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Board of Governors
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INTERNATIONAL STATUS AND PROSPECTS FOR NUCLEAR POWER 2021

Report by the Director General

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(GC(65)/1 and Add.1)

International Status and Prospects for Nuclear Power 2021

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 2021

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 2017 (document GOV/INF/2017/12-GC (61)/INF/8) was issued. This section highlights some of the most important developments affecting the status and prospects for nuclear power.

A.1.2. International Developments

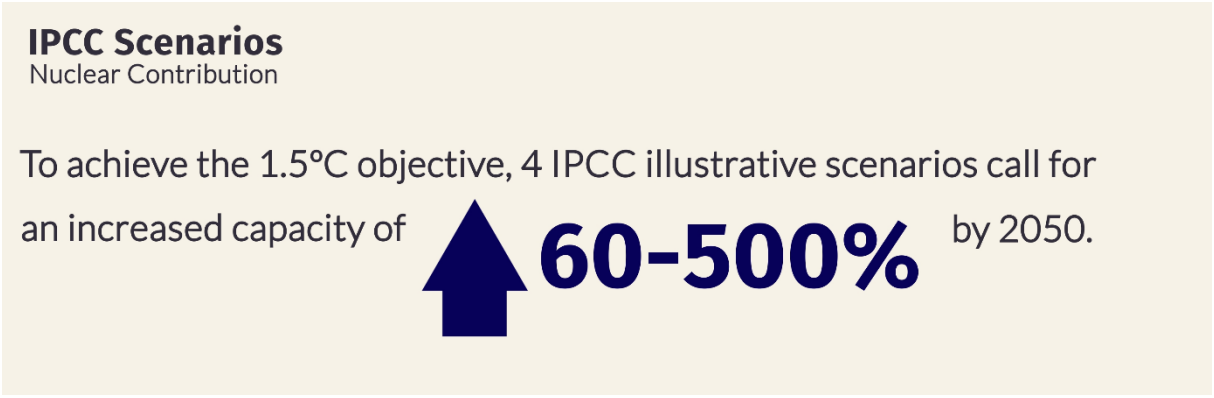
2. There is growing global recognition that access to affordable, reliable, sustainable and modern energy for all (United Nations Sustainable Development Goal (SDG) 7) is critical to achieving virtually all of the other 16 SDGs. The SDGs, adopted by world leaders in September 2015, call upon all countries to mobilize efforts up to 2030 to end all forms of poverty, fight inequalities and tackle climate change. These efforts go hand in hand with strategies that build economic growth and address social needs, including education, health, social protection and job opportunities, while tackling climate change and environmental protection. According to the United Nations Department of Economic and Social Affairs (UN DESA), which acts as the secretariat for the SDGs, SDG 7 is crucial to achieving almost all of the other SDGs, "from poverty eradication via advancements in health, education, water supply and industrialization to mitigating climate change". That same point has been repeatedly affirmed by the International Energy Agency (IEA) of the Organisation for Economic Co-operation and Development (OECD), which in March 2018 stated that "energy is at the heart of many of these Sustainable Development Goals – from expanding access to electricity, to improving clean cooking fuels, from reducing wasteful energy subsidies to curbing deadly air pollution that prematurely kills millions around the world".

3. Estimations of how much carbon dioxide (CO_2) has been effectively avoided by the use of nuclear power in the last 50 years vary between 70 gigatonnes (Gt) and 78 Gt, and depend on what technologies would have been deployed if nuclear power plants (NPPs) had not been built. Calculating avoided emissions from the current installed fleet is complex, since the alternative to nuclear power could range from gas to a combination of gas and renewables. Between 1970 and 2010, the clear alternatives to nuclear power were oil, coal and later, gas. Countries that deployed nuclear on a large scale, such as

France and Sweden, managed to decarbonize their electricity mix in two to three decades. In 2019, nuclear power produced 10.4% of the world's electricity, with 2657 terawatt-hours (TWh) of low carbon electricity produced. Had this level of generation been produced by gas, about 1.5 Gt CO2 would have been emitted. Life cycle analyses of electricity generation technologies show that nuclear power is among the least carbon intensive of all technologies, on a par with hydro and wind power. Nuclear power remains a key option for decarbonizing the electricity sector in the decades to come, together with variable renewables such as wind and solar photovoltaics (PV).



4. International acknowledgement of the significant role played by nuclear power in climate change mitigation and sustainable development has been steadily advancing. Many national and international organizations have analysed the needs to decarbonize the energy system consistent with achieving the goals of the Paris Agreement; and many of their scenarios call for a substantial increase in global nuclear power capacity, including all four illustrative scenarios described by the Intergovernmental Panel on Climate Change (IPCC) in its 2018 *Special Report on Global Warming of 1.5°C*. Indeed, to achieve the 1.5°C objective, the four IPCC illustrative scenarios call for an increase in nuclear power capacity of between 60% and 500% by 2050. At the same time, nuclear power is increasingly seen as an important option for the developing world to meet rising energy demand and improve living standards without increasing greenhouse gas (GHG) emissions. According to the IEA's Sustainable Development Scenario from its World Energy Outlook 2019, nuclear power needs to expand significantly beyond its historical markets embarking countries, including developing ones, and also beyond the power sector if the world is to have a reasonable chance of meeting climate change goals as well as the other energy related SDGs.



5. In October 2019, the Agency organized its first International Conference on Climate Change and the Role of Nuclear Power. The event, which drew more than 500 participants from 79 Member States and 17 international organizations, for the first time brought together the heads of the major international organizations dealing with energy and climate change (United Nations Framework Convention on Climate Change, IPCC, IEA and UN DESA) for discussions on the role of nuclear power in addressing global warming. Nuclear power has a major role to play in decarbonizing the energy sector to achieve global climate goals but will need enabling policies to achieve its full potential, said Conference President Mikhail Chudakov, IAEA Deputy Director General and Head of the Department of Nuclear Energy, in his concluding summary.

6. In its May 2019 report *Nuclear Power in a Clean Energy System*, the IEA warned that a failure to make timely decisions on nuclear power would raise the costs of the clean energy transition while also making it much more difficult to achieve the net-zero goals. The IEA reiterated that same point in its landmark report *Net Zero by 2050: A Roadmap for the Global Energy Sector*, issued in May 2021, which describes a potential pathway for the world to eliminate greenhouse gas emissions by mid-century. That report sees nuclear generating capacity nearly doubling by 2050, with annual grid connections rate reaching some 30 gigawatts in some years, even as nuclear power's overall share of global electricity production declines slightly to 8% in 2050. The rest of the electricity mix in 2050 is, according to this Net Zero scenario, dominated by renewables, in particular solar and wind. But the IEA also pointed out in a recent report *The role of critical minerals in clean energy transitions*, that wind, solar and battery technologies are very dependent on critical minerals, the availability of which could slow down the deployment of these technologies. Nuclear power, on the other hand, is along with hydropower, one of the low carbon technologies with the lowest mineral intensity.

7. The Massachusetts Institute of Technology (MIT) Energy Initiative, in a report published in September 2018, called for a major increase in global nuclear generating capacity to meet net-zero goals. To achieve this increase, the report outlined policies that would establish a more level playing field for nuclear power to compete with other low carbon energy technologies, as well as steps needed to lower the cost of nuclear new build projects. Like the IEA report, the MIT study concluded that without a significant contribution from dispatchable nuclear power, the clean energy transition would be much more expensive and more difficult to achieve.

8. According to the December 2020 report *Projected Costs of Generating Electricity*, jointly produced by the IEA and the OECD Nuclear Energy Agency, extending the operational lifetime of existing NPPs is the most cost-effective investments in low carbon electricity generation. The report noted that while hydro power can provide similar contributions at comparable costs, it remains highly dependent on the natural resources of individual countries.

9. According to a March 2021 report by the United Nations Economic Commission for Europe, nuclear energy is an "indispensable tool" for achieving the SDGs, with a vital role to play in providing affordable energy, mitigating climate change, eliminating poverty, achieving zero hunger, generating economic growth, and providing both industrial innovation and clean water. Reliable nuclear energy can be a critical part of decarbonized energy systems for countries seeking to meet climate change and sustainable development goals, according to the report, entitled *Application of the United Nations Framework Classification for Resources and the United Nations Resource Management System: Use of Nuclear Fuel Resources for Sustainable Development – Entry Pathways*.

10. The Joint Research Centre (JRC), the science and knowledge service of the European Commission, said in a March 2021 technical assessment that "there is no science-based evidence that nuclear energy does more harm to human health or to the environment than other (low carbon) electricity production technologies already included in the EU Taxonomy as activities supporting climate change mitigation". The assessment was carried out with the respect to the 'do no significant harm' criteria of the European Union's 'Taxonomy Regulation', which establishes the framework for facilitating sustainable investments and will eventually provide the foundation for scaling up low carbon energy investments across the European Union. The JRC report cited 2016 data showing that nuclear power performs very well in evaluations of its health impacts compared with other energy sources, using the disability-adjusted life year measure of overall disease burden expressed as the cumulative number of years lost due to ill health, disability or early death.

11. Investments in clean energy sources such as solar, wind and nuclear have an impact on gross domestic product (GDP) that is two to seven times stronger than spending on fossil sources such as gas, coal and oil, according to a working paper published by the International Monetary Fund (IMF) in March

2021, entitled *Building Back Better: How Big Are Green Spending Multipliers?*. Nuclear power produced the biggest economic multiplier effect of any clean energy source, the paper said, adding that nuclear power produces about 25% more employment per unit of electricity than wind power and that workers in the nuclear sector earn one-third more than those in the renewable energy industry.



B. Nuclear Power Today

12. At the end of 2020, the world's total nuclear power capacity was 392.6 GW(e)[1], generated by 442 operational nuclear power reactors in 32 countries. Countries demonstrated adaptability to the coronavirus disease (COVID-19) pandemic by taking effective measures, reflecting strong organizational culture. At the outset of the pandemic in early 2020, the Agency established the COVID-19 Nuclear Power Plant Operating Experience Network to share information on measures taken to mitigate the pandemic and its impact on the operation of NPPs. None of the 32 countries with operating NPPs reported that the pandemic had induced an operational event impacting safe and reliable NPP operation.



13. Nuclear power supplied 2553.2 terawatt-hours of GHG emission-free electricity in 2020, accounting for about 10% of total global electricity generation and nearly a third of the world's low carbon electricity production.

14. Some 5.5 GW(e) of new nuclear capacity was connected to the grid, from five new pressurized water reactors (PWRs): 1110 megawatts (electrical) (MW(e)) at Belarusian-1 in Belarus, 1000 MW(e) at Tianwan-5 and 1000 MW(e) at Fuqing-5 in China, 1066 MW(e) at Leningrad 2-2 in the Russian Federation and 1345 MW(e) at Barakah-1 in the United Arab Emirates. The start-up of Belarusian-1 in

[1] GW(e), or gigawatt (electrical), equals one thousand million watts of electrical power. All data on nuclear power reactors as reported to the IAEA Power Reactor Information System (PRIS) as of 1 June 2021.

Belarus and of Barakah-1 in the United Arab Emirates marked the first instances of nuclear electricity generation in these two countries.

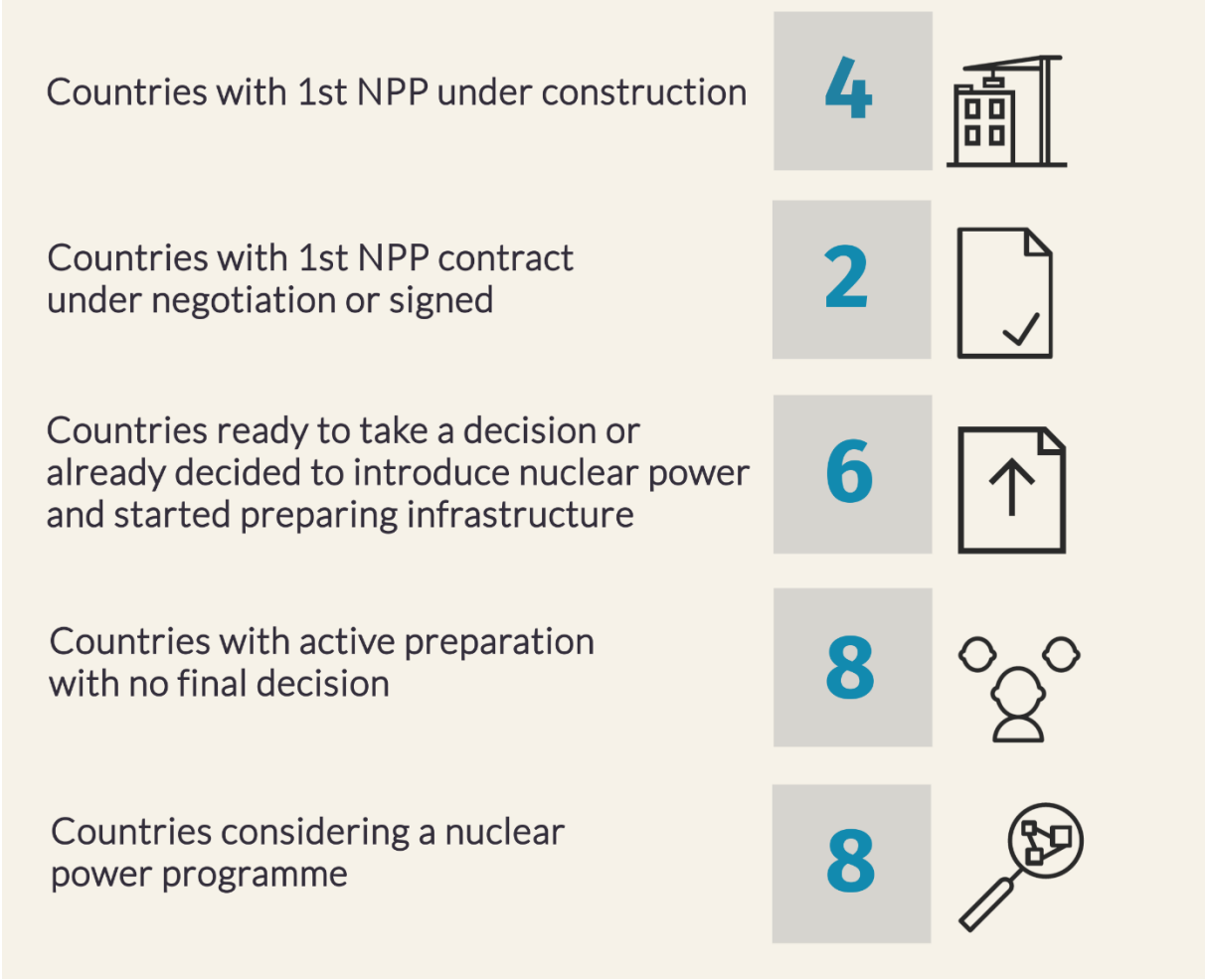
15. The world's first advanced small modular reactor (SMR) and only floating NPP, Akademik Lomonosov, started commercial operation in 2020. It is located just off the Arctic coast in the Russian Federation and features two 35 (MW(e)) KLT-40S SMR units.

16. Globally, some 89.5% of operational nuclear power capacity comprised light water moderated and cooled reactor types; 6% were heavy water moderated and cooled reactor types; 2% were light water cooled, graphite moderated reactor (LWGR) types, while 2% were gas cooled reactor types. Three reactors were liquid metal cooled fast reactors. The remaining 0.5% were three liquid metal cooled fast reactors with a total capacity of 1.4 GW(e).

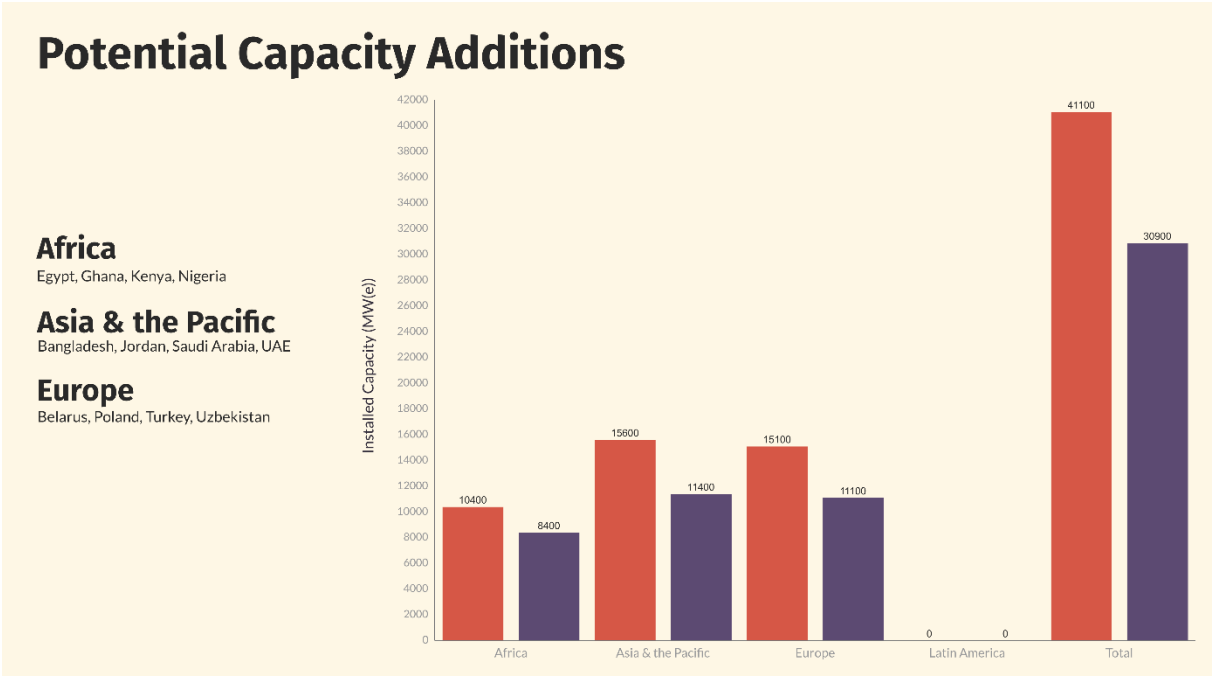
17. During 2020, 5.2 GW(e) of nuclear capacity was retired, with six nuclear power reactors permanently shut down: Fessenheim-1 (an 880 MW(e) PWR) and Fessenheim-2 (an 880 MW(e) PWR) in France, Leningrad-2 (a 925 MW(e) LWGR) in the Russian Federation, and Duane Arnold-1 (a 601 MW(e) boiling water reactor (BWR)) and Indian Point-2 (a 998 MW(e) PWR) in the United States of America. Ringhals-1 (an 881 MW(e) BWR) in Sweden was shut down on the last day of 2020, after more than 46 years of service.

18. Overall, nuclear power capacity in the past decade has shown a gradual growth trend, including some 23.7 GW(e) of new capacity added by new reactors or upgrades to existing reactors. Nuclear power generation has demonstrated continuous growth, expanding by more than 6% since 2011.

19. Out of the 52 reactors currently under construction, 9 are in embarking countries. A total of 28 countries have expressed interest in nuclear power and are considering, planning or actively working to include it into their energy mix. Another 24 Member States participate in the Agency's nuclear infrastructure related activities or are involved in energy planning projects through the technical cooperation programme. Ten to twelve embarking Member States plan to operate NPPs by 2030-2035, representing a potential increase of nearly 30% in the number of operating countries. Several embarking countries have also expressed interest in SMRs technology, in particular Estonia, Ghana, Jordan, Kenya, Poland, Saudi Arabia and Sudan, as well as expanding countries such as South Africa. Based on its Milestones Approach, the IAEA offers the Integrated Nuclear Infrastructure Review (INIR) service to both embarking countries and those that are expanding their nuclear power programme, to help ensure that the infrastructure required for the safe, secure and sustainable use of nuclear power is developed and implemented in a responsible and orderly manner.

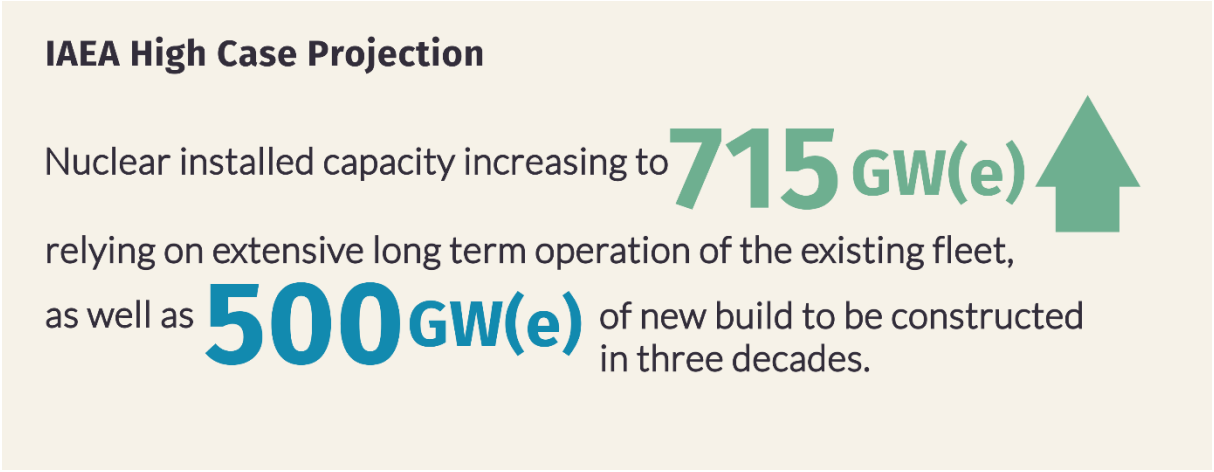


20. The Integrated Nuclear Infrastructure Review (INIR) continues to be a sought-after service of the Agency, supporting Member States in reviewing the status of their national nuclear infrastructure and identifying gaps in a systematic and integrated way. To date, 32 INIR missions have been conducted to 22 Member States.



C. The Prospects for Nuclear Power

21. Scenario modelling consistent with the objectives of the 2015 Paris Agreement generally indicates that nuclear power is key to the success of the decarbonization of the electricity sector, by providing reliable low carbon power to the grid around the clock. With the global increase in electricity demand to satisfy the needs of the world's population and ensure their access to electricity by 2050, and the increased level of electrification of the economy, a major increase in low carbon generation will be necessary. While the bulk of this generation is to be provided by variable renewables, such as wind and solar PV, nuclear will maintain its global share of between 8 and 10%, and provide the necessary flexibility and dispatchability that low carbon electricity systems require. The Agency's high case projections up to 2050 see nuclear installed capacity increasing to 715 GW(e), relying on extensive long-term operation of the existing fleet as well as 500 GW(e) from new builds to be constructed over three decades. In the low case estimate, global nuclear electricity generating capacity will decrease by 7% to 363 GW(e) by 2050, representing a 6% share of global electricity generation versus around 10% in 2019. However, even the low case estimate anticipates a significant construction of new NPPs, assuming that about one third of existing nuclear power reactors will be retired by 2030, while new reactors will add almost 80 GW(e) of capacity. Between 2030 and 2050 it is expected that capacity additions of new reactors will almost match retirements.

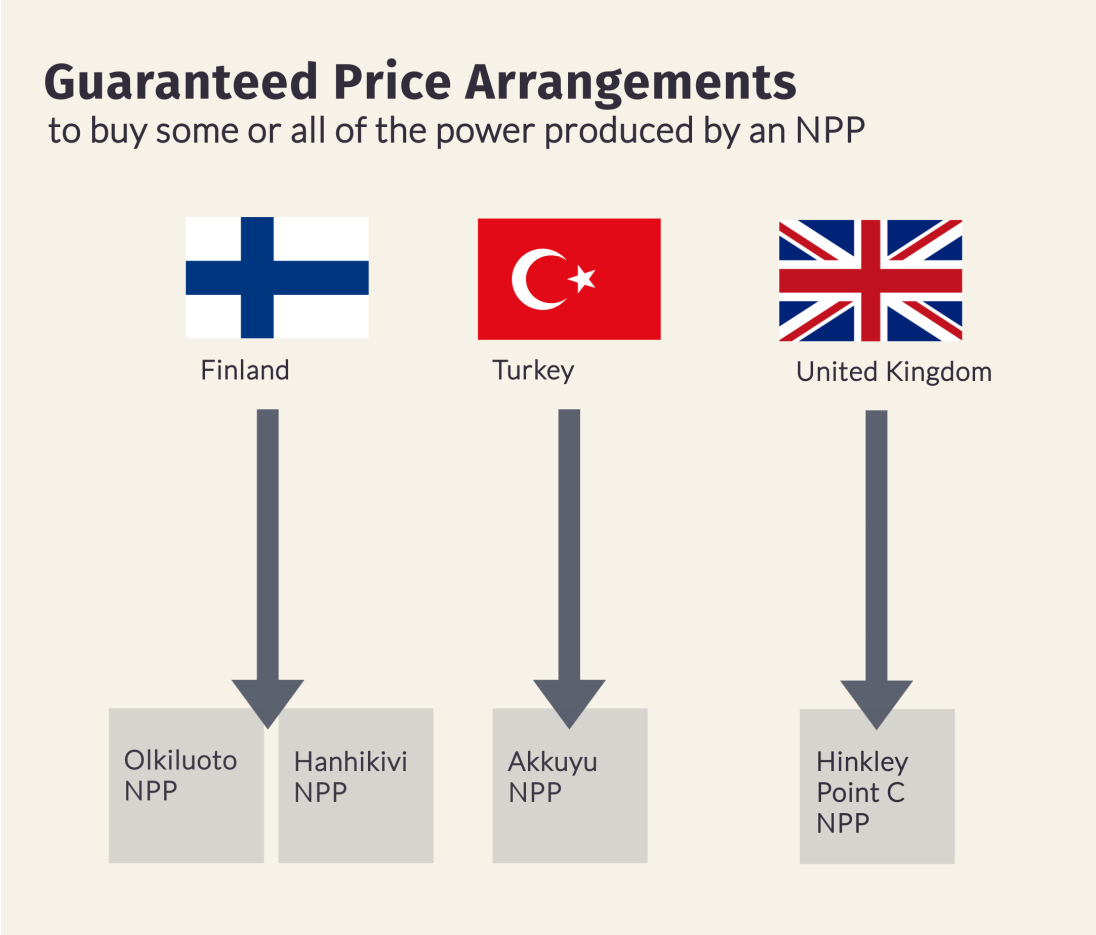


22. To recover from the impact of the COVID-19 pandemic, governments around the world are considering economic recovery packages. These measures are a unique opportunity to align public investments with the needs of the clean energy transition. Hence, attention is being paid to the effects of investments in green technologies. In March 2021, the IMF published a working paper showing that investments in green technologies have a greater impact on national GDP than investments in fossil-related assets. Moreover, investments in nuclear programmes have a greater impact (higher GDP multiplier) than any other green technology investments. Macroeconomic analysis by the Agency has also shown that nuclear power projects lead to the creation of a high number of well-paid jobs and have other positive impacts on the economy.

D. Influential Factors for the Future Deployment of Nuclear Power

D.1. Funding and Financing

23. The capital costs associated with developing a new NPP are substantial and may represent about three-quarters of the levelized cost of nuclear electricity. These interest-related liabilities are discharged throughout a plant's lifetime, offset by the income generated from produced electricity. However, highly capital intensive projects are sensitive to interest rate changes and construction durations, as well as to the nature of these uncertainties. A variety of potential financing models have been developed to address some of these uncertainties, particularly those market risks to which project developers — and providers of finance – may be exposed during the operating phase of a plant's life cycle. Mitigation of such risks may be achieved through arrangements – potentially backed by the government of the country hosting the plant – to buy some or all of the power produced by a plant at a guaranteed price. Such arrangements have been central to developing projects such as Olkiluoto and Hanhikivi NPPs in Finland, Akkuyu NPP in Turkey, and Hinkley Point C in the United Kingdom.



24. Mitigation of risks at earlier stages of the NPP life cycle – those related to construction delays and associated cost overruns – may be accomplished in a number of ways, for example by the host government providing direct sovereign guarantees to lenders, or by nuclear steam supply system vendors agreeing to take an equity stake in the project. The latter happened in the Barakah NPP project in the United Arab Emirates, where the Korea Electric Power Corporation took an 18% equity stake in the Nawah Energy and Barakah One Company; in the Hanhikivi NPP project in Finland, where the Russian Federation's State Atomic Energy Corporation "Rosatom" acquired a 34% share; and in the Hinkley

Point C project in the United Kingdom where French Électricité de France S.A. and China General Nuclear Power Group have two-third and one-third equity, respectively. For recent new build projects in embarking and expanding countries such as Bangladesh, Belarus, Egypt, Hungary, Iran and Pakistan the vendor country and the host government chose to enter into inter-governmental agreements with governmental loans.

25. SMRs may have advantages over large reactors, such as shorter construction times, lower upfront capital costs, applicability to smaller grids and modular expansion possibilities to gradually meet the demand. Such advantages could lead to revisiting the current financial models used for large NPPs. The successful demonstration of SMRs in the next decade or so could encourage more expanding and embarking countries to consider them. Private investors are showing growing interest in SMR technology development, demonstration and deployment.

26. Another important liability concerns the costs arising at the end of the operating lifetime of a facility, such as those related to facility decommissioning and the long-term management of high level radioactive waste. As in the case of 'up-front' costs, provisions must also be made from operating income to address these 'back end' costs. The latter may represent up to 10% of the levelized cost of nuclear electricity. Legislation governing the use of nuclear energy generally lays out requirements for setting aside funds to cover back-end costs during the revenue earning phase of a plant's operating life. Many different approaches are taken, from those requiring owners to make appropriate provisions in the company's books, to a requirement that the relevant funds be transferred to an independent organization that is responsible for their management and their eventual disbursement to cover the back end liabilities

D.2. Electricity Markets and Policies

27. Key developments in the global power markets since 2017 include the continuous deployment of large amounts of renewable energy with decreasing costs (for wind and solar PV), the shifting of electricity demand from OECD to non-OECD countries owing to increased electrification of various sectors, the significant increase in carbon pricing as a result of policies, and changes in emissions trading schemes. Together with the development of 'taxonomies' or, more generally, environmental social and governance (ESG) criteria for sustainable investments, and increased commitment from many Member States to meet net zero emissions by the middle of the century, coal assets have become a liability, and financial institutions are moving away from investments in coal. Nuclear power generation has continued to grow, reaching in 2019 its second highest level ever. In 2020, COVID-19-related lockdowns shook power markets; over several months demand fell significantly and fossil fuel generation fell even further in favour of low-marginal cost technologies such as renewables and nuclear. Emissions have since rebounded with the economic recovery. In addition to focusing on reducing carbon emissions, policy makers have to address the need for security of supply, air quality and resilience.

28. The Paris Agreement should have a positive influence on nuclear power development if nuclear power's potential as a low carbon energy source becomes more widely recognized. The IPCC *Special Report on Global Warming of 1.5ºC*, released in 2018, and the IEA's recently launched *Net Zero By 2050: A Roadmap for the Global Energy Sector* show that most trajectories to net zero include nuclear power, with a doubling of nuclear electricity generation in the next three decades. As yet, the recently updated nationally determined contributions under the Paris Agreement do not seem to indicate a shift in the call for nuclear power to contribute to national climate mitigation strategies. However, in some countries, the climate change issue is an incentive to support continued operation of NPPs or part of the rationale for having a new build programme. One clear potential of nuclear power lies in its ability to help decarbonize 'hard-to-abate' sectors – which cannot be electrified easily. Low carbon heat or hydrogen produced by current fleet and advanced reactors could become key to the success of countries' net zero objectives, provided that the technology becomes commercially viable within the next decade or so. In the meantime, increasing the role of nuclear in producing low carbon electricity and to some

extend heat through the long-term operation of the existing fleet and new nuclear plants remains critically important.

29. The Agency's projections to 2050 suggest that achieving the Paris Agreement objectives will require at least a doubling of current nuclear power capacity levels by 2050, in line with IEA projections. Energy policies and electricity market incentives that promote all types of low carbon solutions, including nuclear power, will play a fundamental role in incentivising investment in nuclear power and will reduce risks and the cost of financing. This is necessary to ensure the timely deployment of nuclear power for climate change mitigation. In parallel, it is necessary to recognize the advantages of security of supply, reliability and predictability that nuclear power offers, as well as its contribution to the climate resilience of energy infrastructures. This is all the more urgent in an electricity environment that relies on increasing amounts of variable renewable technologies such as wind and solar PV. Recent policy examples serve to emphasize the role of electricity markets in nuclear power development: in the United Kingdom, the Contract for Difference or the Regulated Asset Base mechanisms considered for new nuclear projects to secure returns on investment; or the different types of support enacted in several states in the United States of America (New York, Illinois, Connecticut, New Jersey and Ohio) to value low carbon nuclear electricity generation and support existing NPPs.

D.3. Resilience

30. In February 2021, the North American winter storm with blackouts caused by a combination of factors, showed the importance of having resilient energy systems. It is projected that increased frequency of extreme weather events with growing intensities will occur as a consequence of global warming. These events could range from winter storms to intense floods or heat waves and droughts, which can affect generation assets as well as grid infrastructures. While the nuclear sector has reported[2] an increasing number of weather-related outages over the past decades, such outages have led to a relatively limited loss of generation owing to the fact that NPPs are designed to operate safely and efficiently in extreme weather conditions.

31. Specific adaptation measures have been put in place in several plants that are potentially most exposed to flooding or loss of cooling efficiency as a result of heat waves and droughts. However, while investments to ensure the highest levels of safety are made consistently, adaptation measures that are aimed only at improving the performance of a plant in climate-related events may or may not be implemented depending on the expected return on investment. This is an economic decision that utilities have to make by estimating the cost of adaptation and the expected return based on the remaining lifetime of a plant as well as profits from the enhanced performance/generation of a plant. The price at which power can be sold on electricity markets plays a key role – and low wholesale electricity prices that have been witnessed in the past decade in European and North American markets have not been inducive to such adaptation investments. For new builds, siting and sizing of equipment further take into account the potential risks posed by climate events that could happen during the century.

32. During the COVID-19-related lockdowns, Member State actions focused on ensuring the safety and well-being of staff through prompt action to minimize the risk of the pandemic's spread, while maintaining business continuity and adequate levels of safety, security and sustainability of NPPs. No Member State reported the enforced shutdown of any nuclear power reactors resulting from the effects of COVID-19 on their workforce or essential services such as supply chains. Regulatory bodies have generally applied a graded approach during the pandemic and adjusted the scope of regulatory or other inspections based on their safety significance. The Agency received reports of outage impacts at NPPs in 26 of the 32 Member States with operating NPPs. In some cases, outage scopes were reduced by

[2] IAEA Power Reactor Information System (PRIS)

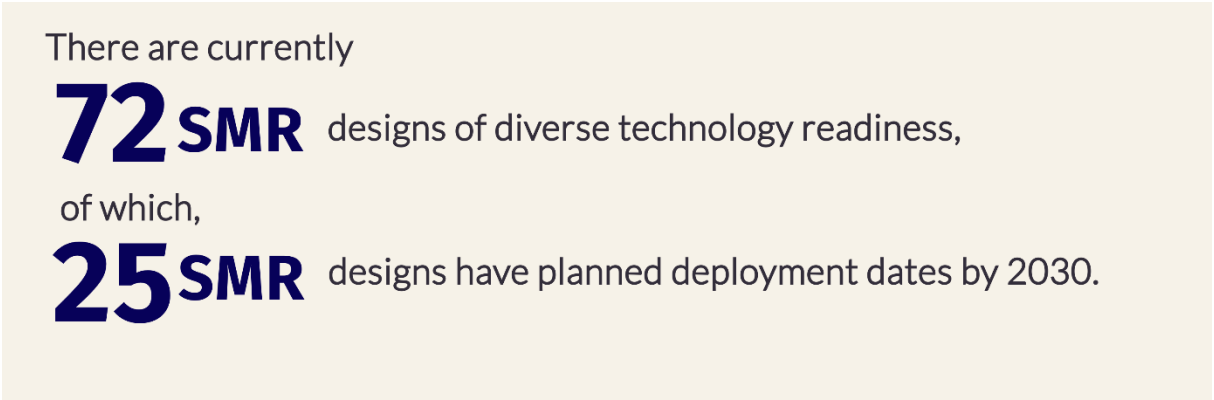
eliminating non-critical work to minimize external staff brought on-site. In other cases, outages were extended to allow work to proceed at a slower pace that accommodated physical distancing constraints. In yet other cases, entire outages were deferred to the following year. The full impact will play out over at least the next year as future outage plans are revised to complete deferred work.

D.4. Advanced Reactors and Non-electric Applications

33. Tangible advances have been made in the technology development of SMRs of all major technology lines, power ranges, utilization categories and deployment types. The key drivers for SMR technology include reduced capital investment, shorter construction times, siting flexibility and applicability to a wide range of uses, including the replacement of retired fossil power plants and for its ability to work in an integrated energy system with renewable energies and non-electric applications such as low carbon heat and hydrogen production.

34. The first SMR was deployed in a marine-based floating power unit in the Russian Federation and has been in commercial operation since May 2020 with a power capacity of 70 MW(e). With regard to land-based SMRs, the first modular high temperature gas cooled reactor (HTGR) is now completing its hot functional tests, with the aim or connecting it to the electricity grid towards the end of 2021 in China. Another example is the integral PWR type SMR in the advanced stage (75%) of construction in Argentina, with start-up and criticality aimed for 2024 and an expected capacity of 30 MW(e).

35. Technological competitiveness of SMRs is expected to be achieved through a high degree of modularization to reduce the costs and schedule of construction, as well as featuring the ‘economy of serial production’ instead of the ‘economy of scale’ in large reactors. There are currently 72 SMR designs of diverse technology readiness[3], of which at least 25 have planned demonstration dates by 2030. If the global deployment environment, including fuel cycle, is fully enabled, there could be about 1.6 additional GW(e) contributed from SMRs. However, SMR technology still needs to overcome deployment issues and reach commercial competitiveness for which several conditions have to be met: demonstration of safety and operational performance of the first-of-a-kind (FOAK) reactors of novel designs and technologies; continuity of orders, cost competitiveness against alternatives, robust supply chain, fuel cycle available at scale, and viable financing schemes; and regulatory frameworks (licensing pathways) must be established through harmonization. The appropriate nuclear infrastructure should be in place for responsible governance of this anticipated broader serial deployment in new markets.



36. Microreactors are another emerging technology, with a power range of between 1 MW(e) and 20 MW(e), which could supply industrial remote or off-grid regions with electricity, provide power

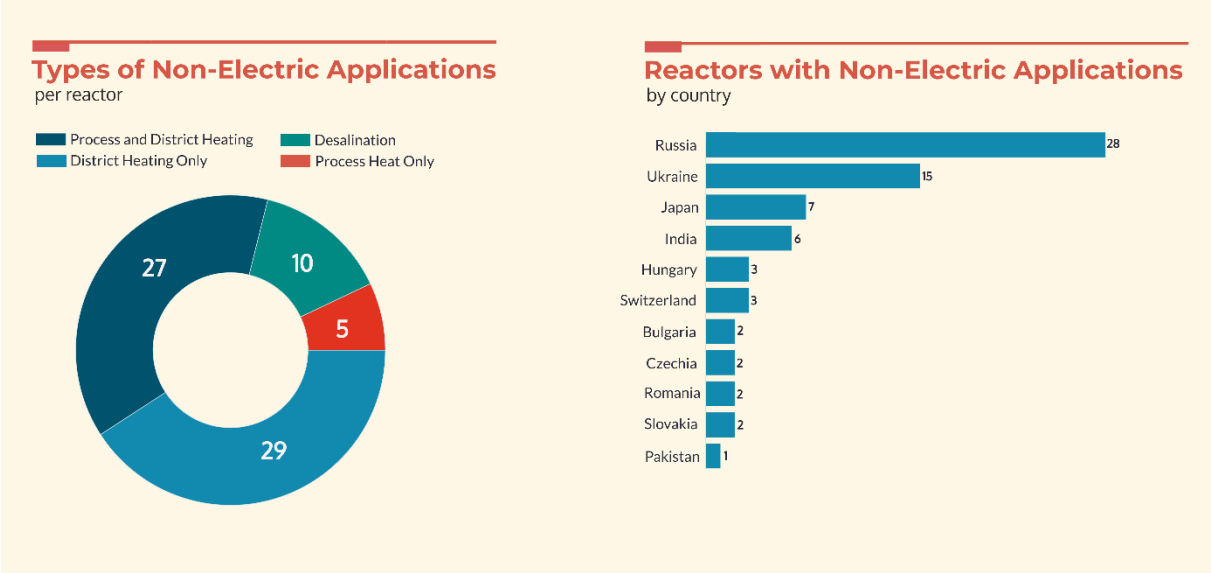
[3] INTERNATIONAL ATOMIC ENERGY AGENCY, Advances in Small Modular Reactor Technology Developments, A Supplement to: IAEA Advanced Reactors Information System (ARIS), IAEA, Vienna (2020).

resilience, serve as an alternative to diesel and be deployed in markets where even 'normal' SMRs would not be suitable.

37. There are five fast reactors already in operation: two operating reactors (BN-600 and BN-800) and a test reactor (BOR-60) in Russia, India's Fast Breeder Test Reactor and the China Experimental Fast Reactor. In the Russian Federation, construction began in June 2021 on the BREST-OD-300 fast reactor, which will be the first reactor for civilian nuclear energy to be cooled with lead. Because lead does not react with air and water, the reactor design can be streamlined, making it more economical compared with other fast reactors. The 300 MW reactor is part of the Proryv project, aimed at demonstrating the stable operation, at one site, of the installations needed for a fully closed nuclear fuel cycle. If successful, it will constitute an important step in the further development of nuclear energy, providing greater sustainability through fuel recycling and a reduced waste footprint. Other countries are also making progress in this field. China, for example, is building two large demonstration fast reactor units and plans to eventually deploy commercial fast reactors. India is completing commissioning of its sodium cooled Prototype Fast Breeder Reactor, the first of several industrial fast reactors the country is planning. TerraPower has announced building of its first next generation nuclear reactor, Natrium, on the site of one of the Wyoming's retiring coal plants. Japan is conducting feasibility studies in its Nuclear Energy x Innovation Promotion (NEXIP) Programme, as the first phase of its Fast Reactor Strategic Road Map for Fast Reactor Development.

38. Innovations in water cooled reactor (WCR) technology, post-Fukushima accident, continue in the areas of safety, construction technology and economics. Safety systems designed into today's advanced WCRs have passive features that do not rely on electric power and include larger water inventories, allowing for coping times of days instead of hours in the event of unplanned conditions, such as extended station blackouts. Additional advantages of advanced WCRs are the lower waste yields, greater fuel utilization, greater reliability, resistance to proliferation and the ability to be integrated into electric and non-electric applications. In improving thermal efficiency and economics, as a logical extension of advanced PWR and BWR designs, the supercritical WCR concepts under development in a number of Member States, highlight this design's favourable features with regard to economics, safety and technology.

39. The need for the decarbonization of the heat and power sector has led to an increased interest in the use of nuclear energy not only for electricity generation but also for other energy intensive non-electric applications such as seawater desalination, district heating, industrial process heat and fuel synthesis (including hydrogen production). There is a great potential to capitalize on nuclear heat from conventional reactors, where 60-70% of it is rejected into the environment as waste heat and lost. Such waste heat can be reused in cogeneration mode, i.e. the simultaneous production of electric power and heat or a heat-derivative product. For example, at the end of 2020 China's Haiyang NPP in Shandong province started providing district heating to the surrounding area, which is expected to avoid the use of 23 200 tonnes of coal annually, cutting CO_2 emissions by 60 000 tonnes.



40. Interest in hydrogen production from nuclear energy is gaining interest in many countries, including China, France, Japan, Poland, the Russian Federation, the United Kingdom, and the United States of America. The actual implementation of nuclear hydrogen production will depend on the market conditions expressed in prices, competitors, total demand and geographical distribution of consumption. In the context of climate policy measures, a large window of opportunity for nuclear hydrogen will be created if an effective discouraging (through taxes) of steam methane reforming is broadly introduced.

41. Nuclear and renewables are the two principal options for low carbon power generation. Nuclear-renewable hybrid energy systems (HESs) leverage the benefits of each technology and their mode of operation in providing reliable, sustainable, and affordable electricity to the grid and low carbon energy to other sectors. In this integration of nuclear and renewable resources heat, electricity and other energy products or services could be produced and, as appropriate, stored. In addition to electricity, nuclear-renewable HESs can deliver energy to various applications, such as hydrogen and hydrocarbon production, district heating or cooling, the extraction of tertiary oil resources, seawater or brackish water desalination, and process heat applications, including cogeneration, coal-to-liquids production and refining, and synthesis of chemical feedstock. However, to achieve a fully operational tightly coupled nuclear-renewable HES, several existing gaps need to be addressed and closed, including achieving a required level of safety of the nuclear-renewable HES that is at least comparable to that of the current stand-alone NPPs; human capital development to operate and maintain such systems; the interaction of the nuclear-renewable HES with the electricity market and grid regulation; and the technology-readiness level of a nuclear-renewable HES, which is strongly dependent on the technology-readiness level of each subsystem and the coupling and operational schemes.

42. Over the past years, fusion technology has seen major advances, resulting in a more substantial engagement of the private sector and new job opportunities. ITER is proceeding at a steady pace and is a critical step towards the goal of harnessing fusion energy. Significant strides will be made in the next five years, and continuing on to 2035, when it is expected that ITER will achieve its ultimate goal: demonstrating the feasibility of fusion energy. Except for plasma physics, the major challenges for fusion reactors are in the areas of materials development for the heat source structures (plasma facing material) and design of cooling systems for high efficiencies. Fusion may not be the energy source of tomorrow, but it could be a solution for the end of the century. Transferring 70 years of experience in peaceful uses of fission energy to upcoming fusion technology would allow for creating a synergy between two nuclear energy sources that could provide sustainable energy for future generations.

D.5. Fuel Sustainability and Innovative Fuel Cycles

43. By 2040, the world annual uranium requirements are forecast to be in the range of 56 640 to 100 225 tonnes of uranium (tU), depending on the number of new build NPPs and life extensions of the existing ones. Therefore, in the Agency's low case scenario, current global uranium supply needs to remain the same as 2019 values. Conversely, in the Agency's high case scenario, uranium annual production needs to increase by about 41 000 tU. This would require significant exploration activities, innovations and the development of new uranium mines.



44. Since 2009, primary production from operating uranium mines has averaged 87% of global demand. The deficit has been made up by secondary supplies which, since 2010, have slowly been depleting. The resources at many major uranium mines are forecast to be depleted in the mid-2030s. Operations in care and maintenance, increased production at existing facilities and final development of advanced projects may not be sufficient to fill the supply gap. Considering the 15-20 years on average to construct and commission a new mine there is concern in the industry about security of supply in the mid to long term. Exceptional events, such as the COVID-19 pandemic, could induce additional stress on supply: in 2020, for instance, a number of major uranium producers suspended operations or significantly reduced production. As a result, primary uranium supply from operating mines was reduced with global production of about 46 500 tU. This represented about 78% of global demand for uranium, thereby putting more pressure on secondary uranium supplies to fill the demand for uranium as nuclear fuel.

45. Continued improvement of technology, including advanced materials and nuclear fuels, remains central to the success of the nuclear industry. The main drivers in the area of nuclear fuel engineering are to increase fuels' operational safety margins, to reduce NPPs' operation and maintenance costs and to minimize nuclear waste generation, by developing new types of fuels for current and new generations of NPPs, as well as by recycling nuclear materials.

46. Advanced technology fuels (ATFs) are being developed as alternative fuel system technologies to further enhance the safety, competitiveness, and economics of commercial NPPs for current and future reactor designs. Made up of new materials, for both fuel and cladding, the ATFs developed in Europe, the Russian Federation and the United States of America sometimes require higher uranium-235 (^{235}U) enrichments to compensate for the loss of neutronic transparency of their cladding materials. Therefore, high-assay low enriched uranium (HALEU) fuels, enriched above 5% (but below 20%), are under production, development, and testing. To increase the economic benefits, work is also being undertaken to increase discharge burnups and extend cycles of fuel operation in NPPs, which also requires higher ^{235}U enrichments. However, new fuel concepts with higher burnups will have an impact on aspects of the back end of the fuel cycle, such as fuel transportation and spent fuel management processes (from storage to disposal through to reprocessing). Significant investments are needed for the construction and licensing of FOAK facilities to deploy advanced fuels.

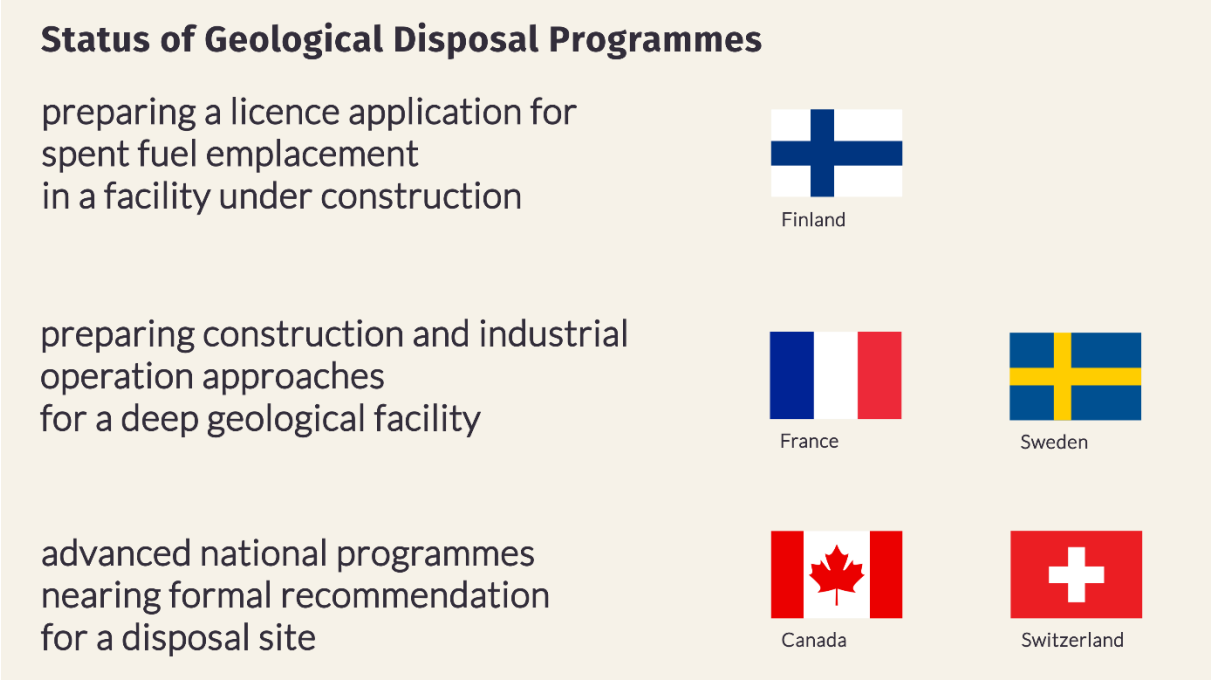
47. As SMRs are of various types (e.g. light water reactors (LWRs), HTGRs, fast reactors and molten salt reactors), traditional and new types of fuels are being developed with, for example, different designs, geometries and enrichments. For some types of SMRs, fuel design and fabrication are based on known technologies, although fuels may require enrichments at the top end of what is defined as low enriched uranium (HALEU fuels with ^{235}U enriched above 5%, but below 20%).

48. Closing the nuclear fuel cycle is a major driver for ensuring the sustainability of nuclear power. Fissile materials can be recovered from spent nuclear fuel to produce new fuel. Reprocessing of uranium oxide fuels and recycling of uranium and plutonium is an industrial practice in LWRs today even though there are currently few LWRs licensed to use recycled fuels. Progress is being made in multi-recycling plutonium in REMIX, CORAIL and MIX fuels. These recycled fuels will enable the transition to plutonium multi-recycling strategies in fast reactors, allowing for a more effective use of natural resources and reducing the burden of generated waste. Significant investments will be necessary to support the industrial implementation of such multi-recycling technologies.

D.6. Radioactive Waste Disposal

49. The capacity to provide solutions for all radioactive waste management steps including the associated waste disposal solutions is a corner stone and key enabler of the continued sustainable use of nuclear technologies. Building on decades of experience and developments around the world, national programmes are making use of tried and proven technologies to implement effective, safe, secure and – where nuclear materials are involved – proliferation resistant solutions through all of the steps of radioactive waste management. All of these steps lead to and include radioactive waste disposal, for which numerous facilities have been implemented and are in operation around the world for very low level waste, low level waste and intermediate level waste.

50. A very robust international pool of knowledge has been built through multiple deep geological disposal programmes for high level waste, which includes spent fuel if declared as waste. As illustrated by some of the leading deep geological repository (DGR) programmes in the world, the past decade has demonstrated significant process in several national programmes towards the disposal of high level waste– a milestone IAEA Director General Grossi referred to as a ‘game changer’ in reference to the specific context of Finland. The most advanced national programmes are nearing the formal recommendation for the disposal site (Canada and Switzerland), preparing construction and industrial operation approaches of their deep geological disposal facility (France and Sweden) or preparing the licence application for spent fuel emplacement in a facility under construction (Finland). A broad group of such national programmes is currently building on a cooperative research, development and demonstration framework – the Implementing Geological Disposal of Radioactive Waste Technology Platform – to further progress with the industrialization and optimization of the deep geological disposal process for high level waste.



51. To further provide for timely and effective management of future radioactive waste arisings, Member States are improving the estimation of their entire national waste streams from all nuclear technology applications and to establish integrated approaches to national radioactive waste management responsibilities. The integrated approach holds great promise for reducing the costs associated with radioactive waste management responsibilities – fully consistent with an 'as low as reasonably achievable' approach integrated at all steps, while optimizing the use of resources and providing for greater clarity of short-and long-term planning. Member States experience shows that developing and implementing waste management solutions and their associated disposal endpoints is feasible. In many instances, however, challenges stemming from past national practices and historical legacies remain. Incomplete inventories and poorly characterized waste hinder further effective processing and limit the options for adequate disposal. Inadequate past resource estimates have prevented the necessary development of capacity and facilities, while past disposal practices have reinforced the general perception that radioactive waste management 'cannot be done'. This has led to negative perceptions about waste disposal, making decision makers hesitant to embrace this responsibility and provide a clear national framework for the sound implementation of solutions.

D.7. Decommissioning

52. While in previous decades deferred dismantling was the dominant decommissioning strategy adopted by facility owners, an immediate dismantling approach has been gaining favour. Moreover, timeframes for beginning final dismantling of retired plants are increasingly being brought forward, with a number of deferred dismantling strategies being changed to immediate dismantling. This change has been driven by a desire to reduce uncertainties over decommissioning costs.

53. Given that decommissioning involves the conversion of redundant facilities into a passively safe state, the ability to proceed with project implementation is strongly dependent on the availability of adequate financial resources and an adequate system for long-term management of spent fuel and radioactive waste. Although no facility for final disposal of spent fuel is yet in operation, spent fuel can be stored safely in storage pools or dry storage facilities, so several permanently shut down plants have erected dry storage facilities adjacent to the site of the nuclear facility, thus enabling progress with dismantling and demolition operations.

54. A large proportion of disused material from decommissioning has insignificant levels of radioactivity, such that it could in many cases be released from regulatory control (depending on the national legal regime) and reused for other purposes. Such an approach works well in several countries, but not all. The latter case includes situations where lack of public acceptance to reuse material originating from nuclear facilities, regardless of its radioactivity level, may prevent such material from being reused or recycled. Given the absence of significant risk associated with such activities, such situations are deemed suboptimal from a scientific and technical perspective.

D.8. Human Resource Development: The Next Generation

55. Acquiring and retaining skilled personnel to ensure a competent workforce for all phases of the nuclear facility life cycle are among the top priorities for the nuclear community. However, long-term career prospects in all phases of the lifecycle of nuclear facilities and organizations makes working in the nuclear industry an attractive option. Moreover, careers in the nuclear field also offer many opportunities for societally meaningful work, such as providing clean energy and water or helping countries achieve socioeconomic development.

56. Concerns about possible shortages of qualified personnel pose different challenges for different countries. A particular challenge for nuclear new build projects is the identification and development of expertise and human capital, as there are few such projects and there are often many years between them (with the exception of China, Japan, the Republic of Korea and the Russian Federation). Innovative approaches, such as digital and blended learning, are being put into practice to make nuclear training, education and capacity building more easily accessible to new generations of the nuclear workforce in both operating and embarking countries. For countries with expanding nuclear power programmes, the challenge is to scale up their existing education and training in order to have the required qualified workforce as soon as it is needed.

57. Countries planning to supply nuclear energy technology can support recipient countries in meeting their national human resource needs by transferring capabilities to build education and training infrastructure. Cooperation between nuclear operating countries and embarking countries has already been proven as beneficial for bridging the experience gap.

58. In the changing global landscape, talent attraction and retention in the nuclear field is further challenged by technological innovation, increased mobility and evolving demographics. At the same time, innovative technological approaches, such as digital and blended learning, are put into practice to make nuclear training, education and capacity building more easily accessible to new generations of the nuclear workforce in both operating and embarking countries.

D.9. Licensing/Regulatory Frameworks/Approaches

59. An enabling environment for the safe, secure, and sustainable introduction or expansion of nuclear energy is supported by the role of governments in setting up the appropriate policies, programmes, and legal framework for nuclear power programmes. All low carbon energy sources require specific policies to support their deployment. Policies should be reflected in the national legal, institutional and regulatory systems, with the aim of ensuring a stable and predictable environment and maximizing their impact.

60. Currently, global nuclear energy deployment is governed by a well-established international legal regime. As nuclear energy plays an important role in mitigating the climate change, issues such as further regulatory harmonization or new-deployment business models could be factored into innovations to reach a cleaner and more sustainable future.

61. Licensing an NPP requires extensive assessment of its design and technical characteristics in terms of safety, security and safeguards. The Agency’s safety standards and security guidance are used by

countries to support the development of their national regulatory frameworks. Broader international cooperation is regarded as of prime importance for knowledge transfer, acquisition of competences in developing and applying the national regulatory framework, and further accelerated deployment.

62. The timely development of an enabling nuclear infrastructure and the related nuclear legal and regulatory framework currently applied to large nuclear reactors in embarking countries is a critical factor for accelerated market preparation to anticipate the deployment of SMRs.

63. Existing regulatory guides and processes for assessing advanced technologies such as SMRs are lagging and in some cases are not yet available. In future, robust, technology neutral regulatory review methodologies would be beneficial to minimize the time needed to adopt and commercialize new nuclear reactor technologies. In any event, regulators and developers will need to work together to facilitate the recognition of the design certification and demonstration of these FOAK reactors so that the path to construction and operation is safe and streamlined, while costs are driven to reach competitive deployment. Currently, the Agency is hosting the SMR regulator's Forum and is reviewing the safety standards applicability with a technology neutral approach when SMRs are considered.

D.10. Public Perceptions

64. Nuclear energy can help address pressing global issues; however, misperceptions about nuclear power continue to impact public acceptance and policy making. Public perception of the benefits and risks associated with nuclear power, and, in particular, concerns about radiation risks, waste management, safety and proliferation remain the areas that most influence public acceptance. As public opinion plays a major role in how governments choose to produce energy, understanding stakeholders' opinions, awareness and knowledge regarding nuclear power is a crucial component for decision making and for the success of a nuclear power programme. Building strong, positive and long-term relationships with stakeholders is a key factor for existing, new and future nuclear power programmes.

65. Experience shows that involving stakeholders in decision making processes, even those stakeholder groups that do not have a direct role in decision making, can enhance public confidence in the application of nuclear science and technology. This includes open and transparent dialogue that builds mutual trust among various stakeholders, from the nuclear industry and government institutions, to the media, local communities and non-governmental organizations. Such interaction helps to build awareness and understanding of all aspects of the nuclear fuel cycle, from uranium mining, to spent fuel and radioactive waste management, but also opens an opportunity for stakeholders to voice their concerns and influence decisions that are affecting their communities.

66. Open and accessible means of stakeholder involvement in existing nuclear programmes has evolved, and these strategies have also become the norm in many areas of waste management facility siting and development. New nuclear power programmes are following this trend. Indeed, stakeholder involvement is one of the 19 infrastructure issues of the Agency's Milestones approach, a sound three-phase process for developing the necessary infrastructure for a nuclear power programme.

67. Engaging stakeholders early, substantively and frequently will also support the development and deployment of new technologies, such as SMRs, as countries assess their viability as an option for low carbon electricity and non-power applications. Experience of both operating and embarking countries as well as lessons learned from the deployment of existing technologies can contribute to the success of new nuclear technologies.

68. Finally, better understanding by various stakeholders of the important role of nuclear power in providing stability to electrical grids, especially those with high shares of variable renewable sources, could lead to increased public acceptance of nuclear power. Such a combination of nuclear power with renewables in HESs can help significantly reduce GHG emissions while providing reliable electricity

for socioeconomic development, addressing the concerns of many stakeholders. Enhanced stakeholder appreciation that nuclear energy can be used to desalinate seawater, produce low carbon hydrogen and generate heat for buildings and industrial applications can further improve public support for this low carbon source of energy, expanding its potential to contribute to climate action and sustainable development.

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