high upfront costs for new large-scale reactors. In such an instance, the potential to reduce investments in networks and storages constitutes a positive

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[283] Commission Decision (EU) 2015/658 of 8 October 2014 on the aid measure SA.34947 (2013/C) (ex 2013/N) which the United Kingdom is planning to implement for support to the Hinkley Point C nuclear power station (recitals 384 – 385).

[284] The Joint Research Centre (JRC) has procured a tender in order to analyse the possibility and the effects of implementing nodal pricing in the European Internal electricity market based on the current and proposed legal framework: Antonopoulos, G. Vitiello, S. Fulli, G. Masera, M., Nodal pricing in the European Internal Electricity Market, EUR 30155, Publications Office of the European Union, Luxembourg, 2020, ISBN 978-92-76-17571-1, doi:10.2760/41018, JRC119977.

[285] RTE (October 2021), Futurs énergétiques 2050, Principaux résultats, p. 31.

[286] US Department of Energy (September 2024), Pathways to Commercial Liftoff: Advanced Nuclear, p. 10.

externality (287), which is neither reflected in wholesale electricity prices nor fully in the fees project sponsors pay for having their newly built generation assets connected to the network (288). This externality may provide an additional rationale for state intervention to support nuclear power development beyond what the Commission has identified to date.

In summary, a well-designed state intervention: (i) should facilitate an efficient risk allocation among stakeholders, including the risks allocated to the state, while using instruments which are the least distortive for the market; (ii) address potential hold-up risk; and (iii) internalise externalities relating to total system costs if there are some.

7.1.4. Costs and benefits market participants do not fully take into account in the context of SMRs and AMRs

SMRs and AMRs are an emerging technology and not yet mature. Promoting the development and adoption of these technologies may benefit from state intervention as well. However, the costs and benefits market participants do not fully take into account justifying the intervention in SMRs and AMRs are likely to be different than for large-scale reactors, which are an established technology. The Commission cleared the State aid application submitted by France to support the Nuward SMR project (289). When assessing the application, the Commission applied the State aid framework for research and development and innovation (RDI framework). The Commission Communication on the RDI framework clarifies the economic rationale to support RDI in early-stage technologies such as SMRs and AMRs: "*Whereas it is generally accepted that competitive markets tend to bring about efficient results in terms of prices, output and use of resources, in the presence of [costs and benefits market participants do not fully take into account] State intervention may be necessary to facilitate or incentivise the development of certain economic activities that, in the absence of aid, would not develop or would not develop at the same pace or under the same conditions and, thereby, contribute to smart, sustainable and inclusive growth. In the context of R&D&I, [costs and benefits market participants do not fully take into account] may arise for instance because market players do not necessarily or at least spontaneously take into account the wider positive effects for the European economy, consider reaching a positive economic result as overly risky, and therefore, in the absence of State aid, would engage in a level of R&D&I activities which is too low from the point of view of society. Likewise, in the absence of State aid, R&D&I projects may suffer from insufficient access to finance, due to asymmetric information, or from coordination problems among firms. [...] The R&D&I Framework applies to all technologies, industries and sectors to ensure that the rules do not prescribe in advance which research paths would result in new solutions for products, processes and services and do not distort market players' incentives to*

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(287) Achieving decarbonisation targets, including further electrification of the economy, will require significant investments in network and storage infrastructure in any scenario. The quoted studies suggest that deploying nuclear energy may allow reducing the investments in networks and storage relative to a decarbonisation scenario without nuclear energy.

(288) If network operators distribute the costs of maintaining and expanding the network across network users, the price signal for individual project developers does not reflect the incremental cost of connecting their project to the network.

(289) Decision C(2024) 2655 final

develop innovative technological solutions even in the presence of high risks" (290). Thus, the economic rationale to support SMRs and AMRs is not specific to nuclear energy, but the same as for all early-stage technologies. Once SMRs and AMRs mature, the Commission may re-assess if any costs and benefits market participants do not fully take into account persist.

7.2. Legislation providing support instruments to manage risks

Several EU Member States plan to include nuclear energy in their future energy mix. This involves facilitating new build projects or the LTO of existing plants. As long as the costs and benefits market participants do not fully take into account described in section 7.1 are present, state intervention can be required to avoid underinvestment in nuclear new build projects and possibly also in LTO projects. Thus, Member States must consider which financing model to employ to realise their plans.

Recent nuclear new build projects around the world exhibit a variety of financing schemes, including two-way contracts for difference (CfDs), power purchase agreements (PPAs), and other mechanisms (291).

- CfDs: New build projects at Dukovany in the Czech Republic and in Poland, LTO of the Doel 4 and Tihange 3 units in Belgium, and the new build project at Hinkley Point C (HPC) in the United Kingdom.
- PPAs: The Barakah and Akkuyu new build projects in the United Arab Emirates and in Türkiye, respectively.
- Mankala model: The Olkiluoto 3 new build project in Finland (292).
- Fully state financed: The Paks II new build project in Hungary is fully state financed, based on an intergovernmental agreement between Hungary and the Russian Federation (293).
- Construction cost recovery: The consortium of utilities realising the Vogtle 3 and 4 units in Georgia in the United States funded the project with equity and were

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(290) Communication from the Commission Framework for State aid for research and development and innovation 2022/C 414/01 (C/2022/7388), OJ C 414, 28.10.2022, p. 1–38

(291) A recent report by the OECD's Nuclear Energy Agency provides a more comprehensive overview: OECD Nuclear Energy Agency (2024), Effective Frameworks and Strategies for Financing Nuclear New Build, https://www.oecd-nea.org/jcms/pl_96124/effective-frameworks-and-strategies-for-financing-nuclear-new-build

(292) Under the Mankala model, several energy-intensive electricity consumers co-own the power plant and retain the right to purchase electricity at cost. Thus, the Mankala model can be viewed as an example of vertical integration along the value chain.

(293) Commission Decision of 6.3.2017 on the Measure / Aid Scheme / State Aid SA.38454 - 2015/C (ex 2015/N) which Hungary is planning to implement for supporting the development of two new nuclear reactors at Paks II nuclear power station, C(2017) 1486 final (recitals 9 – 16). Austria pleaded the General Court for the annulment of this Commission decision in Case T-10. The General Court dismissed the action in its judgment of 30 November 2022. In the ongoing appeal Case C-59/23 P | Austria v Commission, Austria pleaded to set aside in its entirety the Case T-10 judgment and to annul the Commission Decision (EU) 2017/2112 on the State aid. The Court of Justice a set aside the General Court judgment, annulled the Commission decision on the basis that the Commission should have examined procurement-law issues as inextricably linked to the aid's object.

allowed to pass-through partial construction costs in consumers' electricity tariffs already during construction.

- Regulated asset base (RAB) model: The UK government proposes the RAB model for the planned Sizewell C nuclear new build project.

The EU's Electricity Market Design (EMD) reform requires that direct price support schemes for investment in new power-generating facilities including nuclear facilities must take the form of two-way CfDs or equivalent schemes with the same effects ([294]). The EMD reform also encourages Member States to promote the uptake of PPAs ([295]).

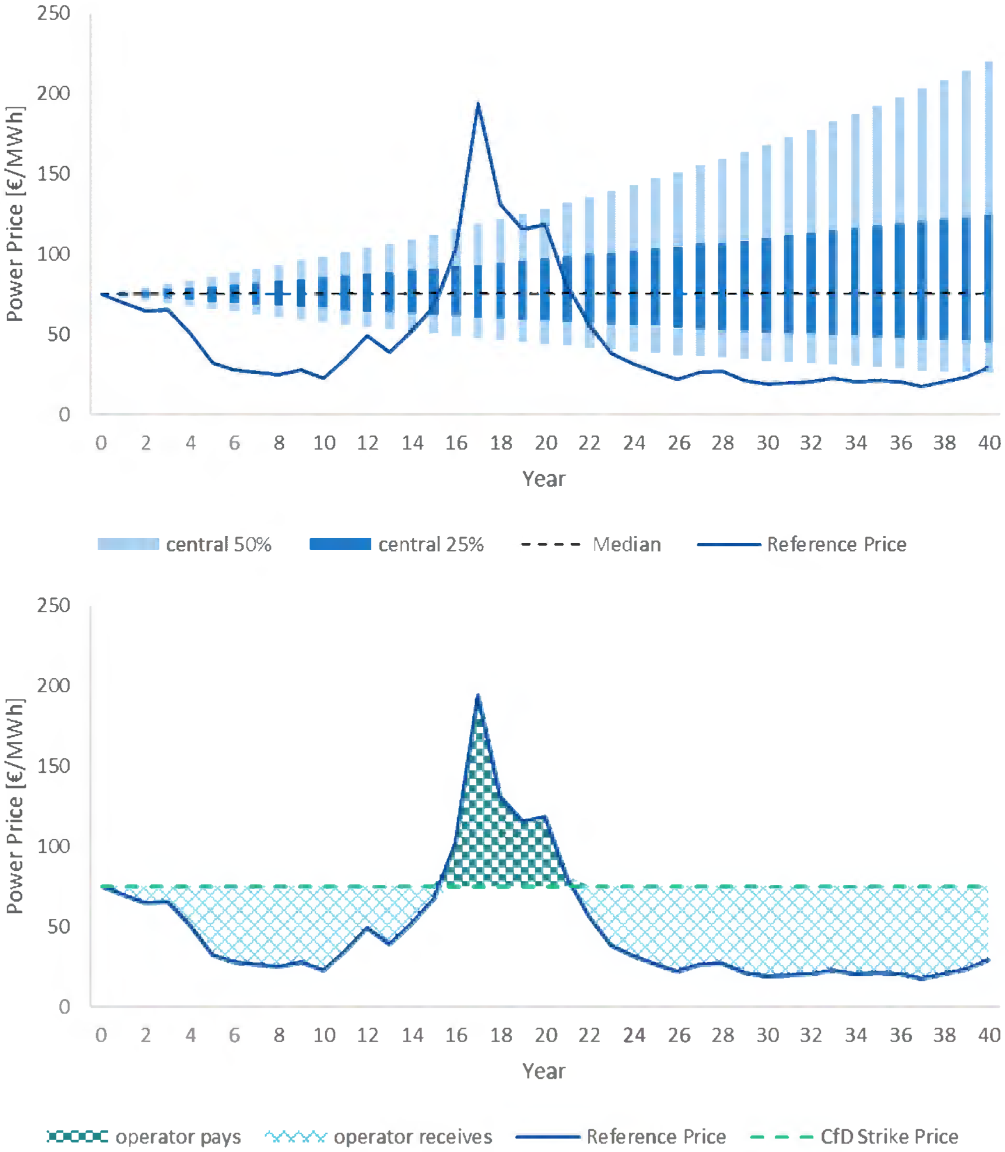
7.2.1. Two-way CfDs

A two-way CfD takes a "reference price" and a "strike price" as inputs. The plant operator is one of the parties to the CfD. When using CfDs for state support, a government-sponsored entity may be the counterparty to the CfD. The counterparty need not be the electricity off-taker. For each unit of electricity produced or for a defined reference quantity, the plant operator pays the difference between the strike price and the reference to the counterparty if the reference price is above the strike price, and it receives the difference from the counterparty if the reference price is below the strike price. Figure 39 illustrates this.

([294]) Art 19d, para. 1, Regulation (EU) 2019/943 of the European Parliament and of the Council of 5 June 2019 on the internal market for electricity, as amended by Regulation (EU) 2024/1747 of the European Parliament and of the Council of 13 June 2024.

([295]) Art 19a, para. 1, Regulation (EU) 2019/943 of the European Parliament and of the Council of 5 June 2019 on the internal market for electricity, as amended by Regulation (EU) 2024/1747 of the European Parliament and of the Council of 13 June 2024.

Figure 39 – Illustration of a CfD



Source: European Commission.

Notes: All numbers are for illustration only and do not reflect any real-world examples. The top panel shows the evolution of a CfD's Reference Price over a period of 40 years. Ex ante, the evolution is uncertain. The dark blue bars and light blue bars represent the inner 25% probability and inner 50% probability area for the materialisation of the reference price, respectively. The solid blue graph represents a random realisation of the Reference Price.

The bottom panel shows the payments between the operator and the CfD counterparty for a given Strike Price (dashed green line) for the realised Reference Price. If the Reference Price is lower than the Strike price, the CfD counterparty pays the difference to the operator (blue crossed areas). If the Reference Price exceeds the Strike Price, the operator pays the difference to the CfD counterparty (green squared area). If the operator sells the produced electricity at the Reference Price, the earnings from the electricity market together with these difference payments result in a combined, stable earnings stream equivalent to having sold the electricity at the Strike Price.

The design choices in a CfD pertain to contract term, the definition of strike and reference prices, reference quantities where applicable, and other features. For instance, the strike price could be a fixed number, it could track some long-term average electricity price, it could be indexed to some inflation measure, or it could reflect the construction cost of the plant. The reference price is typically a price index, but here, too, there are multiple design options.

7.2.2. PPAs

PPAs differ from two-way CfDs in some key respects.

- **Counterparty**: For a given PPA, the supplier's counterparty is the electricity off-taker, i.e. a single, and typically private economic agent (296). In contrast, the counterparty to a CfD is typically a government-backed entity. This has implications for the potential to re-allocate risks using a PPA (see section 7.3).

- **Contract clauses**: The two parties to a PPA are in principle free to negotiate any contract clauses they desire. Supplier and off-taker can agree freely the deliverable quantity, payable price, possible rights for the off-taker to modulate the quantity, and many other rights and obligations of supplier and off-taker (297).

PPAs can facilitate delivering state support. If the off-taker is a private party, the state may provide additional guarantees to the PPA, and thereby improve the risk allocation between the two counterparties. If a state-sponsored entity is trading on the electricity wholesale market, it may directly act as counterparty to the PPA, i.e. as off-taker.

7.2.3. RAB model

The UK government proposes to finance the planned nuclear new build project Sizewell C by adapting the RAB model (298). In the EU, the RAB model has not yet been used for nuclear installations. It has a long track record regarding assets not exposed to competition, as it has been widely used across Member States to set allowed revenues for regulated electricity and natural gas transmission and distribution system operators (299), as well as for some transport infrastructure.

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(296) Project sponsors could aim at selling the plant's production via one PPA to a single counterparty. This approach may be particularly relevant for SMRs, as their smaller size may fit the need of a large off-taker. Alternatively, project sponsors could aim at entering multiple PPAs with a portfolio of off-takers and spread risks over a wider group of economic agents this way. This approach may be more relevant for large-scale reactors. For instance, the Mankala model underlying the Olkiluoto 3 project in Finland foresees that project shareholders, which in this case are consumers from energy-intensive industries, off-take the produced electricity.

(297) Policymakers have considered the potential benefits of supporting the standardisation of PPA contract terms for renewables, e.g. through developing voluntary contract templates. The EU Agency for the Cooperation of Energy Regulators (ACER) investigated the potential benefits of PPA terms standardisation for renewables. Following a stakeholder consultation, ACER concluded in October 2024, "*that it does not need to develop new voluntary PPA contract templates*" [ACER, 15 October 2024, Assessment on the need of ACER's voluntary Power Purchase Agreement contract template(s), https://www.acer.europa.eu/electricity/market-monitoring/ppas#:~:text=Power%20Purchase%20Agreements%20(PPAs)%20are,renewable%20energy%20sources%20(RES).] Given the large size of nuclear power plants, project sponsors who want to use PPAs to develop their projects are likely to prefer bespoke, i.e. tailor-made rather than standardised, contract terms for nuclear new build. If SMRs or even microreactors become wide-spread in the future, potential benefits of standardised contract terms may become more relevant.

(298) Ofgem (06 November 2023), Guidance on our approach to the Economic Regulation of Sizewell C.

(299) ACER (16 December 2024), Electricity infrastructure development to support a competitive and sustainable energy system, 2024 Monitoring Report, p. 28.

If a Member State and project developers proposed to finance nuclear new build projects using a RAB model in the future, they would have to consider at least the following items.

- **Compliance with EMD**: Direct price support schemes for investment in new power-generating facilities shall take the form of two-way contracts for difference (CfDs) or equivalent schemes with the same effects. The Member State and project sponsors would have to ensure compliance with the existing legislation, e.g. by demonstrating that their proposed model qualifies as an equivalent scheme with the same effects (300).

- **Reimbursement of allowed revenues**: So far, the RAB model is mostly used to regulate undertakings which are either licensed monopolists or enjoy a certain degree of market power. The RAB model sets an upper limit for allowed revenues, but the regulated entities must earn revenues from their customers (301). If revenues fall short of the allowed upper limit, e.g. because of low demand, the shortfall may be credited to the allowed revenues in future years. This system works when the regulated entity enjoys sufficient market power, as is the case with licensed monopolists. In contrast, nuclear power plants compete with other generators in the electricity wholesale market and do not enjoy market power if the market performs as intended. Thus, financing power plants through a RAB model would require the Member State to appoint an entity from which the RAB-financed nuclear power plant can claim revenue shortfalls, and to which it would owe revenue surpluses (302). This entity would have to be backed either by electricity consumers or taxpayers (303). In fact, the UK government's proposal for financing Sizewell C through a RAB model proposes the government-owned Low Carbon Contracts Company as the designated revenue collection counterparty (304).

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(300) If the Member State and project sponsor show that their proposed RAB model qualifies as an equivalent measure with the same effects, they would also have to ensure alignment with the remaining provisions of Art. 19d Regulation (EU) 2019/943 of the European Parliament and of the Council of 5 June 2019 on the internal market for electricity, as amended by Regulation (EU) 2024/1747 of the European Parliament and of the Council of 13 June 2024.

(301) EU regulators setting network tariffs using a RAB model oftentimes proceed in two steps. In a first step, the RAB model determines the allowed revenues. In a second step, the regulator applies an ex-ante assumption for the likely quantity sold during the relevant regulatory period to derive regulated network tariffs. In a hypothetical case, where a Member State used the RAB model to finance a nuclear power plant, the second step, deriving regulated prices from allowed revenues, would not be needed.

(302) Supporting a beneficiary through a CfD requires appointing a similar counterparty.

(303) Whereas backing through taxpayers may be possible in principle, EU legislation prescribes that "any revenues, or the equivalent in financial value of those revenues, arising from direct price support schemes in the form of two-way contracts for difference and equivalent schemes with the same effects referred […] shall be distributed to final customers"; Art 19d, para. 5, Regulation (EU) 2019/943 of the European Parliament and of the Council of 5 June 2019 on the internal market for electricity, as amended by Regulation (EU) 2024/1747 of the European Parliament and of the Council of 13 June 2024.

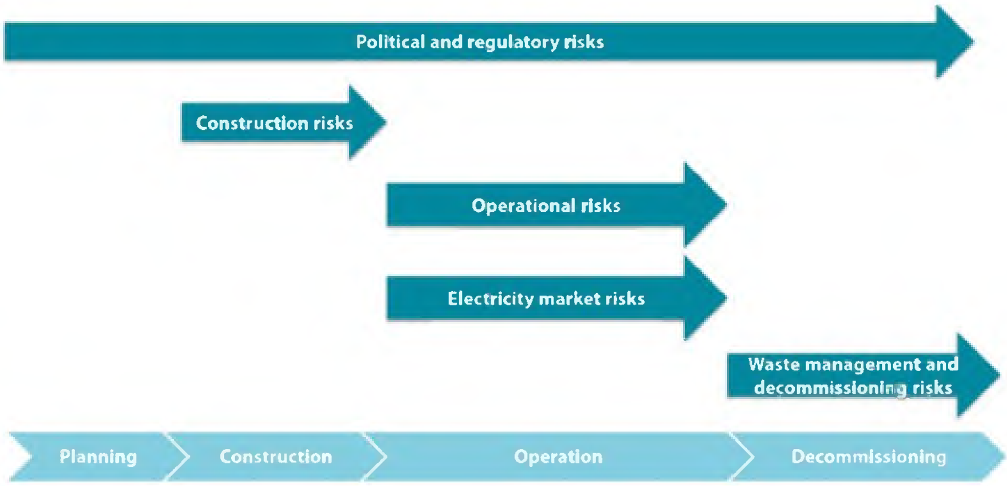
(304) Department for Energy Security and Net Zero and Department for Business, Energy & Industrial Strategy (9 June 2022), Notice given pursuant to Section 16 of the Nuclear Energy (Financing) Act 2022 to designate Low Carbon Contracts Company Ltd as a counterparty for revenue collection contracts for the purposes of the nuclear RAB Model

The RAB model relies on two high-level cornerstones. These are the "regulated asset base" and an administratively allowed rate of return. The regulated asset base is a register of historical capital expenditures, approved by a regulatory authority, that gets depreciated over time. Allowed revenues usually reflect depreciation of the asset base, allowed return on the asset base, and regulatory approved operational expenditures. In practice, there are many different design features that allow fine-tuning of the RAB model. The specific RAB model implementations for network operators vary across Member States, within each Member State, they often vary across the regulated network operators (305), and they may evolve over time.

7.3. Allocating electricity market and construction risk is key

Figure 40 illustrates the main risk categories a nuclear new build project faces during its life cycle. Political and regulatory risks are constantly present. In addition, there are distinct risks in each of the project's life cycle, i.e. construction risk, operational and electricity market risks, and radioactive waste management, and decommissioning risks.

Figure 40 – Risks along the life cycle of a nuclear installation



Source: OECD Nuclear Energy Agency (2024), Effective Frameworks and Strategies for Financing Nuclear New Build, https://www.oecd-nea.org/jcms/pl_96124/effective-frameworks-and-strategies-for-financing-nuclear-new-build, Figure 1.1, p. 18.

A key question for every nuclear new build project is the allocation of construction and electricity market risks (306). Public interventions with the goal to unlock private investment in new build nuclear projects could be particularly effective if project sponsors and policymakers design them in such a way that they allocate both risks. It is important that this does not mean that the investor should be shielded from all risk, as this could result in a lack of incentives to reduce construction cost or to follow market signals in operating the plant, see section 7.4.

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(305) CEER (21 February 2024), Report on Regulatory Frameworks for European Energy Networks 2023, Ref: C23-IRB-70-03

(306) For instance, the Nuclear Energy Agency organised a workshop on "Financing Nuclear New Build Today" in Prague, Czech Republic, on 13 June 2024, where participants compared a number of recently adopted or discussed financing models to better understand the allocation they imply for construction and electricity price risks.

Stakeholders also regularly point to the importance of political and regulatory risk and the importance of a stable and predictable regulatory environment.

7.3.1. *Electricity market risk*

Electricity market risk primarily arises from uncertainty about future electricity prices, which drives uncertainty about earnings. Re-allocating electricity price risk, e.g. through a CfD or a PPA, can lower a project's cost of capital (307).

A two-way CfD transfers the electricity market risk from the plant operator to the CfD counterparty, where precise risk allocation depends on the design of strike and reference prices. Beiter et al. (2024) find that "*CfDs are a floating-for-fixed electricity price swap that transforms a variable electricity price into a fixed electricity price cash flow, with the two parties sharing in the electricity price risk. [...] CfDs share similarities with financial derivatives used to manage risk in other sectors of the economy – for instance, an interest rate swap, where banks trade the difference between interest payments calculated on the basis of short-term versus long-term interest rates, or mortgages with fixed interest rates (to ensure predictability of payments) that are hedged by banks through swapping the long-term fixed rate against short-term rates to match the long-term exposure of the loan.*" (308)

PPAs allow for flexible pricing structures, which enables the two counterparties to re-allocate electricity market risk between the two of them. The absence of a liquid market for long-term PPAs is consistent with the Commission's finding of a lack of market-based instruments for risk allocation in nuclear energy (309). It is also consistent with the EMD requiring Member States to promote the uptake of PPAs.

PPAs allow to re-allocate electricity market risk only between two parties, the supplier and the off-taker. The electricity market risk arising from a GW-scale nuclear power plants may be too large for most private counterparties to take on individually (310). Project developers may be able to spread the risk across multiple off-takers, as is the case with the Olkiluoto 3 plant in Finland. In contrast, the CfD counterparty is usually a state-sponsored entity. This way, CfDs allow re-allocating the electricity market risk exposure of one producer to all electricity consumers connected to the grid, i.e. to a numerous group of other economic agents, reducing the exposure of any individual.

In 2024, the OECD's Nuclear Energy Agency (NEA) prepared a comparative review of several case studies for nuclear new build projects around the world, focusing on the risk allocations implemented by the respective financing models. Figure 41 below shows how the different models allocate electricity market risk. The parties who assume the largest share of electricity market risk in most of the financing models

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(307) Gohdes, Nicholas, Paul, Simshauser, Wilson, Clevo, 2022. Renewable entry costs, project finance and the role of revenue quality in Australia's National Electricity Market. Energy Econ. 114, 106312.

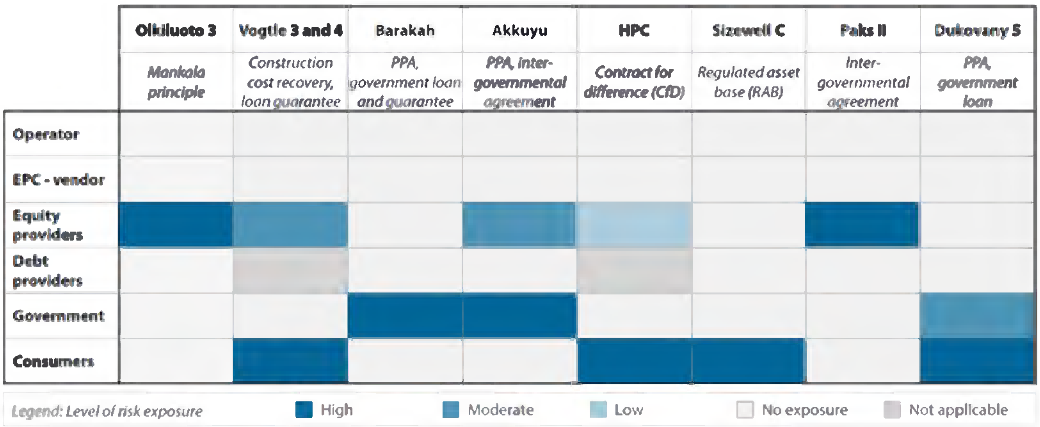
(308) Beiter, P., Guillet, J., Jansen, M. et al. The enduring role of contracts for difference in risk management and market creation for renewables. Nat Energy 9, 20–26 (2024), pp 22, 23.

(309) If market-based instruments for risk allocation in nuclear energy were widely available, one would expect to observe PPAs spanning the operational life of nuclear power plants, as well as other instruments.

(310) An intermediary might be able to pass-on the risk to a larger group of users, but it would require a sufficiently large client base.

surveyed in NEA's study are either electricity consumers or the government, i.e. taxpayers (311).

Figure 41 – Electricity market risk across nuclear new build projects



	Olkiluoto 3	**Vogtle 3 and 4**	**Barakah**	**Akkuyu**	**HPC**	**Sizewell C**	**Paks II**	**Dukovany 5**
	Mankala principle	*Construction cost recovery, loan guarantee*	*PPA, government loan and guarantee*	*PPA, Inter-governmental agreement*	*Contract for difference (CfD)*	*Regulated asset base (RAB)*	*Inter-governmental agreement*	*PPA, government loan*
Operator	□	□	□	□	□	□	□	□
EPC - vendor	□	□	□	□	□	□	□	□
Equity providers	■	▦	□	▦	▤	□	■	□
Debt providers	□	▨	□	□	▨	□	□	□
Government	□	□	■	■	□	□	□	▦
Consumers	□	■	□	□	■	■	□	■

Legend: Level of risk exposure ■ High ▦ Moderate ▤ Low □ No exposure ▨ Not applicable

Source: OECD Nuclear Energy Agency (2024), Effective Frameworks and Strategies for Financing Nuclear New Build, https://www.oecd-nea.org/jcms/pl_96124/effective-frameworks-and-strategies-for-financing-nuclear-new-build, Figure 3.6, p. 76.

Notes: EPC = Engineering, Procurement, and Construction.

7.3.2. *Construction risk*

Construction risk remains a major hurdle to financing nuclear new build (312). From a valuation perspective, construction risk is driven by potential cost overruns and delays during construction. Pure cost overruns increase the present value of construction capex and thereby reduce a project's net present value (NPV). Delays lead to a later start of the operating period, i.e. they postpone the point in time as of which cash flows from operation come in and thereby reduce the present value of cash flows from operation and by extension the NPV of the project. In practice, delays are likely to go hand in hand with cost overruns, compounding the negative impact on the NPV.

CfDs and PPAs, the two instruments featuring in the EMD reform, primarily focus on allocating electricity price risk. However, their features can be designed such that construction risk can also be addressed.

- The strike price of a CfD could be indexed to turnout construction costs, or to price indices for goods or services that are likely to affect construction costs, or there could be a review of the strike price after construction is finished. This would shift the risk of delays and cost overruns to the CfD counterparty. Thus, Member States and project developers may in principle use CfDs to re-allocate construction risk.

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(311) Olkiluoto 3 and Paks II form the only two examples, where the authors classify the electricity market risk to reside with equity providers. However, in the Mankala model applied at Olkiluoto 3, the shareholders are large industrial electricity consumers who are also the plant's off-takers, so one might classify this financing model as allocating the electricity market risk to consumers after all.

(312) IEA (2025), The Path to a New Era for Nuclear Energy, IEA, Paris https://www.iea.org/reports/the-path-to-a-new-era-for-nuclear-energy, Licence: CC BY 4.0

- As the elements of a PPA can be designed freely, the two counterparties may allocate some of the construction risk to the off-taker, if both parties agree to it. In turn, this may allow the plant owner to pass-on some insurance further up the value chain, e.g. to the contractor for Engineering, Procurement, and Construction (EPC). In the case of Olkiluoto 3, off-takers are simultaneously shareholders, which exposed them to construction risk anyhow. Member States may consider designing guarantees to PPAs that cover construction risks.

In practice, as the remuneration of the project developer should be closely linked to the amount of risk born, a reallocation of the construction risk toward the Member State would come with a reduction of its expected remuneration.

The recently completed Vogtle plant in the US and the planned Sizewell C plant in the UK feature financing mechanisms which aim to enhance the re-allocation of construction risk. Vogtle's Nuclear Construction Cost Recovery (NCCR) mechanism, and the RAB model envisaged for Sizewell C allow project developers to collect revenues even before the construction is completed. This feature can avoid that interest during construction piles up in the event of delays. This in turn, allows project developers to earn an agreed return on their capital expenditures with lower nominal earnings during operation than would be the case if earnings only came in once power production began. It may also allow project developers to increase the debt-to-equity ratio of the project earlier, i.e. already during construction, which has the potential to reduce the project's cost of capital.

Figure 42 shows the allocation of construction risk across nuclear new build projects according to NEA's analysis. Most financing models allocate a significant share of construction risk to the Engineering, Procurement, and Construction (EPC) vendor or equity providers, and all models leave at least some construction risk exposure to them. These parties seem best placed to influence the cost and duration of the construction process. Keeping them exposed to construction risk is consistent with providing incentives to deliver the project on time and within budget, see section 7.4 (313).

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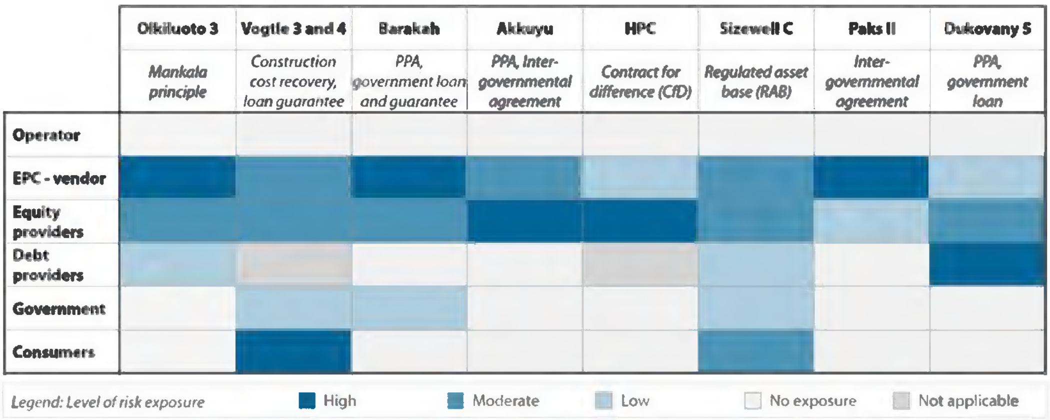
(313) The incentives arising from a support measure and its associated financing model depend on the details of the model and cannot be inferred from a high-level classification or risk allocations as presented in Figure 40.

Figure 42 – Electricity market risk across nuclear new build projects



	Olkiluoto 3	Vogtle 3 and 4	Barakah	Akkuyu	HPC	Sizewell C	Paks II	Dukovany 5
	Mankala principle	Construction cost recovery, loan guarantee	PPA, government loan and guarantee	*PPA, Inter-governmental agreement*	*Contract for difference (CfD)*	*Regulated asset base (RAB)*	*Inter-governmental agreement*	*PPA, government loan*
Operator	□	□	□	□	□	□	□	□
EPC - vendor	■	▨	■	▨	░	▨	■	░
Equity providers	▨	▨	▨	■	■	▨	░	▨
Debt providers	░	▒	□	□	▒	░	□	■
Government	□	░	░	□	□	░	□	□
Consumers	□	■	□	□	□	▨	□	□

Legend: Level of risk exposure ■ High ▨ Moderate ░ Low □ No exposure ▒ Not applicable

Source: OECD Nuclear Energy Agency (2024), Effective Frameworks and Strategies for Financing Nuclear New Build, https://www.oecd-nea.org/jcms/pl_96124/effective-frameworks-and-strategies-for-financing-nuclear-new-build, Figure 3.4, p. 75.

7.3.3. *Political and regulatory risk*

Potential equity investors and stakeholders from the nuclear industry regularly point to the importance of political and regulatory risk and the challenge arising from uncertainty around long-term nuclear energy policy and regulatory frameworks.

Financing investment projects in the nuclear industry as well as in any other industry can become more challenging if there is significant uncertainty around the duration and outcome of key administrative procedures. Member States can aim to reduce the perceived uncertainty around these decisions by providing clear guidelines, streamlining the process, ensuring sufficient resources for regulatory authorities and similar measures.

A more fundamental challenge arises from the fact that governments may retro-actively change previous decisions. This source of uncertainty may interact with the other risks discussed earlier. It is closely related to the challenge of potential "hold-up" discussed before. Some Member States have introduced retro-active changes to their wider energy policy in the past, and have been challenged for it by investors, who considered their energy assets had suffered damages as a result (314). It should be noted that in 2018, the Court of Justice found that investor-State arbitration clauses in intra-EU bilateral investment treaties ("intra-EU BITs") are incompatible with the EU Treaties. To implement this judgement, 23 Member States signed the agreement

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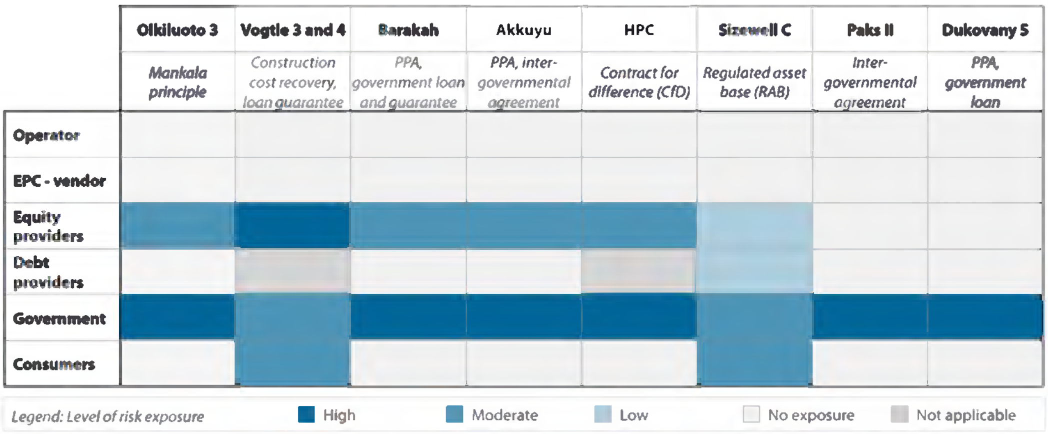
(314) As of 4 March 2025, the World Bank's International Centre for Settlement of Investment Disputes (ICSID) lists 45 concluded cases and 35 pending cases against EU Member States in the economic sector of "Electric Power & Other Energy". https://icsid.worldbank.org/cases/case-database The case of Germany may serve as an example. Swedish state-owned power energy company Vattenfall co-owned and operated two nuclear power plants located in Brunsbüttel and Krümmel, In August 2011, against the backdrop of the nuclear accident in Fukushima-Daiichi, Japan, the German Parliament amended its legislation to statutorily accelerate fixed end dates for the operation of nuclear power plants. The amendment cut short the operational lifetimes of Vattenfall's nuclear power plants that had been fixed in 2010 by a previous amendment. Vattenfall challenged this amendment through the filing of a constitutional challenge with the German Federal Constitutional Court, and through the initiation of an investment arbitration against Germany under the Energy Charter Treaty.

for the termination of intra-EU bilateral investment treaties, which entered into force in 2020.

On the one hand side, retro-active interventions may erode investor confidence in the long-term stability of policy measures. This can reduce the effectiveness of mechanisms designed to manage other risks. For instance, if investors are not confident that the strike price of a two-way CfD will evolve as agreed, they may require the same compensation as if they were fully exposed to electricity price risk, even though the CfD re-allocates this risk on paper. This may drive up the project's cost of capital despite the presence of a CfD, which may make it either costlier than necessary or may stop it from going ahead altogether. Member States committed to nuclear energy may try to re-assure investors through mechanisms that protect them from potential damages of retro-active interventions. For instance, the state may contribute the most junior tranche of capital or offer other guarantees. On the other hand, retro-active changes, e.g. the decision to phase-out nuclear or allocate fewer public funds to supporting clean energy, may reflect an evolving distribution of preferences in the electorate.

Figure 43 shows the allocation of political and regulatory risk across nuclear new build projects according to NEA's analysis. NEA classifies most models as allocating this risk primarily to the government. This reflects that in many of the surveyed cases, the government offered some form of guarantee to protect the other stakeholders from unforeseen changes.

Figure 43 – Political and regulatory risk across nuclear new build projects



	Olkiluoto 3	**Vogtle 3 and 4**	**Barakah**	**Akkuyu**	**HPC**	**Sizewell C**	**Paks II**	**Dukovany 5**
	Mankala principle	*Construction cost recovery, loan guarantee*	*PPA, government loan and guarantee*	*PPA, inter-governmental agreement*	*Contract for difference (CfD)*	*Regulated asset base (RAB)*	*Inter-governmental agreement*	*PPA, government loan*
Operator	□	□	□	□	□	□	□	□
EPC - vendor	□	□	□	□	□	□	□	□
Equity providers	▦	■	▦	▦	▦	▤	□	□
Debt providers	□	▨	□	□	▨	▤	□	□
Government	■	▦	■	■	■	▦	■	■
Consumers	□	▦	□	□	□	▦	□	□

Legend: Level of risk exposure ■ High ▦ Moderate ▤ Low □ No exposure ▨ Not applicable

Source: OECD Nuclear Energy Agency (2024), Effective Frameworks and Strategies for Financing Nuclear New Build, https://www.oecd-nea.org/jcms/pl_96124/effective-frameworks-and-strategies-for-financing-nuclear-new-build, Figure 3.3, p. 74.

7.4. Incentives

The design choices in CfDs and PPAs not only implement a desired risk allocation, but they also set incentives for the project developer and the counterparty. The plant operator cannot control the evolution of electricity prices, but it can control the dispatch of the plant, which affects earnings from the electricity market. Likewise, the project developer cannot fully control the cost and time to completion of a nuclear power plant construction project, but it has some influence on it, e.g. through implementing efficient project management.

However, if the public intervention fully insures against electricity market or construction risk, there is no longer an incentive for efficient behaviour. If the plant operator receives a guaranteed, fixed price per produced unit, there is no longer an incentive to optimise the plant dispatch in response to market signals ([315]). This would interfere with the wider electricity system, e.g. through distorting the plant operator's incentives to provide flexibility to the system. Such interferences would lead to disproportionate distortions of competition and trade in the internal market, and they must be avoided. Likewise, if a support scheme guarantees an agreed rate of return on any construction capital expenditures incurred, the project developer no longer has an incentive to do what is possible to deliver the project on time and within budget.

An incentive-compatible financing mechanism does not insure the project sponsor in full. Instead, the mechanism shares the relevant risks between the project sponsor and a counterparty. The risk sharing mechanism will ensure that the project sponsor is sufficiently protected to lower the project's cost of capital, but at the same time leave the sponsor sufficiently exposed to incentivise efforts towards desirable objectives, including plant dispatch based on market signals, construction on time and within budget, and adherence to the highest safety standards.

As stated before, a lowering of the risk exposure born by the investor would come in parallel with a reduction of the expected remuneration.

7.5. Conclusions

The Commission proposed a reform of the existing electricity market rules in March 2023, as part of the Green Deal Industrial Plan ([316]). They entered into force in July 2024. The Commission will work together with Member States to support them in transposing the rules into national law. This reform established amongst others that direct price support schemes for investments in new generation of electricity from low-carbon sources including nuclear energy must take the form of two-way CfDs or equivalent schemes with the same effects. In addition, Member States shall promote the uptake of PPAs.

The Commission published a Guidance on CfD design ([317]), including on combining CfDs and Power Purchase Agreements (PPAs) as announced in the Clean Industrial Deal ([318]). This Guidance applicable to all energy-related projects, may support Member States in designing CfDs for nuclear projects in an incentive-compatible way, which may streamline State aid procedures.

In line with the approach in the Electricity Market Design, the Commission is engaging with the EIB to promote PPAs in a technology-neutral way.

([315]) Ingmar Schlecht, Christoph Maurer, Lion Hirth, Financial contracts for differences: The problems with conventional CfDs in electricity markets and how forward contracts can help solve them, Energy Policy, Volume 186, 2024; Newbery, D. (2023). Efficient Renewable Electricity Support: Designing an Incentive-compatible Support Scheme. The Energy Journal, 44(3), 1-22.

([316]) The new electricity market design rules consist of the amending Directive EU/2024/1711 and the amending Regulation EU/2024/1747.

([317]) C(2025) 8479 final.

([318]) Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, The Clean Industrial Deal: A joint roadmap for competitiveness and decarbonisation; COM/2025/85 final.

At the third high-level meeting of the Joint European Forum for Important Projects of Common European Interest (JEF-IPCEI) on 9 April 2025, 13 Member States endorsed a potential IPCEI candidate on innovative nuclear technologies. This enables the IPCEI candidate to transition to the design phase, where the Commission's IPCEI Design Support Hub will assist it.

The EIB and the European Investment Fund (EIF) support start-ups and scale-ups across Europe by providing targeted financial products and risk finance through initiatives like InvestEU and the European Tech Champions Initiative (ETCI). These efforts aim to enhance access to finance for SMEs, strengthen European competitiveness, and drive innovation and growth in key sectors.

The European Atomic Energy Community (Euratom) supports the further development of nuclear skills and competences through the Euratom Research and Training programme. Euratom also supports Bulgaria, Slovakia (319), and Lithuania (320) as part of the nuclear decommissioning assistance programmes.

The European Commission is empowered to issue bonds on behalf of Euratom to finance back-to-back loans to investment projects related to nuclear power generation and the nuclear fuel cycle in EU countries (321). Euratom can also finance investment projects related to nuclear safety improvements or the decommissioning of nuclear installations in certain EU neighbourhood countries (322). The total amount of lending for these activities is limited to EUR 4 billion (323), of which EUR 3.67 billion has already been allocated.

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(319) Council Regulation (Euratom) 2021/100 of 25 January 2021 establishing a dedicated financial programme for the decommissioning of nuclear facilities and the management of radioactive waste, and repealing Regulation (Euratom) No 1368/2013.

(320) Council Regulation (EU) 2021/101 of 25 January 2021 establishing the nuclear decommissioning assistance programme of the Ignalina nuclear power plant in Lithuania and repealing Regulation (EU) No 1369/2013.

(321) Council Decision 77/270/Euratom of 29 March 1977 empowering the Commission to issue Euratom loans for the purpose of contributing to the financing of nuclear power stations, OJ L 88, 6.4.1977, p. 9–10.

(322) Council Decision of 21 March 1994 amending Decision 77/270/Euratom to authorize the Commission to contract Euratom borrowings in order to contribute to the financing required for improving the degree of safety and efficiency of nuclear power stations in certain non-member countries, OJ L-84, 29.03.1994 p 4.

(323) Council Decision 90/212/Euratom of 23 April 1990, OJ No L 112, 03.05.1990, p 26.

Annex A Factual summary report on the Call for Evidence (CfE) ([324])

1. OBJECTIVE OF THE CALL FOR EVIDENCE

The 2025 Commission work programme ([325]) and the Action Plan for Affordable Energy ([326]) announced an updated assessment of investment needs in the EU's nuclear sector in the form of a new PINC, to be adopted in 2025. Under Article 40 of the Euratom Treaty, the Commission is required to publish a PINC periodically. These programmes are intended to stimulate action by undertakings and Member States and facilitate coordinated development of their investments in the nuclear field.

The aim of the CfE was to inform Member States, the public and interested stakeholders, and to ask for feedback and insights on the intended initiative. This gives them an opportunity to help assess the EU's nuclear investment needs in a collaborative, transparent and inclusive manner.

This outreach to EU countries and stakeholders complements the Commission's own data and information gathering process and prepares the ground for publishing the new PINC.

2. APPROACH TO THE CALL FOR EVIDENCE

The Commission published the CfE document on the 'Have Your Say' website in 24 languages. There was no questionnaire but the possibility to submit free-text comments or attached documents. The consultation period ran from 14 April to 12 May 2025, lasting four weeks. Prior to publication, the Commission informed Member States about the CfE at the meeting of the Working Party on Atomic Questions on 9 April 2025, and the Commission invited Member States to advertise the CfE.

3. FEEDBACK

3.1. Respondent profile

A total of 215 stakeholders submitted their feedback in response to the CfE. 67 respondents submitted feedback in the form of attached documents. Respondents were asked to identify as one of the following categories: EU citizen, NGO (non-governmental organisation), environmental organisation, business association, public authority, company/business, academic/research institution, trade union, or other. 138 identified as EU citizens, 23 identified as NGO, 21 identified as company/business, 11 identified as public authority, 8 as business association, 6 as environmental organisations, 3 as academic/research institution, 1 as trade union, and 4 as other. Figure 44 illustrates the distribution of respondents.

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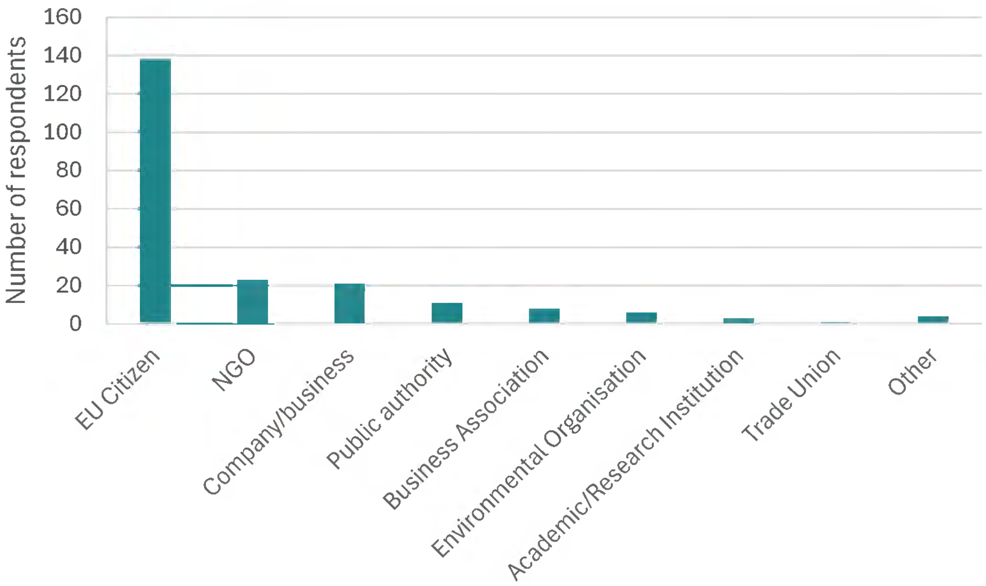
(324) Disclaimer: This Annex should be regarded solely as a summary of the contributions made by stakeholders during the Call for Evidence. It cannot in any circumstances be regarded as the official position of the Commission or its services. Responses to the consultation activities cannot be considered as a representative sample of the views of the EU population.

(325) COM(2025) 45 final, Commission work programme 2025 - European Commission

(326) COM(2025) 79 final, Action Plan for Affordable Energy: Unlocking the true value of our Energy Union to secure affordable, efficient and clean energy for all Europeans - European Commission

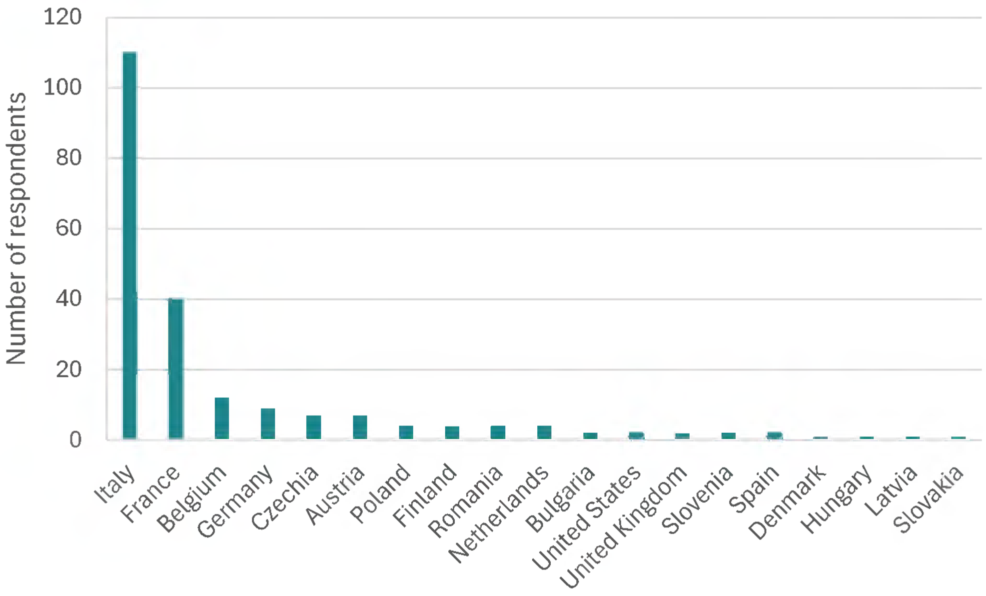
Figure 44 – Distribution of all received responses by respondent category



Source: PINC CfE.

Figure 45 summarises the distribution of feedback by country of origin. A significant share of responses (105 out of 215) came from EU citizens located in Italy.

Figure 45 – Distribution of all received responses by respondent country of origin



Source: PINC CfE.

3.2. Feedback content

This section provides an overview of the contributions received in response to the CfE. It groups respondents' feedback by topic.

Outlook on nuclear energy: The views expressed and evidence presented in the CfE reflect a wide range of viewpoints. Many argued that nuclear energy plays a critical role in achieving the EU's climate and energy security goals while others called for all EU Member States to phase out nuclear energy and to focus on renewables. In general, nuclear energy was seen as contributing significantly to the EU's electricity supply, decarbonisation, economic growth and competitiveness but facing challenges such as high construction and capital costs, concerns about safety and waste management, and regulatory and public acceptance barriers. Most respondents shared the need for a transition to low-carbon energy sources and to minimise dependency on fossil fuels.

Respondents raised the age of the existing fleet of nuclear power plants and the potential for lifetime extensions and new-build projects, the latter of which have often faced delays and cost overruns. They discussed the associated operational and capital expenditures, and the levelised cost of electricity from nuclear plants and other generation technologies. Respondents also commented on the role of nuclear energy in the wider electricity system, the distinction between firm and intermittent generation sources and their complementarity, the need for flexibility between energy sources, the overall integration of the energy system, i.e. requirements for other infrastructure such as networks and storages, and the total system costs.

Non-power uses of nuclear energy: Respondents brought up several uses of nuclear energy besides electricity generation, including the production of medical radioisotopes, heat supply, propulsion systems, and water desalination.

Supply chain: Respondents presented evidence on several aspects of the nuclear supply chain, pertaining to the fuel cycle, to lifetime extensions, potential new build, and to decommissioning and the safe management of radioactive waste and spent fuel. Regarding the supply chain for nuclear fuel, respondents addressed mining and uranium supply (including health and environmental aspects), conversion, enrichment, fuel fabrication, reprocessing, the fuel needs of SMRs and AMRs, and nuclear fuel prices. Respondents also commented on the availability and geographic distribution of uranium sources, the resulting implications for EU's strategic autonomy, and the need to avoid dependence on any single or unreliable suppliers, such as Russia. Regarding the supply chain for nuclear installations, respondents discussed the experiences with recent new-build projects, pointed at potential bottlenecks in the EU supply chain that, if left unaddressed, might challenge Member States' plans. Respondents also raised the question how the supply chain needs to evolve to facilitate the rollout of SMRs. It was furthermore suggested to learn from other countries where new-build projects have been realised without major delays. On decommissioning and the management of radioactive waste and spent fuel ("back-end"), respondents highlighted the need for long-term solutions, appropriate management of back-end funds, and addressing the issue of insurance coverage for nuclear liability risks.

Innovative nuclear technologies: Respondents presented evidence on several innovative nuclear energy technologies, including SMRs, AMRs, and fusion energy. They discussed the potential to roll out of SMRs in the EU, recent developments around demand for electricity arising from data centres, as well as remaining challenges relating to licencing, fuel supply, safety, and radioactive waste and spent fuel potentially emanating from SMRs. In the context of fusion energy, respondents discussed the technology's potential to supply clean energy, its path to commercialisation, recent initiatives by startups, and whether fusion energy needs a separate regulatory framework besides the one existing for fission energy.

Cross-cutting topics: Respondents raised the importance of strong and independent regulatory oversight to ensure the highest levels of safety and also hinted at potential for further evolution of the existing regulatory framework. Proposals were made to streamline legal frameworks and to harmonise licensing procedures in order to reduce delays and costs, and to simplify state aid processes. Respondents stressed the importance of transparency relating to nuclear energy matters, and the need for public participation in key decision-making processes, e.g. siting decisions for nuclear installations. Respondents raised the need to invest in the workforce, and to strengthen EU's international cooperation in the nuclear field. Some respondents also raised interlinkages between civilian and military uses of nuclear technologies, perceiving this as problematic.

Financing: Respondents brought up the significant investments required to use nuclear energy and discussed options to finance these investments from public or private funds, also citing experience in other jurisdictions, e.g. the UK. Several respondents called for technology neutrality and for including nuclear energy in EU funding instruments from which it is currently excluded. Some suggested establishing a dedicated instrument for the funding of nuclear projects or the creation of an IPCEI (Important Project of Common European Interest). Respondents also raised the topic of financing SMRs and sufficient funding for the nuclear back-end (waste management and decommissioning).