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Atoms for Peace and Development

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INTERNATIONAL STATUS AND PROSPECTS FOR NUCLEAR POWER 2025

Report by the Director General

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International Status and Prospects for Nuclear Power 2025

Report by the Director General

Summary

- General Conference Resolution GC(50)/RES/13 requested the Secretariat to provide, on a biennial basis, a comprehensive report on the international status and prospects for nuclear power, beginning in 2008. General Conference resolution GC(60)/RES/12, issued in September 2016, requested the Secretariat to continue to publish the International Status and Prospects for Nuclear Power report on a four-year basis, starting in 2017. This report responds to resolution GC(60)/RES/12.

International Status and Prospects for Nuclear Power 2025

Report by the Director General

A. Clean Energy for Climate and Development: Socioeconomic Context

A.1. The Evolving Context

1. There have been significant national and international developments underscoring the role of nuclear power in mitigating climate change and achieving sustainable development since International Status and Prospects for Nuclear Power 2021 (document GOV/INF/2021/32-GC(65)/INF/6 and GOV/INF/2021/32/Corr.1-GC(65)INF/6/Corr.1) was issued. This section highlights some of the most important developments affecting the status and prospects for nuclear power.

A.1.2. International Developments

2. The power sector and the broader energy industry are poised to undergo a complete transformation in the coming decades. To achieve carbon neutrality and to restrict the average global temperature increase to well below 2°C above pre-industrial levels and pursue efforts to limit it to 1.5°C above pre-industrial levels, as per the Paris Agreement, energy sector investment must be directed towards clean and sustainable technologies. At the same time, the steep increase in energy prices observed in 2022, along with price volatility have placed the question of security of energy supply at the heart of the global energy policy discussions.

3. Many countries recognize nuclear power's role in achieving sustainable development and energy security. Nuclear policies have been updated in several countries, and nuclear power has been included in sustainability taxonomies in the European Union, China, Japan, the Republic of Korea and the Russian Federation.

4. A diversified generation mix where variable renewable energy (VRE) sources are used in conjunction with a sizeable share of low carbon dispatchable technologies, such as nuclear power or hydropower, is key to achieving decarbonization at the lowest economic cost and highest level of reliability, and minimizing risks in the energy transition.

5. Shifting from fossil fuels to cleaner energy sources can impact energy security and affordability. While fossil fuel supply and price volatility risks will reduce, new risks from deploying low carbon technologies, such as VRE, will arise. These technologies require significant amounts of critical minerals and materials, which are geographically concentrated. Supply chain constraints can delay energy infrastructure investments and increase energy costs. Furthermore, systems with large shares of

VRE will become increasingly dependent on weather conditions, challenging the ability of these systems to maintain grid stability and reliability during long periods of low wind or absence of sunshine. On the other hand, with the exception of critical minerals and materials, the value chain of low carbon technologies can be domestically sourced, thus increasing the self-reliance of energy-importing countries.

6. Nuclear energy's low carbon footprint, relatively low reliance on critical minerals and contribution to ensuring power system reliability position it well for decarbonizing the energy system. Furthermore, nuclear power is the only dispatchable technology capable of providing low carbon heat and electricity to the system at scale. On a life cycle basis, the carbon footprint and material intensity per unit of nuclear electricity generation is among the lowest of all electricity generation technologies. Current nuclear power plants (NPPs) can operate at high power levels over extended periods of time (between 12 and 24 months between refuelling and maintenance outages), which allows for operational stability, if needed. As a dispatchable source, NPPs can be operated at a constant power level or the output can be modulated depending on power system needs.

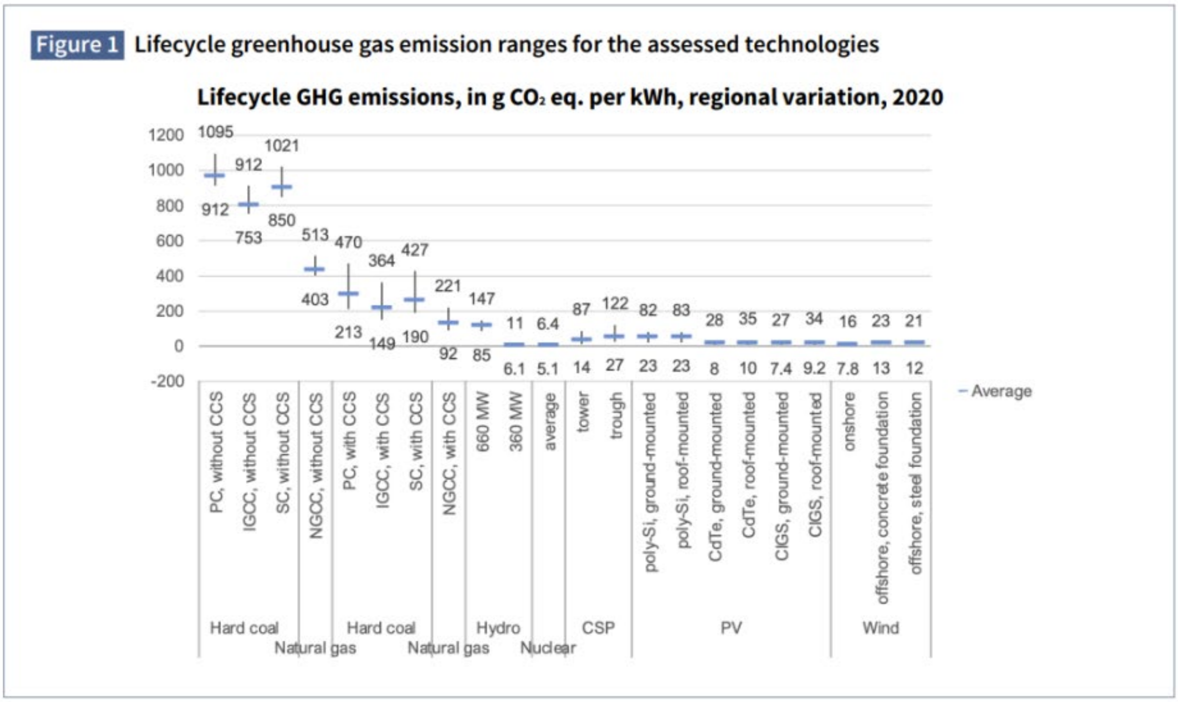


Fig. A.1. Lifecycle greenhouse gas emission ranges for the assessed technologies (Source: UNECE)

7. The operational costs of nuclear power are stable, predictable over time and relatively insensitive to fluctuations in uranium prices. Uranium resources are abundant and diversified globally and there is significant potential for the discovery of new ones, given proper market conditions. However, although resources are expected to be sufficient to support high case nuclear development scenarios, significant investment and technical expertise will be required to bring these resources to market. Owing to uranium's high energy content, a large amount of energy can easily be stored on site at NPPs, protecting utilities from potential fuel supply disruptions. The use of fast spectrum reactors with closed fuel cycles can also address any future concerns about the availability of uranium.

B. Nuclear Power Today

8. As reported in the Nuclear Technology Review 2025, as of the end of December 2024, global operational nuclear power capacity was 377 GW(e), provided by 417 reactors operating in 31 Member States. In addition, 23 reactors licensed for operation and representing capacity of 19.7 GW(e) were in suspended operation during 2024. This includes 4 reactors in India and 19 reactors in Japan.

In 2024, total nuclear electricity production was 2617.5 TW·h. The top three producers were the United States of America (USA) (30%), China (16%) and France (14%).

9. By the end of 2024, 64.5 GW(e) of nuclear capacity (62 reactors) was under construction in 15 countries, with China accounting for 46% of this expansion. Construction had begun on nine pressurized water reactors in China, Egypt, Pakistan and the Russian Federation, totalling 10.2 GW(e). China had started construction on six new reactor units, including four HPR1000 reactors and two CAP1000 units. Construction of Egypt's El Dabaa-4 VVER-1200 reactor had begun, Pakistan had launched the construction of Chasnupp-5 (Hualong-1 design) and in the Russian Federation, construction of Leningrad 2-3 had commenced.

10. About 67% of global operational reactor capacity (254.7 GW(e), 284 reactors) has been in operation for over 30 years. Therefore, investment in long term operation and ageing management programmes is increasing to ensure the reliable, safe and continuous operation of the existing feet and a smooth transition to new capacity.

11. By the end of 2024, the nuclear industry had accumulated approximately 20 200 reactor-years of operating experience at 653 reactors around the world. Nuclear power capacity has remained consistent since 2021, with 24.4 GW(e) connected to the grid. Over 71% of this growth has occurred in Asia, particularly in China, which has connected 7.5 GW(e) to the grid since 2021. Holtec International plans to resume the operation of Palisades NPP by the end of 2025, and Constellation Energy has announced its plan to restart Three Mile Island Unit 1(TMI-1) by 2028. These efforts aim to meet the rising demand for carbon-free energy.

12. Global interest in nuclear power is growing. In addition to the two newcomer countries operating their first NPP (Belarus and the UAE), a further three newcomers are advancing in the construction of their NPPs — namely Bangladesh (2 units), Egypt (4 units) and Türkiye (4 units) — with commissioning activities having already started in Bangladesh and Türkiye. Thirty-seven countries are at various stages of development of their nuclear power programmes, with five new countries (Iraq, Jamaica, Myanmar, Rwanda and Singapore) initiating considerations for nuclear power in 2024 in 2024. Several countries, including Belgium, the Republic of Korea and Sweden, have reconsidered their intentions to phase out nuclear energy and some, including Malaysia and Viet Nam, have decided to restart their programmes. About 20 other countries have expressed interest in nuclear power and initiated studies to include it in their future energy mix.

13. Simultaneously, some countries reconsidering early nuclear phase-out are engaging in unplanned plant life extensions, sometimes encouraged by large industrial end users like data centres. In 2024, the USA initiated efforts to restart reactors that had been shut down for economic reasons.

C. The Prospects for Nuclear Power

14. For the fourth consecutive year, the Agency has revised its annual projections for nuclear power growth upwards. Momentum has increased since nuclear power's inclusion in the Global Stocktake and the pledge by 31 countries since the 28th session of the Conference of the Parties to the United Nations Framework Convention on Climate Change (COP28) to triple current global nuclear capacity by 2050. The first Nuclear Energy Summit, held in Brussels in March 2024, further added to this momentum. The Agency's high case projection now stands at 950 GW(e) by 2050, 2.5 times the current capacity. Achieving this requires large-scale implementation of comprehensive plant life management programmes, continued investment in plant modernization, license extensions, strengthened supply chain resilience across the existing fleet and about 640 GW(e) of new build capacity, with small modular reactors (SMRs) potentially representing nearly a quarter of this. Key prerequisites for this expansion include industry capability to deliver on time and to budget, access to financing, equitable policies for all low carbon technologies and accelerated demonstration of SMRs. The low case projection forecasts an increase to 514 GW(e) by 2050, with SMRs representing 6% of the added capacity.

Fig. XX. Tripling Nuclear Energy by 2050, Net Zero Nuclear Event, at the United Nations Climate Change Conference UNCCC, held at the Expo City Dubai, United Arab Emirates in December 2023 (Source: IAEA)

15. The declaration to triple 2020 global nuclear capacity by 2050 presents both opportunities and challenges. China's rapid nuclear expansion and the Russian Federation's extensive overseas projects

exemplify feasible models for financing and implementation where governments play a major role. But attracting private sector finance will be key to scaling up the deployment of nuclear, through novel approaches that include sustainable finance, public-private partnerships and various market mechanisms. Multilateral development banks, most of which currently exclude nuclear power from their lending policies, could also play an important role in supporting projects in emerging markets and developing economies, and some are currently reviewing their policies regarding nuclear energy. The World Bank's recent decision to lift its ban on financing nuclear power projects has several significant implications. Among others, it signals a potential shift in global energy policy, encouraging other institutions to reconsider their positions on nuclear energy and potentially increasing investment in nuclear infrastructure. De-risking investments, in particular during the construction phases of new build plants, whether large scale or based on SMRs, remains essential.

Fig. XX. IAEA Director-General Rafael Mariano Grossi with Ajay Banga, President World Bank Group as they sign the agreement between the International Atomic Energy Agency and the World Bank to support the safe, secure, and responsible use of nuclear energy in developing countries, during their meeting in Paris, France. June 2025. (Source: IAEA)

16. There is growing interest in advanced and innovative reactor technologies, including SMRs. While advanced large water cooled reactors are expected to make up most of the capacity expansion, SMRs are anticipated to contribute significantly to reaching the high case projection of 950 GW(e), representing about 150 GW(e). In the context of increasing demand for clean energy given AI development, the potential substitution of coal-fired power plants and the electrification of transport, building heating and cooling and industrial applications, SMRs could provide a reliable source. Their role in decarbonizing hard-to-abate sectors could be a game-changer.

D. Influential Factors for the Future Deployment of Nuclear Power

17. To reach the high case projection of 950 GW(e) by 2050, modern construction techniques, such as modularization for large-scale designs and the integration of AI to enhance project efficiency, will be crucial. Regulatory harmonization, though challenging, could streamline international collaboration and accelerate deployment. Key obstacles include securing project financing and garnering political will, which, despite recent improvements, may not progress swiftly enough to achieve the overarching objective. Additionally, the development of robust supply chains for SMRs and advanced designs is essential. Many countries lack demonstrated capabilities in major nuclear project implementation, which could hinder progress. Continuing international efforts to overcome public scepticism and ensure the safe, reliable operation of new technologies will also be vital. International collaboration can play a significant role in sharing demonstrated good practices, enhancing nuclear energy sustainability and fostering innovation without requiring large national investments. To address these challenges, investment in technology, infrastructure and workforce development, and clear, supportive policies will be necessary. Engaging stakeholders and educating the public on the benefits and safety of nuclear power could further bolster acceptance and support. Finally, the availability of fissile/fertile materials and of adequate fuel supply chain infrastructures (especially for the production of high assay low enriched uranium (HALEU)-based fuels) to fuel nuclear programmes will need be ensured in a timely manner for their effective deployment.

18. Solutions demonstrated in some countries have yet to be widely implemented. These solutions involve utility owners/operators, regulators, policymakers, national laboratories, international organizations, NGOs, academia and the broader nuclear power industry. By embracing these solutions the sector will increase its competitiveness and accelerate new nuclear capacity deployment.

D.1. Funding and Financing

19. Historically, the construction of NPPs has relied mostly on government financing. Most existing NPPs have been built by large utilities fully or partially owned by governments, operating in regulated markets where many of the costs and risks associated with a nuclear project could be passed on to the consumer. The current context for nuclear new build is significantly different. Some countries have liberalized their electricity markets, thus reducing the role of government in the electricity sector and transferring most of the risk to electricity generating companies. Other countries that still maintain regulated markets are also seeking the involvement of the private sector, either because their balance sheets would not support full government financing or as a result of imposed government policy.

20. The financing of recent nuclear projects has involved both the host governments and nuclear technology vendors, reducing investor exposure and raising lower-cost financing. Host government financing can be direct or via loan guarantees that assure full repayment in case of default, reducing debt costs and increasing financial leverage. Loan guarantees were used for the Vogtle project (USA) and the Barakah project (UAE). In several projects, suppliers participated as equity and/or debt providers, as seen in the Barakah project with Korea Electric Power Corporation’s 18% equity stake, and in the Akkuyu project (Türkiye) with Rosatom as the majority stakeholder. In embarking and expanding countries like Bangladesh, Belarus, Egypt, Hungary, India, the Islamic Republic of Iran and Pakistan, intergovernmental agreements with government loans have been used.

21. The predictability and stability of revenues during operations are crucial for attracting investments in capital-intensive technologies like nuclear and renewables. While revenue risk is limited in regulated

markets, it is higher in deregulated markets with fluctuating electricity prices. Mechanisms in liberalized markets to secure revenues and mitigate market risks for capital-intensive technologies include long term power purchase agreements, feed-in tariffs and contracts for difference, which guarantee predictable revenues for predetermined periods. Examples include the Barakah project (UAE), the Akkuyu project (Türkiye) and Hinkley Point C (United Kingdom (UK)). Other mechanisms complement market revenues with premiums or capacity payments, like the production tax credit used in the USA for the Vogtle project and the zero-emission credit for existing nuclear plants.

22. The regulated asset base (RAB) model, recently proposed in the UK for the Sizewell C nuclear plant, provides a regulated return to the developer during construction, reducing upfront costs and project risks and translating to lower overall project costs. Hybrid RAB models can share the risks of cost overruns and delays, further reducing risks for developers. These mechanisms share similarities with those in regulated markets.

23. The 'Mankala model', successfully applied in Finland, finances large capital-intensive projects, including NPPs. In this cooperative model, power users provide equity for NPP construction and contribute to operating costs, receiving electricity produced in proportion to their share. This model allows shareholders to undertake large projects collectively, sharing risks and offering an implicit hedge against electricity price volatility.

24. A key factor for successful — and cost effective — nuclear projects is managing and mitigating risks during the development and construction phases. Recent experience in large NPP new build has shown that cost overruns and construction delays can be effectively minimized by:

- Developing the necessary nuclear infrastructure in a timely manner;
- Developing a multi-unit programme allowing all parties to gain experience in nuclear construction;
- Relying on an experienced vendor, with a steady inflow of projects and a well-established and qualified supply chain;
- Adopting a proven design and taking advantage of lessons learned from previous projects, especially in embarking countries;
- Employing qualified and competent contractors with experienced teams;
- Engaging early and effectively with regulators and having a stable and predictable regulatory framework;
- Adopting effective project management and risk-informed procurement, manufacturing and delivery.

Case Study: Finland — corporate financing by power intensive customers in a liberalized market: Mankala

A typical ownership model for energy production companies in Finland is the 'Mankala' model. This cooperative **corporate finance** model allows power users to participate in large, capital intensive projects. The idea is that a group of power users provide equity finance for the construction of an NPP and receive power at cost in proportion to their shares in the project.

The Mankala model **shares and balances risks** faced by power consumers and producers, improving the confidence of lenders. The shareholders nonetheless retain the risk of project failure.

The Mankala cost-price operating model also boosts competition by supporting the entry of new investors into the market, and encourages the sharing of competencies and financial resource.

25. To achieve the significant growth that the Agency foresees in its high case 2050 projection, it will be necessary to attract financing from the private sector, including financial institutions, commercial banks and other investment players.

D.2. Electricity Markets and Policies

26. Governments worldwide have introduced various mechanisms and policies to promote low carbon technologies to address climate change. Most policies target specific technologies and provide revenue support, such as renewable energy targets, preferential grid access, direct investment subsidies, price guarantees, market premiums or tax credits. These policies have helped mature renewable technologies like wind and solar photovoltaic, but have also distorted electricity markets.

27. Other initiatives, such as green bonds and sustainable investment classification systems, aim to mobilize new funding and reduce capital costs for projects supporting environmental and sustainability goals. Green bonds were recently issued by European, Canadian and US utilities to finance essentially lifetime extension investments. Incentives that value low carbon nuclear power generation are also important mechanisms to improve the competitiveness of nuclear projects. Green bond issuance has grown rapidly, with the overall level of investments in sustainable energy reaching over US $500 billion in 2021 and exceeded US $1 trillion in 2024. Governments, market regulators and financial entities have developed taxonomies and guidelines to define ‘sustainable’ investments, facilitating finance flow by providing security for investors, reducing market fragmentation and supporting climate-friendly companies. While sustainable investments have mostly targeted renewable projects, some nuclear projects have also benefited from these initiatives, as in the case of Canadian utility Bruce Power, which raised Can $500 million in 2021 for the lifetime extension of its NPPs.

28. Carbon pricing, via a carbon tax or tradable emission rights, is considered the most economically efficient and least distortive instrument in climate mitigation policy. It makes low carbon technologies more competitive than emitting technologies. A carbon pricing system covering multiple emitting sectors, with an increasing price over time, ensures low carbon technology deployment at the lowest economic cost to achieve climate objectives. However, the share of global greenhouse gas emissions covered by carbon pricing is limited to about one-fourth, and in most cases, the price level does not provide a sufficient market signal for investing in low carbon technologies.

Electricity Market Design Challenges

29. Over recent decades, many countries have implemented electricity market reforms to liberalize the sector and establish competitive markets. Liberalized markets have proven efficient in optimizing existing assets and improving overall power sector efficiency. However, they do not provide sufficient signals for long term investments in capital-intensive technologies. Current energy-only electricity markets have failed to provide the price signals needed for unsubsidized investments in low carbon technologies or to correctly reflect the true cost and value of different technologies. As a result, some jurisdictions struggle to ensure security of supply and decarbonization at the lowest economic cost.

30. Production-based supports, such as feed-in tariffs, contracts for difference, feed-in premiums and tax-credit schemes, have shielded low carbon technologies from market signals. This has affected the efficient dispatch of generating technologies, weakened electricity price signals and distorted electricity markets. Negative electricity prices in EU and US markets are a direct consequence of these policies. The large deployment of low marginal cost renewable technologies has depressed wholesale electricity market prices and increased volatility, heightening market risk. Lower wholesale prices and higher market risk have prevented investments in dispatchable resources needed for system flexibility.

31. Current market structures often fail to adequately remunerate services needed for the functioning of the power system or to fairly allocate the costs imposed by each technology. System benefits include flexible operations and the availability of generation capacity, while system costs include additional costs for transmission and distribution infrastructure and the variability and unpredictability of non-dispatchable technologies. Studies show that the system costs of variable renewable energy (VRE) are substantially higher than those of dispatchable technologies, increasing with their share in the generation

mix. For example, according to the IEA, global investment in renewables (largely VRE) amounted to US $771 billion in 2023, while investment in grids and storage amounted to US $452 billion (largely to accommodate the increase of VRE in clean energy systems). In energy-only markets, system costs are not allocated to the technologies that generate them but are borne by the overall system, which provides a clear advantage in estimating the generation costs of VRE. Important system benefits, like inertia provision, frequency and voltage control and other ancillary services, are often not assigned market value. These services are generally provided by large thermal generators, including nuclear.

32. Different approaches regarding waste management and decommissioning costs are often applied across energy sources. Full life cycle costs, including future decommissioning and waste management, are included in nuclear energy prices but not in those of other energy generating technologies.

33. These factors have resulted in a lack of investment in dispatchable low carbon technologies, affecting energy supply security. In the USA and Europe, some NPPs have been shut down or lifetime extension plans shelved for market-related reasons, thereby withdrawing a large, flexible, low carbon energy source from the system.

Technology Neutral Market Policy

34. To achieve climate goals and ensure a reliable and secure energy supply in a cost-effective manner, energy policies, regulatory measures and electricity market designs need to evolve. Technology-neutral pricing in electricity markets should account for generation, environmental, system and integration costs, as well as contributions to system resilience, independence and security of supply.

35. Appropriate pricing mechanisms should reflect the locational and time value of electricity generation, capacity, flexibility and the different services provided to the system. Maintaining efficient short term markets and exposing each technology to real-time and nodal pricing are crucial for the cost-efficient dispatch of generating resources. This helps to internalize the profile costs of different technologies and encourages better coordination of networks and generation development. Market-based remuneration of dispatchability, flexibility and provision of system services strengthens sustainable energy systems. Implementing a robust, predictable and rising carbon price while phasing out fossil fuel subsidies would enhance competitiveness and provide long term stability for low carbon technology investments.

36. Recent events highlight the need for diverse energy supplies in case of interruptions due to environmental or geopolitical events. However, low carbon technologies are unlikely to be financed solely based on volatile and uncertain electricity market prices. The high capital intensity of these technologies requires specific market arrangements to reduce market risk and provide investors with revenue stability and visibility. Policymakers must balance exposure to wholesale markets with out-of-market support for low carbon technologies.

37. By removing penalties (or incentives) and assigning returns based on total system value, nuclear power may be seen as a viable option depending on system needs, composition and long term outlook. Nuclear power has demonstrated value as a large generator providing system stability, reactive power control, continuity and system restoration capability, alongside low greenhouse gas emissions. Nuclear power requires stable revenues to manage financing risks and provide a return on large capital investments, typically achieved in regulated markets or through secured rate contracts.

38. Different jurisdictions have made decisions to invest in long term operations or new nuclear capacity, recognizing its value in low carbon systems. For example, the UK procured new nuclear generation with guaranteed future revenue stability via a contract for difference. China plans to double the share of nuclear in its power mix to 10% by 2035 compared to 2022. In Canada and some US states, policymakers have committed to the long term operation of existing plants despite higher costs. And the

UAE has selected nuclear power as a new market entrant owing to its ability to provide large volumes of low carbon, dispatchable electricity, despite the lower costs associated with solar generation.

D.3. Resilience

39. Owing to rising average global temperatures, the frequency and intensity of severe weather events are expected to increase significantly. These events could range from winter storms to intense floods, heat waves and droughts, leading to the proliferation of aquatic organisms. All of these factors can impact generation assets as well as grid infrastructures. As these severe weather events become more common, it is crucial for the nuclear industry to align and adjust its strategies accordingly, implementing all necessary safety measures and updating possible threat scenarios to ensure the continued resilience and reliability of NPPs.

40. Several specific measures have already been put in place to combat various weather events. For example, NPPs exposed to flooding have implemented enhanced flood protection systems, such as reinforced flood barriers and improved drainage systems, to prevent water ingress. In regions susceptible to heat waves, some plants have upgraded their cooling systems to maintain efficiency even during extreme temperatures, while others have adapted water management practices to address drought conditions. Additionally, structural reinforcements have been made to withstand the increased frequency and intensity of storms. These proactive measures demonstrate the industry's commitment to maintaining high safety standards in the face of climate-related challenges. Similar measures, when applied to production-related systems, help to mitigate production losses.

41. The economic implications of these adaptation measures for operating NPPs are multifaceted. On one hand, the initial investment in upgrading infrastructure and implementing new safety and reliability measures can be substantial. These costs can pose a financial burden, especially for older plants with limited remaining operational lifetimes. Utilities carefully evaluate the cost of adaptation against the potential benefits, considering factors such as the enhanced performance and extended life span of the plants, as well as uncertainties in the climate scenarios. Some work is still needed to determine scenarios applicable to each specific NPP that can be used to inform investment decisions. On the other hand, new builds can incorporate climate resilience from the outset, taking into account potential risks posed by weather events over the plant's expected operational lifetime. In this way, new NPPs can achieve higher levels of safety and efficiency, ultimately contributing to a more resilient energy system.

42. In addition to external factors like climate change and economic variability, which call for greater resilience in the nuclear system, it is essential to strengthen human and organizational resilience equally, if not more. To foster the development of resilient capabilities that enhance awareness, adaptability, and timely, effective action, the Agency has developed and implemented electronic leadership development tools such as the IAEA Dynamic Leaders' Platform and the immersive, scenario-based, 'safe to fail/safe to learn', "Embedding Leadership Behaviour for Resilient Nuclear Performance" workshop.

43. By facilitating resilient performance in everyday work, the nuclear workforce is better positioned to operate effectively in both emergent and emergency situations. Providing opportunities to safely practice and apply these skills in progressively challenging scenarios, where the only risk of "failure" is learning, best equips the nuclear organization to navigate the volatility, uncertainty, complexity, and ambiguity (VUCA) that is increasingly prevalent in this rapidly changing nuclear landscape.

D.4. Advanced Reactors and Non-electric Applications

44. Initiatives to accelerate innovation in the nuclear power sector aim to address challenges related to performance, cost and safety. These innovations may be entirely new or adapted from other industries

and can be technical (such as passive safety systems, digitalization, AI and advanced manufacturing), organizational, process-based or business-related. Innovation is relevant across all phases of the NPP life cycle, including construction, operation, decommissioning, waste management, regulation, the supply chain, energy policy, financing and stakeholder engagement. Countries with advanced nuclear programmes often implement integrated projects combining multiple innovations. For instance, the Russian Federation's Proryv ('Breakthrough') project seeks to close the nuclear fuel cycle using fast neutron reactors and on-site reprocessing.

45. Most NPPs that are currently operating, under construction or planned are large, gigawatt-scale reactors, expected to remain major contributors to the world's electricity grid for decades. However, large-scale NPPs are not viable in certain energy markets, including countries with small grids, remote regions, mining industries or industrial complexes. SMRs are expected to fulfil the expectations of these markets, as well as to facilitate the deployment of nuclear power by significantly reducing the capital costs. Additionally, there is an increasing need for nuclear energy in non-electric applications, for which SMRs may provide a sustainable solution.

Opportunities Found in SMR Characteristics

46. SMRs can also be deployed in specific scenarios such as barge-mounted energy supply for remote areas, including small island countries. Businesses are attracted by the lower investment costs and fewer components, with designs, fabrication and deployment tailored to various needs. Currently, the Agency lists around 70 SMR designs and technology development activities in more than 20 countries, over 15 of which are progressing towards deployment by 2035. The first commercial SMR power units of the water cooled type have been operational at the Russian Federation's Akademik Lomonosov floating NPP since 2020, with 70 MW used for both electricity generation and district heating. China brought a modular high temperature gas cooled reactor (HTR-PM) into commercial operation in December 2023, generating 200 MW of electricity. Other construction projects are ongoing in Argentina, China and the Russian Federation and various designs are in the advanced development or licensing stages in Canada, Denmark, France, Italy, Japan, the Republic of Korea, the Russian Federation, the UK and the USA.

47. While large NPPs benefit from economy of scale, SMRs are expected to benefit from 'economy of series' through modularized manufacturing of standardized factory-built modules, shorter construction schedules and greater use of commercial-grade items for cost reduction. To compete with larger nuclear reactor designs, SMRs must achieve operational efficiency through innovative concepts like technology enhancements, improved human and system interfaces, increased automation and cogeneration potential.

48. Moving towards the harmonization of operator and regulator requirements and design standardization is key to success. Efforts include developing reactor technologies such as sodium fast reactors, lead cooled fast reactors, very high temperature reactors, gas cooled fast reactors and molten salt reactors. These advanced innovative reactors aim to enhance safety, sustainability, efficiency and cost-effectiveness, sharing common safety and economic objectives. International joint development initiatives are ongoing, emphasizing early dialogue between developers and regulators to facilitate deployment.

49. To coordinate its activities on SMRs and their applications and provide a focal point for Member States and other stakeholders, the Agency established the IAEA Platform on Small Modular Reactors and their Applications in 2021. The Platform serves as a one-stop-shop for requests from Member States and stakeholders regarding SMRs and related applications. In 2022, the Nuclear Harmonization and Standardization Initiative (NHSI) was initiated with the aim of facilitating the global deployment of safe and secure advanced nuclear reactors by advancing regulatory harmonization and standardization of industrial approaches.

Non-Electric Applications of Nuclear Energy and Integrated Energy Networks

50. Power sector emissions account for about 40% of total CO_2 emissions. Other sectors, such as transport and industry, are also the focus of global decarbonization initiatives. Electrification, where possible, is imperative, increasing electricity demand sharply. Additionally, low carbon heat sources, fuels and energy carriers are essential for decarbonizing ‘hard to abate’ sectors like industry or heavy-duty transport. Hydrogen, an essential chemical feedstock in several highly emitting industries, holds significant promise as a key energy carrier for decarbonization. However, hydrogen needs to be produced with low carbon sources to fulfil its potential. Furthermore, nuclear energy holds significant potential to decarbonize the production of potable water from sea water, which currently supports the lives of hundreds of million of people worldwide, while being currently powered mostly with fossil fuels.

51. Nuclear energy has enormous potential for non-electric applications, including hydrogen production, water desalination, district heating and the provision of heat for industrial processes that are difficult to electrify. These applications can help reduce reliance on fossil fuels, mitigate climate change and provide access to clean drinking water. The benefits of nuclear cogeneration continue to be considered by countries operating power plants, countries planning expansion and newcomers. While all nuclear reactors can support a range of non-electric applications, certain advanced concepts are designed specifically for one or more non-electric applications, including supplying high temperature heat to energy-intensive industrial processes.

52. The economic and market constraints of nuclear cogeneration, heat, hydrogen and other non-electric application projects remain major obstacles for commercial implementation. Policy support for hydrogen projects based on production technology rather than carbon intensity skews the playing field against nuclear energy, delaying the energy transition. Large facilities are necessary to demonstrate non-

electric nuclear projects at a commercial scale, but a country supplying nuclear reactors may not be able to justify a large-scale demonstration without a suitable business case. Non-electric applications of nuclear power may require licensing adaptation, new regulations and approval by national regulators.

53. Strong government support, adequate research and development, a level policy playing field with other low carbon technologies and affordable financing for cogeneration projects are key tools to overcome these challenges. Integrating various energy sources for power, heating, cooling, energy storage and commodity production (e.g., hydrogen, synthetic fuels) can maximize the use of diverse energy resources and technologies to provide reliable, efficient, sustainable and flexible energy services. Nuclear reactors can be used for cogeneration via direct steam extraction or for heat supply via a heat exchanger. Nuclear cogeneration projects may result from retrofits of operating NPPs or the optimization of new designs, as in the case of multipurpose SMRs. Cogeneration adds flexibility to NPP production modes, facilitating integration with renewables by enabling the switching between electricity and other products as required, without losing energy production.

54. Hydrogen is a versatile energy carrier, chemical feedstock and electricity vector. However, current hydrogen production is highly carbon-intensive. Nuclear cogeneration supports decarbonization pathways, including low carbon hydrogen production. Hydrogen production using low and high temperature electrolysis is being piloted by several utilities in multiple countries using operating NPPs. Concerns about global warming and water scarcity have also motivated countries to consider nuclear desalination. Desalination and NPP integration deliver diverse technical and economic benefits, including carbon-free electricity, low marginal costs of electricity generation and dispatchable reliability. In regions where water is scarce, the ability of NPPs to produce fresh water is an important asset for increasing the local population’s standard of living and supporting sustainable development goals.

55. In summary, nuclear has the full potential to be a key tool for the decarbonization of emissions, weather directly associated with electricity production or otherwise. While surmountable challenges remain with regard to the large-scale implementation of cogeneration, the opportunities for the clean energy transition are simply too important to be missed.

Maritime Applications

56. Nuclear power has several promising applications in the maritime industry. These applications include the use of floating NPPs to provide electricity and other energy products to coastal facilities and off-shore operations, and the use of SMRs for the propulsion of commercial ships. Nuclear power offers a sustainable, zero-emission alternative, contributing to global efforts to reduce carbon emissions and meet environmental goals.

57. Integrating nuclear power in the maritime industry presents challenges, including safety concerns, regulatory hurdles and public perception issues. Addressing these challenges requires international collaboration and comprehensive national and international nuclear and maritime regulatory frameworks to ensure the safe and efficient deployment of such technology at sea.

Other Applications

58. Radioisotope production at commercial NPPs, such as in Canada, strengthens the global supply chain for radioisotopes, contributing to societal well-being by fighting cancer and other diseases and supporting various industrial applications.

D.5. Supply Chain and the Harmonization of Regulatory Approaches

59. A strong supply chain is a prerequisite to the development of new nuclear builds and the continuous safe and efficient operation of the current nuclear power fleet. In both cases, the supply chain has to be able to effectively address issues related to technology obsolescence, the lead time of certain products, new technologies requiring qualification, the retirement of workforces and their replacement with new generations, suppliers exiting the market and new suppliers learning to produce high quality products and services for the nuclear industry.

60. Varying legislative frameworks and the related regulatory requirements predetermine the need to tailor nuclear projects to each jurisdiction. While legitimate, this poses a challenge due to different codes and standards, including non-nuclear, for products and services and may impede innovation. The following measures are recommended for consideration by policymakers:

- Governments and the nuclear industry need to collaborate to reduce sector risks and make nuclear more appealing. Fostering a transparent environment and promoting a long term outlook for industries is vital for ensuring supplier availability.
- Encouraging public-private cooperation can help develop robust industrial infrastructure. This may include streamlining legislation and regulation, recognizing various different codes and standards series, providing guidance and fostering horizontal and vertical cooperation in the supply chain.
- Direct economic support and incentives may also be possible in some circumstances. Owners/operators and local suppliers can support operation, maintenance and new builds through long term partnerships and empowerment.
- Reactor designers need to cooperate with suppliers early on to lower supply chain-related risks.
- Establishing and supporting nuclear industry organizations can facilitate peer support and information exchange.

61. The Agency’s Nuclear Harmonization and Standardization Initiative (NHSI) aims to harmonize and standardize approaches in both the regulatory and industrial fields. NHSI comprises two tracks: regulatory and industry. The Regulatory Track has produced a framework for regulatory cooperation in design reviews, including 1) a framework for sharing information among regulatory bodies; 2) a multinational pre-licensing joint review process through which regulators can jointly evaluate specific technical areas of a proposed reactor design; 3) a process for leveraging reviews already completed by regulatory bodies in other Member States; and 4) a collaborative review process that allows regulators to work together in parallel during ongoing national regulatory reviews. The Industry Track focuses on 1) harmonization of high-level user requirements; 2) common approaches on codes and standards; 3) experimental testing and validation through the newly established NEXSHARE collaborative data sharing network; and 4) accelerating infrastructure implementation for SMRs.

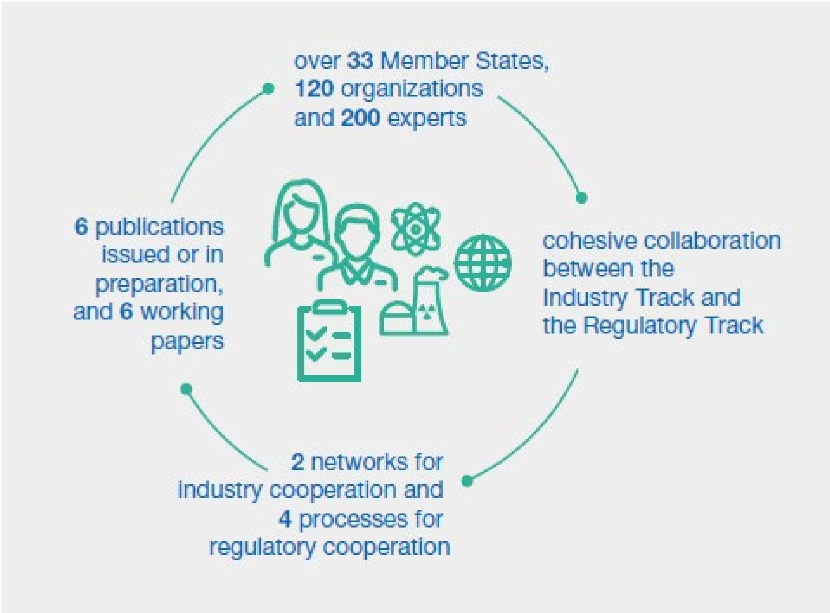


Fig. D.1. The IAEA's Nuclear Harmonization and Standardization Initiative (NHSI) was launched by the IAEA Director General Rafael Mariano Grossi with the aim of facilitating effective global deployment of safe and secure advanced nuclear reactors. (Source: IAEA)

62. During NHSI's initial phase, the Regulatory Track has established an international collaborative framework enabling regulatory bodies to share information and conduct joint reviews of reactor designs, enhancing regulatory efficiency, promoting design standardization and achieving resource savings. At the same time, the Industry Track has published a series of technical publications, including *Suitability Evaluation of Commercial Grade Products for Use in Nuclear Power Plant Safety Systems* (IAEA-TECDOC-2034), which provides information on approaches to evaluating the suitability of commercial grade items for use in NPP safety systems, and six working papers related to generic user recommendations and considerations, codes and standards and assessing infrastructure development issues to accelerate the deployment of SMRs. Additionally, the Industry Track has developed two networks, namely Management, Supply Chain and Quality Network of Excellence (MSCQ) and Network for Experiment and Code Validation Sharing (NEXSHARE), to facilitate information sharing on common practices relating to codes and standards and experimental testing and validation for design and safety analysis computer codes.

63. Cross-industry innovations and a focus on non-power applications of SMRs call for strengthened cooperation with international organizations in adjacent fields. Examples include the International Maritime Organization for barge-mounted SMRs or nuclear-propelled merchant ships, steel industry associations for the decarbonization of industry or coal industry organizations for the conversion of fossil-fuelled power to nuclear power.

- Using competent workforce, suppliers and infrastructure from other safety-critical industries and conventional power plant projects other than nuclear can expedite the deployment of new nuclear power. For example, the use of high-quality industrial grade products in safety systems is becoming more and more frequent.
- Using localized supply chains and local workforce may in some cases help to reduce dependence on logistics bottlenecks, as NPP projects consist of much more than just the primary circuit. This would contribute to the local economy and give an important boost to positive stakeholder

engagement. Repurposing coal-fired power plant sites for nuclear power generation is a good example in this regard.

D.6. Innovation and Artificial Intelligence

64. Artificial intelligence (AI) and nuclear power are two transformative technologies that are increasingly intersecting. This interplay is reshaping the landscape of energy production, safety and technological advancement.

AI Advancements in Nuclear Power

65. AI is increasingly being integrated in the nuclear power industry with the aim of enhancing efficiency, security, safety and operational performance. AI-assisted applications for condition monitoring and predictive maintenance based on real-time data allow for the real-time monitoring and early detection of issues and the prediction of equipment failures before they occur, reducing downtime, maintenance costs and unplanned outages while extending equipment lifespan and enhancing safety. AI algorithms may also optimize energy generation levels on the basis of real-time demand and environmental conditions, including weather, ensuring a stable power supply and maximizing energy production.

66. AI enhances knowledge management in NPPs by organizing vast amounts of technical data, automating document retrieval and preserving expert knowledge for future generations — key factors in supporting long term operation. AI-driven training applications offer adaptive learning experiences, strengthening operator skills and emergency preparedness. Additionally, several organizations have developed AI-powered chatbots to assist plant personnel by answering technical queries, retrieving regulatory guidelines and providing real-time operational support. These innovations could boost human efficiency, minimize human error and ensure seamless knowledge transfer across the industry.

67. AI plays a significant role in the development of advanced reactor designs, including SMRs, by exploring vast design spaces more efficiently than traditional methods. AI-driven design and simulation tools allow for rapid prototyping and testing of new reactor designs while identifying optimal reactor configurations that maximize safety, performance and cost-effectiveness. This reduces the time and cost associated with developing advanced reactors.

68. AI applications may also streamline regulatory compliance by analysing regulatory documents and ensuring adherence to safety standards, facilitating smoother operations and reducing the administrative burden on nuclear facilities.

69. The use of AI and machine learning is also enabling advancements in the nuclear fuel cycle by optimizing uranium extraction and processing, improving efficiency and reducing environmental impact. In the back end, AI may enhance the safety and efficiency of spent fuel management and reprocessing. AI algorithms predict the behaviour of radioactive material over time, aiding in designing safer storage solutions.

Nuclear Power's Influence on AI

70. The demands of nuclear power-related research, particularly in the area of fusion energy, have driven advancements in high-performance computing. AI systems developed for nuclear research have pushed the boundaries of computational capabilities, leading to more powerful and efficient AI models. This has had a ripple effect, benefiting various other industries that rely on high-performance computing.

71. The nuclear sector generates vast amounts of data, which has been invaluable for training AI models. This data-driven approach has led to significant innovations in AI, particularly in machine

learning and predictive analytics. The complexity and scale of nuclear data have pushed AI capabilities further, resulting in more accurate and sophisticated models.

72. The intersection of AI and nuclear power has fostered collaborative research efforts. Experts from fields such as computer science, engineering and physics have come together to develop innovative solutions that benefit both AI and nuclear technologies. This cross-disciplinary approach has accelerated advancements and led to groundbreaking innovations from real-time construction oversight in China to significantly accelerated digitalization of plant design basis data from the 1970s in Switzerland.

Growing Energy Demands

73. The electricity demand stemming from AI applications, particularly those involving large-scale machine learning models and data processing, is expected to double from an estimated 460 terawatt-hours (TWh) in 2022 to over 1000 TWh by 2026. Data centres, which house the servers and infrastructure for these AI operations, are thus major energy consumers.

74. AI data centres operate around the clock, necessitating a continuous and reliable power supply. Unlike renewable energy sources such as solar and wind, which can be intermittent, nuclear power provides a stable and consistent energy output. This reliability is crucial for maintaining the uninterrupted operation of AI systems. In October 2024, X-energy announced a financing round of approximately US $500 million, anchored by Amazon, for the first phase of its TRISO-X fuel fabrication facility in Oak Ridge, Tennessee, USA. In December 2024, Meta announced plans to add 1–4 GW(e) of new nuclear generation capacity in the USA to support its data centres and contribute to a cleaner, more reliable electricity grid. These initiatives highlight the growing recognition of nuclear power's role in supporting AI and other advanced technologies. Google has partnered with Kairos Power, a developer of SMRs, to power its data centres. Kairos Power's reactor is expected to be online by 2030, with additional reactors planned through 2035. Microsoft has signed a deal with Constellation to revive a previously shutdown reactor at Three Mile Island in Pennsylvania. This initiative aims to bring additional nuclear capacity online to support Microsoft's data centres. The project highlights the potential of repurposing existing nuclear infrastructure to meet modern energy needs.

D.7. Fuel Sustainability and Innovative Fuel Cycles

75. Following a persistent downward trend in uranium prices that started in 2011 due to the post-Fukushima drop in uranium demand, the oversupply of uranium due to pre-2011 buildup, weakened utility contracting and secondary uranium supply availability from programmes such as the Russian–US Megatons to Megawatts initiative, expenditures for uranium exploration and mine development decreased dramatically by approximately 82% (about US $2 billion) from 2014 to 2020. In the latter half of 2021, expenditures began to rebound in response to a dramatic rise in uranium prices, peaking at a 24-year high of US $160/lb U_3O_8 in January 2024, with preliminary 2023 data suggesting an increase in expenditures to approximately US $840 million, up from US $377 million in 2020.

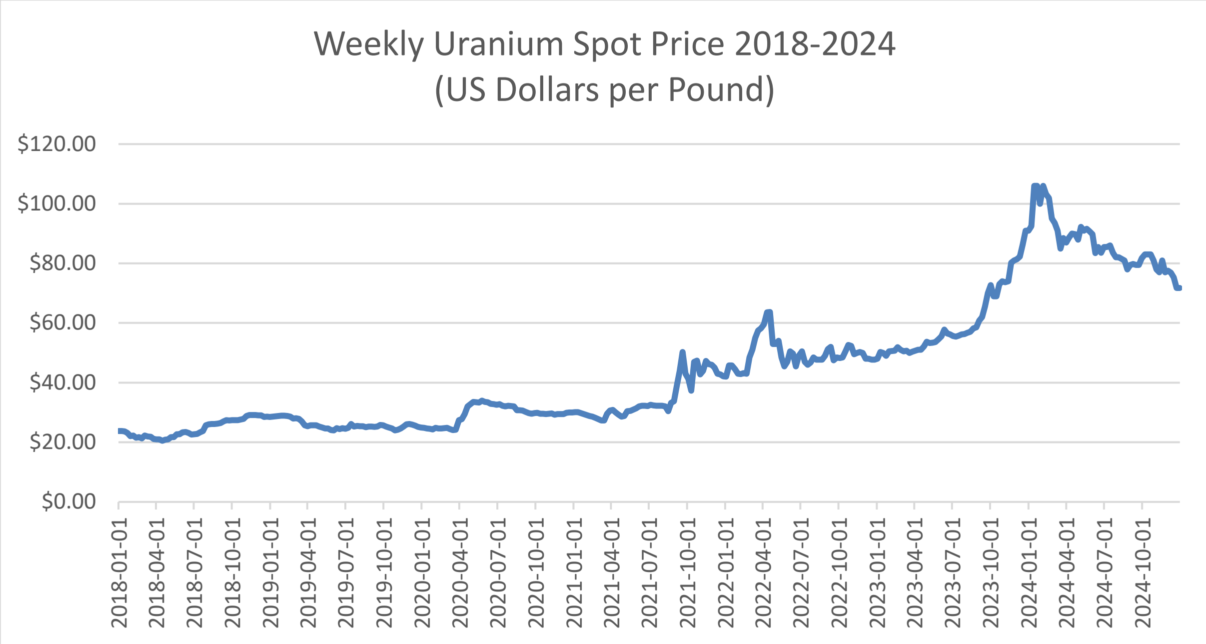
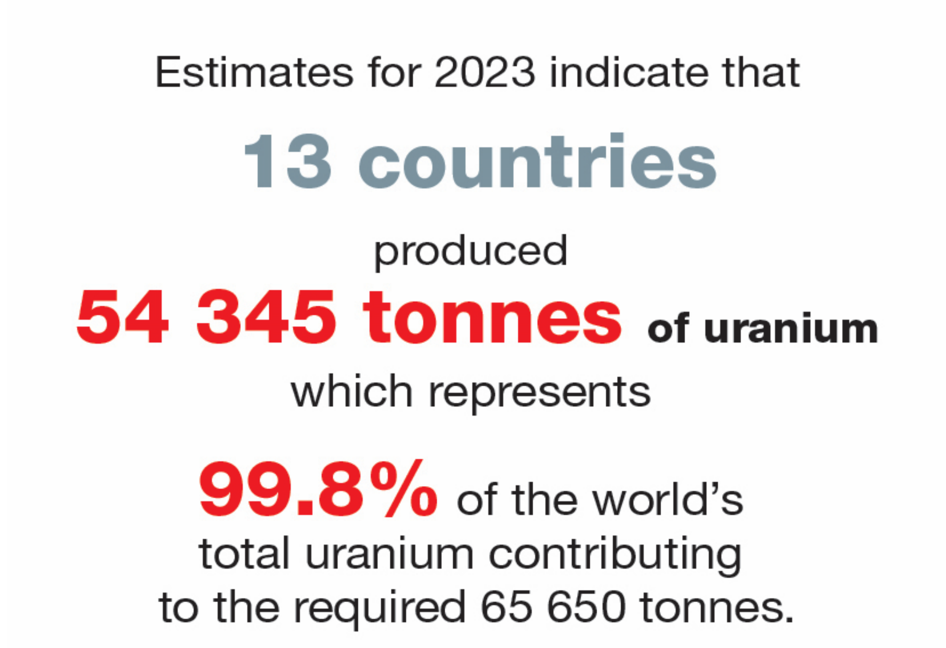


Fig. D.2. Uranium spot price evolution since 2018 (Source: UxC)

76. Estimates for 2023 indicate that 13 countries produced 54 345 tonnes of uranium, which represents 99.8% of the world's total uranium contributing to the required 65 650 tonnes, with the remainder of the demand made up by secondary uranium supplies. Global nuclear capacity is expected to grow as global energy demand rises, especially given the pledge made by 22 countries at COP28 in Dubai, UAE to triple their nuclear capacity by 2050 (with a further six joining the call at COP29 in Baku, Azerbaijan) and the prospective widespread deployment of SMRs. World annual reactor-related uranium requirements are projected to rise to between 90 000 and 142 000 tonnes per year by 2050, necessitating significant investments in uranium exploration, mining and processing.



77. Advanced materials and nuclear fuels are critical for nuclear power deployment. Key goals include improving fuel operational safety margins, reducing costs and minimizing nuclear waste generation. New HALEU-based fuel designs and the anticipated deployment of SMRs will increase uranium demand. As of 1 January 2023, around 5.9 million tonnes of reasonably-assured and inferred uranium resources are recoverable at current market prices, with just over 90% of these resources located in 11 countries. In situ leaching continues to dominate as the main mining method, accounting for nearly 60% of global uranium production in 2022.

78. Fuel designers and utilities have their own quality management systems. Sharing best practices ensures the high reliability and performance of nuclear fuel. Advanced technology or accident tolerant fuels (ATFs) are being developed to enhance the safety, competitiveness and economics of current and future reactors. Increasing discharge burnups and extending fuel operation cycles enhances economic benefits but requires investments in safety demonstrations and licensing facilities.

79. Industrial capacities to convert, enrich and fabricate conventional nuclear fuels exist worldwide; operators just need to ensure the facilities' long term operations, with upgrades and process streamlining to improve output efficiencies while decreasing operational costs and minimizing waste. However, industrial capacities to convert, enrich and fabricate the advanced nuclear fuels (such as LEU+ or HALEU-based fuels) required for advanced reactors, especially SMRs, do not yet exist to meet the expected demand. Therefore, significant investment, licensing and construction efforts will be necessary to assure the supply chain in the front end of advanced nuclear fuel cycles.

80. Spent nuclear fuel management remains a critical issue. Two strategies exist: open cycle (direct disposal) and closed cycle (reprocessing and recycling). Around 70% of spent fuel generated worldwide is in storage, pending decisions on recycling or disposal. Higher fuel burnup produces greater decay heat, leading to increased storage needs. Partitioning and transmutation of minor actinides continue to be researched to reduce heat generation and radiotoxicity of high level waste.

81. Recycling reprocessed plutonium and depleted uranium in mixed oxide (MOX) fuels is a mature technology backed by over 40 years of experience. France, Japan, the Netherlands and the Russian Federation are currently using MOX fuels. Recycling offers benefits such as reduced high level waste volume and toxicity, uranium resource savings and removal of heat-generating materials. Advanced reactor systems like fast reactors and accelerator-driven systems can enhance recycling effectiveness.

82. Recycling, though originally intended for fast reactors, has predominantly been conducted in thermal reactors. Advanced recycling fuel cycle options, including multi-recycling of valuable materials like uranium and plutonium in conventional light water reactors and transitioning to closed fuel cycles with fast neutron reactors, are nearing full-scale demonstration, as in the case of the Proryv project in the Russian Federation.

83. There are variations on the closed cycle option, where the increasing separation and recycling of spent fuel generate decreasing amounts of high level waste but increase fuel cycle complexity and costs. Progress is being made in France and the Russian Federation on plutonium multi-recycling in REMIX, CORAIL and MIX fuels. These recycled fuels enable the transition to plutonium multi-recycling strategies in fast reactors, allowing for more effective use of natural resources and reducing waste. Fully closed fuel cycles with multiple reprocessing and recycling of spent fuels could make nuclear a nearly renewable energy source.

84. National and international research and development efforts have focused on developing advanced sustainable nuclear fuel cycles aimed not only at improving uranium resource utilization, maximizing energy production, minimizing waste generation, improving safety and limiting proliferation risks, but also at recycling long-lived minor actinides, reducing the volume and radiotoxicity of high level waste and lowering decay heat, which reduces the waste burden and repository footprint. Collaborative approaches are crucial, exemplified by the GENIORS project supported by the EU Framework Programmes.

85. Some Member States prioritize recycling plutonium in fast reactors. A major milestone is the commercial fast reactor (BN-800) in the Russian Federation, fully loaded with MOX fuel containing plutonium recovered from spent nuclear fuel.

D.8. Radioactive Waste Disposal

86. One of the most significant challenges for radioactive waste management (RWM) and disposal programmes is overcoming the negative perception that “we don’t know what to do with the waste”. Legacies from the past, such as poorly characterized and conditioned legacy waste streams or inadequate disposal approaches, contribute to this narrative. The lack of initial funding mechanisms for RWM exacerbates the perception of excessive cost, and public opposition has delayed or derailed many earlier disposal programmes.

87. RWM was not an established field when nuclear power was first generated, and the related methods and technologies had to be developed over time. Decades of advancements in waste characterization and processing approaches, as well as in repository science, combined with the many lessons learned from past activities, have, however, brought robust understanding and the current global reality when it comes to addressing RWM responsibilities is significantly better than the perception. Most of the world’s very low level waste and low level waste has already been disposed of. The global community has made significant progress in designing deep geological repositories for high level waste, with countries such as Canada, Finland, France, Sweden and Switzerland leading efforts. Finland is nearing active disposal, Sweden has broken ground for construction in January 2025 and France anticipates first technical feedback during the second half of 2025 from the license application review process. In addition, countries such as China, the Czech Republic, Germany, Hungary, Japan, the Republic of Korea, Spain, the UK and the USA have robust competences and resources assigned to progress their national deep geological repository programmes from generic studies towards or through to a siting process.

88. Countries that do not generate nuclear power — and thus lack significant capacity to generate income and set aside a waste management and decommissioning fund — nevertheless tend to have somewhat comparable technical needs in addressing RWM, albeit at a much smaller scale. One of the more significant challenges they face is access to adequate national budgetary resources to address the long term liabilities associated with nuclear technologies.

89. The greatest opportunity for future RWM, and especially for addressing long term liabilities arising from the deployment of future technologies, such as SMRs, is to learn the lessons from the past 60 years and assess and anticipate those liabilities prior to licensing new nuclear facilities. This calls for the application of suitable national frameworks, methods and technologies to address RWM responsibilities. A sound approach, with early consideration of RWM issues at each step of the nuclear life cycle, including the design of new facilities, operations and decommissioning, can minimize the RWM burden.

90. When waste streams and management liabilities are anticipated on the basis of reactor designs and physical processes comparable to those of existing light or heavy water reactors, it is possible to anticipate future waste processing needs, the ability to store and transport, and disposal options. In the case of advanced reactors, however, prior industrial experience often cannot inform RWM associated with operation, decommissioning or fuel cycle activities. In this case, careful consideration needs to be given to the properties of fuels, coolants or moderators and the approaches taken to manage these. A prerequisite for waste assurance and confidence in disposability is an adequate understanding of waste properties, sufficient to assess the technical feasibility and safety of storing, transporting and ultimately disposing of this waste. Management of the waste may require processing steps for which industrial capacity is not available either in the country in which the waste arises or as industrial option from an international processing service.

91. Reshaping negative perceptions requires holistic approaches, clearer policies, improved waste characterization, novel processing strategies and sustained efforts to establish disposal facilities. Stakeholders have historically viewed nuclear waste as problematic, but fact-based information and involvement in global approaches, as well as clear assessment of long term liabilities prior to establishing new nuclear facilities, can help re-imagine nuclear energy and create a new narrative.

D.9. Decommissioning

92. Nuclear decommissioning and radioactive waste disposal are integral to responsible nuclear energy use. An increasing number of countries are recognizing the critical need to establish robust funding mechanisms, along with technological innovation and regulatory clarity, to support nuclear decommissioning and radioactive waste management. Statistics show an increase in decommissioning projects, with estimates suggesting that over 150 nuclear reactors worldwide will require decommissioning by 2050. This has placed a greater emphasis on incorporating advanced technologies, such as robotics, AI and remote monitoring, to enhance efficiency and safety. Furthermore, decommissioning statistics underscore the importance of international cooperation, with several initiatives focused on sharing best practices and harmonizing regulatory approaches. These trends highlight the need for early-stage planning and adaptable decommissioning strategies that can address both technical challenges and public concerns effectively.

93. The circular economy framework, which emphasizes resource efficiency, waste reduction and sustainable practices, is gaining increasing recognition in nuclear decommissioning. More countries are exploring circular economy strategies, including extending the operational life of nuclear facilities, minimizing premature decommissioning and leveraging advanced technologies for efficient dismantling. These innovations not only lower resource demand, reduce environmental impact and enable material recovery, but also drive economic growth and job creation. Encouraging investment in research and development through supportive policies can accelerate technological advancements in this field. These approaches reflect a growing commitment to sustainable, cost-effective solutions that align with global environmental objectives and optimize decommissioning processes. Additionally, repurposing decommissioned nuclear sites for sustainable activities enhances economic resilience and fosters workforce skills development.

94. Nuclear decommissioning and radioactive waste management entail long term responsibilities. Establishing financial mechanisms and assurances for the sustained monitoring, maintenance and potential remediation of decommissioned sites is challenging, particularly in uncertain economic conditions. Public perception of delayed nuclear projects, budget overruns and associated risks can be barriers to successful circular economy application. Building and maintaining public trust through transparent communication and engagement is therefore crucial.

D.10. Human Resource Development: The Next Generation

95. In some countries, the nuclear power sector has faced challenges in attracting and retaining talent owing to decreasing public and political support. The dynamic nature of the workforce and competition from other hi-tech industries further complicate this. Strategies are needed to engage the workforce effectively, despite the start-stop nature of past projects, which has led to a lack of confidence in nuclear careers.

96. Given that education, training and certification of nuclear professionals require significant effort and investment, retaining their talent is essential. High turnover can lead to a loss of critical knowledge and experience if effective knowledge management processes are not in place, including regarding the

broader nuclear supply chain and its subcontractors, whose experience is vital for ensuring safety and quality.

97. Despite these challenges, opportunities exist in countries with a clear commitment to nuclear power. Promoting the environmental benefits of low carbon energy production and climate change mitigation can attract the next generation. Developing training programmes, career paths and project opportunities can help attract and retain diverse professionals and technical staff.

98. The Agency encourages regional and interregional cooperation for sharing educational experiences and best practices. Collaboration with regional and national networks helps consolidate resources for education and training, leverage capabilities and promote information exchange. Existing organizations and networks support young nuclear professionals and promote nuclear benefits to their generation. International collaboration frameworks offer attractive prospects, innovation and wider perspectives.

99. Governments play a crucial role in supporting the nuclear workforce by demonstrating a clear commitment to nuclear power and establishing a level financial playing field with other green energy sources. They should ensure that science, technology, engineering and mathematics (STEM) programmes and nuclear-related education and training are fit for the industry. Including nuclear science and energy in primary and secondary curricula is essential.

100. Recognizing the changing needs and desires of the young generation can address workforce challenges. Embracing technology and innovation, such as computer-based training and virtual reality, can engage and strengthen workforce development. Highlighting career opportunities through partnerships with other low carbon energy sectors can foster mobility between sectors and destigmatize nuclear power.

101. Enhanced cooperation between government, industry, academia and international organizations can help to improve outreach efforts, identify potential recruits and offer better development opportunities, enhancing the appeal of a nuclear career. Attracting more women and retaining them in the nuclear industry represents a significant opportunity for a diverse and innovative workforce. Gender equality initiatives like the IAEA Marie Skłodowska-Curie Fellowship Programme and the Lise Meitner Programme promote an inclusive workforce.

102. The nuclear industry extensively uses contractors, and their competence and work quality must be ensured. Contractor training and post-job evaluations can mitigate risks.

D.11. Stakeholder Engagement

103. Experience shows that involving stakeholders — even those without direct decision making authority — can enhance public confidence, support informed decision making and strengthen communication among key organizations involved in nuclear power programmes. Engaging with

stakeholders at all stages of the nuclear fuel cycle, up to and including the disposal of radioactive waste and spent nuclear fuel, is increasingly recognized as a strategic necessity and an essential part of any complete nuclear power programme.

104. Open and transparent communication is fundamental to building trust in nuclear projects. Engagement should begin early and continue consistently, with accountability and commitment demonstrated at every stage. This process requires time and must continue throughout the life cycle of a facility. While the format, pace and priorities of engagement may evolve over time, ongoing dialogue remains essential.

105. In recent years, public support for nuclear power has grown, driven by the global energy crisis and the increasing need for clean and reliable energy. This shift was reflected in nuclear power's historic inclusion in the Global Stocktake under the Paris Agreement at COP28 in Dubai, UAE. The 2024 Nuclear Energy Summit in Brussels, organized by the Agency and the Government of Belgium, further strengthened this momentum, culminating in a declaration on nuclear power endorsed by more than 30 world leaders.

106. To maintain this momentum, it is crucial that governments, industry and other key players intensify their efforts to engage diverse stakeholder groups. Proactively addressing concerns before they become obstacles is vital for countries new to nuclear energy, those expanding their programmes and countries operating large NPPs or, in the future, SMRs.

107. Key efforts for effective stakeholder engagement include:

- Commitment from senior management to foster a culture of communication and engagement, with investment in skilled experts and well-resourced departments;
- Collaboration among governments, regulators, operators, advisory bodies and scientific organizations to ensure transparent communication about roles, responsibilities and decisions;
- Recognition of evolving communication needs across a facility's life cycle, including during decommissioning, repurposing and waste disposal;
- Active listening and responsiveness to stakeholder concerns;
- Transparent communication of significant events affecting nuclear facilities;
- Timely responses to information requests and regular updates to stakeholders;
- An open-door policy, including public information centres, plant tours and engagement with schools and organizations;
- Regular reporting on nuclear asset performance, including operational events, emissions and impacts during incidents or emergencies;
- Clear communication about national radioactive waste management programmes and long term responsibilities;
- Following through on commitments to maintain credibility and trust;
- Proactively sharing facts about nuclear energy's societal and environmental contributions.

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