WORLD NUCLEAR ASSOCIATION

The Nuclear Fuel Report: Expanded Summary

Global Scenarios for Demand and Supply Availability 2019-2040

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1. Introduction

The World Nuclear Association has published reports on nuclear fuel supply and demand at roughly two-yearly intervals since its foundation in 1975. The 19th edition of *The Nuclear Fuel Report* was released in September 2019 and includes scenarios covering a range of possibilities for nuclear power to 2040. Forecasts beyond 2040 are beyond the scope of the report and would require a rather different approach to capture the larger range of uncertainty; however, the key issues examined in the report are likely to have continued relevance during that longer period.

This *Expanded Summary* covers the key findings of 19th edition, and explains the methodology and the assumptions 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 over 10% of the world’s electricity production and is expected to continue playing an important role in future electricity supply for several reasons, including:

- Nuclear power produces near-zero greenhouse gas and other pollutant emissions.
- Nuclear power is a reliable and secure power source, which is particularly attractive to industrializing countries and those lacking indigenous energy resources.
- Nuclear power has long-term cost-competitiveness, compared with the levelised cost of both fossil and clean energy sources.
- There are many industrial and human-capital benefits associated with nuclear energy’s development and use.

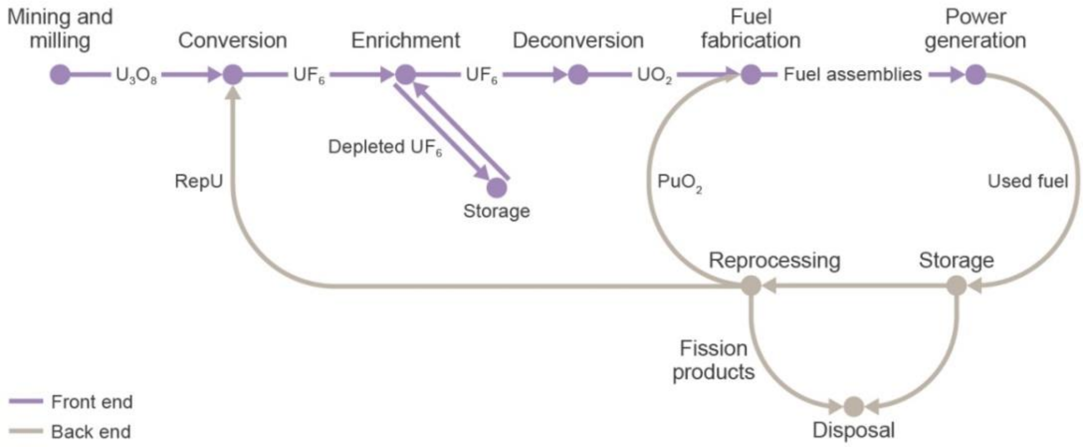
Despite these advantages, nuclear energy faces competitive challenges from other electricity generation sources, especially in deregulated markets as they are currently designed, along with continuing regulatory and political hurdles. Furthermore, electricity demand growth has slowed down especially in the countries where nuclear power is well-established. However, the nuclear sector remains strong in many developing countries and it is in these countries that the majority of nuclear capacity growth is expected.

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 disposal of remaining waste products.

Figure 1: The nuclear fuel cycle



The fuel cost in nuclear power has historically been a minor element of the total production cost. Fuel costs (inclusive of uranium, conversion, enrichment and fabrication) typically comprise less than 20% of the total cost of electricity for a modern nuclear power plant, 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 production has recently (2013-2017) represented about 90% of the global reactor demand. Primary uranium production is characterized by relatively broad geographical distribution (in 2018 uranium was produced in 14 countries), and also by a large number of companies representing major and junior uranium miners. 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 and re-enrichment of depleted uranium. Secondary markets for uranium, conversion and enrichment services are well-established, currently meeting about 15% 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. Whilst 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 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. The 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) 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. The World Nuclear Association scenarios are based on expert opinion from within the nuclear industry and may usefully be compared with the IEA's nuclear scenario forecasts.

The IEA's World Energy Outlook 2018 (WEO 2018), published in November 2018, describes three scenarios for global nuclear capacity based on different policy responses to climate change and the need to reduce greenhouse gas emissions from fossil fuels (see Table 1). The central 'New Policies' scenario projects the impact of new measures, but on a relatively cautious basis, including broad policy commitments that were announced as of August 2018. The 'Current Policies' scenario projects the continuation of policies existing in mid-2018, excluding some ambitious targets declared by governments around the world, and the 'Sustainable Development' scenario projects the implementation of policies aiming to achieve the Paris Agreement's goals of keeping the increase in the global average temperature to well below 2°C above pre-industrial levels.

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

WEO 2018	New Policies	518	WNA 2019	Reference	569
	Current Policies	498		Lower	402
	Sustainable Development	678		Upper	776

The drivers for 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 announced by utilities for nuclear in the next 10-15 years, which (with a few significant exceptions) are generally rather modest.

While the Reference Scenario only assumes that officially announced plans are realized, taking into account country-specific considerations, the Upper Scenario takes into consideration other implications and projects how nuclear can develop if the overall landscape would be more favourable.

In contrast to the IEA Current Policies scenario, 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

[1] 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.

nuclear becomes economically uncompetitive against the decreasing cost of intermittent renewables, that there is a lack of political and/or public support for nuclear energy, and that the importance of security of electricity supply and grid resilience are not sufficiently valued, amongst other factors.

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, it is worth mentioning that in the US alone, nuclear energy currently provides around 55% of the country's carbon-free electricity, and in the European Union it accounts for 53% of the region's carbon-free electricity.

In 2018 the world's nuclear power plants supplied 2,563 TWh of electricity through 396 GWe of operable capacity. This avoided the emission of 2.2 billion tonnes of carbon dioxide compared to the equivalent amount of coal power generation, in addition to total avoided emissions of around 60 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 greenhouse gas emissions should help to create a level playing field for nuclear, a preference for energy market liberalization by policy-makers may hinder the take-up 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, this may tend to favour quicker payback projects such as gas 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 are explained below.

Population growth, urbanization and electrification

Electricity demand is correlated with population growth. Indeed electricity demand growth has been more than double that of population since 2000. With almost 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 of demand growth. Compounding the effect of population growth is the trend towards urbanization.

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 new 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 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 increasing three-fold from 773,600 in 2016 to 2.1 million in 2018. 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.

Alternative generation technologies

Competition between generating technologies has changed significantly in recent years. Nuclear power has to compete with alternative generating technologies both in meeting the demand for electricity from existing plants and especially for new investment. Given nuclear energy's relatively low operating costs, generation from an existing nuclear plant would expect to provide baseload power over an extended period. However, in some circumstances these expectations no longer hold. For example, in the USA, Entergy's Pilgrim nuclear plant was shut down early for economic reasons, and four reactors operated by FirstEnergy Nuclear Operating Company (Beaver Valley 1&2, Davis-Besse, Perry) are scheduled to close prematurely during the next two years if the financial situation does not improve, with some other US plants at risk. For plants closed prematurely, diminished revenue expectations were a factor in the decision. Regarding new investment, alternative generation technologies can decrease expected returns and therefore also the relative attractiveness of nuclear.

The ability to exploit shale gas on a commercial basis has transformed the economics of gas-fired power generation in the USA. 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 total cost of transporting gas to the customer has fallen. Gas prices in the USA have essentially remained below $5/mmBTU 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 – under the form of power purchase agreements, tax credits, amongst others – for renewables; the implementation of constraints on greenhouse gas emissions has not been set yet at a level that would significantly reduce fossil generation. The intention of policy-makers 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 related to guaranteeing supply increase. These system requirements include extensive additional transmission infrastructure, back-up generating capacity and energy storage. A 2019 study by the OECD Nuclear Energy Agency 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 final 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 suitable infrastructure already exists. 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 superior 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.

It is increasingly apparent that battery storage will not be available or affordable on the required scale during the next few decades for mid- to long-term storage. Besides pumped hydro, which has a very limited potential worldwide, there are some expectations placed on new technologies such as power-to-X and hydrogen energy storage, but these are not yet developed and the business models are uncertain.

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 most important of these factors are outlined below.

Operating lifetime extensions

For the purposes of planning or licensing, the operating lifetime of most types of reactor was considered to be 40 years. However, recent years have seen a strong trend towards operating lifetime extensions beyond the initial design lifetime. Operating reactors are subject to continuous upgrading and replacement of components, as well as rigorous licensing and inspection regimes. It is expected that many, if not most, reactors will operate beyond 40 years and therefore apply for extended operational lifetimes. Licence extensions offer the possibility of much extended operating lifetimes and are the most economic way of generating power beyond the design lifetime period.

Carbon neutral energy sources

The global imperative to constrain climate change has seen widespread policy support for renewable energy that has led to dramatically increased use of these energy sources over the last decade. However, despite these policy interventions, global CO_2 emissions continued to rise in 2017 and 2018, widening the gap between current global emissions and the trajectory required to limit climate change to 1.5°C (or even 2°C) above pre-industrial levels.

The nuclear power industry is achieving increasing recognition for its clean energy credentials amongst policy-makers, 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 of onshore wind turbines. The degree to which this recognition results in government policies supporting existing and future nuclear energy production will be 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 base-load coal consumption are, in many countries, only achievable through displacement by other base-load sources, such as gas, hydroelectric power or nuclear power. Given environmental hurdles associated with hydroelectric power 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.

Air pollution imperative for clean energy in growth markets

Air pollution is 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 vastly exceeding acceptable limits. Awareness of the health effects of air pollution has grown dramatically, with estimated deaths from air particulate exposure, in part due to coal-fired power, numbering in the millions per annum.

This led the Chinese government in 2017 to promise to “make the skies blue again” and enact broad policy measures 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 the increasing future energy demand as transport transitions to become electrified and energy sources for domestic heating and cooking are centralized.

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, but there are environmental, social and multi-lateral 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, the extent to which this could add 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. For instance, if efforts to reduce air pollution from industry and domestic cooking/heating fires are not sufficiently effective 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.

Geopolitical security of supply

Nuclear power has a number of features that can be expected to continue to appeal to energy policy-makers in many countries. The most important of these is its contribution 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 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 in the 1970s), as well as to 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, which is responsible for an increasing share of the international trade in fossil fuels.

Geopolitical tensions have increased over the last two 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 hurricane 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 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 trend is likely to continue as weather volatility due to climate change increases and the penetration of intermittent renewables increases.

Improved economics

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

Over the last decade the 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.

Fortunately, the nuclear power sector is currently in a phase of improving capital costs and, therefore, economics. This is partly as 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 built in significant numbers around the world. Moreover, Chinese and Korean reactor builds have demonstrated a substantial improvement in construction time and up-front capital cost, which is likely to continue. 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 builds will have a substantial impact on the relative economics of nuclear power and, therefore, its growth.

New financing models

Reactor vendors have continued to evolve to meet the needs of governments and power utilities, particularly in new markets and developing nations. This evolution has included the emergence of build-own-operate reactor packages, with the provision of associated finance. The continued development of this method of financing reactor construction may help to a certain extent to expand the market for nuclear reactors and therefore reactor demand.

Cost of capital is a key component in the total cost of nuclear power. Large-scale reactors require large capital spending over a long period of construction before generating any revenue. Financing costs may therefore add 30-50% to the cost of construction. In order to reduce costs, the industry and developers have to reduce the construction time and cost, and should also discuss with governments new financing schemes where risk is appropriately allocated, to lower the cost of capital. Given that nuclear power is such a key contributor to economy, governments should play a significant role in their development, similar to the measures implemented for renewables development.

Superior safety record of nuclear

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.

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 exposures 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.

Long-term storage/reprocessing 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.

Advanced reactors

A number of advanced reactors are under development, including SMRs, floating reactors and fast neutron reactors. As these advanced 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.

2. The Nuclear Fuel Report methodology

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 made up of member representatives. The cut-off date for information input was 30 June 2019.

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, commercially sensitive information on inventories was requested, the confidentiality of which 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 in the questionnaires was supplemented by judgements applied by the Association and its working group members, based on published material and other 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 the World Nuclear Association over many years, incorporating the key operating characteristics of reactors throughout the world.

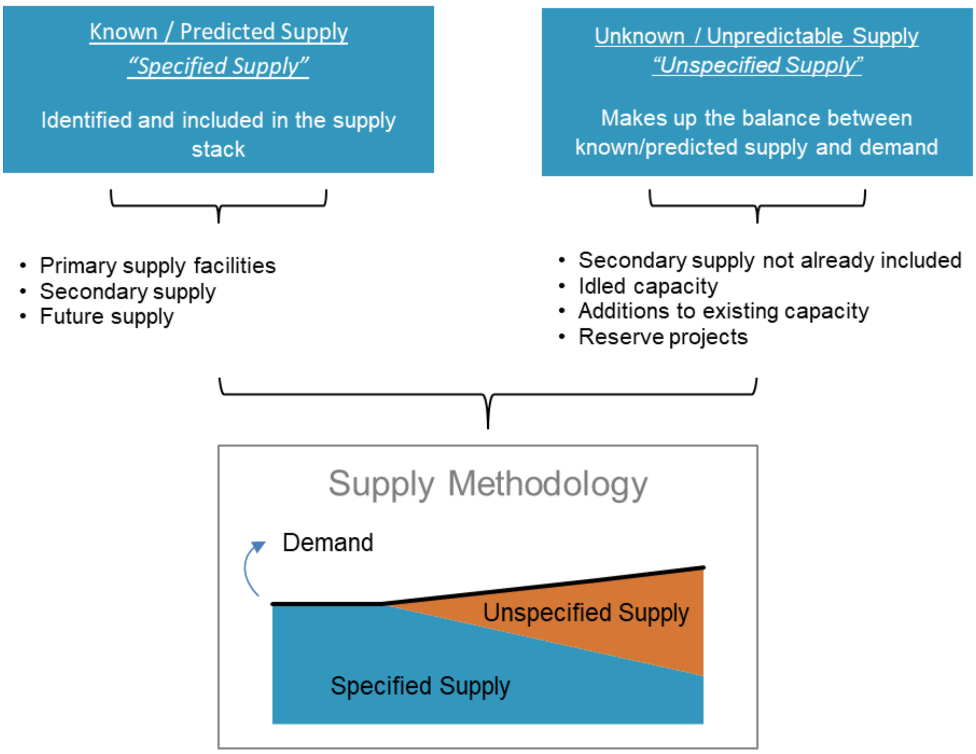
2.1. Supply methodology

For any mineral resource, the future availability of supply depends on many factors beyond the geological availability of the mineral. Uranium supply can also face political and policy uncertainties in some jurisdictions. For this reason, 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, including secondary supply (see Figure 2). Those supply sources allocated to Specified Supply are identified in the supply stack for each component and, in general, include primary supply, secondary supply, and future supply. Those supply sources allocated to Unspecified Supply[2], in general, comprise unspecified secondary supply sources and future primary supply that at this time 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 supplies



[2] The concept of Unspecified Supply as it relates to secondary supplies is discussed in detail in Sections 4.2 and specifically in relation to uranium supply in Section 5.6 of *The Nuclear Fuel Report*.

2.2. Projection methodology and assumptions

Individual country nuclear capacity scenarios are formulated by a World Nuclear Association working group, taking into account responses to a questionnaire survey 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 adjustments to timings or levels of the targets deemed necessary by the drafting group. 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.

For existing reactors, the projection includes an estimation 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 are thus 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.

In every scenario the impact of the following factors to the development of nuclear energy is analysed[3]:

- Economics of nuclear power generation
- The level of political (energy policies)/public support to nuclear energy
- Energy mix decarbonisation
- Electricity market structure/security of electricity supply
- Regulatory standards.

As of mid-2019, world nuclear capacity was 398 GWe (including the idled Japanese reactors). In the Reference Scenario this is expected to rise to 462 GWe by 2030 and to 569 GWe by 2040. In the Upper Scenario, the equivalent figures are 537 GWe in 2030 and 776 GWe in 2040. In the Lower Scenario, nuclear generating capacity is effectively flat throughout the forecast period (see Figure 3).

[3] Three scenarios are examined in Section 2.4.1 of *The Nuclear Fuel Report*.

Figure 3: Nuclear generating capacity scenarios to 2040, GWe

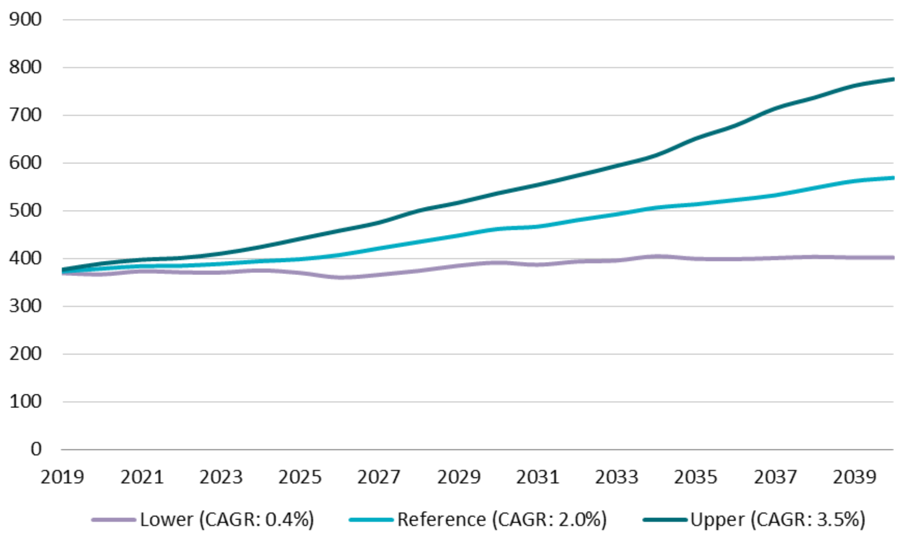
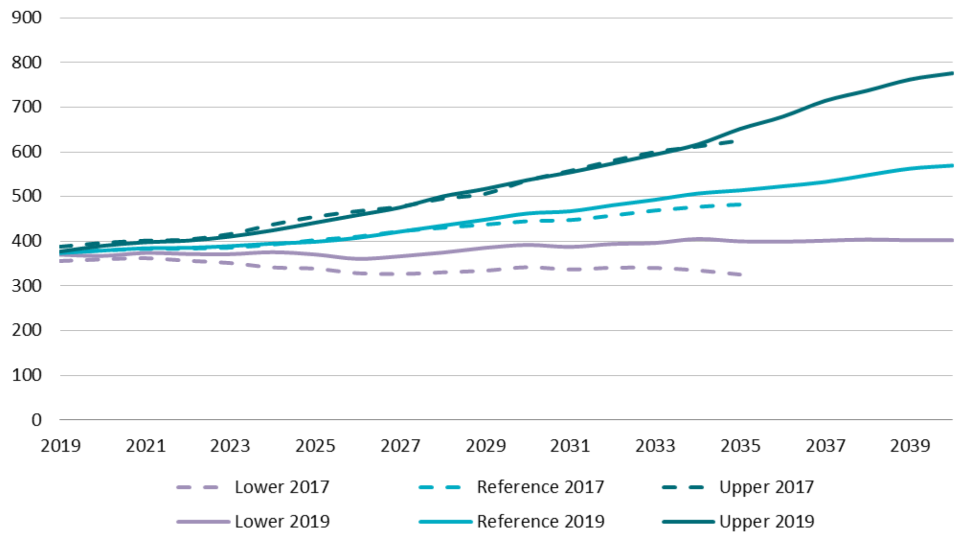


Figure 4 compares the new scenarios with those of the 2017 edition of *The Nuclear Fuel Report* showing the following results: the Upper Scenario and the Reference Scenario almost overlap with the 2017 projections before 2035, and keep rising 2035-2040; the Lower Scenario is significantly lifted (10% annually on average), turning the previous declining trend into a slightly increasing one.

Figure 4: Comparison of 2019 and 2017 generating capacity scenarios, GWe



Since the publication of the previous edition of *The Nuclear Fuel Report* in September 2017, there has been a reversal of the negative trend in nuclear industry development. For the first time since March 2011, this led to a positive trend in nuclear capacity projections over the forecasting period in all three scenarios presented in the 2019 report. There are four main reasons for this:

- In France, the country's energy policy was modified, delaying the timeline of planned reduction of nuclear power in the share of its electricity mix to 50% from the previous 2025 target to 2035, and allowing operating lifetime extensions of existing reactors beyond 40 years.

- In the USA, state legislatures are starting to pass measures that support the continued operation of reactors, recognizing the valuable role of nuclear in providing low-carbon electricity. At the same time, the process of granting a second operating licence extension for US nuclear reactors has begun, allowing reactors to operate for 80 years.
- Both China and India have extensive nuclear expansion programmes. The Reference Scenario projects nuclear generation capacity in India to grow more than six times to approximately 41 GWe from the current level of 6.2 GWe; and China is expected to reach almost 179 GWe in the Reference Scenario, quadrupling its current nuclear capacity.
- The prospects for new reactors in many countries have improved with several newcomer countries launching construction projects (*e.g.* Turkey, Bangladesh, Egypt) and several more demonstrating a clear interest in developing nuclear programmes (*e.g.* Uzbekistan, Kazakhstan, Poland)[4].

4. Secondary supply

Secondary supplies may be defined as the material other than primary production, sourced to satisfy reactor requirements. There is a broad spectrum of secondary supply sources including, but not limited to, commercial and governmental inventories, stockpile drawdowns, fuel assemblies no longer useable in reactors (*e.g.* in Japan, Taiwan, Germany and the USA), and use of recycled materials of various types. In the widest sense, secondary supplies 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.

Specified Supply – secondary supply that 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 reasonable accuracy. For these sources, three scenarios of future secondary supply are provided for uranium, conversion and enrichment[5].

Unspecified Supply – secondary supply that contains the sources that do not offer an adequate level of predictability in terms of expected time 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. In terms of the limited predictability of this group's material, its degree of mobility is included as a new element in the 2019 edition of *The Nuclear Fuel Report*[6]. Table 2 shows the allocation of secondary supply sources among both groups.

[4] A country-by-country analysis of nuclear programmes is detailed in Section 2.4.2 of *The Nuclear Fuel Report*
[5] Three scenarios of secondary supply for uranium, conversion and enrichment are discussed in detail in Section 4.4 of *The Nuclear Fuel Report*.
[6] The concept of market mobility is discussed in the section 'Nuclear Fuel Report methodology' above and examined in detail in Section 4.2.1 of *The Nuclear Fuel Report*.

Table 2: Secondary supply categorized as Specified and Unspecified supply

Category of secondary supply	Specified sources	Unspecified sources
Major commercial inventories (U_3O_8, UF_6, EUP)		x
Unusable fresh fuel bundles (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. A 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 sources	Marketable forms of secondary materials
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
	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 materials	• 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 materials	Commercial entities (enrichers)		• LEU from irradiated tails (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)[7].

The majority of secondary supplies are 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 categorised as a future potential resource, as, up to now, used fuel in most

[7] Commercial inventories are examined in detail in Section 4.3.1 of *The Nuclear Fuel Report*.

countries remains destined for interim storage rather than for further use in the nuclear fuel cycle in the medium term.

A substantial quantity 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[8]. 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 primarily on back-end policy and the timely availability of the supply chain to process these materials. ERU and MOX fuel developments are therefore influenced only marginally by natural uranium market price levels.

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

The potential for underfeeding enrichment plants is also an important source of secondary supply. In certain circumstances, particularly if enrichment capacity is underemployed as it is today, 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' some surplus uranium which can be sold. In this report, underfeeding is regarded as an additional source of secondary supply as it has become increasingly important 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 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. The concept 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 district that does not have a reprocessing programme.

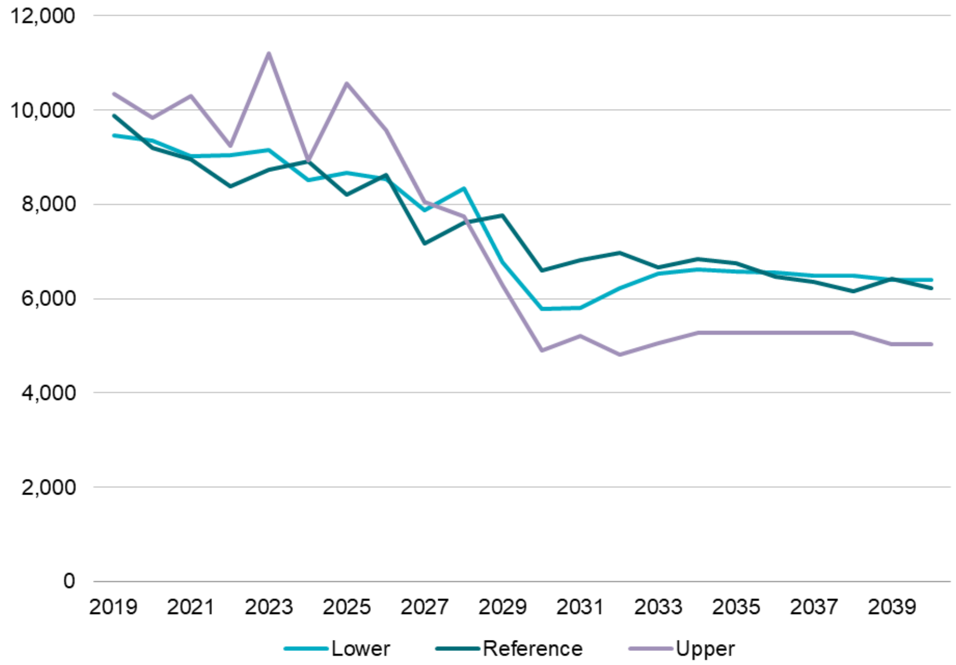
[8] More details about recycling of materials from reprocessing could be found in Section 4.3.6 of *The Nuclear Fuel Report.*

Thus, sources of Unspecified secondary supply can be divided into two major parts:

- 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 supplies for uranium[9] are compared in Figure 5. As can be seen in all scenarios, the share steadily declines to 2040. In the Reference Scenario, secondary supply provides 15% in 2019, 11% in 2025, declining to 8% in 2030 and ending up at 5% in 2040, with shares a few percent higher for the Lower Scenario and a few percent lower for the Upper Scenario.

Figure 5: Secondary supply scenarios for uranium*, tU*



For the near term picture, secondary supplies are currently at a level of around 10,000 tU/yr for all scenarios, slightly declining to 8,000 tU/yr towards 2028 and staying in the range of 5,000 to 7,000 tU/yr from 2030 to 2040.

[9] Three scenarios of secondary supply for conversion and enrichment could be found in Section 4.4 of *The Nuclear Fuel Report*.

5. Uranium supply and demand

5.1. Reactor requirements (uranium demand)

The World Nuclear Association's reactor requirements model was revised for the 2019 edition of *The Nuclear Fuel Report*, with a reassessment of the various factors affecting nuclear fuel demand, such as enrichment levels, characteristics of first core loads and fuel burn-ups. For the first time, fast neutron reactors were included in the model. Capacity factor assumptions, for current and future reactors, were revised and updated using the most recent data.

Forward reactor requirements can be calculated knowing the nuclear generating capacity in operation together with various data about reactor operations and fuel cycle characteristics (*e.g.* load factors, tails assay, burn-up level). This provides a good measure of how much fissile material and fuel cycle services will be required to prepare the fuel to be physically loaded into reactors in a given year. The World Nuclear Association bases its demand projections in this report on such calculations, using data provided by utilities and from other sources about reactor operations and fuel cycle characteristics. Reactor requirements are a measure of the longer-term demand for nuclear fuel. They underpin many of the multiannual supply contracts negotiated in the market. However, current primary uranium production levels and other market activity are not closely related to requirements.

Primary production levels in the short term are much more closely related to expected utility procurements in the next few years. Although utility requirements may also be partly met from other sources, such as inventories held by producers, traders or governments, utility procurement is the main driver of primary production in the short term. For longer-term planning of production levels (*e.g.* decisions on investments in new mines), reactor requirements will be the more important indicator. As this report covers a period of 20 years, reactor requirements are the principal demand measure considered. Whenever the term 'demand' is used, it means 'reactor requirements'.

5.2. Overview of the uranium market

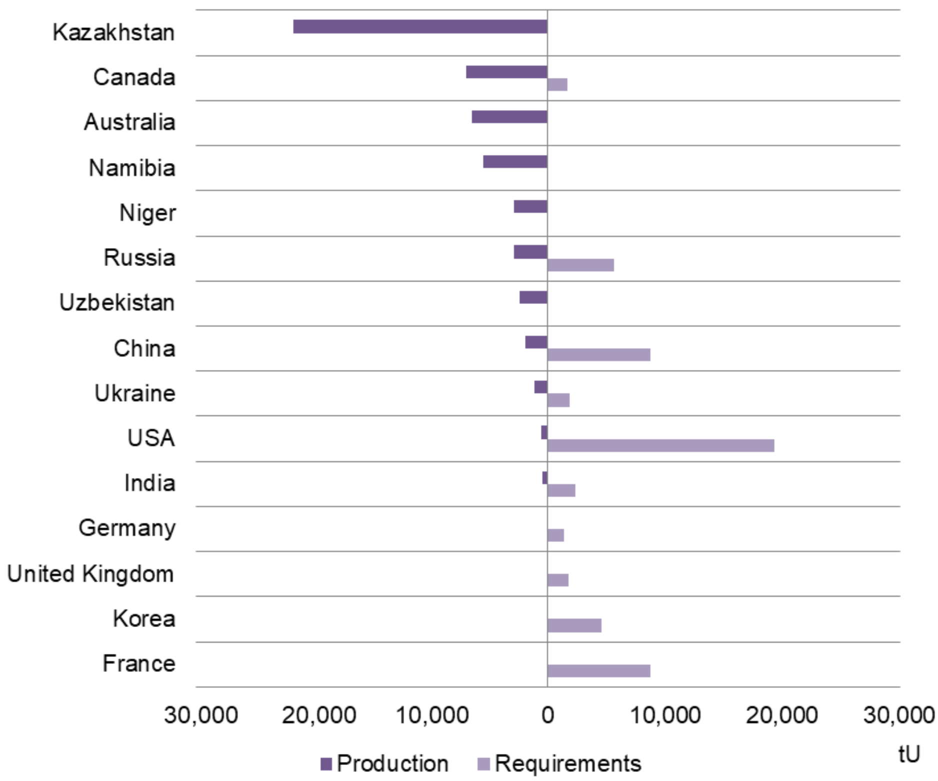
The uranium market is primarily composed of transactions between:

- 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, entering into short-term (spot) or long-term contracts to buy or sell uranium ore concentrate (U_3O_8). However, the main aim of this report is to consider reactor uranium requirements, which is driven by utilities (as the main buyers) and comprises 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 UF_6, 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, as of end 2018, tU



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 some strategic inventory based on their perception of future supply risk. Long-term contract arrangements suit utilities because they know their likely requirements many years in advance. The stability and certainty associated with such arrangements also suit the uranium miners on the other side of the long-term contracts.

World reactor requirements for uranium in 2019 are estimated at about 67,600 tU. In the Reference Scenario, these are expected to rise to 84,850 tU in 2030 and 100,000 tU in 2040. In the Upper Scenario, uranium requirements are expected to be about 103,500 tU in 2030, and 137,600 tU in 2040. These requirements are relatively consistent with those for the same scenarios in the 2017 edition of *The Nuclear Fuel Report* (2019 through 2035). Requirements in the Lower Scenario are on average 10% higher compared than in the 2017 edition.

Geologically established resources of uranium globally are more than adequate to satisfy reactor requirements to well beyond 2040. 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 total resources (26% of the total), with Kazakhstan and Canada having an almost equal resource base, roughly 11% of the total each.

Table 4: Uranium resources by country in 2017, ranked by 2017 total[10], thousand tU

Country	2017 Reasonably assured resources	Inferred resources	Total
Australia	1,401	654	2,055
Kazakhstan	435	470	905
Canada	593	254	846
Russia	260	397	657
Namibia	369	173	541
South Africa	260	190	449
Niger	336	89	426
China	137	154	290
Brazil	156	121	277
Ukraine	138	81	219
India	149	8	157
Uzbekistan	58	82	139
United States	101	NA	101
Others	425	502	926
Total	**4,815**	**3,173**	**7,988**

5.3. Recent uranium production

After peaking in 2016, uranium production then decreased as a result of deteriorating market conditions. This reduction in production was led by Canada, where the biggest mine, McArthur River, was idled at the beginning of 2018, and Kazakhstan, which in 2017-2018 ceased its continuous expansion programme to follow a 'market-centric' approach that reduced production for at least three years. As the existing production centres shut down or idled capacity, as well as reduced production levels, capacity utilization factors fell globally. For example, in October 2017 Areva NewCo (now Orano) announced a 20% reduction of uranium production at its Somair mine in 2018, effectively achieving a 15% reduction of uranium production at both its uranium mines in Niger in 2018.

In aggregate, uranium production showed a decreasing trend over three consecutive years from 2016 through to 2018. The results of these production changes can be seen in Table 5 above. In fact, if McArthur River's nameplate capacity of 9,616 tU/yr were included in the 2018 figures, then the industry capacity utilization would have been an all-time low of 63% instead of 72% (see Table 5).

[10] 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, 2015-2018, ranked by 2018 production, tU

	Production				Nameplate capacity				Capacity utilization			
	2015	**2016**	**2017**	**2018**	**2015**	**2016**	**2017**	**2018**	**2015**	**2016**	**2017**	**2018**
Kazakhstan	23,800	24,576	23,321	21,705	25,640	25,714	29,764	29,764	93%	96%	78%	73%
Canada*	13,313	14,039	13,116	7,001	17,038	16,282	16,538	6,922	78%	86%	79%	100%
Australia	5,654	6,315	5,865	6,517	10,059	7,497	10,655	10,655	56%	84%	55%	61%
Namibia	2,993	3,507	4,224	5,525	5,462	5,654	11,232	9,232	55%	62%	38%	60%
Niger	4,116	3,479	3,448	2,911	4,400	3,600	3,600	3,600	94%	97%	96%	81%
Russia	3,055	3,004	2,916	2,904	4,885	4,885	4,600	4,600	63%	61%	63%	63%
Uzbekistan	2,385	2,404	2,404	2,404	2,400	2,400	3,000	3,000	99%	100%	80%	80%
China	1,616	1,616	1,692	1,885	1,500	1,808	1,808	1,923	108%	89%	94%	98%
Ukraine	1,223	1,005	836	1,180	1,650	1,650	1,650	1,650	74%	61%	51%	71%
USA	1,238	1,125	960	582	7,539	2,780	3,596	1,673	16%	40%	27%	35%
India	385	385	423	423	610	610	610	610	63%	63%	69%	69%
South Africa	393	490	308	346	1,269	1,269	769	769	31%	39%	40%	45%
Others	315	276	116	116	812	812	116	116	39%	34%	100%	100%
Total	**60,486**	**62,221**	**59,629**	**53,498**	**83,264**	**74,962**	**87,939**	**74,514**	**73%**	**83%**	**68%**	**72%**

**McArthur River produced 77tU in 2018, but its capacity is not included in Canada's capacity in 2018. Other idled mines are treated likewise.*

Table 6 shows the top ten uranium mines based on 2018 production results. At least three of these top ten mines (Rössing, Arlit (SOMAÏR) and Ranger), representing 10% of 2018 production, are scheduled/expected to close before the end of the 2020s and will need to be replaced by new mine capacity by then, in order not to cause further reduction of primary uranium production.

Table 6: Ten largest world uranium mines, ranked by 2018 production, tU

Mine	Country	Main owner	Type	tU	% of world
Cigar Lake	Canada	Cameco/Orano	Underground	6,924	12.9
Olympic Dam	Australia	BHP Billiton	By-product	3,159	5.9
Husab	Namibia	Swakop Uranium (CGN)	Open-pit	3,028	5.7
Inkai 1-3	Kazakhstan	Kazatomprom/Cameco	ISR	2,643	4.9
Rössing	Namibia	Rio Tinto	Open-pit	2,102	3.9
Budenovskoye 2	Kazakhstan	Uranium One/Kazatomprom	ISR	2,081	3.9
Tortkuduk	Kazakhstan	Orano/Kazatomprom	ISR	1,900	3.6
Arlit (SOMAÏR)	Niger	Orano	Open-pit	1,783	3.3
Ranger	Australia	Rio Tinto/ERA	Open-pit	1,695	3.2
Kharasan 2	Kazakhstan	Kazatomprom	ISR	1,631	3.0
Others				26,553	49.6
Total				**53,498**	**100**

5.4. Primary uranium supply

The Nuclear Fuel Report describes the worldwide uranium market by balancing the material produced from primary uranium production with the uranium feed requirements for the conversion stage of the nuclear fuel cycle. Any imbalances are addressed in the chapter where secondary supplies are described[11], which captures inventory build-up or depletion, and any uranium substitution impacts from more refined products such as enriched uranium or uranium hexafluoride.

[11] Secondary supplies are examined in Chapter 4 of *The Nuclear Fuel Report*.

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, it is unlikely that uranium producers will continue to produce for long if they are unable to secure customers for their production. When assessing likely future uranium supply, it is important to distinguish between production capacities subject to different levels of uncertainty. The operational or development status of a project is related to the certainty of start-up 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.

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

Current capacity refers to mines already in operation and expected to continue at least into the near future. Production figures for projects included in the current capacity category account for only known reserves reasonably well characterized and included in production planning. These projects may be extended by further exploration and delineation of resources (see Appendix I.1).

Idled current capacity refers to mines that were previously included into the 'current capacity' category, but are now temporarily taken offline for economic reasons and can be brought back online rather quickly, within approximately one year, when market conditions become more favourable. Once restarted, they would be referred to as 'idled-restarted' in future supply-demand aggregated scenarios (see Appendix I.2).

Mines under development refers to mines for which development decisions have been made, financing has been achieved, and mine pre-strip or construction of production or processing facilities has begun (see Appendix I.3).

Planned mines refers to mines for which bankable or definitive feasibility studies have been completed and all major approvals (environmental, social, regulatory, operating) have been achieved (see Appendix I.3).

Prospective mines refers to mines for which some level of feasibility assessment has been completed, *e.g.* scoping study, preliminary economic assessment, preliminary feasibility study (see Appendix I.3).

Reserve mines refers to uncategorized supply positioned to meet future demand. Some examples of supply pipeline possibilities include material from new resource discoveries, development of early stage discoveries, restart of cancelled or deferred projects, re-opening of temporarily closed mines, unexpected mine lifetime extensions and additions of reserves/resources at existing operations. Projects considered to be included into this category have completed technical reports on resources (see Appendix I.4).

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

Three supply-demand scenarios for uranium have been developed, which correspond with the three scenarios for nuclear generating capacity. The three scenarios for uranium supply differ based on discounts to the full capacity levels and delays to the expected start-up dates assuming 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 (y)	Expected utilization	Delay (y)	Expected utilization	Delay (y)	Expected utilization
Current capacity	0	90%	0	95 - 100%	0	85%
Restarted idled capacity	-3	30 - 90%	-2	40 - 100%	-5	30 - 50%
Mines under development	-2	60 - 90%	-2	80 - 100%	-4	30 - 50%
Planned mines	-3	60 - 90%	-2	75 - 100%	0	0%
Prospective mines	-4	50 - 90%	-3	70 - 100%	0	0%

For existing mines, projections of future uranium production for approximately 90% of them are derived from either official company announcements or from the questionnaire responses received by the Association at the beginning of 2019. As a result, for the scenarios, the utilization factors are applied to current capacities rather than using nameplate capacities.

In addition, dynamic utilization factors are introduced in this report for the first time. These 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 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 finally remain at the upper limit in the years beyond 2035.

Three scenarios for uranium production to 2040 have been developed by evaluating current and future mine production capabilities. Based on this report's methodology, production volumes are projected to remain fairly stable until the late 2020s in all three scenarios, then decrease sharply in the last five years of the forecasting period, mainly due to the end of production life of a quarter of all mines listed in the model, resulting in a 30% decrease of uranium production over the five-year period (2035 through to 2040).

Figure 7: Reference Scenario supply, tU

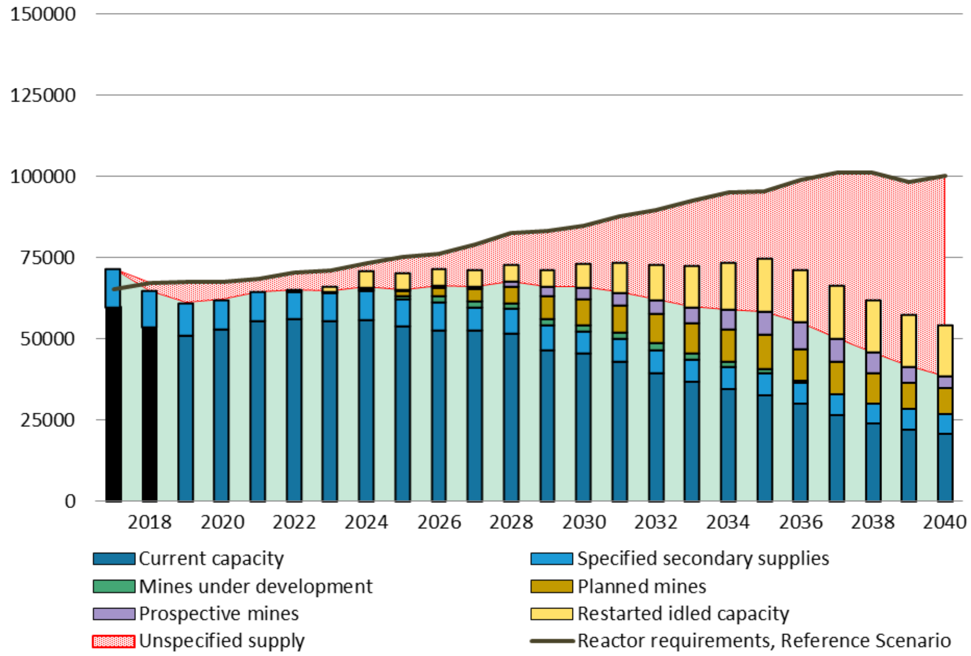
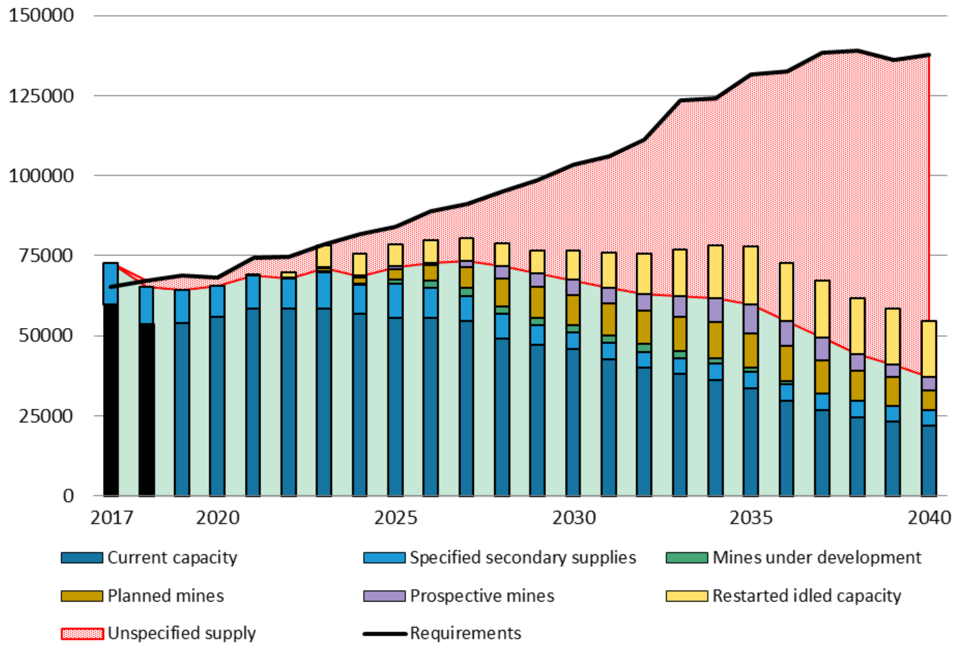
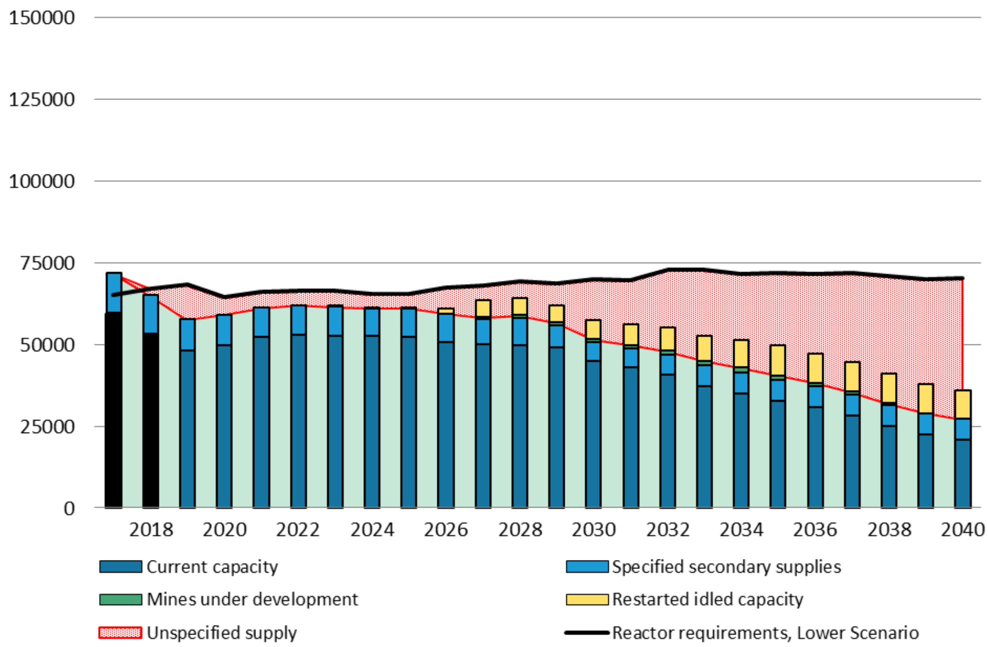


Figure 8: Upper Scenario supply, tU



In the Reference case, world uranium production is expected to be 66,400 tU in 2030 before declining to 48,100 tU in 2040. In the Upper case, the equivalent figures are 71,500 tU and 49,400 tU, respectively. The partial return of idled mines to production is expected to commence in 2022 and in 2023 in the Upper and the Reference Scenarios, respectively, and in 2026 in the Lower case.

Figure 9: Lower Scenario supply, tU



5.5. Unspecified uranium supply

As a new component of this edition of the report, the concept of 'unspecified supply' is being used to characterize the material that will fill the gap between identified supply sources (both primary 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 potential supply that will compete for market access; however, the conditions necessary to achieve such market access differ according to each source of potential supply.

The following supply sources are included in unspecified supply:

- Unspecified secondary supplies.
- Idled production capacity.
- Expansion of production capacity.
- Reserve projects.

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 Supplies

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

- Major commercial inventories (U_3O_8, UF_6, EUP),
- Unusable fresh fuel bundles (EUP),
- Other 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 are characterized by having declining degrees of mobility, with commercial inventories being the most available and others having higher technical thresholds and longer times to reach the market[12].

Idled Production Capacity

To date, the depressed market conditions have resulted in substantial closures of existing capacity – almost 18,000 tU/yr. Cameco placed Rabbit Lake mine and its US ISR operations (Smith Ranch, Highland, and Crowe Butte) on care and maintenance in 2016. Furthermore, in 2018 Cameco ceased production at McArthur River mine, the largest uranium mine worldwide with production of 6,945 tU U_3O_8 in 2016. In 2017-2018 production was also suspended at Langer Heinrich mine in Namibia, and at several other mines in the USA: Willow Creek, White Mesa and Alta Mesa.

[12] Various sources of secondary supplies are examined in Section 4.3 of *The Nuclear Fuel Report*.

Idled production capacity consists of previous production capacity that has voluntarily been removed from the market as a result of market fundamentals or economic conditions. It differs from shutdown operations, as the production facility remains available for redeployment under conditions that meet the requirements of their owners and the unique aspects of each of the sites.

For uranium production facilities, idled production capacity implies that there are significant reserves and/or resources remaining and an operating licence is either still in place or can be received in short order. For fuel cycle facilities, idled production implies that the facility also has an existing operating licence and has been moved into care and maintenance, is operating below nominal production rates, its capacity has been redeployed for purposes other than its intended use, or otherwise has existing capacity available for production.

In general, idled production capacity exists as a result of economic (market prices versus production costs) or market (oversupply) conditions being unfavourable to continue production at its previous level or at all.

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 being achieved.

For production facilities that do not produce uranium, 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.

Reserve Projects

The final component of unspecified supply is Reserve projects (See Table 9). These consist of uncategorized supply required to meet future demand and are 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’ mines 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. They are included in the ‘unspecified supply’ category since they currently do not have publicly available startup dates and other qualifying criteria.

Reserve projects for all fuel cycle components require particular market conditions to be in place in order to support their development, not the least of which is for a 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 (namely commercial inventories), followed by the return of idled capacity, followed by expansions at existing production facilities, and finally, reserve projects.

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) and the lowest cost idled capacity 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 either bring back additional idled capacity, expand production capacity, and/or advance reserve projects.

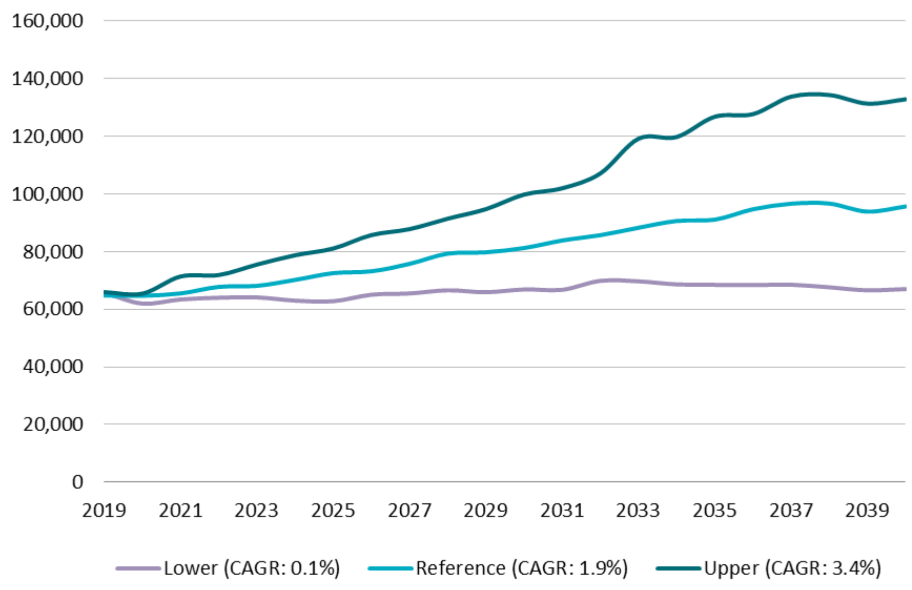
6. Conversion supply and demand

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.

The uranium conversion sector is characterized by a small number of companies producing UO_2 for those reactors fuelled with natural uranium and UF_6 for those using enriched uranium. For the last eight years the market was in oversupply caused by reduced conversion requirements and the accumulation of sizeable UF_6 stockpiles.

In contrast to conversion capacities which have been drastically reduced, conversion requirements show an upward trend, both in the Reference and in the Upper Scenarios, with requirements broadly stable in the Lower Scenario.

Figure 10: UF_6 conversion requirement scenarios to 2040, tU



Today, annual primary production is far lower than annual conversion requirements.

As a result of weaker demand and excess inventories, in the last five years, four primary producers have either reduced (Cameco) or suspended production at their conversion facilities (ConverDyn), or closed permanently (Springfields Fuels and two out of three Rosatom facilities), while only one new conversion plant (Orano's Philipe Coste) has come online – to replace equivalent shuttered capacity at the same site.

Identified idled capacity among the primary Western converters is listed in Table 8.

Table 8: Idled conversion production capacity, tU

Company	Conversion facility	Estimated idled Capacity
ConverDyn	Metropolis	7,000
Cameco	Port Hope	2,500
Total		**9,500**

In deriving a worldwide supply and demand Reference Scenario 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 35% of nameplate capacity but this will increase to 70-85% on average.
- Springfields Fuels will remain shutdown.
- Orano, which is transitioning to the new Philippe Coste plant, will have a production ramp-up period within the next three years.
- 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 2019 onwards.

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

Figure 11: Reference Scenario global UF_6 conversion supply and demand, tU

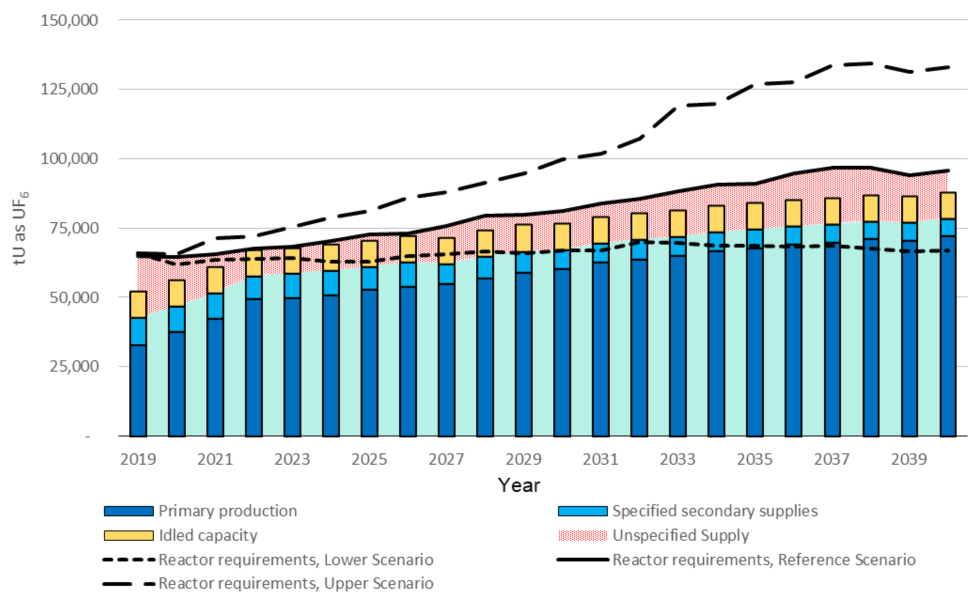


Figure 11 demonstrates that supply will need to rise to meet growth in demand in both the Reference and Upper Scenarios. Unspecified supply is deemed to satisfy this gap between identified supply sources and the demand line.

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 currently make up the balance of supply between existing primary supply and demand.

As growth in demand occurs and inventories are depleted, additional unspecified supply is needed to meet it. As low-mobility secondary supplies encounter limitations to market access, it is likely that the return of at least some of significant existing idled capacity (see Table 8) will meet this growth in demand.

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

However, it is uncertain that the combination of Unspecified secondary supplies and idled capacity would satisfy the growing demand over the forecast horizon, and construction of additional primary conversion capacity may be necessary. This hypothesis would materialize either: in the 2030-2040 time period under the Reference and Upper Scenarios for demand; or if an existing conversion facility would be prevented from producing as expected (a risk that may increase with the age of current facilities). This would require expansion of capacity at existing facilities or the construction of new conversion facilities.

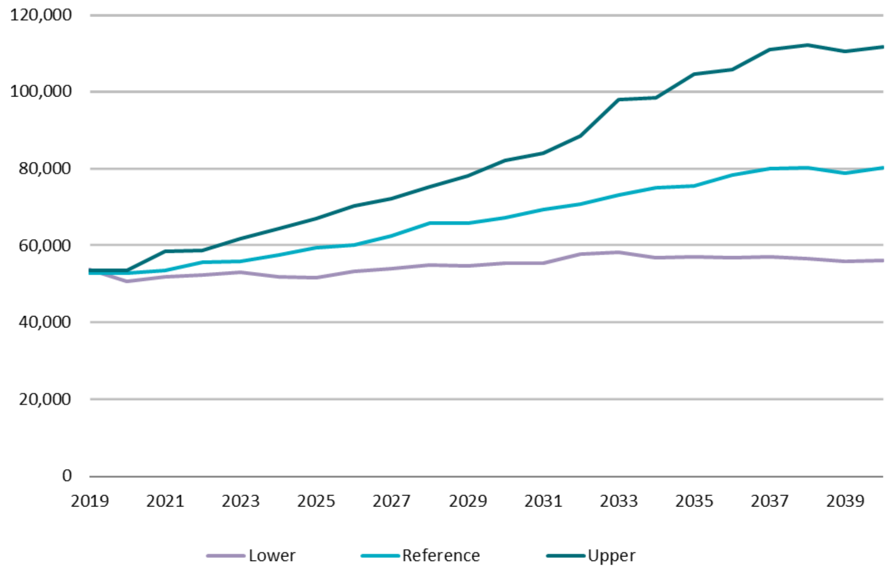
7. Enrichment supply and demand

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-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, the World Nuclear Association has assumed a tails assay of 0.22%[13] for determining global SWU requirements. The tails assay assumption is held constant for all years and all demand scenarios for nuclear generation. The 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.

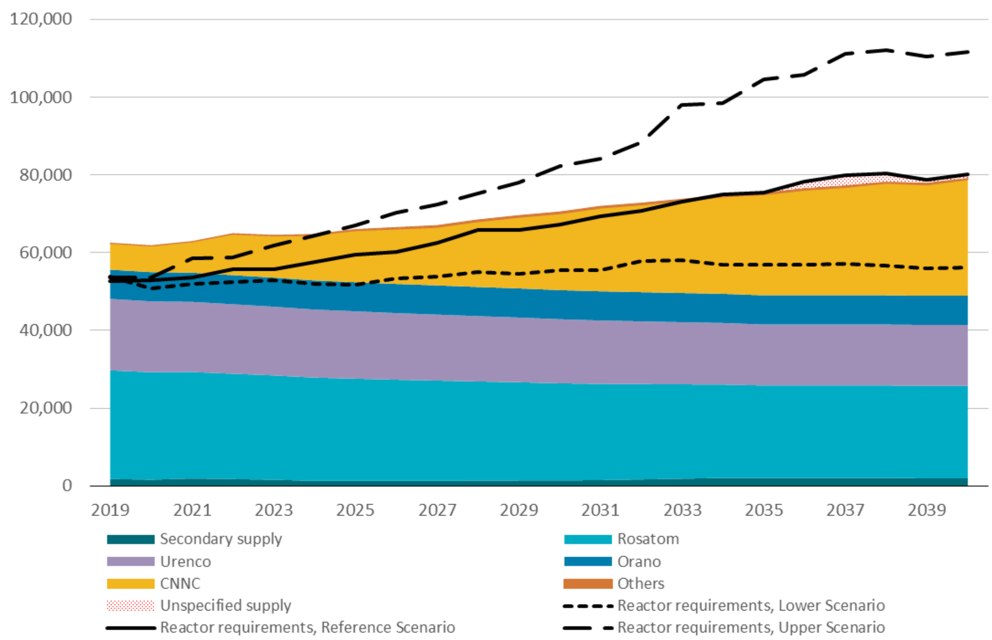
[13] Chapter 3 of *The Nuclear Fuel Report* explains why tails assay assumptions must be closely examined.

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 showing an increasing deficit in the supply of SWU, which is insufficient for the Reference Scenario enrichment demand beyond 2033-2034.

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



Excess global enrichment capacity has resulted in the extensive use of existing capacity for underfeeding and tails re-enrichment. Currently the global enrichment capacity used for underfeeding and tails re-enrichment is estimated in the region of 5,000-7,000 tonnes of natural uranium equivalent, depending on the scenario, declining steeply by the end of 2020s.

Of the major suppliers of enrichment services, CNNC will be the only one to significantly expand its capacity over the forecast period due to the Chinese target of achieving self-sufficiency. The three other major suppliers will not need to expand their capacity through to 2040 in the Reference Scenario. In the Upper Scenario, additional capacity might be needed as early as in the first half of the next decade. However, given the modular nature of centrifuge technology and the construction times for nuclear power reactors, enrichment capacity expansion can take place in a timely way, and supply challenges should be avoided.

8. Fuel fabrication supply[14] 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 to the other three front-end fuel cycle businesses (mining, conversion and enrichment) as nuclear fuel is not a fungible commodity but a hi-tech product accompanied by specialist support.

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

- Designers have both design and manufacturing capabilities, integrated with a reactor original equipment manufacturer (OEM). Designers are the main fuel vendors nowadays. As reactor vendors, they often supply the initial cores and early reloads for reactors, built to their own designs.
- Manufacturers have manufacturing capabilities only, with commercial and export activities. In the regions, manufacturers are also represented by smaller local manufacturers, which mainly act on the local markets to supply domestic demand only and usually are not present on 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 by fuel type.

Segment 1, by reactor type:

- Light water reactor (LWR) sub-categories:
    - 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) introduced in this report for the first time.

This categorization does not, however, adequately 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

[14] Fuel fabrication primary supply is analyzed in Section 8.4 of *The Nuclear Fuel Report*.

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 sub-categories of fuel assembly design.

Those sub-categories depend in particular on the reactor OEM and the fuel assembly structure (fuel assembly array, number of fuel rods, positioning of guide tubes), the main one being the PWR17 encompassing Westinghouse, Framatome, and the newly-introduced Kvadrat-fuel of the Russian design. Chinese vendors are also working on their proprietary PWR17 designs such as CNNC's CF3 or CGN's STEP12 fuel assemblies.

Other PWR designs worldwide include: PWR14, PWR15, PWR16, CE14, CE16, KWU15x15, 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 as PWR fuel, the assemblies have hexagonal cross-sections. VVER fuel assemblies are manufactured by Rosatom and Westinghouse and have several designs: VVER-440, VVER-600, 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 plant.

CANDU/PHWR 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 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. 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.

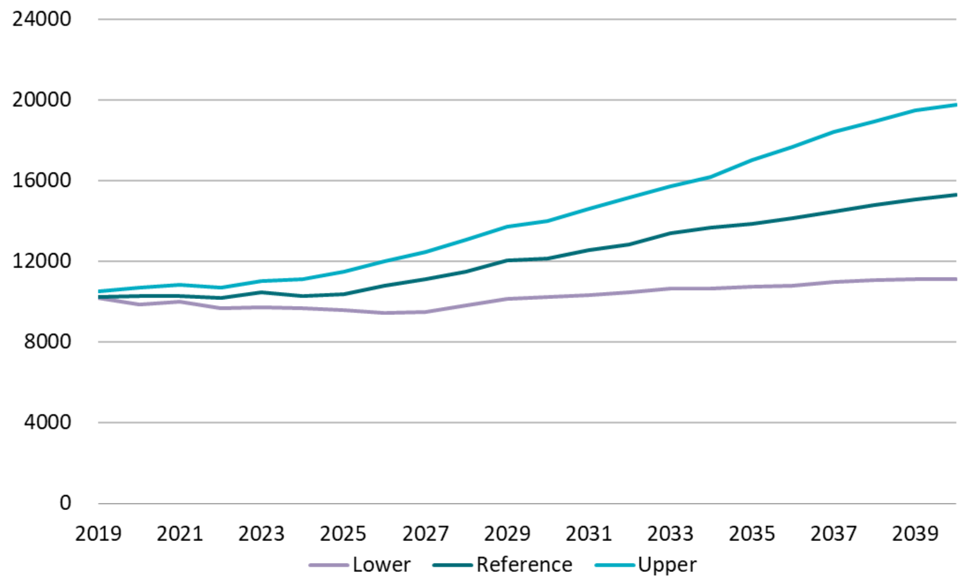
The overwhelming majority of world demand remains for reloads rather than first cores (which have different specifications to reloads).

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

Projections are made both for reload demand and first core demand. As well as the assessment of the global and regional fabrication requirement trends, reload requirement projections according to fuel type are also analysed. 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 type of reactor will be constructed.

Figure 14 shows the projection of global reload fabrication demand for all fuel designs[15], including LWRs, PHWRs, AGR, RBMK and unknown fuel. Whilst there is little change to overall demand before 2024, steady increases appear from around 2025 in all three scenarios, albeit 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, fabricators usually provide onsite services for utilities. To simplify the data presented in this chapter, reactor requirements are combined into four large 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 (African and Arabic countries, Iran, Turkey, Kazakhstan and Uzbekistan).

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

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[15] Regional reload demand by fuel type (PWR17, BWR, VVER, etc.) is illustrated in Section 8.3.2 of *The Nuclear Fuel Report.*

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

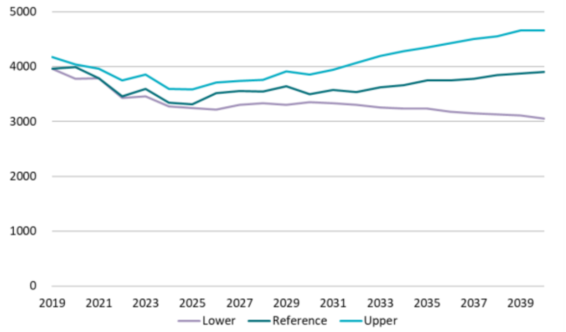


Figure 16: Reload requirement scenarios to 2040, Europe, tHM

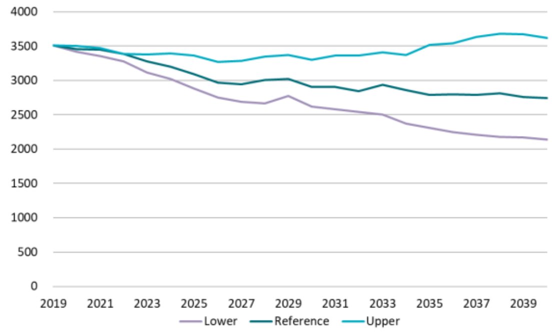


Figure 17: Reload requirement scenarios to 2040, Asia, tHM

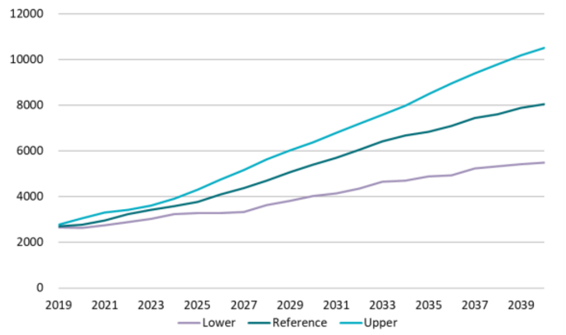
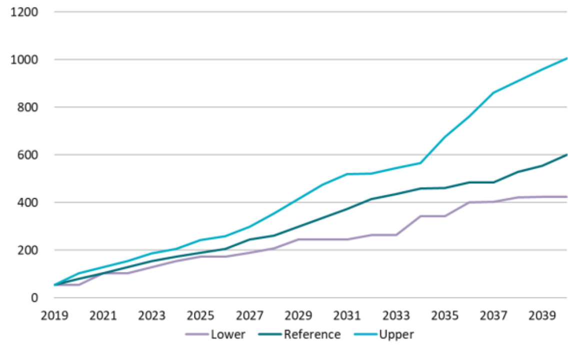


Figure 18: Reload requirement scenarios to 2040, Africa, Middle East and Central Asia, tHM



In the Americas region (see Figure 15), although a decline is expected before 2025, demand then exhibits an upward trend in the Reference and Upper Scenarios, while in the Lower case the downward trend is relatively slow from 2025.

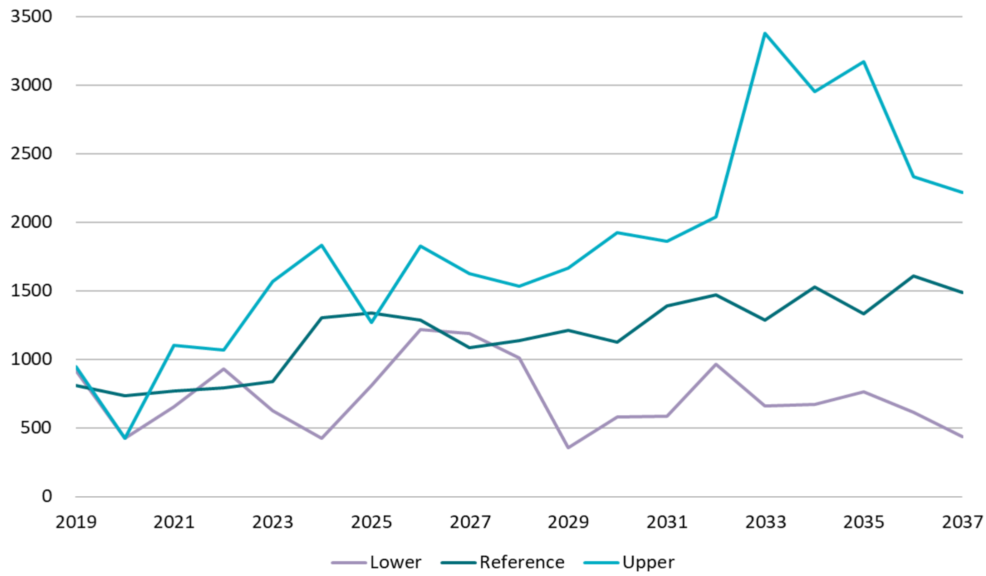
In Europe (see Figure 16), while the fuel demand is fairly stable in the Upper Scenario, declines are expected in both Lower and Reference Scenarios, which are largely caused by the expected closures of RBMK reactors in Russia and AGR reactors in the UK.

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 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 1,000 tHM/yr in the Lower, Reference and Upper Scenarios.

The expected first core fabrication demand for the three demand scenarios is 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



First cores are assumed to be required two years in advance of a reactor start-up. 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.

At present, existing fuel fabrication capacities are sufficient to cover anticipated demand for both first cores and reloads; however, in some circumstances it is still possible that supply bottlenecks could occur for certain designs.

9. Key findings of The Nuclear Fuel Report

9.1. Uranium

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

The most recent (2018 edition) Red Book highlighted that global uranium exploration mine development expenditures fell by 69% from $2.12 billion in 2014 to $663.7 million in 2016. 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 a solid 1.9% compound average growth rate (CAGR), mainly resulting from nuclear expansion in the Far East, driving uranium requirements to over 80,000 tU/yr within the next decade. The Upper Scenario doubles uranium requirements within 15 years with demand growth of 3.4% CAGR. The Lower Scenario provides a solid baseline as existing reactors support the currently-operating production facilities

Several mines are expected to be closed before the end of the 2020s due to resource depletion and will need to be replaced by either the restarting of idled capacity or launching of new projects.

Regardless of the particular scenario (Reference, Upper or Lower), in the long term the industry needs to at least double its infrastructure of current, idled, under development, planned and prospective projects by 2040. Undoubtedly there are more than adequate project extensions, uranium resources and reserve projects in the pipeline to accomplish this.

However, the issue remains that, due to current oversupply and associated low market prices, very few participants are able or willing to begin investing to convert these resources into reserves and ultimately into mines to keep the market in balance. Some state-owned strategic developments are proceeding, but there continues to be a lack of long-term fixed-price contracts, which are needed to underpin new projects controlled by market-based companies.

9.2. 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 from the current level of about 10,000 tU/yr to 5,000-7,000 tU/yr from the beginning of the 2030s. Besides the secondary supply that can be quantified, a large amount of unspecified secondary supply exists, which includes 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 re-sale. 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 are playing an increasingly important role in the market, as many participants try to benefit from the current low prices of uranium and enrichment, increasing their stockpiles.

9.3. Conversion

The most likely scenario for conversion supply and demand remains as follows:

- In the near term, highly mobile secondary supplies will bridge the gap between new primary supply and demand (such as in the case today where fuel buyers rely heavily on inventory to meet demand).
- In the medium term, it is expected that idled capacity will return as the demand side of the market requires.

- In the long term, it is possible that the market will require capacity expansion at existing facilities or even the construction of new conversion plant.

For expansion of primary conversion capacity or new projects to be economically justified before 2030, either:

- The most optimistic demand scenario must occur.
- The return of idled capacity, when required over the medium 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 *The Nuclear Fuel Report* is characterized by a heavy reliance and corresponding reduction in inventories as a result of a curtailment of primary conversion production. After these inventories are exhausted over the near to medium term, the market should incentivize the restart of idled capacity, and potentially the expansion or construction of a new conversion plant.

9.4. Enrichment

Enrichment requirements are expected to rise over the projection period from 2019 to 2040 due to prospective new nuclear build, primarily in Asian and Middle Eastern countries, particularly China and India. However, production capacities appear to be sufficient to cope with demand. Moreover, as a result of the current market oversupply, the major suppliers have delayed, postponed or abandoned the new SWU projects that were featured in earlier editions of *The Nuclear Fuel Report*.

The enrichers are also trying to reduce existing capacity by not replacing centrifuges that have reached the end of their operation. Excess global enrichment capacity is used for underfeeding and tails re-enrichment, which results in an annual gain of approximately 5,000-7,000 tUeq.

9.5. Fuel fabrication

The fuel fabrication market differs significantly from other stages of nuclear fuel cycle due to the specificity of the product: fuel assemblies are highly engineered and technological products. Moreover, the market itself is more regional in character than global. In addition, the fuel supply should be split into reloads and first cores, with their own specific characteristics. As a result, the market should be segmented both regionally and technologically, thus leading to a more complex analysis.

The fuel fabrication market has historically shown strong competition among different vendors and manufacturers, either regional or national fuel suppliers. World fuel fabrication capacity outweighs global requirements and this conclusion can be mostly applied at a regional level. Also, with nuclear fuel demand increasing in Asia and decreasing in the West, fuel vendors are likely to shift from a regional to a global market approach. This would help to balance the supply-demand equilibrium, increase competition and enhance security of supply.

10. 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. The *Harmony* goal is for nuclear energy to provide at least 25% of electricity by 2050.

The Nuclear Fuel Report scenarios are based on an 'outlook' approach which projects potential development from 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 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 *Harmony* goal would require a tripling of nuclear generation from its present level. This equates to 1250 GWe of total nuclear capacity in 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, which is comparable to that already achieved in the 1980s.

Achieving the *Harmony* goal would mean that there were more reactors than outlined in the Upper Scenario. Unless there is also a radical transformation in reactor technology during that time frame, 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 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 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.

Appendix tables: Existing and prospective primary uranium supply by project

Table I.1: Existing mines at nameplate capacity as of the end of 2018

Country		Mine	Type	Operator	Capacity (tU)	
					By mine	By country
African countries	Namibia	Husab	Open-pit	Swakop Uranium (CGN)	5,770	13,601
		Rössing	Open-pit	Rio Tinto	3,462	
	Niger	Arlit (SOMAÏR)	Open-pit	Orano	2,200	
		Akouta (COMINAK)	Underground	Orano	1,400	
	South Africa	Vaal River Region	By-product	Harmony Gold	769	
Australia		Ranger	Open-pit	Rio Tinto/ERA	4,616	10,655
		Olympic Dam	By-product	BHP Billiton	4,500	
		Four Mile	ISR	Quasar	1,539	
Canada		Cigar Lake	Underground	Cameco	6,922	6,922
Kazakhstan		Inkai 1-3	ISR	Inkai JV	4,000	29,764
		Katco (Moinkum, Tortkuduk)	ISR	Katco JV	4,000	
		Budenovskoye 2	ISR	Karatau JV	3,200	
		Central Mynkuduk	ISR	Ortalyk	2,000	
		Kharasan 1	ISR	Khorassan-U JV	2,000	
		South Inkai 4	ISR	SMCC JV	2,000	
		Budenovskoye 1, 3 & 4	ISR	Akbastau JV	1,931	
		Kharasan 2	ISR	Baiken JV	1,530	
		Semizbai	ISR	Semizbai-U	1,200	
		Akdala	ISR	SMCC JV	1,000	
		Eastern Mynkuduk	ISR	SaUran	1,000	
		Kanzhugan (including Kainar)	ISR	SaUran	1,000	
		Karamurun, North and South	ISR	RU-6	1,000	
		Western Mynkuduk	ISR	Appak JV	1,000	
		Zarechnoye	ISR	Zarechnoye JV	970	
		Moinkum 1,3 (Central)	ISR	SaUran	900	
		Irkol	ISR	Semizbai-U	731	
		Uvanas	ISR	SaUran	300	
Russia		Priargunsky 1, 8	Underground	ARMZ	3,000	4,600
		Khiagda	ISR	ARMZ	1,000	
		Dalur	ISR	ARMZ	600	
USA		Nichols Ranch-Hank	ISR	Energy Fuels	577	1,673
		Lance	ISR	Peninsula	442	
		Lost Creek	ISR	Ur-Energy	385	
		White Mesa mines	Underground	Energy Fuels	269	
Uzbekistan		Navoi Mining	ISR	Navoi	3,000	3,000
Other	China	Domestic use	ISR & conventional	CNNC	1,923	4,299
	India	Domestic use	Underground	UCIL	610	
	Iran	Domestic use	Underground	Iran (Gachin)	71	
	Pakistan	Domestic use	Underground	PAEC	45	
	Ukraine	VostGOK mines	Underground	VostGOK	1,650	
World total						**74,514**

Table I.2.: Idled mines at nameplate capacity as of the end of 2018

Country	Mine	Type	Operator	Capacity (tU) By mine	Capacity (tU) By country
Namibia	Langer Heinrich	Open-pit	Paladin/CNNC	2,000	2,000
Australia	Honeymoon (SX plant)	ISR	Boss Resources	338	338
Canada	McArthur River/Key Lake	Underground	Cameco	9,616	11,924
	Rabbit Lake	Underground	Cameco	2,308	
USA	Cameco US ISR (Smith Ranch, Crow Butte, Highland)	ISR	Cameco	1,923	3,577
	Alta Mesa	ISR	Energy Fuels	577	
	White Mesa (Tony M, Daneros, Whirlwind)	Conventional	Energy Fuels	577	
	Willow Creek (Irigaray & Christensen Ranch)	ISR	Uranium One	500	
World total					**17,840**

Table I.3: Mines 'under development', 'planned' and 'prospective' mines, estimated capacity

Mines under development						
Country		**Project/Mine**	**Type**	**Operator**	**Estimated capacity (tU)**	**Startup**
Russia		Priargunsky No 6	Underground	ARMZ	2,300	2023
USA		Canyon	Open-pit	Energy Fuels	385	2020
Other	Brazil	Cachoeira	Underground	INB	340	2023
	Brazil	Engenho	Open-pit	INB	300	2019
World total					**3,325**	

Planned mines						
Country		**Project/Mine**	**Type**	**Operator**	**Estimated capacity (tU)**	**Startup**
African countries	Namibia	Etango	Open-pit	Bannerman Resources	4,231	2024
	Tanzania	Mkuju River	Open-pit	Uranium One	3,513	2025
Australia		Mulga Rock	Open-pit	Vimy Resources	1,346	2021
		Honeymoon (IX plant)	ISR	Boss Resources	931	2021
Other	Brazil	Santa Quiteria	By-product	INB	1,346	2023
	Spain	Salamanca	Open-pit	Berkeley Resources	1,692	2021
World total					**13,060**	

Prospective mines						
Country		**Project/Mine**	**Type**	**Operator**	**Estimated capacity (tU)**	**Startup**
Mauritania		Tiris	Open-pit	Aura	385	2020
Australia		Angularli	Open-pit	Vimy Resources/Rio Tinto	769	2025
Canada		Wheeler River/Gryphon	Underground	Denison Mines	3,462	2024
		Wheeler River/Phoenix	ISR	Denison Mines	2,308	2030
Russia		Elkon	Underground	ARMZ	5,000	2035
USA		White Mesa (Roca Honda, Bullfrog)	Conventional	Energy Fuels	2,000	2024
		Sheep Mountain	Heap Leach	Energy Fuels	577	2025
Other	Finland	Talvivaara	By-product	Terrafame	250	2020
	Greenland	Kvanefjeld	By-product	Greenland Minerals and Energy	385	2021
World total					**15,135**	

Table I.4.: Reserve projects, estimated capacity

Reserve projects					
Country		**Project/Mine**	**Type**	**Operator**	**Estimated capacity (tU)**
African countries	Namibia	Trekkopje	Open-pit	Orano	3,200
	Niger	Imouraren	Open-pit	Orano	5,000
		Dasa	Open-pit	Global Atomic Fuels	2,154
		Madaouela	Underground	GoviEx	1,000
		Azelik/Teguida	Open-pit	CNNC	692
	Malawi	Kayelekera	Open-pit	Paladin	1,269
	South Africa	Ezulwini (Cooke 4)	By-product	Sibanye-Stillwater	500
Australia		Yeelirrie	Open-pit	Cameco	2,968
		Kintyre	Open-pit	Cameco	2,308
		Valhalla/Mount Isa	Open-pit-Underground	Paladin	1,923
		Westmoreland	Open-pit	Laramide Resources	1,539
		Wiluna	Open-pit	Toro Energy	695
		Manyingee	ISR	Paladin	385
Canada		Patterson Lake South (PLS)	Open-pit/ underground	Fission Uranium	5,000
		Arrow	Underground	NexGen	5,000
		Nunavut (Kiggavik)	Conventional	Orano	3,000
		Millennium	Underground	Cameco	2,500
		Shea Creek	Underground	Orano	2,500
		Michelin	Open-pit/ underground	Paladin	1,923
		Midwest	Open-pit	Orano	1,500
Kazakhstan		Zhalpak	ISR	Ortalyk	500
USA		Cameco US ISR expansion	ISR	Cameco	615
		Reno Creek	ISR	UEC	577
		Church Rock/Crownpoint	ISR	Laramide Resources	385
		Hobson (Palagana, Burke Hollow, Goliad)	ISR	UEC	385
Other	India	Kyelleng-Pyndengsohiong, Mawtahbah (KPM)	Open-pit	UCIL	340
		Gogi	Underground	UCIL	130
		Lambapur-Peddagaltu	Underground	UCIL	130
	Mongolia	Zoouch Ovoo	ISR	Orano	2,050
	Peru	Macusani	Open-pit	Plateau Uranium	2,300
	Turkey	Temrezli	ISR	Westwater Resources	308
World total					**52,777**

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This Expanded Summary of the *The Nuclear Fuel Report: Global Scenarios for Demand and Supply Availability 2019-2040* covers the main findings and conclusions of the 2019 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 19th 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.

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