The Nuclear Fuel Report: Expanded Summary

Global Scenarios for Demand and Supply Availability 2021-2040

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1 Introduction

World Nuclear Association has published reports on nuclear fuel supply and demand at roughly two-yearly intervals since its foundation in 1975. The 20th edition of *the Nuclear Fuel Report* was released in September 2021 and includes scenarios covering a range of possibilities for nuclear power to 2040. Forecasts of the years beyond 2040 are beyond the scope of this report and would require a rather different approach to capture the larger range of uncertainty; however, the key issues examined here are likely to have continued relevance during that longer period.

This *Expanded Summary* covers the key findings of 20th edition, and explains the methodology and the assumption underlying the report's three scenarios for future nuclear fuel demand and supply.

The full version of *The Nuclear Fuel Report* can be purchased from the World Nuclear Association's online shop.

Nuclear power currently contributes approximately 10% of the world's electricity production. It is expected to play an increasingly important role in future electricity and energy supply for several reasons, including:

- The near-zero carbon dioxide and other pollutant emissions associated with nuclear power generation.
- The on-demand reliable and secure nature of nuclear power, attractive to developing countries, those lacking indigenous energy resources, and to developed countries intent on introducing high shares of renewables, while maintaining grid stability.
- Its long-term cost-competitiveness.
- The industrial and human-capital benefits associated with its development and use.
- The ability to produce near zero-carbon heat, in addition to electricity, that could help to decarbonize many hard-to-abate sectors of the economy.

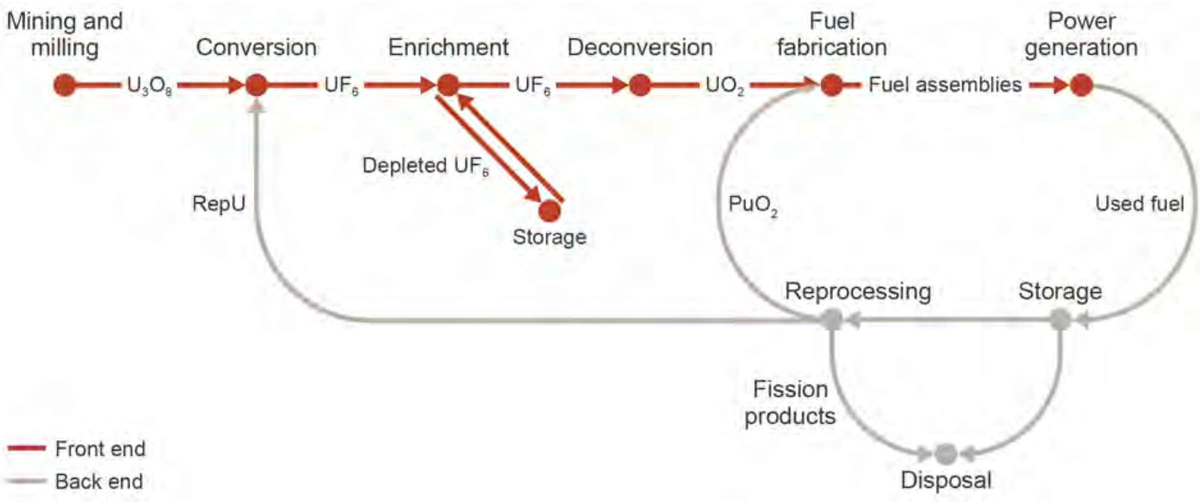
Despite these advantages, nuclear energy faces several competitive challenges from other electricity generation sources, especially in deregulated markets as they are currently designed, along with continuing regulatory and political hurdles. Furthermore, electricity demand growth has slowed down, especially in the countries where nuclear power is well-established. At the same time, the nuclear sector remains strong in many developing countries, and it is in these countries that the majority of nuclear capacity growth is expected. China and India alone account for over half the projected new reactors.

1.1 Features of the nuclear fuel market

The nuclear fuel market operates in a very different way to other energy markets. Uranium concentrate produced by a mine cannot be fed into a nuclear reactor directly; it has to be processed or pass through different stages of the nuclear fuel cycle (see Figure 1).

The nuclear fuel cycle is complex, beginning with the mining of uranium and ending with the disposal of nuclear waste. In order to use uranium in a nuclear reactor, it has to undergo mining and milling, conversion, enrichment and fuel fabrication. These steps make up the 'front end' of the nuclear fuel cycle. The ‘back end’ refers to all stages subsequent to removal of used fuel from the reactor. The used fuel may then go through a further series of steps including temporary storage, reprocessing, and recycling before wastes are disposed of.

Figure 1: The nuclear fuel cycle



The fuel cost in nuclear power has historically been a minor element in the total production cost. Fuel costs of new nuclear plants are usually under 20% of the total operational costs, compared with up to 80% in fossil fuel-fired plants.

Uranium supply can be characterized by two main categories: primary and secondary supply. Primary supply refers to uranium that is newly mined and processed, while secondary supply includes uranium received after reprocessing and returned back to the fuel cycle.

Primary uranium production has recently (2012-2017) represented about 90% of the global reactor demand. It is characterized by broad geographical distribution, and also by a large number of companies representing major and junior uranium miners. The uranium was produced by a quite small number of companies, representing solely major uranium miners: 85% of the world uranium was supplied by the ten largest uranium producers. The intermediate stages of the nuclear fuel cycle – conversion, enrichment and fuel fabrication – are services provided by specialist companies.

Secondary supply includes natural and low enriched uranium inventories, high enriched uranium, mixed uranium and plutonium oxide (MOX) fuel, reprocessed uranium (RepU) and re-enriched depleted uranium. Secondary markets for uranium, conversion and enrichment services are well-established, currently meeting about 17% of demand. However, the recycling of nuclear material depends largely on political as well as economic factors.

An important feature of the nuclear fuel cycle is its international dimension. Uranium is relatively abundant throughout the Earth’s crust, but distinct trade specialization has occurred, due partly to the high energy density and therefore the low costs of transport, in comparison with coal, oil and gas. For example, uranium mined in Australia can be converted in Canada, enriched in the UK and then fabricated as fuel in Sweden for a reactor in South Africa. Recycled reactor fuel may follow similar international routes, with their related political as well as economic implications.

A further aspect of the nuclear fuel cycle's international dimension is the amount of licensing, surveillance and national and multinational regulations in place throughout the fuel cycle to ensure that safety and non-proliferation objectives are met. These are administered by governments, regional organizations, such as the Euratom Supply Agency in the EU, and by the International Atomic Energy Agency (IAEA).

The political influence on the uranium market has always been significant. Decisions taken to increase uranium production, to build new reactors, and to allow new fuel cycle facility construction, trade or transport in nuclear materials to take place, often contain significant non-economic dimensions.

1.2 Energy and electricity demand

Nuclear power must be regarded within the wider framework of trends in energy demand and supply. World Nuclear Association does not prepare its own forecasts of world energy and electricity demand and supply, but relies on the analyses of international organizations such as the International Energy Agency (IEA), the Intergovernmental Panel on Climate Change (IPCC) and others. The IEA in particular uses general equilibrium modelling of energy markets that explicitly incorporates the interactions of different sectors and the relationship of the energy sector to the wider economy. World Nuclear Association scenarios are based on expert opinion from within the nuclear industry and may usefully be compared with the IEA's nuclear forecasts.

The IEA's *World Energy Outlook 2020* (WEO 2020[1]), published in October 2020, describes scenarios for global nuclear capacity based on different policy responses to climate change and the Covid-19 crisis, as well as the need to reduce carbon emissions from fossil fuels (see Table 1). The 'Stated Policies Scenario' (STEPS), which is based on today's policy settings, projects the global economy to return to pre-crisis levels in 2021 and reflects policy commitments and targets that were announced as of mid-2020. The 'Sustainable Development Scenario' (SDS) projects the implementation of energy policies and investments aiming to achieve sustainable energy objectives in full, including the Paris Agreement, energy access and air quality goals.

Table 1: IEA and World Nuclear Association nuclear capacity scenarios for 2040, GWe[2]

(Sources: IEA World Energy Outlook 2020, World Nuclear Association)

WEO 2020*	Stated Policies	479	WNA 2021**	Reference	615
				Lower	449
	Sustainable Development	599		Upper	839

** IEA World Energy Outlook 2020 (gross GWe)*
*** World Nuclear Association (net GWe)*

The IEA's *Net Zero by 2050* report, published in May 2021, presents the normative 'Net-Zero Emissions by 2050 Scenario' (NZE) that extends the SDS by setting out what additional measures would be required to put the world as a whole on track to reach net-zero emissions by mid-century.

[1] World Energy Outlook 2020, International Energy Agency, October 2020

[2] The IEA figures are gross GWe while the World Nuclear Association figures are net GWe, *i.e.* net of process requirements. Net capacity is typically approximately 4-5% lower than gross capacity.

The World Nuclear Association scenarios embrace broader changes than climate change policy alone. The Reference Scenario is largely a reflection of current government policies and plans officially announced by utilities for nuclear in the next 10-15 years, which (with a few significant exceptions) are generally rather modest. The Upper Scenario is underpinned by more favourable conditions for nuclear development, largely reflecting the targets, recently announced in many countries to achieve net-zero carbon emissions by mid-century, and the assurance that nuclear power will play an indispensable role in reaching this goal. However, the Upper Scenario is not a normative net-zero scenario aiming to achieve Paris Agreement decarbonization goals.

In contrast to the IEA 'Delayed Recovery Scenario' (DRS), the Lower Scenario does not foresee a noticeable impact of climate change policy and mainly focuses on other factors; for example, it is assumed that nuclear becomes economically uncompetitive against the decreasing cost of intermittent renewables, there is a lack of political and/or public support for nuclear energy, and the importance of security of electricity supply and grid resilience are not sufficiently valued, amongst other factors.

Advantages of nuclear

A key advantage of nuclear is its proven ability to provide reliable and economic base-load power on a near zero-carbon full life-cycle basis. For example, in the USA alone, nuclear energy currently provides around 52% of the country's carbon-free electricity, and in the European Union it accounts for 43% of the region's carbon-free electricity.

In 2020 the world's nuclear power plants supplied 2,553 TWh of electricity through 393 GWe of operable capacity. This avoided the emission of 2.1 billion tonnes of carbon dioxide compared to the equivalent amount of coal power generation, in addition to total avoided emissions of around 74 billion tonnes since 1970. Nuclear power also avoids the emission of pollutants including oxides of sulfur and nitrogen, and is therefore favoured by some countries as a solution to combat air pollution.

In the future, nuclear energy could contribute substantially more, given the expectation of rapidly rising electricity demand and the changes in energy consumption. The transport sector offers great potential with electric vehicles, and programmes to implement higher use of passenger electric vehicles are under way in numerous countries worldwide. Apart from electricity generation, nuclear represents a credible low-carbon source of process heat for various applications, such as district heating, water desalination, oil and chemical refining, and hydrogen production.

Whilst policies aimed at curbing carbon emissions should help to create a level playing field for nuclear, a preference for energy market liberalization by policymakers may hinder the uptake of nuclear power if this leads to shorter-term investment horizons. Nuclear power plants take longer to build than, for instance, gas-fired plants, and have considerably higher initial capital investment. Therefore, if electricity prices are unpredictable, quicker payback projects such as gas may be favoured over the long-term commitment that is necessary to make a nuclear project financially viable.

1.3 Factors affecting electricity demand growth

There are many factors that affect electricity demand growth, some of the most important explained below.

Population growth, urbanization and electrification

Growth in electricity demand is correlated with population growth. Indeed, electricity demand growth has been more than double the growth in population since 2000. With more than one billion people without access to electricity globally, the extent to which large developing nations achieve universal access to electricity will be a key driver in demand growth. Compounding the effect of population growth is the trend towards urbanization and also towards electrification of new-build domestic and industrial processes.

Global economic growth

Economic growth rates affect electricity demand, both industrial and household, particularly in developing economies where growing incomes and standards of living enable more consumption of domestic appliances, and domestic cooling and heating. However, in advanced economies, growth in gross domestic product has a lower correlation with electricity demand, primarily due to energy efficiency initiatives.

Electrification of transport

The electrification of transport has played an important role in reversing projected electric power demand declines in developed industrial economies and in supporting grid power growth in China. The most visible electrification is that of passenger vehicles, with global plug-in vehicle sales more than quadrupling in the four years from 2016 (774,000 vehicles) to 2020 (3.24 million vehicles[3]). Initiatives are under way in numerous countries to expand the electrification of motorcycles, buses, trucks, trains and water transport to reduce urban pollution and vehicle emissions. The effectiveness of emissions reduction measures relies on low-emission electricity for charging transport, providing an opportunity for nuclear power.

Deep electrification

Beyond the electrification of transport, the decarbonization imperative has resulted in a push to convert all residential, commercial and industrial systems to electrical power, rather than hydrocarbons. The aim is to convert domestic appliances – *e.g.* heating, cooking and water heating – from gas or other fossil fuels to electricity, which is then sourced from emissions-free power. Similarly, the attainment of economy-wide decarbonization goals will, following the decarbonization of electricity production, ultimately require emitting industrial processes to electrify. The achievement of deep electrification is anticipated to increase grid demand in the developed world, in particular for clean energy.

Alternative generation technologies

The growth of electrical demand will be influenced by alternative power output technologies. For instance, the ability to exploit shale gas on a commercial basis has transformed the economics of gas-powered building heating and process-heating in the USA. The growth of gas in this market has been partly curtailed by environmental pressures, such as the prohibition of natural gas infrastructure to new

[3] Figures from EV-volumes.com

buildings in large parts of California. Other, less significant alternative technologies include direct heating from bioenergy and geothermal energy.

The production of hydrogen as an alternative to fossil fuel use in transport will, if successfully implemented, affect the rate at which fossil fuel is displaced in transport. The role of nuclear power in manufacturing hydrogen is discussed below.

Nuclear power offers excellent prospects for emissions-free district heating and process heat generation, which would be available as a direct product of reactor heat, rather than being produced from electricity.

Competitive power alternatives

The natural gas resource base has been greatly increased by the addition of unconventional gas. Moreover, the cost of exploiting natural gas has fallen. Unconventional gas is widely available and the cost of transporting gas has fallen. Gas prices in the USA have essentially remained below $5 per million BTU since 2011, the price at which gas-fired generation can be expected to start undercutting nuclear. The availability of low-cost gas combined with a lower than expected level of power demand has affected the decisions of some US utilities to invest in nuclear capacity uprates as well as in new reactors.

As with any source of energy, the exploitation of unconventional gas bears risks, including the productivity and longevity of wells, the impact on water resources and other environmental concerns, the outcome of which will become apparent only over time. At the global level, there is considerable uncertainty as to how far unconventional gas might be developed in other parts of the world. To date, the widespread exploitation of unconventional gas appears to be largely a US phenomenon. The EU is believed to have quite extensive resources but to date exploitation has yet to be demonstrated and in some countries hydraulic fracturing and even exploration have been prevented by regulation. China has made significant efforts to identify and scope its unconventional gas resources, which appear to be very significant. In other countries where nuclear is an important contributor to electricity generation such as South Korea, Russia and India, little information on unconventional gas has been made publicly available or exploration activities are at an early stage.

The development and promotion of renewable energy over the last decade or so has resulted in new sources of power generation. The driving force behind renewable generation has been mainly the political decision to set high levels of subsidies for renewables – under the form of power purchase agreements and tax credits, amongst others. The implementation of constraints on carbon emissions has not yet been set at a level that would significantly reduce fossil generation. The intention of policymakers has been to develop the market for renewables not only to provide low-carbon electricity but also to reduce the costs of renewable power. Politicians have expressed the hope that subsidy support can be reduced and eventually removed, and in some countries – for example Germany, Spain and the UK – this has happened to a degree.

The ambition to induce lower renewable costs has been met with limited success for bioenergy and geothermal, with some success for onshore wind power and considerable success for solar power. However, in the EU, where renewables have received the highest levels of support, the generation of renewable power sits uneasily with existing power market structures and practices. Intermittent renewables, such as solar and wind, generate power with very low operating costs yet incur high capital costs. These power sources generally bid into the power market at very low (even negative) prices and greatly increase the volatility of supply. This volatility reduces the capacity factors of other producers, including nuclear, as well as increasing the maintenance costs arising from frequent changes in output.

When the renewable generation is intermittent (as with solar and wind), the system costs of guaranteed supply also increase due to the need for extensive additional transmission infrastructure, back-up generating capacity and energy storage. A 2019 study by the OECD Nuclear Energy Agency[4] shows that when intermittent renewables supply more than 30% of the electricity generated, system costs will grow exponentially and may double the price of electricity to the end user.

Grid storage technology

Challenges associated with the intermittency of renewables are hoped to be partly addressed through the introduction of large-scale grid storage. Technologies such as pumped storage hydroelectricity, lithium-ion batteries and vanadium flow batteries have been deployed at a commercial scale for both stability enhancement and stored power release. Pumped hydro has been effective in limited geographic circumstances where there is suitable infrastructure. Lithium-ion battery storage has been challenged by competition for resources in the electric vehicle market, limitations associated with cycle times and the cost of scaling up to meet grid demands. Vanadium flow batteries have demonstrated excellent performance and lifecycles, although large-scale deployment is challenged by vanadium supply availability and price volatility resulting from consumption from the steel industry. The timeframe for commercialization of other technologies in the research and development stage remains uncertain.

Batteries have proven to assist with instantaneous grid stability, hour-to-hour storage duration, peaking demand management and renewables integration. In spite of this, it is becoming increasingly apparent that battery storage will not be available or affordable on the required scale over the next decades for mid- to long-term storage durations, in order to balance the effects of longer climatic events or seasonal variation on intermittent renewables. As a consequence, other solutions to intermittency will need to be developed, alongside nuclear and hydropower. Delays in the implementation of these solutions will lead to reduced grid availability, volatile power prices and risks of power disruption – all of which may negatively affect the rate of electrification and therefore electricity demand growth.

Energy intensive technology applications

The rapid expansion of technology infrastructure has introduced electrical demand that was not contemplated several years ago. For example, data centres are estimated to consume up to 1.5% of global electricity production, with the world's largest data centres each requiring more than 100 MW of power. Efficiencies in computing power and hardware improvements have maintained relatively modest growth over the last several years, despite strong growth in global computing applications and data consumption. However, the growing use of data and trends towards energy-intensive applications such as artificial intelligence may accelerate demand growth.

Cryptocurrencies and other tokens have experienced high levels of adoption over the last two years. The 'mining' of cryptocurrency is highly energy-intensive, however the significant appreciation in the value of key cryptocurrencies has supported expanded investment into the computer hardware and power costs to support mining. The Cambridge University Centre for Alternative Finance[5] estimated in February 2021 that the mining of Bitcoin alone consumed approximately 0.6% of the world's electricity – more power than most countries' national grids. The Ethereum network consumes around a quarter

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[4] The Costs of Decarbonisation: System Costs with High Shares of Nuclear and Renewables, OECD Nuclear Energy Agency (January 2019)

[5] Cambridge Bitcoin Electricity Consumption Index

as much power. There are more than 4,500 mineable coins and tokens in existence[6] and, whilst Bitcoin mining is particularly energy-intensive, the continued expansion of blockchain applications and the financial appreciation of successful cryptocurrencies has the potential to generate substantial new demand for global electricity.

1.4 Factors affecting nuclear power growth

There are many factors that will determine the rate of growth of nuclear power around the world. The more important of these factors are outlined below.

The decarbonization of major economies

The global imperative to constrain climatic change has seen widespread policy support of renewable energy that has led to dramatic increases in these energy sources over the last decade. However, despite these policy interventions, global carbon dioxide emissions continued to rise in 2019 and 2020, widening the gap between current global emissions performance and the trajectory required to limit climate change to 1.5 °C (or even 2 °C) above pre-industrial levels.

A majority of all countries have committed to decarbonization goals, including China (2060), Japan (2050), the European Union (2050), South Korea (2050), the UK (2050) and the USA (2050). The United Nations estimates that more than 65% of global emissions fall under such pledges. The introduction of decarbonization goals by the world's two largest emitters, China and the USA, has increased the focus on decarbonization solutions and improved the understanding of grid dynamics by policymakers and within government. In turn, this is leading to a greater understanding of total system costs of various clean energy sources.

The nuclear power industry is achieving increasing recognition for its clean energy credentials amongst policymakers, environmentalists and the public. There is also increasing awareness of environmental and societal effects from land consumption and decommissioning of solar energy, as well as public resistance to onshore wind turbines. The degree to which this recognition results in government policies supporting existing and future nuclear energy production is a key factor affecting the growth prospects for nuclear fuel demand.

The potential for government policy to play a positive role for nuclear energy will depend on many factors. Should governments increase the urgency with which they seek to decarbonize energy production, nuclear power stands to benefit from policies to avoid early closure of reactors and enable operating lifetime extensions. Government policies to reduce baseload coal consumption are, in many countries, only achievable through displacement by other baseload sources, such as gas, hydropower or nuclear power. Given the environmental hurdles associated with hydropower installations and carbon emissions from gas, nuclear power is the logical choice for coal displacement in most instances. However, many governments have been cautious in supporting nuclear power because of the vocal role of interest groups, who have opposed nuclear power for both ideological and competitive reasons, and also because of the complexity in assessing either system costs or the socio-economic contributions of nuclear.

[6] See, for example, CoinMarketCap

Decarbonization targets by large corporations

Many of the world's largest corporate entities have committed to decarbonization of their own supply chains, in many instances more aggressively than the governments of the countries in which they operate. Corporations typically have more levers to achieve such goals, including procurement of clean electricity and other inputs. Many industrial corporations are dependent on consistent availability and pricing of electricity, which positions nuclear and hydropower as preferred choices over renewable energy. As this trend gains further momentum, these preferences are likely to influence utility generators and encourage the construction of small modular reactors.

Air pollution in growth markets

Air pollution has become an acute challenge in two of the most important growth markets for nuclear power: China and India. Over the last two years, both nations have experienced instances of widespread urban particulate pollution exceeding acceptable limits. Awareness of the health effects of air pollution has grown dramatically, with estimated deaths from air particulate exposure, largely attributed to coal-fired power, numbering in the millions per annum.

This has led the Chinese government in 2017 to promise to "make the skies blue again" and enact broad policies to control air pollution. Immediate measures have included suspending factories and reducing vehicle traffic during air crises, as well as cancelling and suspending operation of coal-fired power plants. Longer-term policies are directed at displacing coal power with clean energy, ensuring that clean energy sources would be used to meet future energy demand, as transport transitions to become electrified and energy sources for domestic heating and cooking are decarbonized.

Nuclear power is positioned particularly well as a solution to Chinese urban air pollution. As a baseload power source, nuclear offers the preferred source of energy to displace coal-fired power without sacrificing grid stability. China is the world leader in hydroelectric power production and there are environmental, social and multilateral constraints to expanding this energy source further. Moreover, most of China's air pollution crises occur during low pressure weather conditions in winter, when solar power generation is seasonally low and still conditions reduce or suspend the contribution of wind power.

Although policies to reduce air pollution are already supporting the expansion of nuclear power in China and India, further impetus to nuclear approvals and construction in both countries depends on the effectiveness of current policies in addressing air pollution and the extent to which other clean energy sources can contribute to reducing thermal power. If efforts to reduce, for instance, industrial air pollution and domestic cooking/heating fires are not sufficiently effective in reducing air pollution then further measures may be required to displace coal-fired power. Similarly, if intermittent renewables underperform at crucial times or put too much pressure on grid stability, there is an opportunity for nuclear power to play a greater role in the clean energy mix.

Potential for hydrogen production

Numerous governments have adopted strategies for developing hydrogen technologies, which could displace fossil fuels, provide an energy storage mechanism and the potential for export. Other growth prospects for the hydrogen economy include the replacement of coking coal in steelmaking and other metallurgical processes, utilization of 'green' hydrogen in existing industrial applications and as a feedstock for synthetic fuels such as ammonia.

Nuclear power is well placed to produce zero-carbon hydrogen. As well as utilizing off-peak capacity to run cold electrolysis production, the combination of heat and power generated by nuclear reactors is expected to lead to the commercialization of high-temperature steam electrolysis (HTSE) processes to produce hydrogen significantly more efficiently than cold electrolysis from non-heat producing clean energy sources. Furthermore, several direct thermochemical processes using Generation IV reactor technology are being developed for producing hydrogen.

Estimates of potential growth of hydrogen production vary. The International Energy Agency's *Energy Technology Perspectives 2020* report projects global annual hydrogen production growing rapidly to around 445 Mt for energy use plus 75 Mt for process use by 2070[7] (compared with today's total annual consumption of around 70 Mt).

Nuclear energy clearly has a major role to play in the future hydrogen economy. The degree to which this leads to increased demand for nuclear power by 2040 and beyond will depend on the rate of growth of the hydrogen economy, the extent to which the anticipated relative advantages of HTSE and thermochemical processes are realized and the adoption of a level playing field in the treatment of hydrogen generated from nuclear power and intermittent renewable energy sources.

Security of supply

Nuclear power has a number of features that can be expected to continue to appeal to policymakers in many countries. The most important of these contributes to a country's security of energy supply. Nuclear power plants consume relatively little fuel compared with fossil-fired plants, which means that, if it is thought necessary, several years' supply can easily be stockpiled. Uranium is in any case available from a diverse range of countries spread around the world, making a major disruption from primary suppliers unlikely. Countries with nuclear programmes are thus less exposed to large swings in fossil fuel prices and to supply disruptions (such as occurred with oil in the 1970s), as well as to short-term currency fluctuations.

There are also heightened fears today about dependence on imported energy, given the concentration of oil and gas reserves in a limited number of countries. Indeed, this was the main motivation for countries such as France and Japan taking the decision to pursue substantial nuclear programmes in the 1970s, after the first oil crisis. Today this argument has returned, particularly in Europe with increasing dependence on gas imports, but also in East Asia, where there is an increasing share of the international trade in fossil fuels.

Geopolitical tensions have increased over the last years, perhaps to levels not seen since the collapse of the Soviet Union, as a result of trade disputes, tensions on the Korean peninsula, instability in the Middle East, and the return of Cold War rhetoric between the USA and Russia. These tensions are likely to lead to an increased focus on energy security, which will benefit nuclear power growth.

Grid resilience

The large-scale expansion of intermittent renewables has placed increasing pressure on grid infrastructure and reduced the grid resilience to non-conducive weather conditions and climatic aberrations such as the hurricanes, heatwaves and extreme cold events experienced in the USA in recent years. For example, the weakening of the polar vortex in 2014 and 2019 resulted in extreme low temperatures in the USA, causing widespread power disruption. In many regions nuclear power was

[7] Projections from the Sustainable Development Scenario presented in Energy Technology Perspectives 2020, International Energy Agency (September 2020)

the only power source, with renewables unable to function and coal and gas power supply chains left disabled by extreme conditions. Nuclear power's role in offering grid stability in all climatic conditions has led to increased recognition of the economic and social value of grid resilience, particularly in developed industrialized nations, evident by the US Federal Energy Regulatory Commission launching proceedings in 2018 to examine the resilience issue. This is likely to continue as weather volatility due to climate change increases and the penetration of intermittent renewables increases.

As the trend towards deep electrification increases, grid reliability will become even more crucial, given that most transport, residential and industrial processes will rely on grid power to operate. This concentration of dependency on the electrical grid – and away from relatively reliable hydrocarbon supply chains – will increase the value of resilient power sources, particularly for grids that have accepted a high degree of intermittent renewable energy penetration.

Improved economics

The cost of nuclear generation mostly depends on the initial capital cost of reactor construction and the financing of it, with nuclear fuel representing only a minor proportion of the total cost of power production. Accordingly, changes in the capital cost of new nuclear have substantial impacts on the cost-competitiveness of nuclear power compared with other energy sources.

Over the last decade, the Western nuclear sector has endured several examples of large cost overruns in the construction of first-of-a-kind reactors. In addition to the financial burden this places on vendors and financiers, these outlying capital costs have increased the average capital costs attributed to the nuclear sector and the perceived cost of nuclear power. Furthermore, the detractors of nuclear power frequently use these figures selectively in order to portray nuclear power as being more expensive than alternative energy sources.

The Western nuclear power sector is currently in a phase of lowering capital costs and, therefore, improving the economics of nuclear generation. This is partly a result of moving through the inevitable first-of-a-kind construction phase associated with new reactor models.

More significant, however, are the cost benefits associated with reactors being produced in significant volumes around the world. For instance, Chinese and Korean reactor builds have demonstrated a substantial improvement in construction time and up-front capital cost, which is likely to continue with the Hualong Two[8] design targeting capital costs of less than $2,000 per installed kilowatt. In recognition of the need to improve both the perception and reality of nuclear construction costs, the industry is focused on a range of initiatives to reduce construction times, costs and risk.

Continued progress in reducing the capital cost of new nuclear build will have a substantial impact on the relative economics of nuclear power and, therefore, its growth. The increasing understanding on total system costs of clean energy alternatives is also expected to enable fair comparisons of the cost of nuclear energy with intermittent renewable energy.

New financing models and expansionary monetary policies

Large-scale reactors require large capital spending over a multi-year period of construction before generating any revenue. In order to lower the cost of capital, and thereby reduce generating costs, the industry and developers have to reduce construction time and cost, as well as arrange with

[8] Hualong Two is an advanced model of the Chinese third-generation Hualong One nuclear reactor. CNNC is expected to launch its construction in 2024

governments new financing schemes where risks are appropriately allocated to the stakeholders best placed to mitigate them. Given that nuclear power is such a key contributor to national economies, governments should play a significant role in their development, similar to the measures implemented for renewables development.

A shift to expansionary monetary policies as a means to stimulate economic growth after the Covid-19 pandemic will also present opportunities for the efficient financing of nuclear energy. In many economies risk-free interest rates are zero and governments are engaged in expansionary spending on large-scale infrastructure projects. Sovereign finance costs improve the relative attractiveness of nuclear energy and, when system costs are taken into account, position nuclear energy as the cheapest form of electricity in many markets.

Nuclear safety record

Public acceptance of nuclear reactors typically requires host communities to consider nuclear power on its merits through the evaluation of facts. One of the most relevant facts supporting nuclear power is its superior safety record – a fact that is not widely understood by the public. Independent analysis of the fatality rate of the full lifecycle of various energy sources (including renewables) has confirmed that nuclear power is the safest form of energy ever used when measured as deaths per TWh generated. Over its lifetime, nuclear power has had a fatality rate of approximately 22 deaths[9] for every 1,000 TWh of power generation – this increases to about 45 deaths per 1,000 TWh after allowing for an estimated 2,200 potential deaths[10] associated with acute exposure (>100 mSv) suffered by emergency workers at Chernobyl.

Furthermore, as more evidence becomes available on the effects of radiation exposure, bodies such as the United Nations Scientific Committee on the Effects of Atomic Radiation have concluded that low-to-moderate exposure to ionizing radiation present significantly less danger to health than is commonly perceived. As these statistics become better understood, public acceptance of nuclear power can be expected to increase.

Used fuel solutions

Another potential barrier to public acceptance of nuclear power is concern over the permanent storage of waste products. The industry continues to make progress with the development of long-term storage facilities in Finland, France and other countries, together with ongoing development of fast neutron reactors and reprocessing technologies.

Generation IV reactors

A number of innovative reactors are under development, including SMRs, floating reactors and fast neutron reactors. These reactors have not been specifically considered in this report, as it is not yet clear how quickly progress will be made on prototype development, regulatory approvals, demonstration-scale installations, commercialization and deployment of the various technologies. However, as these reactors have distinct advantages and applications, they have the potential to expand nuclear power beyond large-scale Generation III/III+ reactors. Whilst some designs have passed through the regulatory and demonstration stages, the total impact on nuclear power growth will depend on the timing of their development.

[9] Anil Markandya and Paul Wilkinson, Electricity generation and health, *The Lancet*, 370 (9591), p.979-990, Table 2 (September 2007)

[10] Sources and Effects of Ionizing Radiation: United Nations Scientific Committee on the Effects of Atomic Radiation 2008 Report, Volume II, Annex D (Health effects due to radiation from the Chernobyl accident), Table D24

2 The Nuclear Fuel Report methodology

This edition of *The Nuclear Fuel Report* follows previous practice by making extensive use of information from the World Nuclear Association's members who represent all aspects of the nuclear fuel cycle on a worldwide basis. Some of these contributions have been made via working groups consisting of member representatives. The cut-off date for information input was 30 June 2021.

Questionnaires to both World Nuclear Association member and non-member organizations active in the fuel cycle were used to help produce the projections for nuclear capacity and uranium production included in this report. In addition, in the very limited circumstances where potentially commercially-sensitive information on inventories was requested, the confidentiality of this data was secured by having answers compiled by a firm of accountants, with only regionally-aggregated data being provided to the World Nuclear Association. The information provided in response to the questionnaires was supplemented by judgements applied by the Association and its working group members, based on publicly-available material and other public information deemed to be accurate. Sources of information include regular reports produced by industry participants, conference papers, and the publications of public bodies such as the Energy Information Administration (EIA) in the USA and the Euratom Supply Agency (ESA) in the EU.

The projections for fuel requirements were generated by a proprietary model developed at World Nuclear Association over many years, incorporating the key operating characteristics of reactors throughout the world.

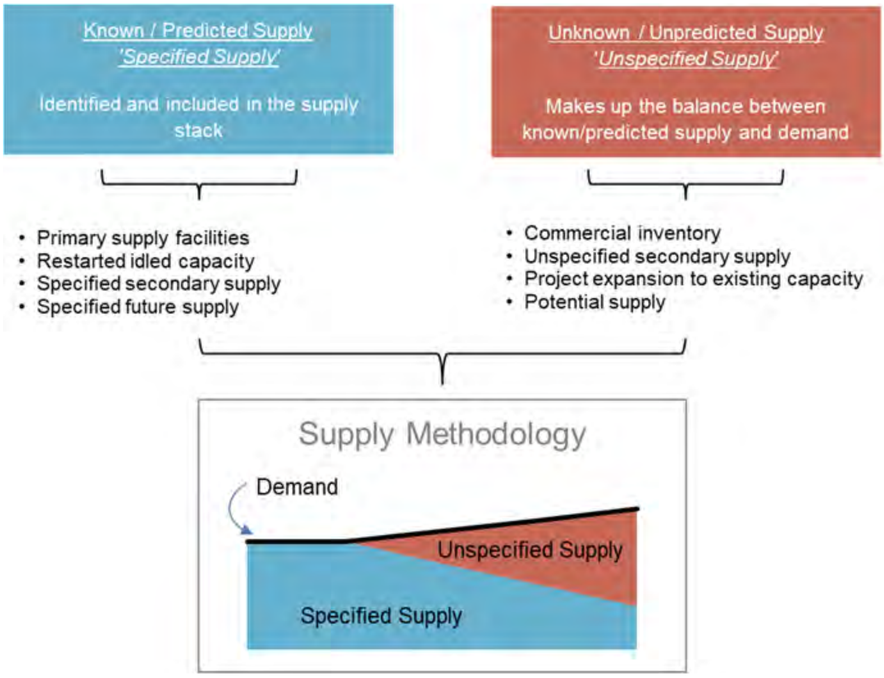
2.1 Supply methodology

Both primary and secondary supply sources are classified according to two main groups:

- Specified Supply: supply that is either known or has a sufficient degree of certainty so that its volume and timing can be predicted.
- Unspecified Supply: supply that is either unknown or lacks a sufficient degree of certainty so that its volume and timing cannot be predicted.

This classification is applied to each category of supply within the report. 'Specified Supply' comprises those supply sources that are identified in the supply stack for each component and, in general, include primary supply, secondary supply, and specified future supply. 'Unspecified Supply' comprises those supply sources that generally consist of unspecified secondary supply sources and that part of the future supply that nowadays cannot be predicted with any degree of certainty due to technical and economic factors, as well as policy constraints.

Figure 2: Methodology of Specified and Unspecified Supply



2.2 Projection methodology and assumption

Individual country nuclear capacity scenarios are formulated by a World Nuclear Association working group, taking into account responses to a questionnaire and publicly-available information. New reactor additions for each country and area are considered on the basis of existing plans and policies within three categories: those under construction; those in the planning and licensing process; and those which are proposed but on which no firm commitments have been made. Where official nuclear targets or objectives have been published, they are used to inform the Reference Scenario projections, with any necessary adjustments to timings or levels of the targets. In countries where the official objective is to limit or reduce the nuclear contribution, this is factored into the projections. The Upper Scenario projections consider where realistic opportunities exist for improved plans for existing and new reactors. In the Lower Scenario, plans for new reactors may be scaled down or cancelled. None of the three scenarios involve a normative assessment of what nuclear capacity would be needed to achieve net-zero targets.

For existing reactors, the projection includes an estimate of the operating lifetimes, which is based on consideration of technical, licensing and policy issues within the framework of each scenario.

3 Scenarios for nuclear generating capacity

To reflect the range of uncertainties which surround any projection, three scenarios are considered; these are referred to as the Lower, Reference and Upper Scenarios. No attempt is made to attach probabilities to the scenarios. In principle, the starting point is that all three must be entirely plausible as representations of future events and worthy of the reader's consideration. If a scenario is judged to be very unlikely it would not be included in the report. Although there is a natural tendency to consider the Reference Scenario as the most probable, the Upper and Lower cases should not be ignored, as they are considered to be fully plausible, depending on underlying political and economic trends.

As of mid-2021, world operable nuclear capacity was around 394 GWe (from 442 units), and about 60 GWe (57 units) was under construction. In the Reference Scenario, nuclear capacity is expected to rise to 439 GWe by 2030 and to 615 GWe by 2040. In the Upper Scenario, the equivalent figures are 521 GWe in 2030 and 839 GWe in 2040. The Lower Scenario shows a slight increase that becomes more pronounced after 2030 due to the commissioning of new reactors in China, India and several newcomer countries, compensating for reactor closures in the USA and Western Europe (see Figure 3).

Figure 3: Nuclear generating capacity scenarios to 2040, GWe

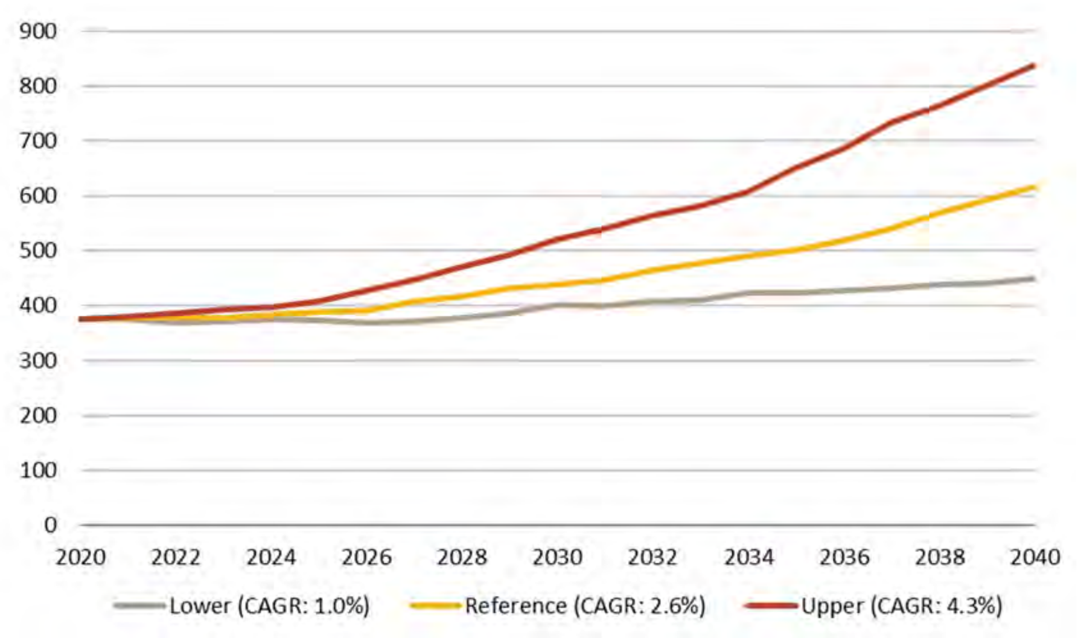


Figure 4 compares the new scenarios presented in this edition of *The Nuclear Fuel Report* with those of the 2019 edition. All three scenarios demonstrate some changes compared to the previous edition of the report. The positive difference in the Lower Scenario is predominantly caused by changes assumed in two countries – Russia and Ukraine:

- In Ukraine, the state enterprise Energoatom has launched an extensive modernization programme for all 15 operable reactors to be completed by the mid-2020s, targeting both lifetime extensions and power uprates. In the Lower Scenario all 15 reactors are expected to stay in service longer: 60 years for VVER-1000 and 50 years for VVER-440.
- In Russia, the Lower Scenario was adjusted in accordance with the "Scheme and programme for the development of the Unified Energy System (UES) of Russia for 2020-2026"[11]. This resulted in the operating lifetimes of more than a dozen reactors being increased and are now the same in the Reference Scenario.

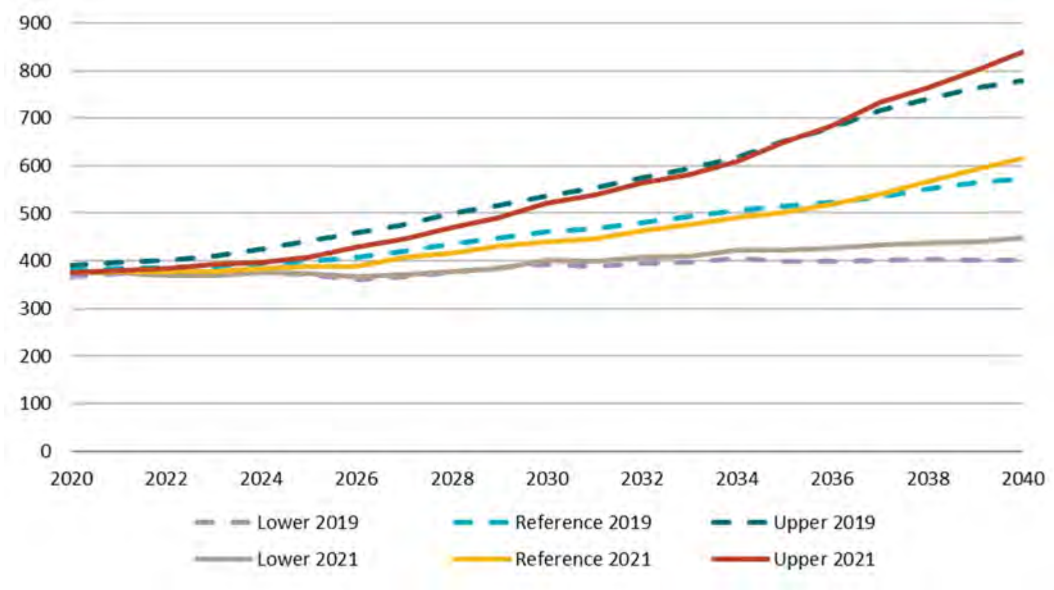
This positive impact has overcome quite a significate negative effect caused by projected earlier shutdowns of eight US units, which have been brought forward compared to the 2019 edition of *The Nuclear Fuel Report* (Byron 1&2, Dresden 2&3, Braidwood 1&2 and LaSalle 1&2)[12]. These eight

[11] Scheme and programme for the development of the Unified Energy System (UES) of Russia for 2020–2026, Ministry of Energy (30 June 2020)

[12] Exelon announces early shutdown of four Illinois reactors, World Nuclear News (27 August 2020)

reactors were not expected to be closed so early in the 2019 edition, but were not included in the 22 units[13] that were assumed to have operational lifetimes extended up to 80 years.

Figure 4: Comparison of generating capacity scenarios with those of the 2019 edition, GWe



The negative difference in the first decade of the Upper Scenario is largely caused by:

- Near-term delays in commissioning of prospective reactors and reactors under construction in China.
- Further delays in the restart of the Japanese reactors suspended in 2011 due to more time being needed to implement additional backup safety measures[14] in compliance with new regulatory requirements set by Nuclear Regulatory Authority (NRA).
- Delays to the startup years of the Russian reactors under construction, Kursk II-1&2, having been postponed by 2 and 3 years respectively; and deferred plans of construction of the majority of the Russian prospective reactors according to the "Scheme and programme for the development of the Unified Energy System (UES) of Russia for 2020-2026" .

However, in the last half of the second decade these negative trends are substantially exceeded by: increased projections in China; more ambitious plans for the development of nuclear power in Netherlands, Uzbekistan, South Africa, Ukraine; and further newcomer African countries expected to start nuclear construction projects before the end of the next decade, namely Ghana, Nigeria and Uganda, in addition to those already included in the Reference and Lower Scenarios.

[13] The Nuclear Fuel Report: Global Scenarios for Demand and Supply Availability 2019-2040, World Nuclear Association, p.57.
[14] Backup control centres are a requirement of new regulations introduced in July 2013 in response to the March 2011 accident at the Fukushima Daiichi plant. The NRA ruled in November 2015 that such facilities must be completed within five years after regulatory approval of each plant's engineering and construction work programme. That programme is the second step in the NRA's three-step process of assessing reactor safety prior to restart. The third and final stage includes pre-operational inspections to ensure the unit meets the new safety requirements.

4 Secondary supply

Secondary supply may be defined as all material other than primary production sourced to satisfy reactor requirements. This chapter gives an in-depth account of the broad spectrum of secondary supply sources including, but not limited to, commercial and governmental inventories, stockpile drawdown, fuel assemblies no longer useable in reactors (for example in Japan, Taiwan, Germany, the USA), and use of recycled materials of various types. In the widest sense, secondary supply may be regarded as previous uranium production returned to the commercial nuclear fuel market.

For the purposes of this report, all secondary supply sources are divided into two major groups:

The first group, ‘specified’ secondary supply, comprises supply sources that have been specifically identified to enter the market in a form, quantity, and timeframe that can be estimated or predicted to a high degree of accuracy. For these sources, three scenarios of future secondary supply are provided for uranium, conversion and enrichment.

The second group, ‘unspecified’ secondary supply, contains the sources that do not offer an adequate level of predictability in terms of expected timing of market access or availability for consumption for several reasons, including limitations in information sources, arbitrary and proprietary policies of individual entities, technical challenges, geopolitics, and economics. While the market entry of unspecified secondary supply is difficult to predict, its degree of mobility is dependent on the source of this material. Table 2 shows the allocation of secondary supply sources among both groups.

Table 2: Specified and unspecified sources of secondary supply by category

Category of secondary supply	Specified sources	Unspecified sources
Major commercial inventories (U_3O_8, UF_6, EUP)		x
Unusable fresh fuel assemblies (EUP)		x
Other government stocks		x
Spent fuel and products derived from it		x
US DOE material inflows		
- High assay depleted uranium (DUF_6)		x
- High assay low-enriched uranium (HALEU)		x
- Environmental management (EM) transfers of natural UF_6	x	
- Energy Northwest (ENW) depleted UF_6 (DUF_6)	x	
Plutonium recycled as MOX	x	
RepU recycled as ERU	x	
Underfeeding	x	
Tails re-enrichment	x	

These categories of secondary supply originate from various stages of the nuclear fuel cycle. This categorization of secondary sources of supply by originating stage is given in Table 3.

Table 3: Categorization of various secondary supply sources by originating stage

Originating stage	Economic role	Owners	Type of initial secondary source	Marketable forms of secondary material
Pre-irradiation in nuclear reactors (front end)	Targeted (desired) products	Commercial entities (producers, traders, utilities)	Commercial inventories	• Natural U_3O_8, UF_6; • LEU as UF_6, UO_2, fabricated fuel and its feed/SWU components
		Governments and their contractors	Military-related materials and depleted uranium	• LEU from surplus weapons-grade HEU
		International fuel banks	Comparable to commercial inventories in terms of specification	• LEU as UF_6 stocks
	By-products (including underfeeding)	Commercial entities (enrichers) or governments and their contractors	Legacy tails and underfeeding	• Natural uranium equivalent as UF_6 from tails
		Commercial entities (enrichers)		• LEU from tails or underfeeding as UF_6
Post-irradiation in nuclear reactors (back end)	Reusable products	Commercial entities or governments and their contractors	Recycled material	• Reprocessed uranium • Enriched reprocessed uranium (ERU) mostly as UO_2 • MOX fuel containing plutonium from spent fuel or defence • Unprocessed spent fuel (potential source)
	By-products of recycled material	Commercial entities (enrichers)		• LEU from slightly irradiated uranium (DSIU) • Depleted RepU as UF_6 or UO_2

Uranium that has been mined and held as inventory for a period of time before it is further processed is the simplest form of secondary supply. This inventory normally accounts for only a relatively small portion of total supply. However, in the current market situation, given historic low U_3O_8 prices, this source has become more significant not only for primary producers and utilities, but also for numerous intermediary parties (*e.g.* traders, investment funds, banks).

The majority of secondary supply is derived from uranium that has undergone transformation in reactors, enrichment plants and reprocessing facilities. The second largest potential secondary resource by mass is the world's inventory of not yet treated used nuclear fuel, held largely at reactor sites. It is a potential resource, as, up to now, used fuel in most countries remains destined for interim storage rather than for further use in the nuclear fuel cycle in the medium-term.

A substantial quantity of around 130,000 tonnes of used nuclear fuel has already been reprocessed in the civil nuclear sector, leading to separated plutonium and uranium. These are gradually being used as mixed oxide (MOX) fuel and enriched reprocessed uranium (ERU) fuel. Natural uranium requirements so far displaced by these sources are relatively modest. The future developments in reprocessed uranium (in ERU fuel) and plutonium (in MOX fuel) utilization depend particularly on back-end and environmental policy, on the timely availability of the supply chain to process these materials, and only marginally on natural uranium market price levels. MOX fuel has been used by Japanese utilities as well as by some European utilities. It should be noted, however, that the quantity of secondary supply from reprocessed uranium (RepU) as ERU fuel and plutonium as MOX fuel is limited.

Depleted uranium (known also as 'tails') is the largest form of potential secondary supply by mass. Tails offer a number of opportunities for future use. One major use is re-enrichment although not all tails re-enrichment is economically viable.

The potential for under- or overfeeding enrichment plants is also an important source of secondary supply. In certain circumstances, particularly if enrichment capacity is underemployed, it can be financially and operationally worthwhile for an enrichment facility to have an operational tails assay below the level that was contracted with the customer, making use of more enrichment capacity. This so-called underfeeding of the facility 'creates' surplus uranium which can be sold. In this report, underfeeding is regarded as an additional source of secondary supply as it has become increasingly prevalent in the current market.

4.1 Concept of market mobility

Regarding the availability for consumption, it is important to differentiate between primary supply and secondary supply. Primary supply refers to fresh fuel in the form of uranium, conversion, enrichment or fabricated fuel that is transferred from a producer to a consumer, either directly or through various intermediaries. In contrast, secondary sources, with the exception of commercial inventories, often require additional operations or processing (*e.g.* reprocessing or recycling) applied to the material (many of them highly technical in nature) before it can be returned to the nuclear fuel cycle at various stages. Further processing (at conversion, enrichment or fuel fabrication facilities) also extends the time needed for certain secondary sources to re-enter the market and become available to the consumer.

The *Nuclear Fuel Report* examines the *degree of mobility* of unspecified secondary supply sources. This term can be interchanged with, for example, 'availability for consumption', or 'market predictability'. The definition of 'degree of mobility' is the availability of the supply source to access the market and contribute to satisfying reactor requirements. A source's mobility does not necessarily refer to its movement (for example, from a non-end user to an end user); rather, any ability of the source to offset the need for newly-produced uranium, conversion, or enrichment concerns its degree of mobility.

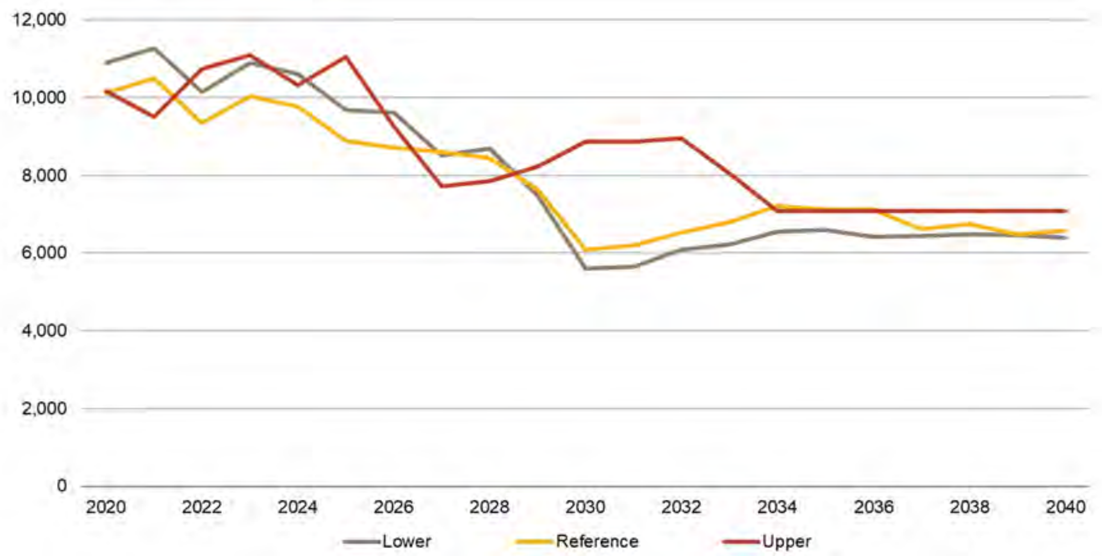
In other words, a supply source with the highest degree of mobility is the one that is available for immediate consumption – the most relevant here would be fabricated, utility-owned fuel inventory that can be consumed in a reactor almost immediately. Alternatively, an example of a source with a very low degree of mobility would be spent fuel that requires reprocessing but resides in a country that does not have a reprocessing programme.

Thus, unspecified secondary supply sources can be divided into two subcategories:

- A high degree of mobility but insufficient predictability in terms of quantity and timing of consumption (*e.g.* commercial inventories and some government stocks).
- A notable future potential for market access but low degree of mobility due to any number of commercial, policy, technical, and/or capacity-related limitations (*e.g.* spent fuel or products derived from it).

Three scenarios of future secondary supply for uranium are compared in Figure 5. As can be seen in all scenarios, this share steadily declines until 2040. In the Reference Scenario, secondary supply provides 17% in 2021 declining to 13% in 2025, then declining to about 8% by 2035 and ending up at 6% in 2040. As for the Lower and Upper Scenarios, there is not much difference compared to the Reference Scenario.

Figure 5: Secondary supply scenarios for uranium, *tU$_{eq}$*



In the medium-term, secondary supply declines from the current level of approximately 11,000 tU/yr in the Lower Scenario and 10,500 tU/yr in the Reference Scenario to 5,600 tU/yr and 6,000 tU/yr respectively by 2030, remaining in the range of 6,000 to 7,000 tU/yr until the end of the next decade. The Upper Scenario shows a similar development, with slightly higher level at the end of this decade.

5 Uranium supply and demand

5.1 Introduction to the uranium market

The uranium market is primarily composed of transactions between:

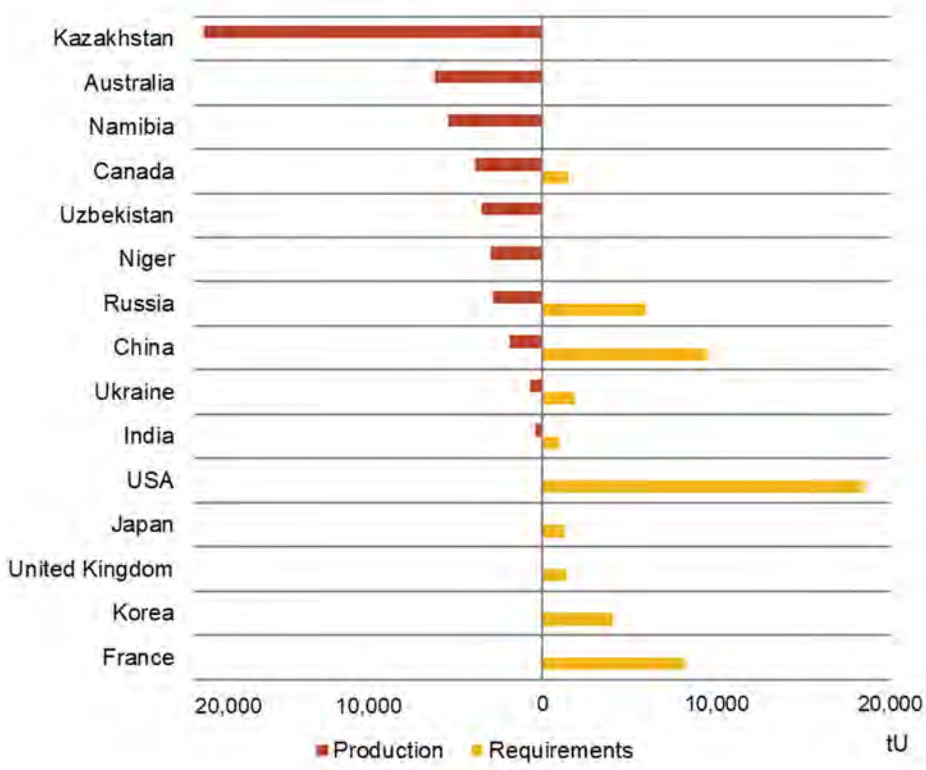
- Producers or suppliers (uranium miners, convertors, enrichers or fuel fabricators).
- Public and private electrical nuclear utilities or fuel consumers.
- Various other uranium market participants that buy and sell uranium (agents, traders, investors, intermediaries).

These organizations carry out a great number of daily transactions, enter into short-term (spot) or long-term contracts to buy or sell uranium concentrate. However, the main aim of this report is to consider reactor uranium requirements, which are driven by end-user utilities (as the main buyers) and comprise the vast majority of primary uranium demand, along with primary uranium supply, *i.e.* the uranium produced by miners, which might be displaced by other forms of uranium, such as uranium hexafluoride (UF_6), enriched uranium product (EUP) or secondary sources.

Figure 6 shows how uranium production and reactor requirements are distributed around the globe, listing the major uranium producing and consuming countries.

Figure 6: Uranium production and reactor requirements for major producing and consuming countries in 2020, tU

(Source: OECD-NEA, IAEA, World Nuclear Association)



Utilities have a relatively stable demand for uranium based upon the amount needed to manufacture the fuel for operating their reactors. They typically purchase their requirements a number of years in advance, due to the long time taken to process and convert natural uranium into fuel assemblies, as well as to hold strategic inventory based on their perception of future supply risk. Long-term contract arrangements suit utilities because they know their forward requirements many years in advance. The stability and certainty associated with long-term contracting arrangements also suits the uranium miners.

World reactor requirements for uranium in 2021 are estimated at about 62,500 tU. In the Reference Scenario, these are expected to rise to 79,400 tU in 2030 and 112,300 tU in 2040. In the Upper Scenario, uranium requirements are expected to be about 99,000 tU in 2030, and 156,500 tU in 2040. In the Lower Scenario, the requirements are expected to rise to nearly 70,000 tU in 2030 and 79,400 tU in 2040. In all three scenarios world reactor requirements for uranium in 2040 are approximately 12% higher compared with the 2019 edition.

Uranium resources are quite widely distributed around the world and Table 4 shows the distribution of resources by country. Three countries traditionally lead this list: Australia hosts the largest volume of resources (25% of the total), followed by Kazakhstan (12%) and Canada (11%).

Table 4: Uranium resources by country in 2019 versus 2017, ranked by 2019 total[15], thousand tU

(Source: OECD-NEA & IAEA)

	2017			2019		
Country	**Reasonably assured resources**	**Inferred resources**	**Total**	**Reasonably assured resources**	**Inferred resources**	**Total**
Australia	1,401	654	2,055	1,285	765	2,049
Kazakhstan	435	470	905	465	504	969
Canada	593	254	846	652	221	873
Russia	260	397	657	257	405	662
Namibia	369	173	541	321	184	504
South Africa	260	190	449	258	190	448
Niger	336	89	426	316	124	439
Brazil	156	121	277	156	121	277
China	137	154	290	123	147	270
India	149	8	157	188	8	196
Ukraine	138	81	219	122	65	187
Uzbekistan	58	82	139	51	82	132
United States	101	NA	101	102	NA	102
Others	425	502	926	430	532	962
Total	**4,815**	**3,173**	**7,988**	**4,724**	**3,346**	**8,070**

5.2 Recent uranium production

After peaking in 2016, uranium production then decreased as a result of deteriorating market conditions. In addition to that, in 2020 the market situation was compounded by the Covid-19 pandemic. This reduction in production primarily impacted Canada and Kazakhstan. Notably, the four largest uranium producers have had reduced production output in 2016-2020. The shutdowns or temporary suspension of production at existing production centres, as well as reduced production levels, have resulted in a sharp decrease of global capacity utilization factor. In aggregate, uranium production showed a decreasing trend over the 2016-2020 five-year period. The results of these production changes can be seen in Table 5.

In 2020, all producers were faced with restrictions and/or the need to implement protocols in order to protect the workers and to effectively manage the risk of Covid-19 outbreaks and the risk these posed to onsite staff and to local communities. Temporary suspension of production occurred in mines in Canada, Kazakhstan, Namibia, South Africa and the USA. This resulted in reduced staff levels onsite due to social distancing measures, which is expected to further impact production in 2021.

[15] The resources in this table are recoverable resources in the <$260/kgU category. Recoverable resources are uranium recoverable from mineable ore, *i.e.* taking into account mining and milling losses, as opposed to quantities contained in mineable ore.

Table 5: World uranium production, nameplate capacity and capacity utilization, 2016-2020, ranked by 2020 production, tU

(Sources: Company reports, presentations and press releases, OECD-NEA/IAEA, World Nuclear Association estimates)

	Production					Nameplate capacity					Capacity utilization				
	2016	2017	2018	2019	2020	2016	2017	2018	2019	2020	2016	2017	2018	2019	2020
Kazakhstan	24,689	23,321	21,705	22,808	19,477	25,714	29,764	29,764	29,764	29,063	96%	78%	73%	77%	67%
Australia	6,315	5,882	6,517	6,613	6,203	7,497	10,655	10,655	6,807	6,807	84%	55%	61%	97%	91%
Namibia	3,654	4,224	5,524	5,476	5,413	5,654	11,232	9,232	9,328	9,328	65%	38%	60%	59%	58%
Canada*	14,039	13,116	7,001	6,938	3,885	16,282	16,538	6,922	6,924	6,924	86%	79%	100%	100%	56%
Uzbekistan**	3,325	3,400	3,450	3,500	3,500	3,500	3,500	3,500	3,500	3,500	95%	97%	99%	100%	100%
Niger	3,479	3,448	2,911	2,983	2,991	3,600	3,600	3,600	3,400	3,400	97%	96%	81%	88%	88%
Russia	3,005	2,917	2,904	2,911	2,846	4,885	4,600	4,600	4,900	4,900	62%	63%	63%	59%	58%
China***	1,616	1,692	1,885	1,885	1,885	1,808	1,808	1,923	1,923	1,923	89%	94%	98%	98%	98%
Ukraine	808	707	790	800	744	1,650	1,650	1,650	1,650	1,650	49%	43%	48%	48%	45%
India***	385	423	423	308	400	610	610	610	610	610	63%	69%	69%	50%	66%
South Africa	490	308	346	346	250	1,269	769	769	769	769	39%	40%	45%	45%	33%
USA	1,125	960	582	58	6	2,780	3,596	1,673	1,404	385	40%	27%	35%	4%	2%
Others	277	116	116	116	131	812	116	116	116	336	34%	100%	100%	100%	39%
Total	**63,207**	**60,514**	**54,154**	**54,742**	**47,731**	**76,061**	**88,438**	**75,014**	**71,095**	**69,594**	**83%**	**68%**	**72%**	**77%**	**69%**

** McArthur River produced 77 tU in 2018, but its capacity is not included in Canada's nameplate capacity in 2018. Other idled mines are treated likewise.*
*** Estimated numbers for Uzbekistan uranium production in 2020.*
**** Estimated uranium production for China and India.*

To date, uranium idled capacity has reached more than 20,000 tU/yr (see Table 5), thus the world total available nameplate capacity for 2020 was considerably reduced. But even with the reduced nameplate capacity, the 2020 capacity utilization factor has fallen by 8% from the 2019 level. In other words, in 2020 the existing mines produced uranium at much lower levels compared to the year 2019.

Table 6: Ten largest world uranium mines, ranked by 2020 production, tU

(Sources: Company reports and press releases, World Nuclear Association, OECD-NEA/IAEA)

Mine	Country	Main owner	Type	tU	% of world
Cigar Lake	Canada	Cameco/Orano	Underground	3,885	8.1
Husab	Namibia	Swakop Uranium (CGN)	Open-pit	3,302	6.9
Olympic Dam	Australia	BHP	By-product/ underground	3,062	6.4
Inkai	Kazakhstan	Kazatoprom/Cameco	ISR	2,693	5.6
Karatau (Budenovskoye 2)	Kazakhstan	Kazatomprom/Uranium One	ISR	2,460	5.2
Rössing	Australia	CNNC	Open-pit	2,111	4.4
Arlit	Niger	Orano	Open-pit	1,879	3.9
Four Mile	Australia	Quasar	ISR	1,806	3.8
South Inkai 4	Kazakhstan	Uranium One/Kazatomprom	ISR	1,509	3.2
Kharasan 1	Kazakhstan	Kazatomprom/Uranium One	ISR	1,455	3.0
Others				23,569	49.4
Total				**47,731**	**100**

Cigar Lake, being the largest uranium mine in 2020, operated at approximately half of its capacity, while Husab is planning to expand its output year-on-year ramping up to meet Chinese domestic nuclear industry strategic aims.

Three of these top ten mines (Cigar Lake, Rössing and Arlit), representing nearly 17% of 2020 production, are expected to close by 2030 (barring additional reserves being identified), so they will need to be replaced by new mine capacity by then if further reductions to primary uranium production are to be prevented.

5.3 Expected primary uranium supply

Uranium supply assumptions are based on the premise that supply and demand will balance over time via market mechanisms. As future production remains heavily dependent on uranium demand, both the continuation of existing production and the development of new supply requires suppliers to secure customers for their production at prices that provide an incentive to produce. This report does not attempt to categorize the production incentive prices for primary uranium supply and instead groups primary supply according to the level of other uncertainty of that production being available to meet demand.

When assessing likely future uranium supply, it is important to categorize mining projects according to the extent to which they have resolved inherent mining development uncertainties. The operational or development status of a project is subject to achievement of startup dates and annual production. For example, experience shows that delays almost always occur for planned mines and not all planned mines reach their nameplate capacity, or even reach production.

Six categories of production capacity are therefore considered according to their level of uncertainty.

Existing mines refers to mines already in operation that are expected to continue at least into the near future. Future production figures for projects included in the existing mines category account for only established mining reserves (that is, mineral resources that are well characterized and included in production planning). These projects may be extended by the conversion of known resources into mining reserves as well as further exploration and delineation of resources.

Idled existing mines refers to mines that were previously in operation but are now placed into care and maintenance for economic and technical reasons and can recommence production within approximately one to two years from the time when market conditions become more favourable and the company decides to restart production. This category excludes, for example, mines that face significant unresolved technical, regulatory or permitting barriers to recommencing production. Once restarted, they would be referred to as ‘restarted idled mines’ in future supply-demand aggregated scenarios.

Mines under development refers to mining projects for which final investment decisions have been made, financing has been achieved, and mine pre-strip or construction of production or processing facilities has begun. This category excludes mines that have commenced construction activities but do not have in place the financing to get to the first stage of production or have otherwise commenced on peripheral activities without the ability to keep going to the production stage. This category can also include expansions or life extensions at existing mines.

Planned mines refers to mining projects that are highly advanced in their technical, financial and regulatory processes but for which a final investment decision has not been made. To qualify for this category the project must have completed bankable or definitive feasibility studies and all major approvals (environmental, social, regulatory, operating) have been achieved. Subject to local legislation and regulations, where the definitive feasibility study is needed, it must be sufficiently recent to be relevant to and in accord with the proposed project. This category can also include expansions or life extensions at existing mines.

Prospective mines refers to mining projects that have some prospects for becoming an economic feasible mine in the future. To qualify for this category the project must have completed some level of feasibility assessment (*e.g.* scoping study, preliminary economic assessment, preliminary feasibility study) and must be located in a jurisdiction which allows uranium mining and therefore has a process to allow development through to production. This category can also include expansions or life extensions at existing mines.

Potential supply refers to mining or exploration projects that will have the potential to provide mined supply in the future, evidenced by completed technical reports demonstrating the presence of mineral resources and economic feasibility in future. Some examples of potential supply that could deliver future mined uranium include early-stage mineral discoveries, deferred projects or temporarily closed mines that require further feasibility work, potential mine lifetime extensions from additional mineral resources at existing operations.

The distinction between existing mines, mines under development, planned mines and prospective mines is based on the assessment of the probability of production reaching the market.

Three scenarios are developed below, based on discounts to the full capacity levels and delays to the expected mine startup dates as estimated by uranium producers. The discounts applied to the capacities in the three scenarios are derived from historic variations in mine capacity utilization. The methodology used to derive primary uranium supply scenarios is based on the assumption that existing mines operate near their capacity levels, that some delays in the commissioning of planned and prospective mines can be expected, and that a portion of the mines currently being considered for development will never be developed due to surplus supply, a lack of financing, technical issues discovered in further feasibility assessments, or changes in market conditions. These assumptions are outlined in Table 7.

Table 7: Production capacity utilization and delay assumptions by scenario

	Reference		Upper		Lower	
	Delay (yr)	Expected utilization	Delay (yr)	Expected utilization	Delay (yr)	Expected utilization
Existing mines	0	90%	0	95 - 100%	0	85%
Restarted idled mines	-2	55 - 90%	-1	65 - 100%	-3	40 - 55%
Mines under development	-2	60 - 90%	-2	80 - 100%	-4	30 - 50%
Planned mines	-3	60 - 90%	-2	75 - 100%	-5	30 - 50%
Prospective mines	-4	50 - 90%	-3	70 - 100%	-7	20 - 50%

For existing mines, projections of future uranium production for approximately 90% of them is derived from either official company announcements or from the questionnaire responses received by the Association at the beginning of 2021. As a result, for the scenarios, the utilization factors are applied to the expected production levels rather than using nameplate capacities.

In addition, dynamic utilization factors are applied, which are based on the assumption that the production and likelihood of development of uranium mines will gradually increase in the long term due to the anticipated change in the supply-demand balance, as demand should keep growing and some existing mines will be exhausted. Thus, in Table 7, a range of utilization factors is given for different categories. It is assumed that the mines in the categories will be operated at the lower limit of the range until 2030, then gradually increase to the upper limit in 2030-2035, and remain at the upper limit in the years beyond 2035.

5.4 Unspecified uranium supply

The concept of 'unspecified supply' is used to characterize the material that will fill the gap between identified supply sources (both primary supply and specified secondary supplies) and requirements for the various fuel cycle components.

Unspecified supply is therefore a reflection of the future potential of the fuel market as it recognizes that there are various sources of supply that will compete for market access; however, the conditions necessary to achieve such market access differ according to each source of these future supplies.

The following supply sources are included in unspecified supply:

- Unspecified secondary supplies.
- Expansion of production capacity.
- Potential supply.

Each source, depending on its characteristics, will be available to the market either as uranium and/or conversion and/or enrichment to satisfy demand.

Unspecified secondary supply

Unspecified secondary supply is not predicted to enter the market in any defined quantity or volume, but nonetheless have varying degrees of mobility. Unspecified secondary supply comprises:

- Major commercial inventories (U_3O_8, UF_6, EUP).
- Unusable fresh fuel bundles (fabricated EUP).
- Government stocks.
- Spent fuel and products derived from it.
- US DOE material inflows: high assay depleted uranium (DUF_6); high assay low-enriched uranium (HALEU).

These unspecified secondary supplies listed above are characterized by having declining degrees of mobility, with commercial inventories being the most available and the others having higher technical thresholds and longer times to reach the market.

Expansion of production capacity

Expansion of production capacity is the expansion of existing production facilities beyond their nominal capacity and is another source of potential unspecified supply.

In some cases, the licensed capacity at existing production facilities already allows for production beyond what has historically been produced at the facility. Here, primarily the lack of economic incentive to make the necessary investment (as well as some potential development hurdles) prevents higher production rates from being achieved.

For non-uranium mining fuel cycle production facilities, this category would refer to expansions at existing facilities beyond their nominal licensed capacity (additional conversion, SWU, or fabrication capacity at established facilities). The uncertainty surrounding the quantity and timing of this category of unspecified supply is high considering the proprietary nature of these developments and the associated economic and/or technical hurdles unique to each of the production facilities.

Potential supply

The final component of unspecified supply is 'potential supply'. It consists of uncategorized supply required to meet future demand and is associated with the greatest amount of uncertainty within unspecified supply. The category includes those projects for which activities are insufficient for them to be categorized as planned or prospective but for which development work has been undertaken in the past and for which there is knowledge of the orebody and the likely costs of its exploitation.

Potential supply projects for all fuel cycle components require particular market conditions to be in place in order to support their development, not least of which is for a supply gap (or imminent supply gap) to exist.

Materialization of unspecified supply

As can be inferred in the descriptions of the unspecified supply components, there is a natural order of probability in how they will ultimately materialize as supply: unspecified secondary supplies, followed by expansions at existing production facilities, and finally, potential supply.

With the exception of price inelastic secondary supply and state-owned commercially insensitive operators, economics plays the crucial role in how the supply side will materialize in the future, especially when it comes to unspecified supply. In general, in a low-price environment for the fuel component, there is a high probability that only the most mobile unspecified secondary supplies (commercial inventories) will be the sources of unspecified supply made available to the market. In the event that those supplies are insufficient to meet demand, then the conditions must arise to support the necessary commercial investment in order to expand production capacity and/or advance 'potential supply' projects.

5.5 Uranium supply and demand

Historically, despite both supply and demand being transparent and readily visible compared with other commodities, the uranium market has not always functioned efficiently in balancing supply and demand.

New projects categorized as under development, planned and prospective are well-known for the near and medium term, but in the longer term the source of the primary production that will meet demand is less certain. Given that there are sufficient reserves and resources to cover demand (even in the Upper Scenario), supply is assumed to meet demand in the long term. Of course proper market incentives including long-term contracts, favourable economics and capital availability are all required to move these projects from resources to reserves to physical production within the timeframes necessary.

Primary supply should be able to adjust to higher demand over the medium to longer term and for secondary supply to respond in shorter timescales. Figures 7-9 illustrate how this could take place in the three scenarios.

Figure 7 shows the projected Reference Scenario reactor requirements in comparison to projected supply. Figures 8 and 9 show the projected reactor requirements and supply for the Upper and Lower Scenarios, respectively.

Figure 7: Reference Scenario for uranium supply and demand, tU

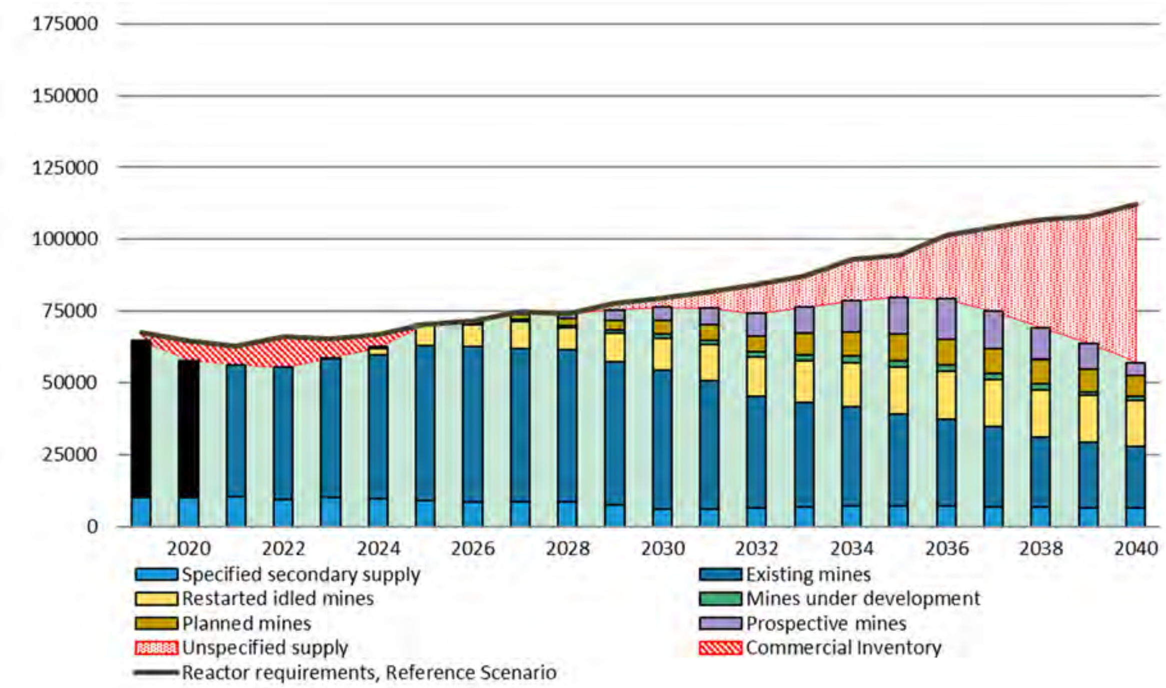


Figure 8: Upper Scenario for uranium supply and demand, tU

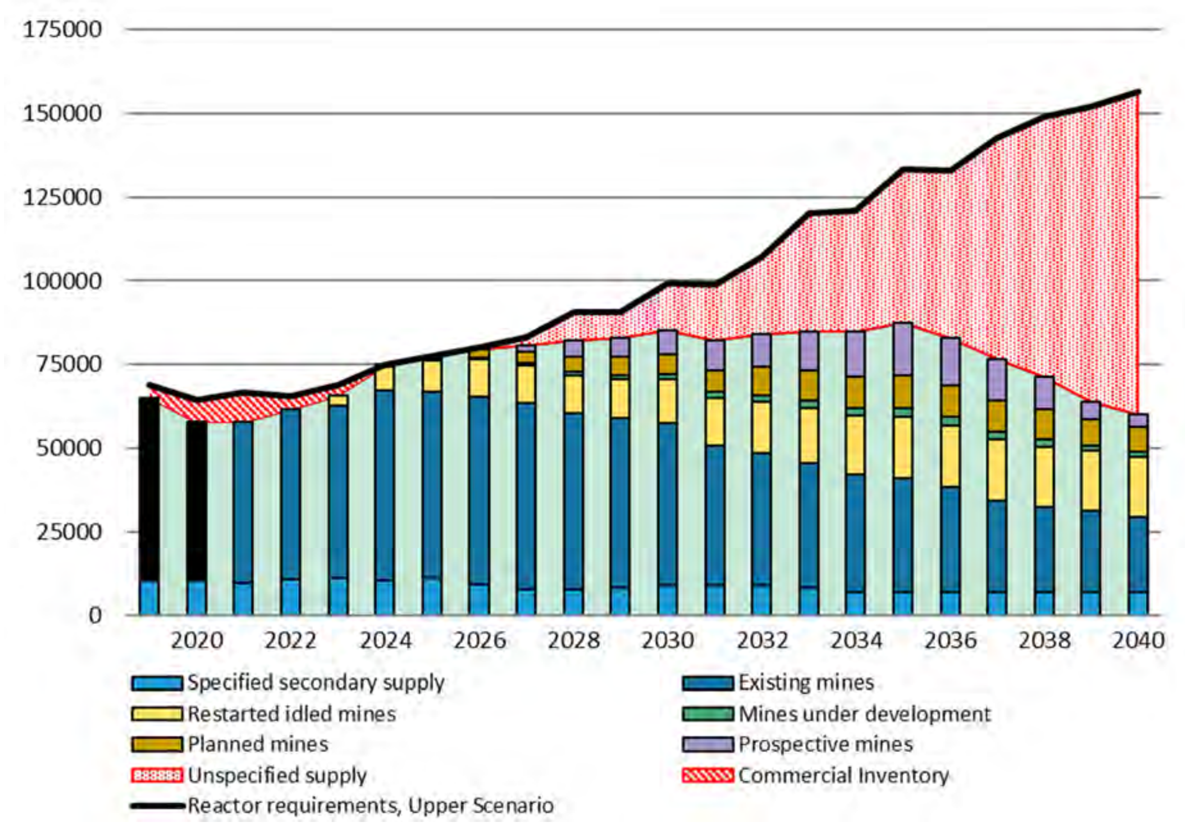
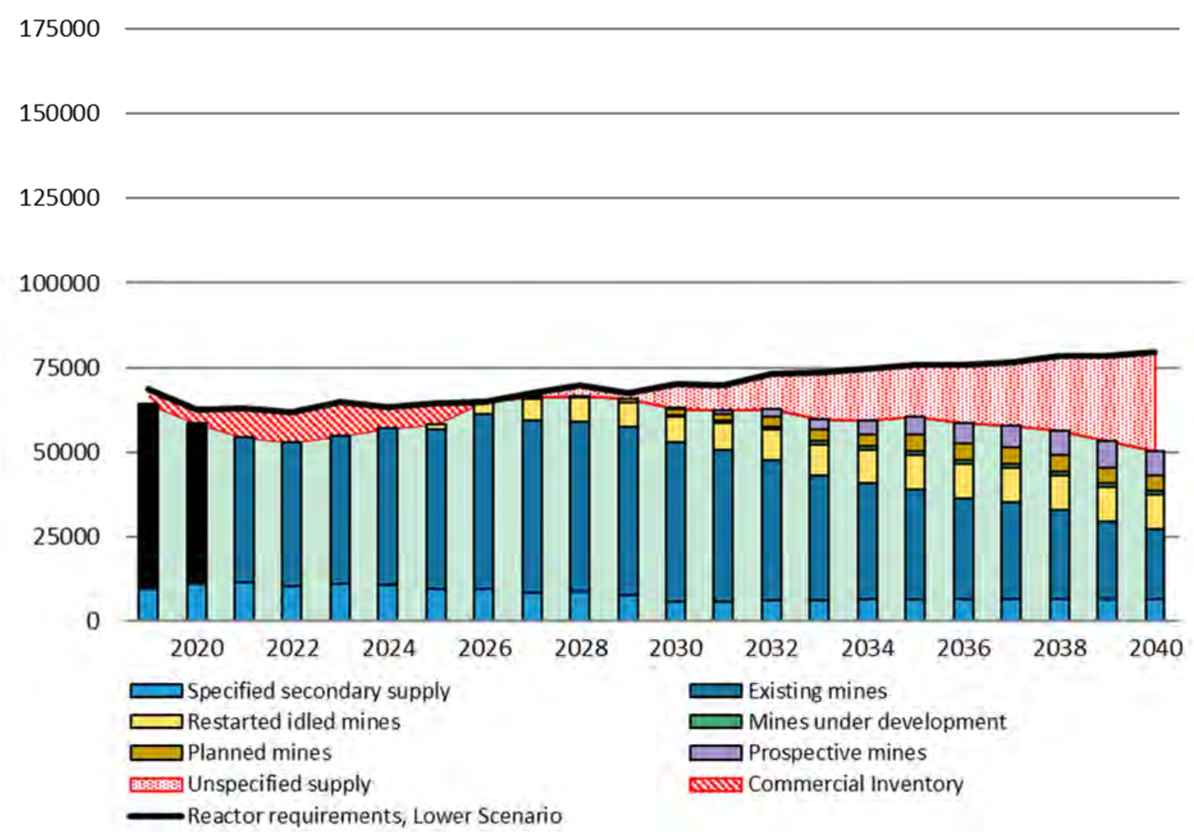


Figure 9: Lower Scenario for uranium supply and demand, tU



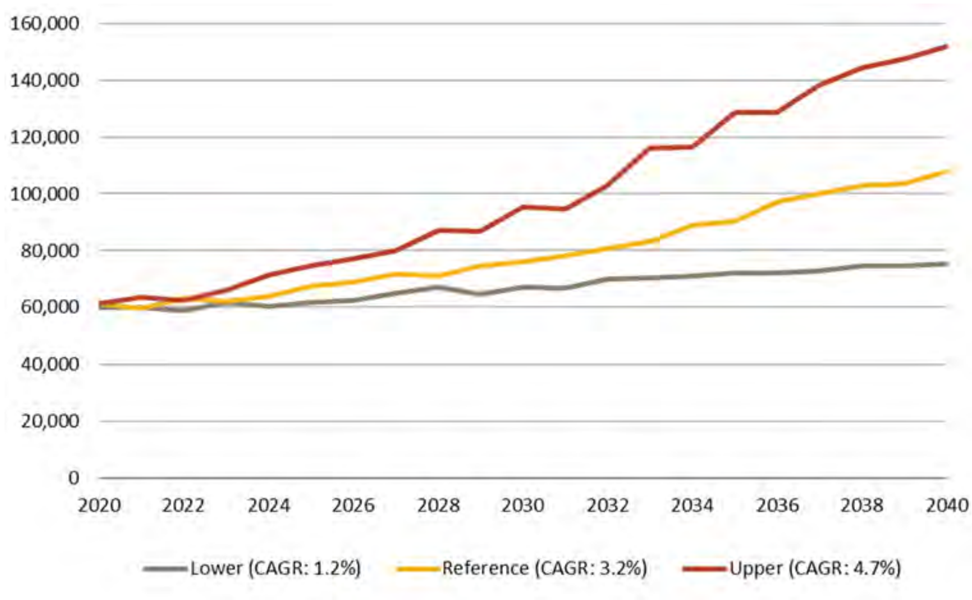
6 Conversion supply and demand

Uranium conversion is commercially important, although historically it has represented the smallest share in the overall cost of the components in the front end of the nuclear fuel cycle. The commercial purchase of conversion services is made largely by electrical utilities, and the resulting natural UF_6 is shipped to enrichment facilities for which it is essential, as uranium hexafluoride gas is the only form that can be processed at all enrichment plants currently in operation.

Today, annual primary production is far lower than annual demand. This has led to a period of rebalancing, with the market relying heavily on the drawdown of inventories to satisfy near-term demand from numerous sources, which has resulted in a significant increase in conversion market prices since the beginning of 2018.

In contrast to the conversion capacities which have been drastically reduced, overall conversion requirements show an upward trend. The World Nuclear Association's Reference Scenario shows a compound average growth rate (CAGR) of 3.2%, mainly resulting from nuclear expansion East and South Asia, driving conversion requirements to nearly 108,000 tU/yr by the end of the next decade (from around 61,500 tU in 2020). In the Upper Scenario the conversion requirements are more than doubled by the end of the forecasting period. The Lower Scenario shows a growth rate of 1.2% CAGR, slightly exceeding 75,000 tU/yr by the end of the reporting period.

Figure 10: UF_6 conversion requirement scenarios to 2040, tU



As illustrated in Table 8, the primary converters have a combined nameplate capacity of 62,000 tU/yr. Current world operating capacity (*i.e.* capacity utilization) is expected to be around 32,000 tU/yr, which is lower than in the 2019 edition of *The Nuclear Fuel Report*. Worldwide conversion production operating capacity has now been in consistent decline for more than 10 years.

Table 8: Estimated UF_6 conversion capacity and utilization for 2020, tU
(Sources: Companies reports and presentations, industry press, World Nuclear Association estimates)

Converter	Country	Location	Nameplate capacity (tU)	Capacity utilization (%)	Capacity utilization (tU)
Cameco	Canada	Port Hope	12,500	72%	9,000
CNNC *	China	Lanzhou & Hengyang	15,000	53%	8,000
ConverDyn **	USA	Metropolis	7,000	0%	0
Orano ***	France	Pierrelatte, Malvési	15,000	17%	2,600
Rosatom	Russia	Seversk	12,500	96%	12,000
Total			**62,000**	**51%**	**31,600**

** Estimated capacity according to the assumption that China will develop its conversion capacity sufficient to supply the needs of the domestic reactor fleet.*
*** In January 2021 MTW announced a restart plan targeting to resume its production in 2023.*
**** Orano's new conversion facility is still in the process of production ramp-up, which is expected to be finalized by 2023[16].*

In deriving a worldwide supply reference case for UF_6 conversion, various assumptions were agreed upon that are believed to be reasonable, though the market could be affected by many additional factors that are more difficult to model.

Model assumptions include:

- In aggregate, Western primary conversion facilities are currently operating at approximately 40% of the nameplate capacity but from 2026 onwards Western primary conversion facilities shall operate at 90% of their nominal production capacity.
- Orano, which is transitioning to the new Philippe Coste plant, will finalize production ramp-up by 2023[17].
- Russian conversion facilities will produce enough feed to meet domestic enrichment capacity requirements, net of secondary sources.
- Chinese conversion facilities will produce enough feed to meet domestic enrichment capacity requirements, net of underfeeding, from 2020 onwards.

[16] Q&A: Orano Conversion & Enrichment CEO Jacques Peythieu, World Nuclear News (31 August 2021)
[17] Orano, Annual Activity Report 2020, p.36

Figure 11 shows the projected Reference, Upper, and Lower Scenario reactor requirements in comparison to projected conversion supply.

Figure 11: Projected UF_6 conversion supply compared to requirement scenarios, tU

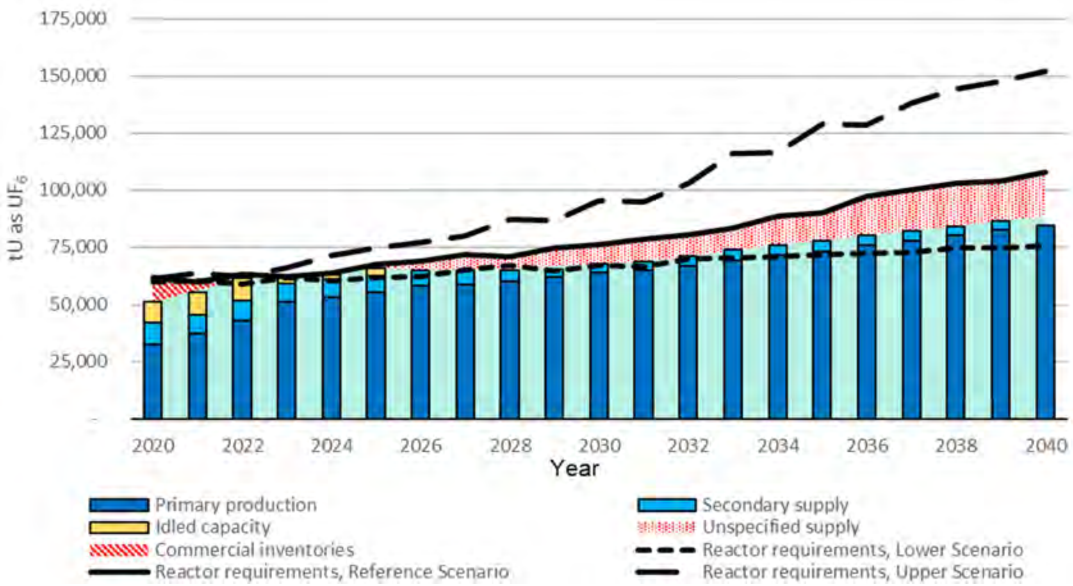


Figure 11 demonstrates that supply will need to rise in the near-term to meet existing demand, and over the mid- and long-term to meet growth in demand in both the Reference and Upper Scenarios. As already mentioned, unspecified supply is deemed to satisfy this gap between identified supply sources and the demand line[18].

In the near-term, any gaps between supply and demand are likely to be filled by the most mobile sources of unspecified supply, primarily the commercial inventories. The inventories held by the various industry participants, predominantly utilities, currently make up the balance of supply between existing primary supply and demand.

The presence of a gap in Reference supply and demand is likely to provide an incentive for the primary converters to increase capacity utilization factors.

It remains uncertain whether the combination of unspecified secondary supplies and unutilized capacity will satisfy the growing demand over the forecast horizon, and it is likely that construction of additional primary conversion capacity will eventually be necessary. This outcome would materialize either in the 2030-2040 time period under the Reference and Upper Scenarios for demand, or if an existing conversion facility fails to produce at expected levels (a risk that may increase with the age of current facilities). This would require expansion of capacity at existing facilities, the construction of new conversion facilities, or both.

7 Enrichment supply and demand

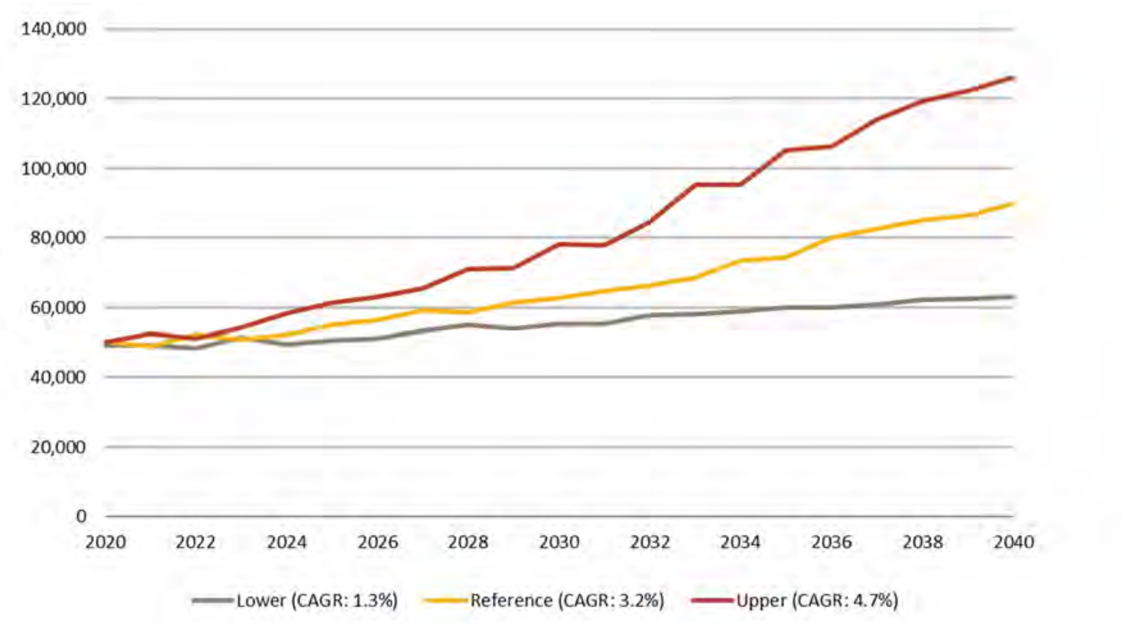
Uranium and enrichment costs constitute the two largest components in front-end nuclear fuel costs, with uranium costs representing the larger share since 2004 (predominantly due to the less energy-

[18] The concept of unspecified supply is explained in Sections 2.1 and 5.4.

intensive gas centrifuge technology replacing gaseous diffusion). Because natural uranium is needed to produce enriched uranium, there is a fundamental link between enriched uranium and natural uranium (feed) requirements, but the relationship is not simply linear. A number of factors have the potential to significantly affect the level of the enrichment (product) assay of enriched uranium needed for commercial power applications. These include nuclear generating capacity, load factors, burn-ups, and cycle lengths.

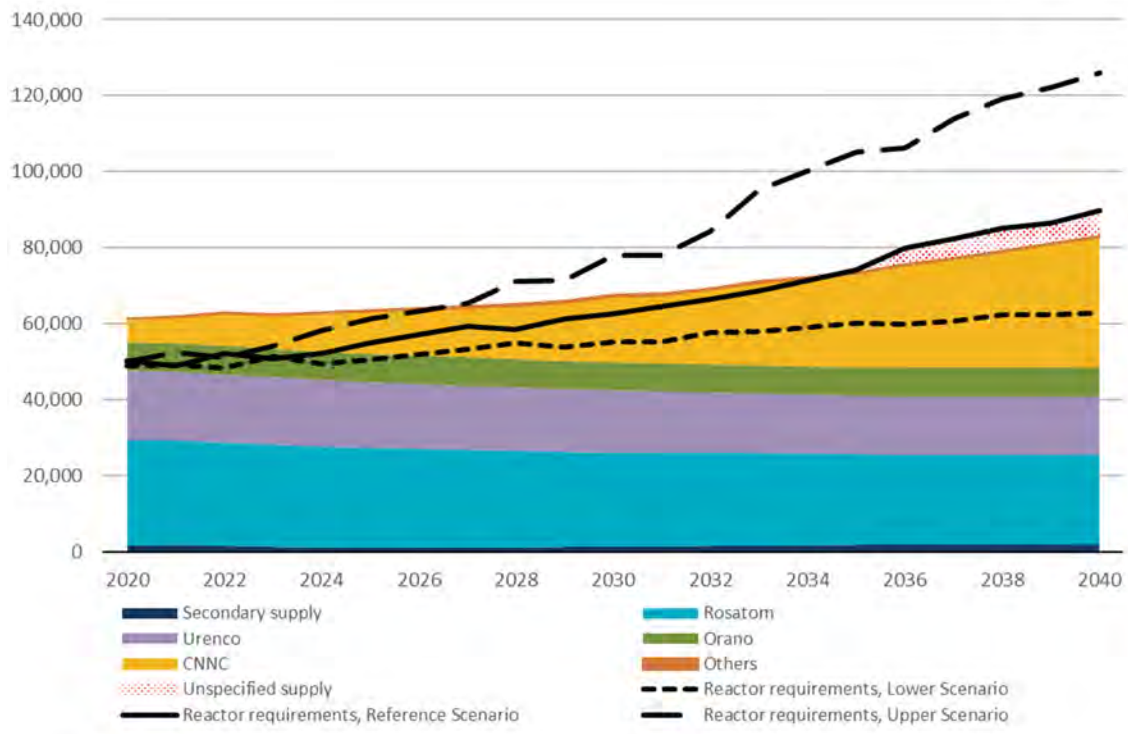
Figure 12 shows three scenarios of worldwide enrichment requirements in the period through to 2040. In projecting uranium and enrichment requirements in this report, World Nuclear Association has assumed a tails assay of 0.22% for determining global SWU requirements. The tails assay assumption is held constant for all years and all demand scenarios for nuclear generation. World Nuclear Association also has annualized reactor requirements, although operating parameters and reactor-specific supply contracts are often cyclical – for example, reactors are normally refuelled in cycles that generally range from 12 to 24 months.

Figure 12: Enrichment requirements by scenario to 2040, thousand SWU



As shown in Figure 13 for the Reference Scenario, projected primary supplier capacities in the near term will be in an oversupply position; however, even with additions of small portions of secondary supplies of 1.2-1.8 million SWU/yr for the Reference Scenario, mainly from MOX fuel, the Reference Scenario shows an increasing deficit in the supply of SWU from 2034-2035.

Figure 13: World enrichment demand scenarios versus installed capacity, thousand SWU



Since projections of installed capacity cannot be reliably estimated beyond around 10 years, should future demand requirements exceed SWU supply, such as in the period after 2030 in Figure 13, the unspecified SWU supplies could be met either by reducing underfeeding capacity, additional capacity expansions or from the inventories built up by some utilities. As for new projects and increase of capacity, given the modular expansion capability of gas centrifuge designs and the required timelines for building new nuclear plants, enrichment capacity should be able to meet higher demand scenarios or replace secondary supply sources as warranted by market demand.

8 Fuel fabrication supply and demand

In common with uranium, conversion and enrichment requirements, fuel assembly demand is made up of a mixture of first cores and reloads. However, fuel design and fabrication is a fundamentally different market from the other three front-end fuel cycle businesses (mining, conversion and enrichment) as nuclear fuel is not a fungible commodity but a high-tech product accompanied by specialist support.

The fuel fabrication market is split between the designer (responsible for the product performance in the reactor) and the manufacturer.

- Designers have both design and manufacturing capabilities and are the main fuel vendors nowadays. As reactor vendors, they often supply the initial cores and early reloads for reactors, built to their own design.
- Manufacturers have manufacturing capabilities only, with commercial and export activities. In some regions, manufacturers may be represented by smaller local manufacturers, which mainly act on the local markets to supply domestic demand only and usually are not present in other markets.

As a fuel assembly is not a fungible commodity but a complex product incorporating design, licensing and R&D activities, it is specific to each reactor type. The fuel fabrication market can be categorized according to reactor type and fuel type.

Segment 1, by reactor type:

- Light water reactor (LWR) subcategories:
  - Pressurized water reactors (PWRs) including Russian VVER reactors.
  - Boiling water reactors (BWRs).
- Pressurized heavy water reactors (PHWRs), mainly CANDU.
- Gas-cooled reactors (GCRs), mainly advance gas-cooled reactors (AGRs) in the UK.
- Russian high-power channel reactors (RBMKs).
- Future and other reactor designs (Generation IV reactors, including fast breeder reactors, high-temperature gas-cooled reactors, SMRs).

This categorization does not, however, precisely reflect the complexity of this market in terms of fuel design. The cost and time to develop a fuel assembly design – which depends on the reactor model and assembly structure – is significant. Designers are the owners of the fuel-related intellectual property and are the ones who define the specifications for manufacturing their fuel designs. Some manufacturers operate under technology licences granted by the designers.

Segment 2, by fuel type:

PWR fuel is a major fuel type that has the highest requirements worldwide and is itself a diversified sector in terms of the various subcategories of fuel assembly design.

Those subcategories depend in particular on original equipment manufacturer (OEM) of the reactor and the fuel assembly (fuel assembly array, number of fuel rods, positioning of guide tubes), the main one being the PWR17 encompassing different product lines of Westinghouse, Framatome, Mitsubishi Nuclear Fuel, and TVEL. Chinese vendors are also working on their proprietary PWR17 fuel designs.

Other PWR designs worldwide include: PWR14, PWR15, PWR16, CE14, CE16, KWU15x15, KWU16x16, KWU18x18, B&W15, and many others. These are classed as 'PWR-others' sub-segment in the report, in order to simplify the analysis.

Although VVER fuel is classed PWR fuel, the assemblies have characteristic hexagonal cross-sections. VVER fuel assemblies are designed and manufactured by TVEL and Westinghouse and encompass several sub-designs customized to different reactors: VVER-440, VVER-1000 and VVER-1200. For the purposes of this report, two fuel types are covered, VVER-440 and VVER-1000 (for VVER-600, VVER-1000 and VVER-1200 fuel designs).

BWR fuel includes several design arrays, such as BWR10x10 and BWR11x11, which can be loaded in the same reactor.

CANDU/PHWR units use deuterium oxide ('heavy water') as moderator, and non-enriched uranium as fuel. Current common designs of bundles consist of 37-element rods with Zircaloy cladding. CANDU assemblies have a circular cross-section.

RBMK is a very specific type of fuel which comprises two bundles, two tailpieces, and central rod with a bar or a supporting tube with a central void (to accommodate sensors), fasteners and retainers.

AGRs are operated in the UK and use fuel assemblies consisting of a circular array of 36 stainless steel clad fuel rods. They employ a vertical fuel channel design, and use carbon dioxide gas as the primary coolant.

RBMK and AGR fuel as well as other types of fuel (such as fuel for fast neutron reactors and high-temperature gas-cooled reactors) are taken into account in the model but are not covered in this chapter due to their limited application.

Whilst the market categorization by reactor type is sufficient for analysis of fuel manufacturers, the division by fuel type is required for the fuel designers. Each fuel assembly design is a specific product that requires significant development costs and time.

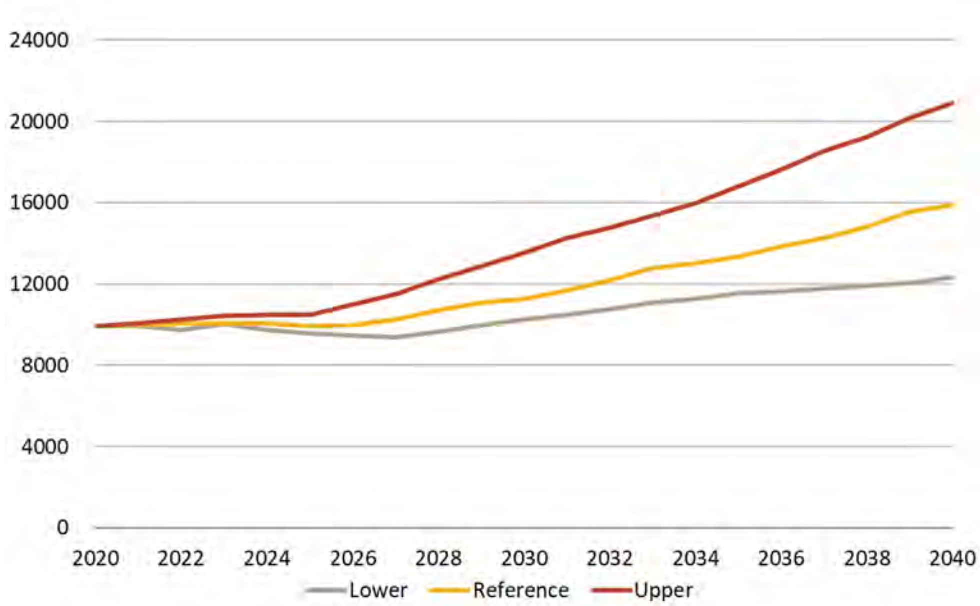
The overwhelming majority of the world demand remains for reloads rather than first cores (which have different characteristics from those of the reloads).

While fabrication of reloads (only a portion of the reactor core) is linked to operating cycles, and consequently easy to plan for fabricators, fuel for first cores represents a large number of fuel assemblies (full core), thus creating a significant demand on fabrication that depends upon the reactor startup date.

Projections are made both for reload demand and first core demand. As well as the trends in global and regional fabrication requirements, projections of reload requirements according to fuel type are also analyzed (Segment 2). In addition to the fuel types listed above, the ‘unknown fuel type’ category has been introduced for those reactor types that have not yet been determined. This category becomes more widely employed closer to the end of the forecasting period, where, from the current perspective, it is not possible to say with a high degree of certainty what types of reactor will be constructed.

Figure 14 shows the projection of global reload fabrication demand for all fuel designs, including LWRs, PHWRs, AGR, RBMK and unknown fuel type. While there appear to be no significant changes to overall demand before 2024 compared to the current level in all scenarios, steady increases appear in around 2025 in all three scenarios, with different growth rates.

Figure 14: World reload requirement scenarios to 2040, tHM



Geographical distribution is extremely important for the fuel fabrication market as utilities tend to choose local suppliers due to transport being technically challenging and costly. In addition, designers as well as fuel fabricators can provide additional services and supplies, such as core components, onsite services as well as engineering services for utilities. To simplify the data presented in this chapter, reactor requirements are split into four main regions:

- Americas (North, South and Latin America).
- Europe (Western and Eastern Europe, Armenia, Belarus, Russia and Ukraine).
- Asia (East Asia, South Asia, Southeast Asia).
- Africa, Middle East and Central Asia.

Regional projections for reload demand are shown in Figures 15-18.

Figure 15: Reload requirements scenarios to 2040, Americas, tHM

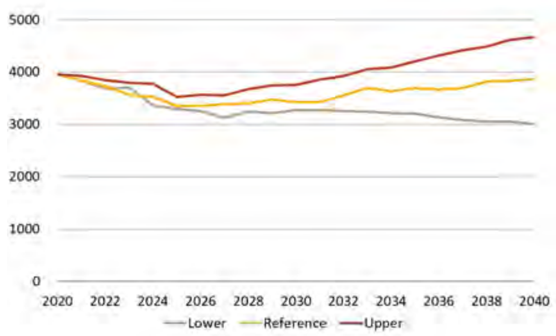


Figure 16: Reload requirements scenarios to 2040, Europe, tHM

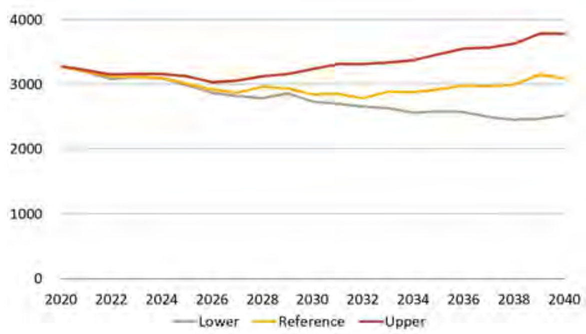


Figure 17: Reload requirements scenarios to 2040, Asia, tHM

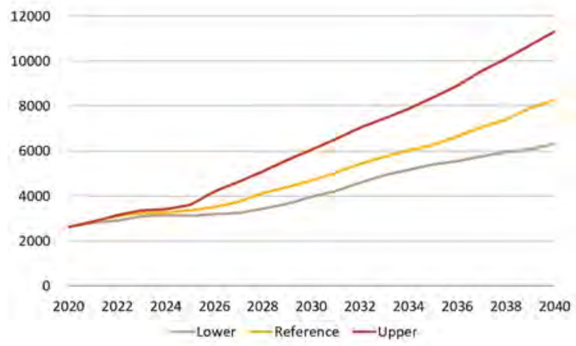
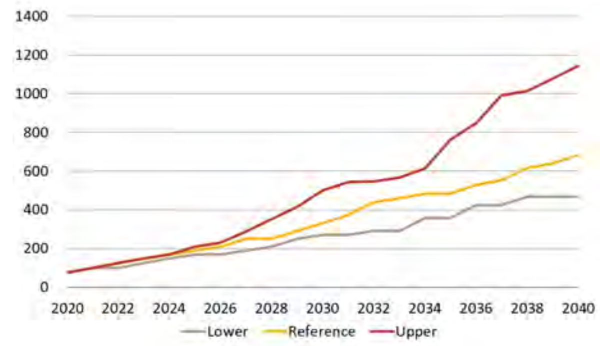


Figure 18: Reload requirements scenarios to 2040, Africa, Middle East and Central Asia, tHM



In the Americas region (see Figure 15), although some decline is expected around the mid-2020s, the demand then exhibits an upward trend in the Reference and Upper Scenarios, while in the Lower case a steady but rather moderate downward trend can be seen in the second decade of the forecast period.

In Europe (see Figure 16), while the fuel demand is fairly stable in the Upper Scenario in the first decade and slightly increasing from 2030 onwards, declines are expected in both the Lower and Reference Scenarios, which are largely caused by the expected closures of reactors in Belgium, Germany and Spain due to political reasons; as well as Generation II RBMK reactors in Russia and AGR reactors in the UK.

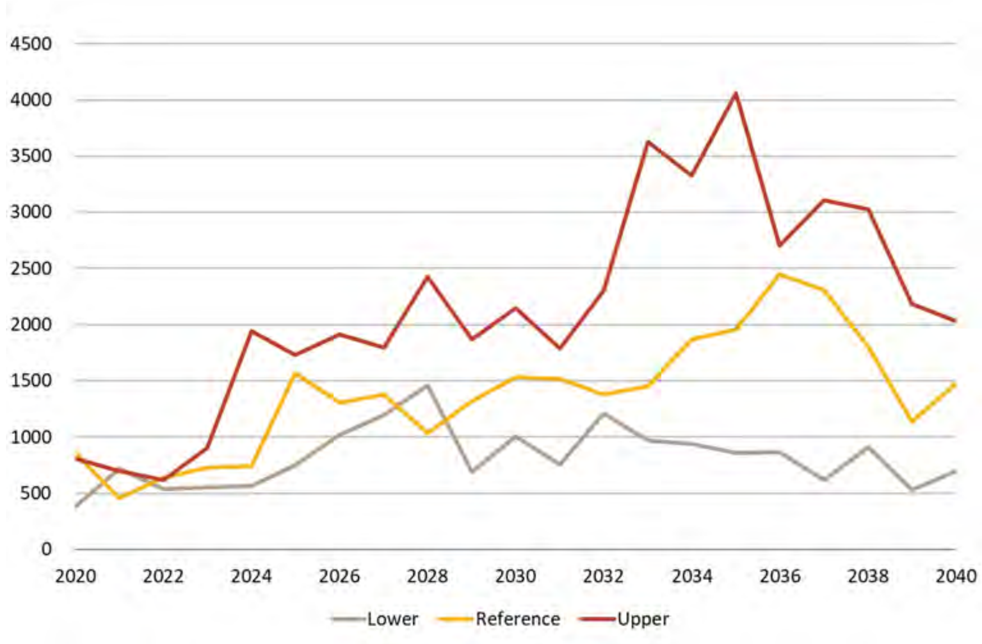
Asia (see Figure 17) is where the majority of growth comes from. With China and India, as well as many other developing economies in the region, fuel demand is expected to double, triple or quadruple in the Lower, Reference and Upper Scenarios, respectively. Growth is observed in all fuel types utilized in this region, even in the Lower Scenario.

Similar rapid growth is also expected in Africa, Middle East and Central Asia (see Figure 18), though at a much smaller scale. Fuel demand is expected to reach 400, 600 and 1,100 tHM/yr in the Lower, Reference and Upper Scenarios by 2040.

First cores are assumed to be required two years in advance of a reactor startup. These first core requirements become significant with expansive reactor plans, which affect the demand for fabrication capacity in two ways. The demand for reloads increases in line with the newly-installed reactor capacity, approximately 16-20 tonnes/year per GWe. Additionally, the first cores create a temporary demand peak, since their volume equals around three times the annual reload batches of currently operating LWRs.

The expected first core fabrication requirements for the three demand scenarios are displayed in Figure 19. This is calculated in the same way as for the reloads – according to uranium demand.

Figure 19: First core fabrication demand by scenario, tHM



In the Reference Scenario, a capacity of around 1,500 tHM/yr will be needed globally for first cores by the end of the projection period. A first core delivery normally has to be performed in a short period of time although the fabrication period may be longer as the time needed for plant construction largely exceeds the time needed for first core manufacturing. This requires a considerable number of costly transport containers as well as storage capacity in the fabrication plants since the readiness for fuel receipt at the new reactor is prone to delays.

9 Harmony programme

Harmony is the global nuclear industry's vision for the future of electricity. To meet the growing demand for reliable, affordable and clean electricity, we will need all low-carbon energy sources to work together as part of a diverse mix of power sources. The *Harmony* goal is for nuclear energy to provide at least 25% of electricity by 2050.

The *Nuclear Fuel Report* scenarios project potential development taking into account current policies and trends. The scenarios derived from such a bottom-up method are based on assessing each country individually (according to the criteria of the scenario) in order to determine the likelihood of individual projects going ahead. The *Harmony* goal, however, is derived from a 'normative' approach, which starts with a vision and specific target and backcasts to identify the pathway to achieve the target. Normative scenarios present future visions that are achievable (or avoidable) only through certain actions. The scenario itself becomes an argument for taking those actions.

The *Harmony* goal is to meet the growing demand for low-carbon energy and achievement of the aims of the December 2015 Paris Agreement. The *Harmony* goal of 25% of global electricity by 2050 to be provided by nuclear energy would require a tripling of nuclear generation from its present level. This equates to 1250 GWe of total nuclear capacity by 2050, including approximately 1000 GWe of new nuclear capacity.

While the *Harmony* goal is ambitious, it is achievable. In order for nuclear energy to reach the *Harmony* goal and to support the world in keeping global temperature increases below 2 °C, a rapid ramp-up of new nuclear build to an annual connection rate of 33 GWe within the next decade is required. This annual connection rate of 33 GWe is comparable to that already achieved in the 1980s.

Achieving the *Harmony* goal means there will be more reactors than is currently expected from trends in this report's Upper Scenario. Unless there is also a radical transformation in reactor technology during that timeframe, it will require greater amounts of uranium, enrichment, fuel fabrication, transport and used fuel services.

As proven during the past decades in any mineral mining industry, *e.g.* the oil and gas industry, exploration and extraction techniques constantly improve over time and it is anticipated as nuclear power expansion gets under way, that additional and unconventional resources would greatly extend known uranium reserves. In the longer term, the development of advanced reactors and fuel cycles that recycle nuclear fuel could permit much greater amounts of energy to be obtained from each tonne of uranium.

Uranium resources are unlikely to be a limiting factor for the expansion of nuclear programmes. However, the availability to the market of adequate uranium supplies is unpredictable in the absence of proper incentives. The development of new mines, both to replace exhausted existing mines and to expand overall production capacity, will require large investments over the coming decades. In addition, licensing and developing new mines, often in remote areas, can take many years. However, the corresponding lead time for nuclear power expansion under *Harmony* is also long enough to allow sufficient time to provide the appropriate market signals – whether for the development of uranium reserves or capacity of fuel cycle facilities – so that these facilities should be developed as and when they are needed.

10 Key findings of *The Nuclear Fuel Report*

10.1 Uranium

Excessive oversupply of primary uranium production has contributed to very low uranium prices, which have been depressed for more than a decade. This situation has resulted from: all Japanese reactors being taken offline in 2011 and a slower than expected return to operation; premature reactor closures in the USA, Germany, and other Western European countries; cancellation of several planned reactor construction projects, and delay of others due to the economic slowdown following the global financial crisis as well as revisions of safety standards. These unfavourable market conditions caused a sharp fall in investment at existing and new mining projects, as well as a reduction of production levels at existing mines.

The most recent (2020 edition) *Red Book* highlighted that global uranium exploration and mine development expenditures fell by more than 75% from $2.12 billion in 2014 to $0.48 billion in 2018. Besides cutting investment in exploration and mine development, uranium producers delayed investment in current, developing and planned mines, waiting for positive supply-demand signals in order to start reinvesting.

Over the longer term, the Reference Scenario shows demand for uranium growing by 3.1% compound average growth rate (CAGR). This is mainly driven by nuclear expansion in East and South Asia, with uranium requirements exceeding 112,000 tU/yr by the end of the next decade. The Upper Scenario doubles uranium requirements within 15 years and results in a 4.6% CAGR. The Lower Scenario shows a modest growth rate of 1.2% CAGR.

In the long term, several mines are expected to be closed before 2030 due to resource depletion, barring additional reserves being identified, otherwise the demand will need to be satisfied by either return of idled capacity or launching new projects.

Today, however, very few participants are able or willing to begin investing to convert these resources into reserves and ultimately into mines to meet future demand projections. Some state-owned strategic developments are proceeding, but there continues to be a lack of long-term contract support, at sufficient price levels to launch new projects controlled by market-based companies.

10.2 Secondary supply

Whilst there is likely to be a continuing high level of secondary supply, the relative contribution of it to overall uranium supply will gradually diminish, being projected to decrease from the current level of about 10,000 tU/yr to approximately 6,500-7,000 tU/yr from 2035 onwards. Besides the secondary supply that can be quantified, a large amount of unspecified secondary supply exists, including commercial inventories held by utilities, producers and other market participants. Although the size of these inventories cannot be accurately estimated mainly due to commercial sensitivities, they could be immediately available for direct consumption or resale. It is expected that any supply gap or shortfall in the short or medium term will be covered by commercial inventories.

As a major component of secondary supply, commercial inventories play an indispensable role in the current market, characterized by undersupply at two critical stages of the nuclear fuel cycle: primary uranium and conversion. Market participants are continuously reassessing their inventory levels, which, on aggregate, have started to decrease. This will eventually lead to a more balanced market.

10.3 Conversion

The most likely scenario remains that over the near-term, utility held inventories will predominantly bridge the gap between new primary supply and demand. Over the medium-term, it is expected that capacity utilization factors will be increased as the demand side of the market requires and as producers can accommodate with existing capacity. Over the long-term, it is possible that the market will require capacity expansion at existing facilities or even the construction of a new conversion plant.

For expansion of primary conversion capacity or new projects to be economically justified before 2030, any of the following should take place:

- The most optimistic demand scenario must occur.
- The increase of capacity utilization, when required over the mid-term, does not occur because of technical or regulatory difficulties.
- The market sees an unexpected and long-term closure of an existing primary conversion facility.
- Chinese plans to achieve 'self-sufficiency' in conversion supply are not realized.

Overall, the change in the conversion market over previous versions of this report is characterized by a significant curtailment in primary production levels resulting in a heavy reliance and corresponding reduction in inventories. After these inventories are exhausted over the near to medium-term, the market will incentivize increased production output via increased capacity utilization factors, the expansion of existing conversion plants, or even the construction of a new conversion facility.

10.4 Enrichment

Enrichment requirements are expected to rise over the projection period from 2021 to 2040 due to prospective new nuclear build, primarily in East and South Asia, particularly in China and India. In the near-term, no expansion of the production capacities is expected from any producer. Moreover, the enrichers may continue to reduce existing capacity by not replacing centrifuges that have reached the end of their operation. In the long-term, given the modular nature of centrifuge technology and the fact that new nuclear plants take longer to complete than new enrichment plants, enrichment supply should be able to keep pace with any new reactor build, once the market has recovered from the current oversupply. Developments are expected in the production of LEU+ and HALEU due to rapid progress of ATF and advanced reactor technologies. To prepare for the potential demand, enrichers are either considering, or have already implemented, measures towards supplying material with enrichment above 5%.

10.5 Fuel fabrication

The fuel fabrication market differs significantly from the uranium concentrate, enrichment and conversion markets as fuel assemblies are highly engineered and technological products, and the market itself is regional rather than global. In addition, fuel supply is split into reloads and first cores, with their own specific characteristics. As a result, the market is segmented both geographically and technologically, thus leading to a more complex analysis.

The fuel fabrication market has historically shown strong competition among different OEM vendors and manufacturers, either regional or national fuel suppliers. Fuel fabrication capacity outweighs requirements, both globally and particularly at a regional level.

Appendix tables: Existing and prospective primary uranium supply by project

Table 1.1: Existing mines: nameplate capacity in 2020 and uranium production in 2019-2020, tU

Country	Mine	Type	Operator	Nameplate capacity (tU)	Production (tU)	
					2019	2020
Australia	Four Mile	ISR	Quasar	2,307	1,764	1,806
	Olympic Dam	By-product/ underground	BHP	4,500	3,364	3,062
	Ranger*	Open-pit	Rio Tinto/ERA	-	1,485	1,335
Brazil	Engenho	Open-pit	INB	220	0	15
Canada	Cigar Lake	Underground	Cameco	6,924	6,938	3,885
Kazakhstan	Budenovskoye 1, 3 & 4	ISR	Akbastau JV	1,931	1,550	1,363
	Western Mynkuduk	ISR	Appak JV	1,000	800	633
	Kharasan 2	ISR	Baiken JV	1,530	1,560	1,181
	Inkai	ISR	Inkai JV	4,000	3,209	2,693
	Karatau (Budenovskoye 2)	ISR	Karatau JV	3,200	2,600	2,460
	Katco (Moinkum, Tortkuduk)	ISR	Katco JV	4,000	3,252	2,833
	Kharasan 1	ISR	Khorassan-U JV	2,000	1,599	1,455
	Central Mynkuduk	ISR	Ortalyk	2,000	1,694	1,308
	Karamurun, North and South	ISR	RU-6	1,000	864	660
	Eastern Mynkuduk	ISR	SaUran	1,000	1,541	1,230
	Kanzhugan (including Kainar)	ISR		1,000		
	Moinkum 3 (Central)	ISR		500		
	Irkol	ISR	Semizbai-U	731	960	753
	Semizbai	ISR		1,200		
	Akdala	ISR	SMCC JV	1,000	800	760
	South Inkai 4	ISR		2,000	1,600	1,509
	Zarechnoye	ISR	Zarechnoye JV	970	778	648
Namibia	Husab	Open-pit	Swakop Uranium (CGN)	5,512	3,400	3,302
	Rossing	Open-pit	CNNC	3,816	2,077	2,111
Niger	Akouta (Cominak)**	Underground	Orano	1,400	1,071	1,112
	Arlit	Open-pit	Orano	2,000	1,912	1,879
Russia	Dalur	ISR	ARMZ	600	595	585
	Khiagda	ISR	ARMZ	1,300	1,016	1,021
	Priargunsky (Mine 1, 8)	Underground	ARMZ	3,000	1,300	1,240
South Africa	Vaal River Region (est.)	By-product	Harmony Gold	769	346	250
Ukraine	VostGOK mines	Underground	VostGOK	1,650	800	744
USA ***	Lost Creek	ISR	Ur-Energy	385	18	4
Uzbekistan	Navoyi MCC mines (est.)	ISR	Navoi MCC	3,500	3,500	3,500
Others	China (est.)	ISR & conventional	CNNC	1,923	1,885	1,885
	India (est.)	Underground	UCIL	610	308	400
	Iran (est.)	Underground	Iran (Gachin)	71	71	71
	Pakistan (est.)	Underground	PAEC	45	45	45
World Total				**69,594**	**54,742**	**47,731**

Table 1.2: Nameplate capacity of idled mines, tU

Country	Mine	Type	Operator	Year taken offline	Capacity (tU) By mine	Capacity (tU) By country
Canada	McArthur River/Key Lake	Underground	Cameco	2018	9,616	11,924
	Rabbit Lake	Underground	Cameco	2016	2,308	
Namibia	Langer Heinrich	Open-pit	Paladin	2018	2,269	2,269
Malawi	Kayelekera	Open-pit	Lotus	2014	1,270	1,270
USA	Alta Mesa	ISR	Energy Fuels	2013	577	5,088
	Lance	ISR	Peninsula	2019	442	
	Nichols Ranch-Hank	ISR	Energy Fuels	2020	770	
	Smith Ranch, Crow Butte, Highland	ISR	Cameco	2018	1,923	
	White Mesa (Tony M, Daneros, Whirlwind, Rim, La Sal)	Underground	Energy Fuels	2020	625	
	Willow Creek (Irigaray & Christensen Ranch)	ISR	Uranium One	2018	750	
World total						**20,551**

Table 1.3: Mines 'under development', 'planned' and 'prospective' uranium production capacity, tU

Mines under development				
Country	**Project/Mine**	**Type**	**Operator**	**Estimated capacity (tU)**
Kazakhstan	Zhalpak	ISR	Ortalyk	500
Russia	Priargunsky No 6	Underground	ARMZ	3,000
USA	Pinyon Plain (former Canyon)	Open-pit	Energy Fuels	300
Total mines under development				**3,800**

Planned mines				
Country	**Project/Mine**	**Type**	**Operator**	**Estimated capacity (tU)**
Australia	Honeymoon	ISR	Boss Resources	942
	Mulga Rock	Open-pit	Vimy Resources	1,346
Brazil	Santa Quiteria	By-product	INB	1,800
Finland	Talvivaara	By-product	Terrafame	250
Namibia	Etango	Open-pit	Bannerman Energy	2,769
Tanzania	Mkuju River	Open-pit	Uranium One	3,200
USA	Hobson (Palangana, Burke Hollow)	ISR	Uranium Energy Corp	385
Total planned mines				**10,692**

Prospective mines				
Country	**Project/Mine**	**Type**	**Operator**	**Estimated capacity (tU)**
Australia	Angularli	Underground	Vimy Resources/Rio Tinto	769
Brazil	Cachoeira	Underground	INB	340
Canada	Wheeler River/Gryphon	Underground	Denison Mines	2,923
	Wheeler River/Phoenix	ISR	Denison Mines	2,308
Mauritania	Tiris	Open-pit	Aura	315
Niger	DASA	Underground	Global Atomic Fuels	360
	Madaouela	Open-pit/undergound	GoviEx	1,035
USA	White Mesa (Roca Honda, Bullfrog)	Conventional	Energy Fuels	900
	Sheep Mountain	Heap leach	Energy Fuels	575
Zambia	Mutanga	Open-pit	GoviEx	962
Total prospective mines				**10,487**
Total production capacity for mines under development, planned and prospective mines				**24,980**

Table 1.4: Potential supply, tU

Country		Project/Mine	Type	Operator	Estimated capacity (tU)
Africa	Namibia	Langer Heinrich Expansion (Stage 4)	Open-pit	Paladin	1,850
		Trekkopje	Open-pit	Orano	3,000
		Tumas	Open-pit	Deep Yellow	1,154
	Niger	Azelik/Teguida	Open-pit	CNNC	700
		Dasa (Phase II)	Open-pit/ underground	Global Atomic Fuels	360
		Imouraren	Open-pit	Orano	5,000
	South Africa	Ezulwini (Cooke 4)	By-product	Sibanye-Stillwater	500
Australia		Kintyre	Open-pit	Cameco	2,290
		Manyingee	ISR	Paladin	462
		Mount Isa	Open-pit	Paladin	1,924
		Westmoreland	Open-pit	Laramide Resources	1,539
		Wiluna	Open-pit	Toro Energy	577
		Yeelirrie	Open-pit	Cameco	2,968
Canada		Arrow	Underground	NexGen	5,000
		Michelin	Open-pit/ underground	Paladin	2,308
		Midwest	Open-pit	Orano	1,500
		Millennium	Underground	Cameco	2,500
		Nunavut (Kiggavik)	Conventional	Orano	3,000
		Patterson Lake South (PLS)	Open-pit/ underground	Fission Uranium	5,000
		Shea Creek	Underground	Orano	2,500
Mongolia		Zoouch Ovoo	ISR	Orano	2,050
Peru		Macusani	Open-pit	Plateau Uranium	2,346
Russia		Elkon	Underground	ARMZ	5,000
USA		Cameco US ISR Expansion	ISR	Cameco	615
		Church Rock	ISR	Laramide Resources	385
		Hobson (Goliad)	ISR	UEC	769
		Reno Creek	ISR	UEC	769
		White Mesa (Anderson, Slick Rock)	Open-pit/ underground	UEC	577
Other	Greenland	Kvanefjeld	By-product	Greenland Minerals and Energy	385
	India	Gogi	Underground	UCIL	130
		Kylleng-Phendengsohiong Mawthabah	Open-pit	UCIL	340
		Lambapur-Peddagaltu	Underground	UCIL	130
	Spain	Salamanca	Open-pit	Berkeley Resources	1,692
World total					**59,323**

Drafting group

Co-Chairs

Alexander BOYTSOV	TENEX
James NEVLING	Exelon Generation

Chairs of sub-groups

Pierre BERTRAND	EDF
Emilio BOBO PEREZ	ENUSA
Nikko COLLIDA	ConverDyn
Rolf KWASNY	Consultant
Jean-Noël LACROIX	Orano
Brandon MUNRO	Bannerman Energy
Julian TAPP	Vimy Resources

Other contributors

Jose AYCART	GE Hitachi Nuclear Energy
Ulf BENJAMINSSON	Westinghouse
Dylan BRYNGELSON	Cameco
Raizwan BUTT	Urenco
Leonardo COSTA	Eletronuclear
Michael CULPEPPER	Centrus Energy
Nicole DELLERO	Orano
Sergio DE MARIA	ENUSA
Alexandre DOUCE	EDF
Christopher FRANKLAND	Nuclear Fuels Corporation
Luminita GRANCEA	OECD Nuclear Energy Agency
Steve HARDING	Urenco
Arthur Dwight HYDE	Segra Capital Management
Kyeong Lak JEON	KEPCO Nuclear Fuel
John-Paul JONES	Urenco
Ilyas KENZHEGALIYEV	Kazatomprom
Nadezda KOLOSOVSKAYA	TVEL
Alejandro LECINANA	Conuar
Robert LEE	Exelon Generation
Matt LICHTENWALD	Cameco
James MALONE	Lightbridge
Tim MCGRAW	Cameco
Lawrence MERCIER	Framatome
Marie MOATTI	EDF
Valeria NAZIMOVA	TENEX
Cécilia PARK NANTIER	EDF
Richard PATTERSON	Uranium Solutions
Ilya PLATONOV	Rosatom
Mikhail PLATOV	TENEX
Christian POLAK	Orano
Riaz RIZVI	Kazatomprom
Eric ROCKETT	Rockett Science
Anthony SCHILLMOLLER	Uranium Solutions
Gabriele SCHNEIDER	Namibian Uranium Association
Patrick SIGNORET	Orano
Francisco TARÍN GARCIA	ENUSA
Jeanne TORTORELLI	Exelon Generation
Bram VANDERELST	Curzon Uranium Trading
Christopher VELUPILLAI	EDF
Kate WILLIAMS	Exelon Generation
Min XIAO	CGNPC Uranium Resources

World Nuclear Association secretariat

Hongzhao (Rico) LI	Visiting Research Officer
Keiyu MARUYAMA	Visiting Research Officer
Olga SKORLYAKOVA	Senior Project Manager

Figure and Table references used in The Nuclear Fuel Report

<u>Appendix tables:</u>

World Nuclear Association
Tower House
10 Southampton Street
London WC2E 7HA
United Kingdom

+44 (0)20 7451 1520
www.world-nuclear.org
info@world-nuclear.org

This Expanded Summary of the *The Nuclear Fuel Report: Global Scenarios for Demand and Supply Availability 2021-2040* covers the main findings and conclusions of the 2021 edition. Published since the foundation of the World Nuclear Association in 1975, *The Nuclear Fuel Report* compiles data from the nuclear industry, international agencies and other public sources to produce authoritative projections of global nuclear fuel supply and demand.

The 20th edition of *The Nuclear Fuel Report* includes scenarios covering a range of possibilities for nuclear power to 2040. The main focus is on the front end of the nuclear fuel cycle but the report also examines the impact of recycled nuclear fuel.

The World Nuclear Association is the international organization that represents the global nuclear industry. Its mission is to promote a wider understanding of nuclear energy among key international influencers by producing authoritative information, developing common industry positions, and contributing to the energy debate.