Nuclear Technology Development and Economics
2024

High-Assay Low-Enriched Uranium

Drivers, Implications and Security of Supply

OECD
BETTER POLICIES FOR BETTER LIVES

NEA
NUCLEAR ENERGY AGENCY

Nuclear Technology Development and Economics

High-Assay Low-Enriched Uranium: Drivers, Implications and Security of Supply

NEA No. 7685

NUCLEAR ENERGY AGENCY
ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

The OECD is a unique forum where the governments of 38 democracies work together to address the economic, social and environmental challenges of globalisation. The OECD is also at the forefront of efforts to understand and to help governments respond to new developments and concerns, such as corporate governance, the information economy and the challenges of an ageing population. The Organisation provides a setting where governments can compare policy experiences, seek answers to common problems, identify good practice and work to co-ordinate domestic and international policies.

The OECD member countries are: Australia, Austria, Belgium, Canada, Chile, Colombia, Costa Rica, Czechia, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Israel, Italy, Japan, Korea, Latvia, Lithuania, Luxembourg, Mexico, the Netherlands, New Zealand, Norway, Poland, Portugal, the Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Türkiye, the United Kingdom and the United States. The European Commission takes part in the work of the OECD.

OECD Publishing disseminates widely the results of the Organisation's statistics gathering and research on economic, social and environmental issues, as well as the conventions, guidelines and standards agreed by its members.

NUCLEAR ENERGY AGENCY

The OECD Nuclear Energy Agency (NEA) was established on 1 February 1958. Current NEA membership consists of 34 countries: Argentina, Australia, Austria, Belgium, Bulgaria, Canada, Czechia, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Korea, Luxembourg, Mexico, the Netherlands, Norway, Poland, Portugal, Romania, Russia (suspended), the Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Türkiye, the United Kingdom and the United States. The European Commission and the International Atomic Energy Agency also take part in the work of the Agency.

The mission of the NEA is:

- to assist its member countries in maintaining and further developing, through international co-operation, the scientific, technological and legal bases required for the safe, environmentally sound and economical use of nuclear energy for peaceful purposes.
- to provide authoritative assessments and to forge common understandings on key issues as input to government decisions on nuclear energy policy and to broader OECD analyses in areas such as energy and the sustainable development of low-carbon economies.

Specific areas of NEA competence include the safety and regulation of nuclear activities, radioactive waste management, radiological protection, nuclear science, economic and technical analyses of the nuclear fuel cycle, nuclear law and liability, and public information. The NEA Data Bank provides nuclear data and computer program services for participating countries.

Cover photos: Globe (Mahesh Patil/Shutterstock); Pipeline (e-crow/Shutterstock).

Foreword and acknowledgements

Interest in nuclear energy as a baseload, low-carbon source of power is growing as countries around the world strive to cut carbon emissions and maintain energy security. While established nuclear technologies are a big part of this, new advanced designs such as small modular reactors (SMRs) are quickly gaining favour. Many of these innovations will run on new types of fuel, particularly high-assay low-enriched uranium, which is enriched to a higher level than current commercial nuclear fuel.

The Nuclear Energy Agency (NEA) is working with its member countries on questions related to securing a stable supply of such fuel as well as on the various policy matters this can raise in terms of safety, security, regulation, markets and technology. Production of HALEU is currently very limited in OECD countries, so developing conversion, enrichment and deconversion capacities for these particular types of fuels will be of strategic interest for nations that want a leading role in advanced nuclear technologies.

This report examines the fundamental drivers motivating the use of HALEU fuel in advanced nuclear technologies and SMRs today. It aims to provide an informed overview of the implications of using HALEU fuels in the nuclear fuel cycle, highlighting areas for further consideration to guide decision makers through this evolving sector. It explores, among other things, the impact of HALEU usage on fuel cycle requirements for some SMR concepts being developed today, particularly concerning natural uranium resources. It underscores the need for new infrastructure, the benefits of international co-operation to create markets, harmonise regulations and share best practices, and the need to consider back-end waste management. This includes developing experimental qualification platforms and benchmarking initiatives that may prove necessary for licensing various HALEU fuel types.

Dr Franco Michel-Sendis, Nuclear Technology and Fuel Cycle Specialist, of the Division of Nuclear Development and Economics, NEA, was the lead author and co-ordinator of this report.

Ms Diane Cameron, Head of the Division of Nuclear Development and Economics, and Mr Nick Sherman, Deputy Head of the Division of Nuclear Development and Economics provided effective managerial oversight and valuable input.

This report also benefited from the input and review of NEA Divisions of Radioactive Waste Management (RWMD), in particular through the contribution of Ms Una Baker, and Nuclear Science and Education (SCI), in particular through the contribution of Ms Michelle Bales.

List of abbreviations and acronyms

ATF	Accident-tolerant fuel
DU	Depleted uranium
EUP	Enriched uranium product
HALEU	High-assay low-enriched uranium
HEU	High enriched uranium
HMI	Heavy metal initial
HTGR	High-temperature gas-cooled reactors
IAEA	International Atomic Energy Agency
LFR	Lead-cooled fast reactors
LEU	Low-enriched uranium
LWR	Light water reactor
MOX	mixed oxide fuel
MSR	Molten salt reactors
NEA	Nuclear Energy Agency
NU	Natural uranium
OECD	Organisation for Economic Co-operation and Development
SFR	Sodium-cooled fast reactors
SMR	Small modular reactor
SWU	Separative work units
TRISO	Tristructural isotropic
WGFS	Working Group on Fuel Safety (NEA)

Table of contents

List of appendices

List of figures

List of tables

Executive summary

The challenge of achieving net zero by mid-century has reasserted the importance of nuclear energy in global policy discussions as a key contributor to a decarbonised energy mix. Over 20 nations are now calling for global installed nuclear energy capacity to triple by 2050. NEA analysis of the pathways to net zero considered by the UN Intergovernmental Panel on Climate Change found that, on average, they foresee a tripling in nuclear installed capacity, from around 400 GWe in 2020 to nearly 1 200 GWe by 2050 to reach net zero emissions (NEA, 2022).

The effort to attain such strong growth has led to an increase in the use of existing nuclear technologies, with refurbishments, long-term operations of existing reactors and the construction of new large-scale reactors. It has also sped up the development of numerous innovative nuclear technologies, with small modular reactors (SMRs) and Generation IV modular reactors emerging as a credible, even game-changing, tool to enable various low-carbon power and non-power applications. These applications include providing high-temperature process heat for industrial production, microreactors for off-grid applications, and propulsion for transport solutions ranging from marine to space.

Many of the current SMR concepts that incorporate advanced nuclear technology, particularly Generation IV technologies, propose to use high-assay low-enriched uranium (HALEU), which is defined as enriched uranium with a proportion of the fissile isotope uranium-235 (U-235) that is higher than today's commercial fuel but below 20%. Securing a stable fuel supply for advanced nuclear technologies is a significant yet often underestimated challenge that has emerged as a strategic priority.

Commercial HALEU production in OECD countries remains limited. Current geopolitical uncertainties continue to pose questions around HALEU supply amid the possibility of future disruptions to international nuclear fuel supply chains. Some OECD and NEA countries are looking for diversification opportunities to ensure the security of energy supply. Developing both additional low-enriched uranium (LEU) and HALEU conversion, deconversion and enrichment capacities in the near-term represents a strategic interest for those nations seeking to preserve an independent, leading role in advanced nuclear technology markets.

The nuclear energy industry has historically operated with commercial enrichment of up to 5%, with the associated industrial supply chain and the legal and regulatory frameworks designed accordingly. Moving to higher than 5% enrichment will have implications along the entire fuel cycle. These implications are even more pronounced if the enrichment levels are above 10%.

Additional work will be needed to better understand the potential impacts on the full fuel cycle – from the quantity of natural uranium supply necessary to characterising the waste produced at the back end of the fuel cycle. There could be significant implications for uranium mining, conversion and enrichment markets, as well as fuel cycle strategies to prepare for HALEU-ready infrastructures.

This report examines these issues and offers an understanding of the role and implications of HALEU. Its goal is to support policymakers from NEA member countries with the necessary evidence-based analysis to inform decisions regarding the adoption and integration of HALEU fuel. The specific objectives of this report are to:

- explore the driving forces and implications of HALEU utilisation in the nuclear energy sector and assist policymakers in understanding the potential advantages and challenges associated with HALEU fuel adoption;

- foster a strategic vision about the role of HALEU fuel in achieving energy goals, optimising nuclear power operations from a fuel-cycle perspective, ensuring safety and security, and addressing environmental concerns, including resource utilisation and final waste considerations;
- provide areas for future consideration to assist policymakers looking to facilitate the emergence of a HALEU-based and/or HALEU-ready fuel cycle. This encompasses suggestions for research and development support, regulatory frameworks, international collaboration and public engagement.

Chapter 1. **Nuclear energy today**

The current nuclear technology landscape

The vast majority of operational commercial nuclear power reactors today (357 out of the 415 in operation worldwide in March 2024, are light water reactors (LWRs). These LWR technologies use low-enriched uranium (LEU) fuel, typically containing around 3% to 5% of the U-235 isotope content in the weight of total uranium, to generate fission energy. A notable exception is the use of pressurised heavy water reactors (PHWRs), particularly CANDU reactors. These technologies employ non-enriched, natural uranium fuel and constitute around 10% of the total number of the operational commercial reactors.

The prevalence of LWR technologies and their specific fuel requirements has shaped the established fuel cycle practices and fuel supply chain of the nuclear sector for over six decades.

Over this period, the widespread use of LWR technologies has generated a wealth of experimental, industrial and operational experience. This knowledge and the lessons learnt have, in turn, contributed to a deep understanding of LWR technologies. LWR technologies using LEU fuel now benefit from a robust characterisation and validation basis from a regulatory framework point of view. Diversifying from established LEU fuels and systems by introducing high-assay low-enriched uranium (HALEU) presents substantial initial challenges.

Uranium enrichment

This section presents some essential terminology and definitions related to uranium enrichment to clarify any potential ambiguities in their practical usage.

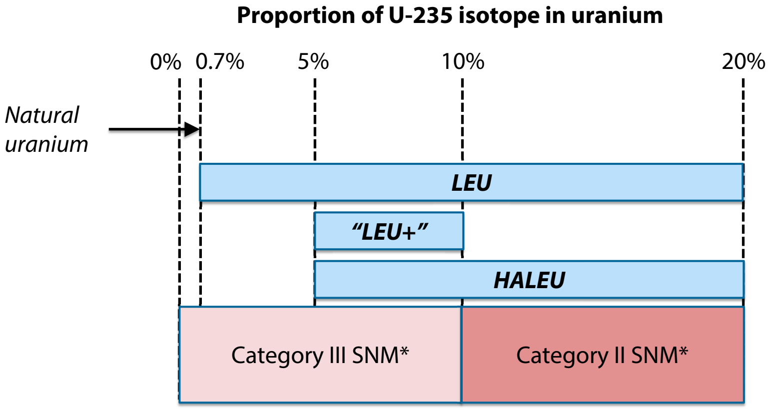
Enriched uranium is defined (IAEA, 2001) as "uranium having a higher abundance of the fissile isotope U-235 than natural uranium." Natural uranium comprises 0.7% of the U-235 isotope by mass, with the remaining 99.3% composed of U-238.

Subsequently, the IAEA provides two subcategories for enriched uranium through a straightforward classification:

- Low-enriched uranium (LEU): This category includes uranium with less than 20% of the U-235 isotope.
- High-enriched uranium (HEU): This pertains to uranium containing 20% or more of the U-235 isotope.

Figure 1.1 illustrates the usage of terminology as a function of the ranges of enrichment where they apply, and sometimes overlap. The International Atomic Energy Agency (IAEA) distinguishes material enriched to more than 10% of U-235 as falling into a more stringent category under its "Special Nuclear Materials" definitions, reflecting a transition from "low" to "moderate" strategic significance and into a more stringent safeguards category (from Category III to Category II), per the IAEA definitions (IAEA, 2011) for facilities handling HALEU enriched to more than 10%. Some stakeholders use "LEU+" to refer to uranium enriched between 5 and 10%.

Figure 1.1: **LEU, LEU+ and HALEU definitions**



* Above 10 kg of special nuclear material (SNM).

Chapter 2. Significance of HALEU fuels in the emerging small modular reactor landscape

Small modular reactors: A new paradigm for advanced nuclear energy

Small modular reactors (SMRs) are a broad category of innovative reactor concepts designed to be compact and modular. SMRs are generally reactors with a thermal power output ranging from tens of MW to several hundred MW. This contrasts with conventional large reactors, which typically boast a thermal output of around 2-3 GW.

Research reactors with thermal power outputs spanning from zero (critical assemblies) to very low power (a few MW) up to several hundred MW predate the deployment of commercial reactors. Additionally, small, compact nuclear cores have existed since the late 1950s for naval propulsion purposes and have been constructed and operated reliably on nuclear submarines and icebreakers.

What differentiates SMRs is the incorporation of standardised and modular construction methods that are conducive to factory-based production. This modularity and the associated production techniques carry potential benefits for construction processes, costs and risks, but also delivery methods, new applications and business models (NEA, 2021).

This marks a departure from the traditional model of commercial nuclear power, which has traditionally revolved around an economic approach that seeks "economies of scale" by maximising the size of centralised production sites dedicated solely to electricity generation.

The SMR landscape today

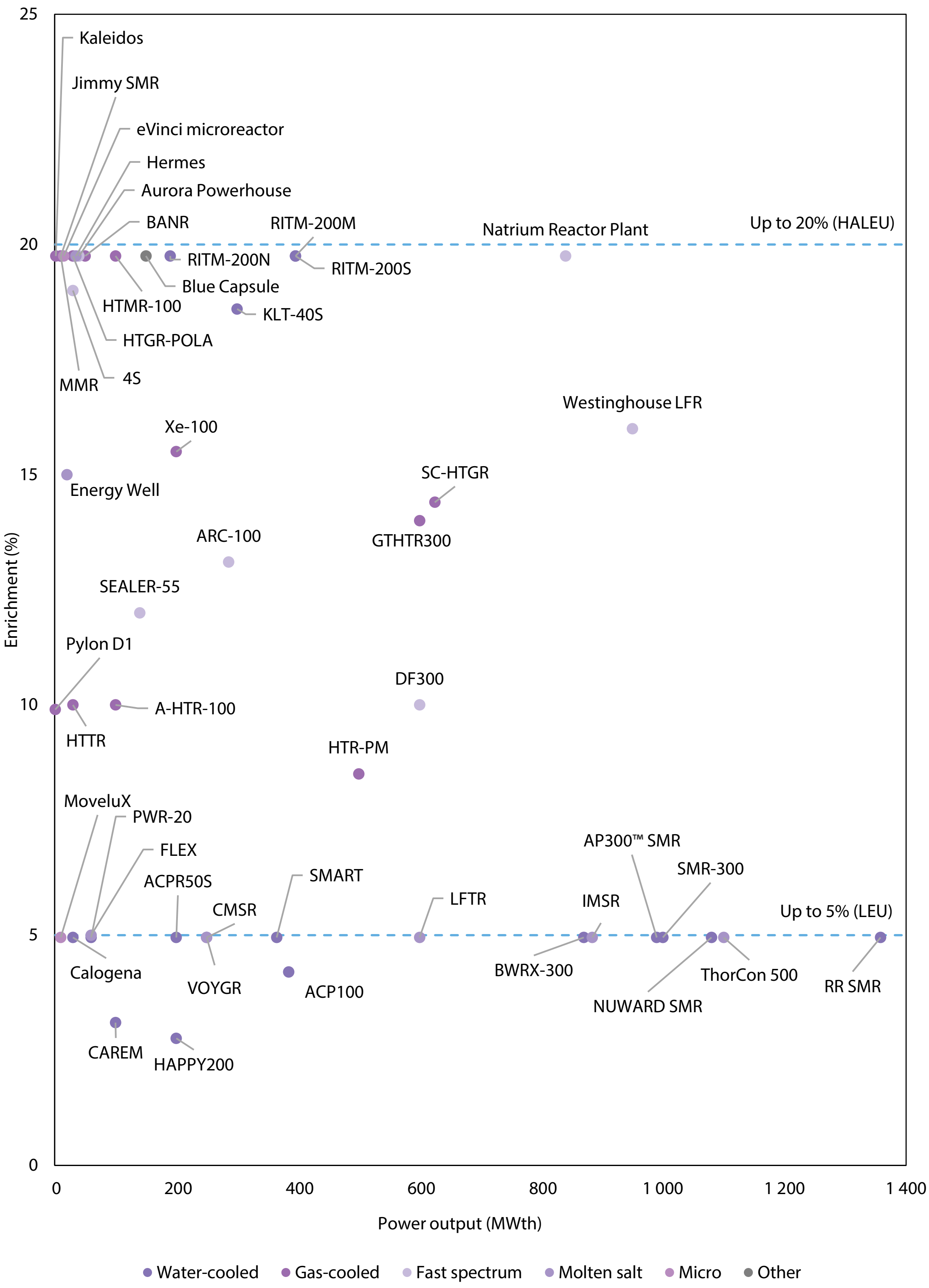
Today's SMR ecosystem includes various reactor technologies, fuels and proposed power outputs. Since the beginning of 2023, the NEA has assessed 98 SMR concepts in its *NEA Small Modular Reactor Dashboard* publication series (NEA 2023a, 2023b, 2024). Looking beyond technical feasibility, the *NEA Small Modular Reactor Dashboard* defines criteria for assessing real progress in six dimensions of readiness: licensing, siting, financing, supply chain, engagement and fuel. The *NEA Small Modular Reactor Dashboard* has identified significant diversity in SMR technologies and proposed fuel utilisation, with differences across various parameters, such as:

- fuel enrichment levels;
- average discharge burn-up of fuels;
- nominal thermal power capacities;
- nominal electric power capacities;
- outlet temperatures.

Figures 2.1, 2.2 and 2.3 illustrate the distribution of a selection of SMR designs across some of these parameters as a function of the different enrichment levels proposed for their fuel. These figures feature designs that have provided information on the aforementioned parameters. This explains why the number of designs in different graphs is not always the same: some SMR designers have not provided all information publicly.

All of the SMR designs considered in this document are included in the *NEA SMR Dashboard* publication (NEA, 2024).

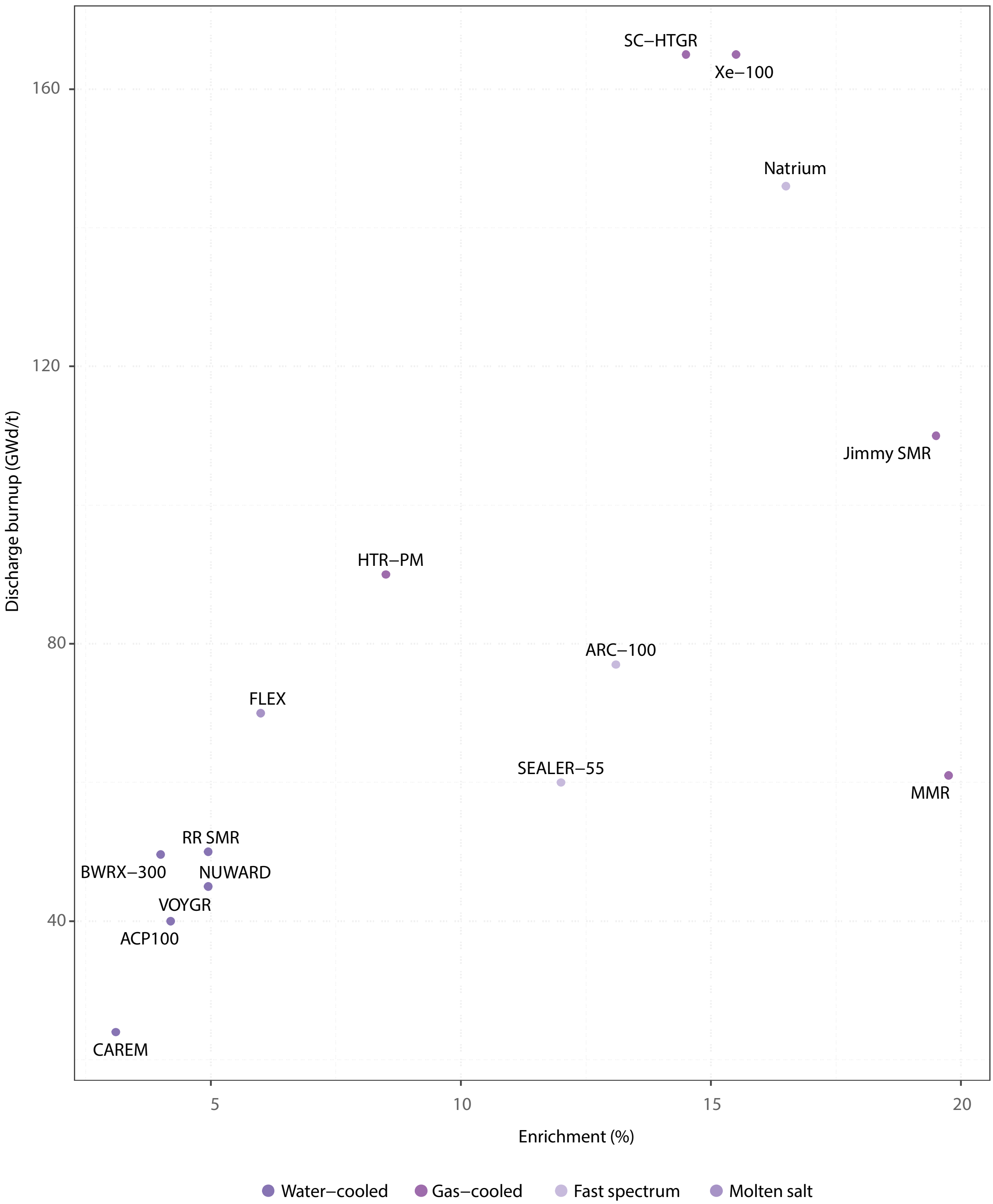
Figure 2.1: **SMRs: Range of sizes (thermal power output) and uranium enrichment levels**



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

Figure 2.2: **SMRs: Range of outlet temperatures and uranium enrichment levels**

Figure 2.3: **SMRs: Range of discharge burn-up rates and uranium enrichment levels**



HALEU-based fuel technologies

Generation IV reactor fuel technologies propose a wide range of fuel designs that differ from conventional light water reactor (LWR) fuels. These advanced fuel designs are intended to operate under conditions that are different than those of LWR fuels, including variations in neutron energy spectra, fuel temperatures, cladding and coolant, and potentially interacting with other adjacent materials. Additionally, the chemical composition of the fuel may undergo significant changes compared to conventional LWR fuels, and in some cases, even in liquid fuel forms, as seen in certain molten salt reactor concepts.

The role of HALEU for decarbonisation

SMRs may be suitable for applications beyond electricity production to play a role in the decarbonisation of hard-to-abate sectors by providing industrial process heat to energy-intensive industries that are currently run on fossil fuels. SMRs, owing to their smaller size and modularity, offer opportunities to integrate with industrial customers. As a result, they are being considered to provide process heat for various industrial applications, potentially leading to a substantial reduction in CO_2 emissions and air pollution in the energy-intensive industrial sector (NEA, 2022).

Moreover, numerous energy-intensive industries with significant carbon emissions require heat at significantly higher temperatures than current reactor technologies can provide. SMR concepts capable of delivering these elevated temperatures are primarily based on advanced, frequently Generation IV reactor technologies, many of which are specifically designed to use HALEU fuels. This does not imply a direct cause-and-effect relationship between fuel enrichment and reactor outlet temperature. However, it does suggest that among the various technological options under consideration for SMR deployment, Generation IV technologies using HALEU fuels are among the leading contenders for applications that deliver higher outlet temperatures. HALEU-fuelled SMRs may, as a result, emerge as a vital component in the process of decarbonising hard-to-abate industrial sectors.

Chapter 3. Drivers of the use of HALEU

Higher burn-up of fuels, increased cycle lengths

The burn-up rate of a nuclear fuel, often simply referred to as "burn-up", is the amount of total energy that a given mass of fuel has produced through the process of nuclear fission during the entire lifespan of the fuel inside a reactor. It is therefore a key quantity that has direct economic implications, as it is the ratio of a desired output (energy) per given input (mass of fuel). It is often expressed in terms of electrical energy per mass of initial fuel (e.g. gigawatt-days per ton, or GWd/t).

Historically, drivers in the nuclear sector for increasing uranium enrichment past the 5% standard have almost exclusively been focused on the objective of increasing the final average burn-up of discharged fuels.

Higher discharge burn-up produces higher, more efficient fuel utilisation. However, it also means increased structural damage, through irradiation, to both the fuel pellets and the cladding. As a result, there is a burn-up limit within which currently licensed fuel technologies must operate to reduce the likelihood of such structural damage.

In the United States, for instance, the currently approved burn-up for conventional light water reactor (LWR) fuel rods with uranium dioxide (UO_2) ceramic pellets is around 60 GWd/t of rod-average burn-up (equivalent to around 70 GWd/t for peak pellet burn-up). Historically these burn-up levels used to be much lower, around 30 GWd/t before the 1980s.

Figure 3.1 sets out the trends of average fuel discharge burn-up for two types of LWRs (pressurised water reactors, or PWRs, and boiling water reactors, or BWRs) from the late 1960s to the present in the United States. In the early years, the increases in burn-up were partly due to improved fuel management strategies within the core based on experience. In the 1980s and 1990s, the US Department of Energy (DOE) collaborated with nuclear fuel suppliers to enhance fuel efficiency. This effort resulted in the US Nuclear Regulatory Commission approving the current limit of 62 GWd for all US fuel suppliers (Geelhood, 2019). Uranium enrichments have gradually increased, and recent designs have effectively reached the 5% enrichment level (4.95% nominally in practice), to allow for manufacturing tolerances (IAEA, 2020b).

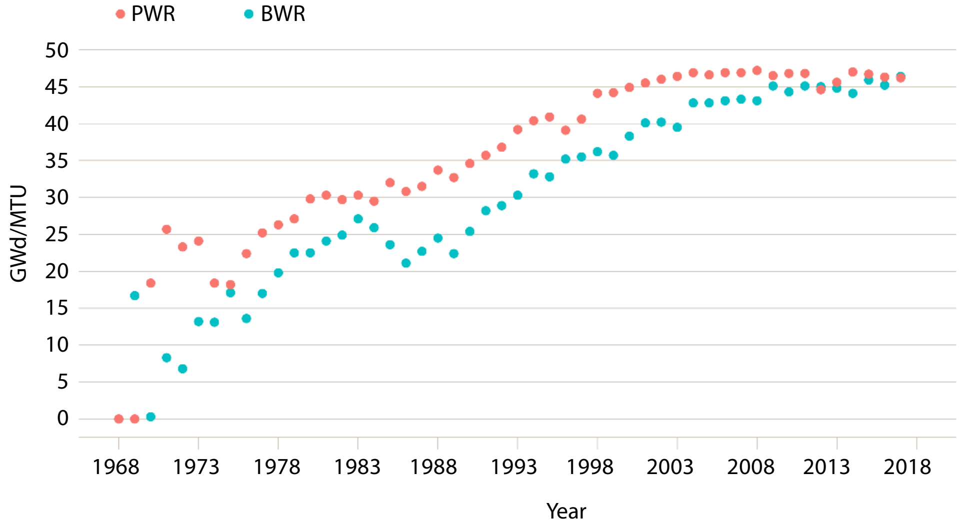
The average discharge burn-up in present LWR technologies is not solely determined by the fuel enrichment but is primarily restricted by material and structural limitations of the fuel cladding and pellet-cladding interaction under extended irradiation. New fuel or cladding material technologies are necessary if significantly higher burn-ups are sought.

High-assay low-enriched uranium (HALEU) fuels can enable much higher burn-ups. Some SMR designs (see Figure 2.3) announce discharge burn-ups that are double, triple or more of those in current LWR technologies, burn-up and are only made possible with innovative fuel forms and cladding materials. This allows for longer cycle lengths (the time intervals at which the reactor is shut down for fuel shuffling, fresh fuel loading and maintenance).

Higher burn-ups and longer cycle lengths have a direct positive economic impact, as more energy is produced with the same amount of fuel. However, the characterisation of the associated waste streams needs to be properly studied for a meaningful comparison to be possible.

HALEU-based fuels are necessary for some SMR concepts because very high burn-ups are an essential enabler of their economic and operational value proposition.

Figure 3.1: **Average spent fuel discharge burn-up for commercial US reactors, 1968-2017**



Source: US Energy Information Administration, *Nuclear Fuel Data Survey* (2018).

Compactness of SMR cores

The fundamental concept that links the notion of nuclear criticality to the geometry (and, consequently, the size) of a reactor is the concept of critical mass. Critical mass is defined as the minimum quantity of fissile material, such as U-235, required to maintain a sustained nuclear chain reaction. This establishes a correlation between enrichment and the dimensions of the critical system in general.

Figure 3.2 illustrates this with the example of a critical sphere of uranium with different enrichments and shows how increasing the enrichment of the uranium sphere decreases the minimal size required for the sphere to be critical (i.e. sustain a continuous fission chain reaction). While nuclear reactor core designs are naturally far more intricate than a sphere made of a single material, this example illustrates the fundamental concept that the compacity desired for a reactor core will influence the minimum required enrichment.

Smaller cores tend, in general, to incur increased neutron leakage because, often, a smaller core has a larger surface-to-volume ratio. Moreover, in the case of fast-neutron spectrum systems, un-moderated neutrons, having a much longer mean free path in a reactor's material environment, will tend to escape more. This affects the overall neutron balance available to trigger fission; hence, a higher fissile content (either through higher enrichment or higher fuel density) is generally needed. This requires case-by-case technology and design choices.

For these reasons, it is not uncommon to observe that, in general, very compact core designs – as seen in some SMR cases – require higher levels of uranium enrichment.

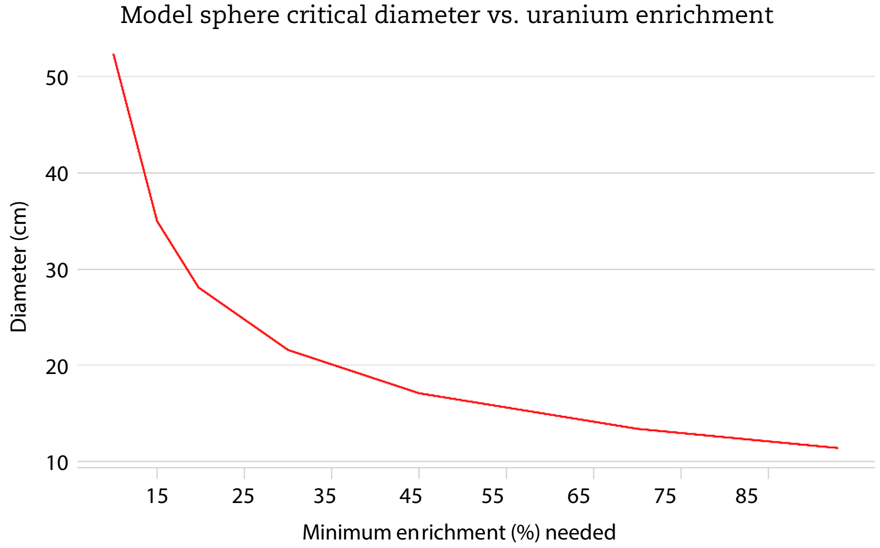
Higher outlet temperatures

As illustrated in Figure 2.2, different SMR concepts can produce a range of outlet temperatures, from lower than 100°C to over 1 000°C. SMRs based on LWR concepts using current standard fuel with less than 5% enrichment produce outlet temperatures around 285°C. Some low-temperature SMRs have outlet temperatures of 100°C or lower. Many fast reactor designs enable outlet temperatures around 500°C. Molten salt SMRs may reach around 700°C. Gas-cooled concepts may reach and exceed 800°C, with some as high as 1 000°C or more.

Among the various technological options under consideration for SMR designs, Generation IV technologies utilising HALEU fuels present some of the leading candidates for applications delivering higher outlet temperatures.

In most, but not all, designs, higher outlet temperatures are enabled by higher levels of enrichment in the fuel, though it is not always true that higher temperatures require higher enrichments. This depends on other design choices and parameters.

Figure 3.2: **Modelling results: Enrichment levels needed for various sizes of critical spheres of uranium**



Source: Data from (Glaser, 2006).

Note: MCNP calculated data, with uranium density set at 19.0 g/cc.

HALEU as an alternative to plutonium in fast reactor initial cores

HALEU can play a role in supporting the transition from open fuel cycle to fully closed cycles that implement continuous recycling. For reasons that find their origin in nuclear physics (related to the neutron balance resulting from the relative probability of neutron absorption by radiative capture and neutron emission by fission in fast spectrum systems), start-up inventories for fast spectrum reactors typically require fissile enrichments above the 10% level.

Generation IV fast-neutron reactors that fully implement these types of fuel cycle options, to fully exploit the uranium-plutonium fertile/fissile cycles, require either a starting inventory of plutonium (usually in the form of mixed oxide fuel, or MOX) or HALEU.

While the approach to fast reactors in countries such as France, which employs MOX fuel fabrication and reprocessing capabilities, starts with plutonium inventories, HALEU could provide an alternative for other countries where a plutonium start-up inventory is not available, enabling the development of fast reactor systems and continuous-recycle fuel cycles.

Non-SMR HALEU applications

Accident-tolerant fuels

The metal cladding of current uranium dioxide (UO_2) fuel technologies is primarily composed of zirconium alloys. These alloys exhibit superior neutronic properties – they are more transparent to neutrons, a desirable characteristic – when compared to stainless steels. However, zirconium-based alloys have come under renewed scrutiny following the nuclear accident at Fukushima Daiichi. This is because the oxidation of zirconium through an autocatalytic metal-steam interaction at extremely high temperatures can generate hydrogen and additional heat, potentially resulting in severe consequences.

Accident-tolerant fuels (ATFs) may reduce problematic hydrogen generation. Some of these concepts involve using stainless steel claddings, while others explore replacing UO_2 fuel with cermet materials (a combination of ceramic and sintered metal). These alternatives are expected to require fuel enriched above 5% for various reasons, one of which is that using stainless steel will necessitate higher fissile enrichments to compensate for increased neutron absorption in the metal, as compared to zirconium-based UO_2 fuels (NEA, 2018).

Research reactors and medical radioisotope production

HALEU fuels play an important role enabling the operation of research reactors. Research reactors are indispensable for a wide array of scientific experiments, including material tests, fuel irradiation tests, semiconductor doping and fundamental nuclear research endeavours, which, in turn, are necessary to advance the frontiers of nuclear science and technology and its applications. HALEU is now critical to these functions given the transition (for non-proliferation reasons) in recent years from HEU to HALEU-based fuels at research reactors.

Because many medical isotopes are produced in research reactors, HALEU fuels are also instrumental in the supply chain infrastructure of these isotopes, which serve as vital components in the diagnosis and treatment of various medical conditions, notably cancer. Securing reliable HALEU production is, therefore, essential to guarantee the reliability and independence of these important applications, contributing significantly to advancements in scientific research, next-generation nuclear technologies and healthcare.

Chapter 4. Implications of the use of HALEU in the nuclear fuel cycle

Importance of reactor technology and fuel cycle strategies

Fuel cycle strategies play a defining role in ensuring the economic viability, safety and security of nuclear energy. These strategies involve decisions impacting choices at the front and back end of the nuclear fuel cycle that concern reactor technology, fuel types, recycling options and waste management solutions.

At the centre of these fuel cycle strategies is the choice of reactor technology and fuel management options. The choice of fundamental parameters such as neutron spectrum, average discharge fuel burn-up and cycle length, among many others, impact important characteristics of overall fuel utilisation, affect the waste characterisation, waste volumes and overall efficiency of recycling, as well as the feasibility of disposal solutions – and consequently the overall economics of the fuel cycle.

For example, many technologies offer once-through strategies, with plans to permanently dispose of spent fuel in geological repositories after one cycle. This strategy prioritises waste containment but vastly underutilises the fuel's energy potential. Others use fuel recycling, reprocessing and recovering materials for reuse in new fuel assemblies. Fast-neutron spectra in advanced reactors create opportunities to enhance fuel recycling capabilities, extracting additional energy from used nuclear fuel. These are all examples of different fuel cycle strategies.

Beyond technological considerations, comprehensive fuel cycle strategies must also weigh economic, geopolitical and public acceptance factors. Balancing these factors is crucial.

Incorporating high-assay low-enriched uranium (HALEU) into coherent fuel cycle strategies, which may vary based on national or regional priorities, requires an examination of the entire life cycle of nuclear fuel – from extraction to disposal. This assessment should also consider global impacts, especially if nuclear energy becomes an even more significant contributor to worldwide energy production in the future.

A well-informed vision of these fuel cycles, considering the various magnitudes of fissile material involved, can help to effectively address the challenges associated with SMR deployment and shape the long-term viability of technology choices.

The nuclear fuel cycle

The nuclear fuel cycle refers to the series of processes involved in extracting and converting uranium into a fuel technology capable of producing fission energy in a reactor, potentially reprocessing and recycling the used fuel, and safely disposing of the final waste forms. These processes occur at different facilities and involve various physical and chemical transformations of uranium. Figure 4.1 illustrates the main stages of the nuclear fuel cycle, from mining to final disposal. The regulated transport of uranium in different forms between these facilities is also an important consideration in the nuclear fuel cycle.

Figure 4.1: **Simplified view of the nuclear fuel cycle**

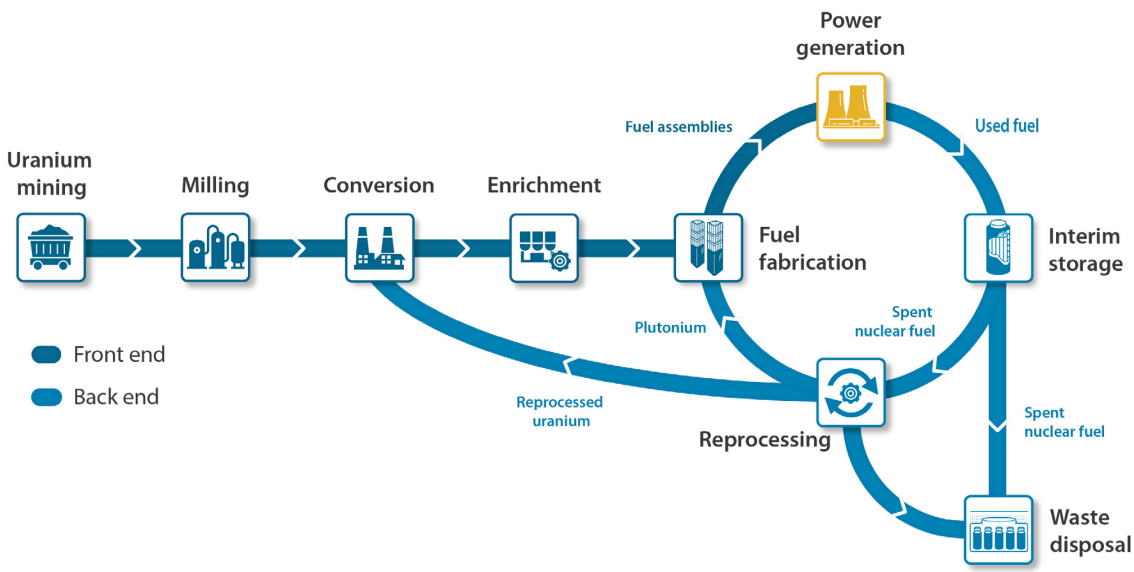


Table 4.1 sets out the main stages of the front end of the nuclear fuel cycle, with typical uranium forms at each stage. The following sections include preliminary analysis of the foreseen impacts of introducing HALEU in the nuclear fuel cycle.

Table 4.1: **Main stages in the front end of the fuel cycle and associated uranium forms**

Stages	Output
Mining	Natural uranium in ores.
Milling	Natural uranium in U_3O_8 powder, known as “yellowcake”.
Refining	Yellowcake is chemically processed into uranium trioxide (UO_3).
Conversion	Natural uranium in UF_6 form (gas).
Enrichment	Two ouput streams: Enriched and depleted uranium in UF_6 form (gas).
Deconversion	Enriched uranium in chemical form suitable for fuel fabrication. For LWR technologies, this is UO_2 (powder).
Fuel fabrication	Enriched uranium fuel. For LWR technologies, this is UO_2 pellets in fuel pins and assemblies.
Reactor irradiation	Used fuel, usually containing higher fissile contents than natural uranium, containing also plutonium, fission products and other minor actinides.

Mining, milling and refining

The utilisation of HALEU is not foreseen to result in modifications to the fundamental infrastructure for the primary extraction and processing of uranium ores. At the mining, milling and refining stages, the effects are anticipated to result primarily in greater demand for natural uranium (NU) and, consequently, heightened requirements for production and processing capacities. For instance, the amount of natural uranium required as feed for enrichment is proportional to the desired enrichment level. To produce 1 ton of uranium enriched to 20%, approximately five times more natural uranium must be mined and processed compared to the amount needed to produce 1 ton of uranium enriched to 4% (which is roughly the average enrichment level for today's LWR fuel).

Conversion

In general, conversion is the step that processes uranium concentrate to the chemical form required for the subsequent enrichment process. This usually entails the direct or indirect transformation from uranium oxide forms (such as tri-uranium octoxide, U_3O_8, commonly known as "yellow cake") to the chemical form required for enrichment, typically uranium hexafluoride (UF_6). As the uranium at this stage is in its natural, unenriched form, using HALEU only impacts this stage by leading to increased demand for conversion capacities.

Enrichment

For countries already proficient in the enrichment process, there are no technological barriers to enriching uranium to levels exceeding 5%, and even surpassing 20%. However, there is a necessity for safeguards, specifically at this stage of the fuel cycle.

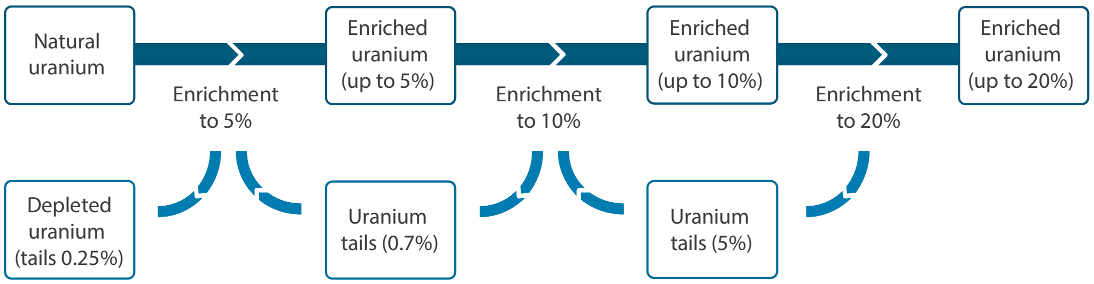
An essential consideration is how the required enrichment levels will impact the fuel cycle infrastructure per the International Atomic Energy Agency (IAEA) Special Nuclear Material (SNM) categorisation, reflecting low or moderate strategic significance, respectively. In particular, infrastructure handling uranium enriched to more than 10% will be categorised per the IAEA (IAEA, 2011) under a more stringent safeguards category (category II) than present infrastructures handling uranium enriched to less than 5% (category III). This may have operational and economic costs.

At the enrichment stage, the generic implications of the need for HALEU relate naturally to the necessary enrichment capacities to meet potential demand. More strategically, the enrichment stage also involves the manner in which the enrichment infrastructure could be optimised to cater to the different levels of enrichment requested by the international market in an economically efficient way.

The enrichment process can be conceptualised as a transformation of uranium feed (usually in UF_6 form) into two output streams (also in UF_6 form): one enriched and one depleted (uranium tails).

Reaching HALEU level enrichments up to 20% could be potentially done in one, two or three tiers, each delivering an enriched uranium product (EUP) at different ranges of enrichments. In a two- or three-tiered enrichment infrastructure, lower-enriched uranium is used as feed in a higher-enrichment facility, with tails from one facility used as feed for another. This is done to optimise the size and, therefore, the cost of higher-category facilities, which require higher security investment. Figure 4.2, based on (Kim, 2023), illustrates such a potential three-tiered infrastructure.

Figure 4.2: **A potential three-tiered HALEU enrichment infrastructure scheme**



Deconversion and fuel fabrication

Deconversion involves transforming enriched uranium, typically in UF_6 form, from the enrichment stage into a chemical form suitable for the fuel fabrication process. It also encompasses the transformation of depleted uranium (DU) UF_6 tails from the enrichment process into a more stable form for storage or disposal, typically uranium tetrafluoride (UF_4) or U_3O_8.

HALEU-based advanced fuel technologies will employ HALEU in various chemical forms, compounds or alloys, each with distinct properties. This may entail different fabrication constraints and transportation requirements, presenting a challenge for the front end of novel fuel cycles. These cycles will need to "deconvert" HALEU into the appropriate chemical form to serve as feed for the fuel fabrication process.

As an example, Table 4.2 gives a non-exhaustive list of primary fuel forms currently under consideration in advanced reactor fuel technologies for uranium enrichments higher than 5%:

Table 4.2: **Main fuel forms currently under consideration for advanced reactor technologies using HALEU**

Fuel forms	General description
Metallic alloys	Alloys including varying percentages of uranium-zirconium (U-Zr), or a combination of uranium-plutonium : (U-Pu-Zr), with or without Minor Actinides (MA) (U-MA-Zr, and other alloys with silicium (Si), aluminium (Al), molybdenum (Mo), among others.
Ceramics (oxides)	UO_2 and $(U,Pu)O_2$ mixed oxide compounds (MOX), other fuels in different stoichiometric compounds.
Ceramics (carbides)	Uranium carbide (UC) and uranium oxycarbide (UCO) fuels in different stoichiometric compounds.
Ceramics (nitrides)	Uranium nitrides (UN) fuels in different stoichiometric compounds.
Ceramics (silicides)	Uranium silicides (USi) fuels in different stoichiometric compounds.
Molten salts	Various compound salt formulas under study, involving U with chlorine (Cl), fluor (F), lithium (Li), beryllium (Be), sodium (Na), potassium (K), plutonium (Pu), and thorium (Th), among others.
Tristructural isotropic (TRISO) fuel	Coated particles composed of a kernel of uranium oxide (UO_2) or oxycarbide (UCO) surrounded by several layers of pyrolytic carbon and carbide.

Indicative fuel cycle quantities of interest

There are four key fuel cycle quantities associated with the enrichment stage emphasised here. These quantities will later be used to evaluate the overall impact of HALEU on the fuel cycle:

- natural uranium (NU) requirements (in tonnes);
- depleted uranium (DU) production (in tonnes);
- indicative masses of EUP (HALEU) needed (in tonnes);
- enrichment capacity needs (in SWU).

SWU are a measure of the magnitude of the effort of the separation task in the enrichment phase. SWU are equivalent to mass units and are expressed as a complex function of the different assays in the three streams (one feed, which is natural uranium, and two output streams: enriched uranium and depleted uranium, or tails) of the enrichment process. Appendix A gives a closer look at this unit of measure, but for the purposes of this document it is sufficient to know that SWU expresses enrichment capacities and that it is a function of the desired enrichment level of the product and the desired tails assay.

Notably, this document uses these quantities normalised per unit of energy produced (all of the above expressed per gigawatt-electric-year, or GWe.y). What makes these quantities particularly interesting is that they can be determined if another four key design parameters of the reactors and fuel are known for a once-through fuel cycle. These parameters are the enrichment level of the fuel, its average discharge burn-up, and the electrical and thermal output of the reactor. Further details on the mathematical relations linking these reactor parameters with the four fuel cycle quantities above can be found in Appendix A.

The following sections analyse the evolution of these four fuel cycle quantities across various SMR designs for which the four reactor parameters (enrichment, discharge burn-up, thermal and electrical power) are known.

Application to SMR example concepts

For a selection of SMR concepts representing diverse reactor technologies (and for which sufficient information is available in the public domain), the four fuel cycle quantities of interest previously introduced are calculated.

These fuel cycle quantities, shown in Table 4.3 (NEA, forthcoming) are calculated through a consistent methodology based on self-reported data. They represent an objective comparison of the impact that different SMR concepts have in the fuel cycle, in terms of: natural uranium consumption, depleted uranium production, required amount of enriched uranium product, and required enrichment capacities, per unit of energy produced.

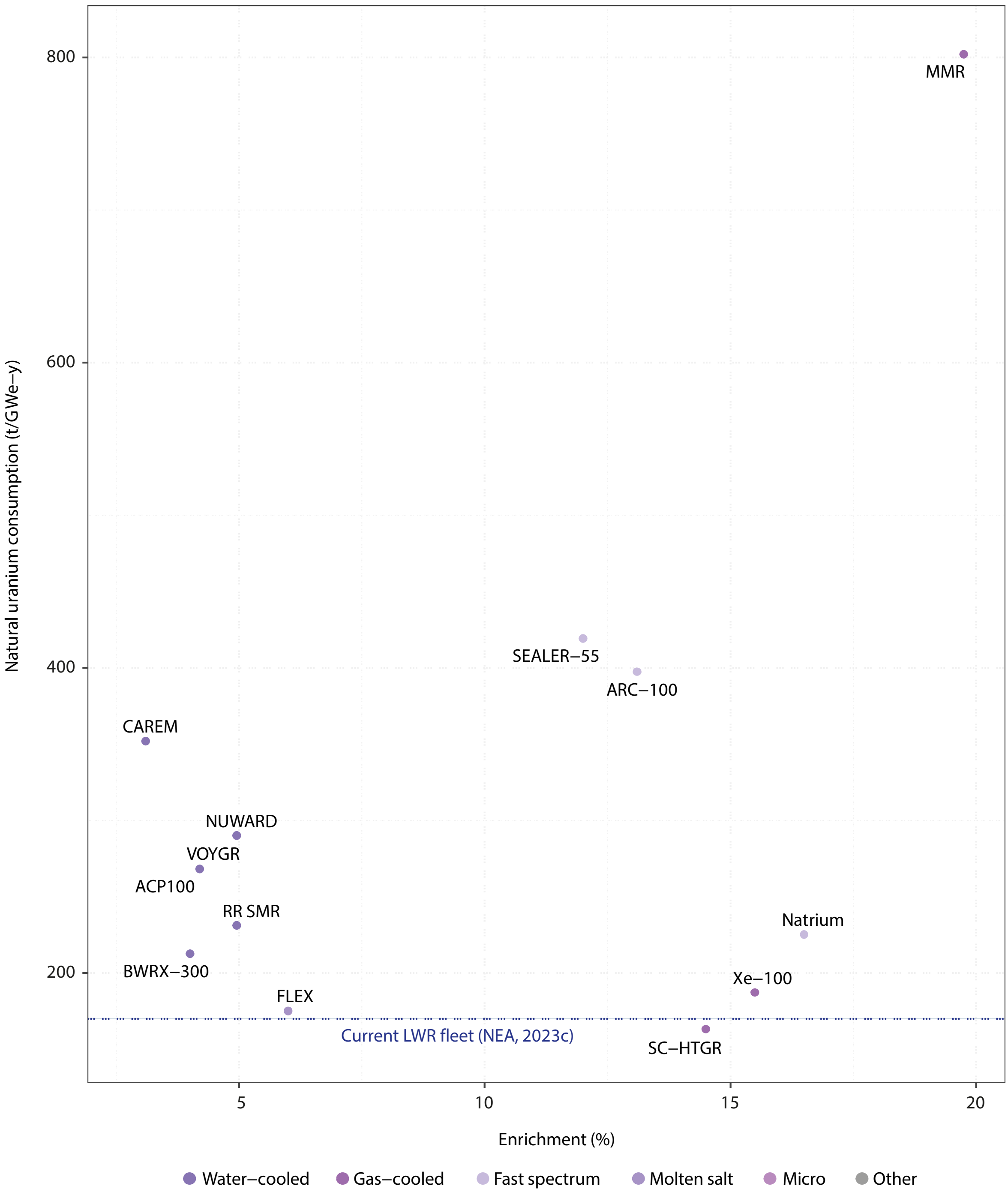
Figures 4.3 to 4.7 illustrate the distribution of these calculated quantities across the different enrichment levels. They lead to an important, general observation: under the assumption that SMR concepts shown here implement once-through fuel cycles, the impact of deploying them, in terms on the above-mentioned fuel cycle parameters, is very diverse.

Table 4.3: **Calculated fuel cycle requirements for a selection of SMR concepts**

SMR name	Design organisation	Self-reported data				Calculated quantities			
		Thermal output (MWth)	Electric output (MWe)	Enrichment (%)	Burn-up (GWd/t)	NU (t/GWe.y)	DU (t/GWe.y)	EUP (t/GWe.y)	SWU (thousand /GWe.y)
ARC-100	ARC Clean Technology	286	100	13.1	77	397	384	14	349
BWRX-300	GE Hitachi Nuclear Energy	870	270	4.0	50	213	189	24	138
CAREM	CNEA (Argentina's National Atomic Energy Commission)	100	30	3.1	24	352	301	51	203
FLEX	MoltexFLEX	40	16	6.0	70	175	162	13	131
MMR	USNC (Ultra Safe Nuclear Corporation)	15	5	19.8	61	802	784	18	742
Natrium Reactor Plant	TerraPower	840	345	16.5	146	225	219	6	205
NUWARD SMR	NUWARD	540	170	5.0	45	290	264	26	205
RR SMR	Rolls-Royce SMR	1 358	470	5.0	50	231	210	21	163
SC-HTGR	Framatome	625	272	14.5	165	163	158	5	145
SEALER-55	Blykalla	140	55	12.0	60	419	404	16	364
VOYGR	NuScale Power	250	77	5.0	45	290	264	26	205
Xe-100	X-energy	200	82.5	15.5	165	187	182	5	169

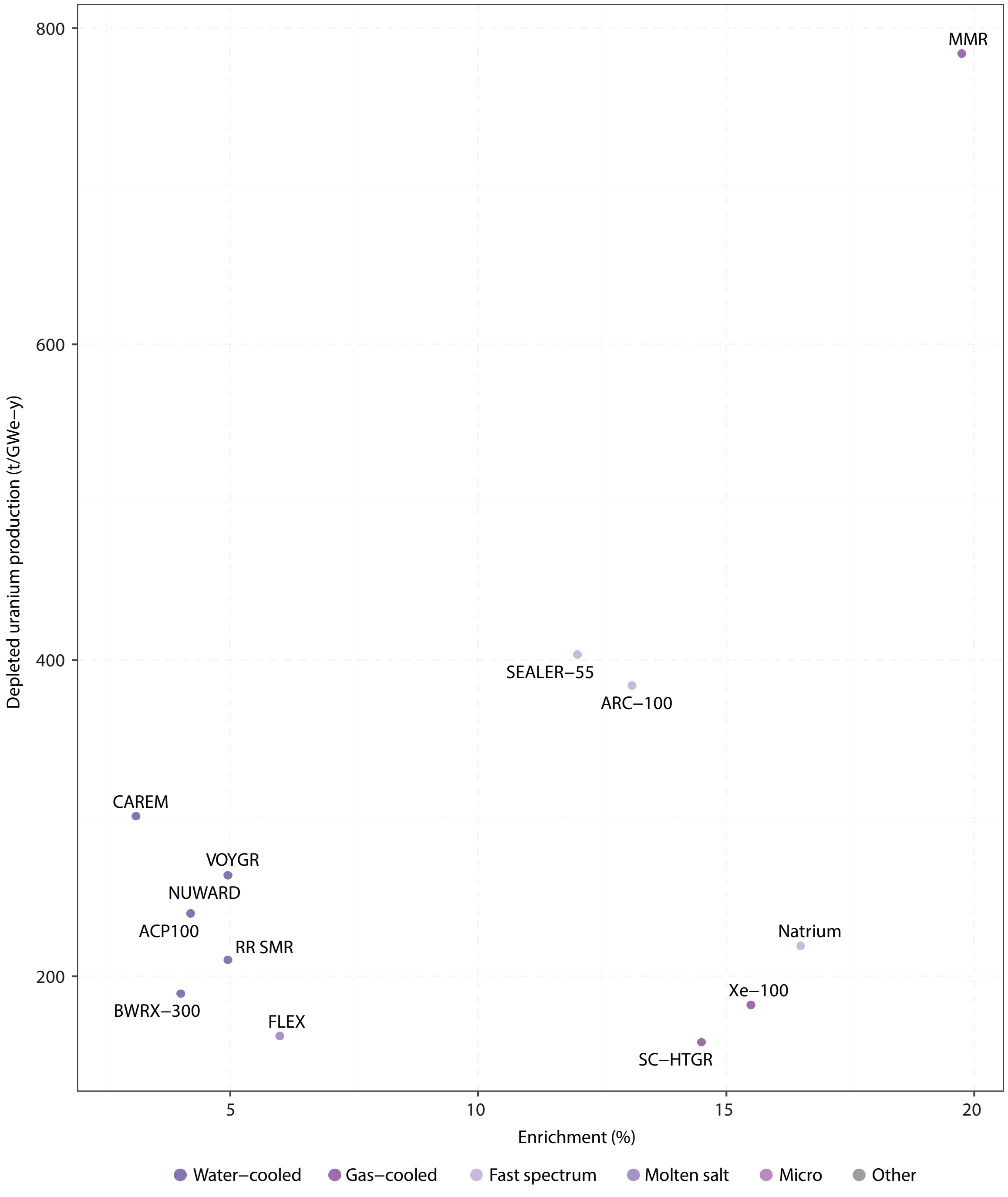
Note: Calculated fuel cycle quantities given here are: NU: Natural uranium requirements; DU: Depleted uranium production; EUP: Enriched uranium product requirements; SWU: Separative work units requirements.

Figure 4.3: **Natural uranium (NU) consumption per electrical unit of energy produced, as a function of enrichment levels, across a selection of SMR concepts**



In terms of natural uranium consumption per unit energy, Figure 4.3 shows how some HALEU-fuelled SMRs greatly depart, by a factor of more than four, from the conventional average value of present LWR technologies (below 200 t/GWe.y).

Figure 4.4: **Depleted uranium (DU) production per electrical unit of energy produced, as a function of enrichment levels, across a selection of SMR concepts**



A very similar distribution to the one shown in Figure 4.3 for natural uranium consumption is shown in Figure 4.4, for the corresponding depleted uranium (DU) production. This is to be expected as the quantities of natural uranium and the resulting depleted uranium are always of comparable magnitude (most of the mass of processed natural uranium turns up as depleted uranium after the enrichment process).

Figure 4.5: **Mass of Enriched Uranium Product (EUP) needed per electrical unit of energy produced, as a function of enrichment levels, across a selection of SMR concepts**

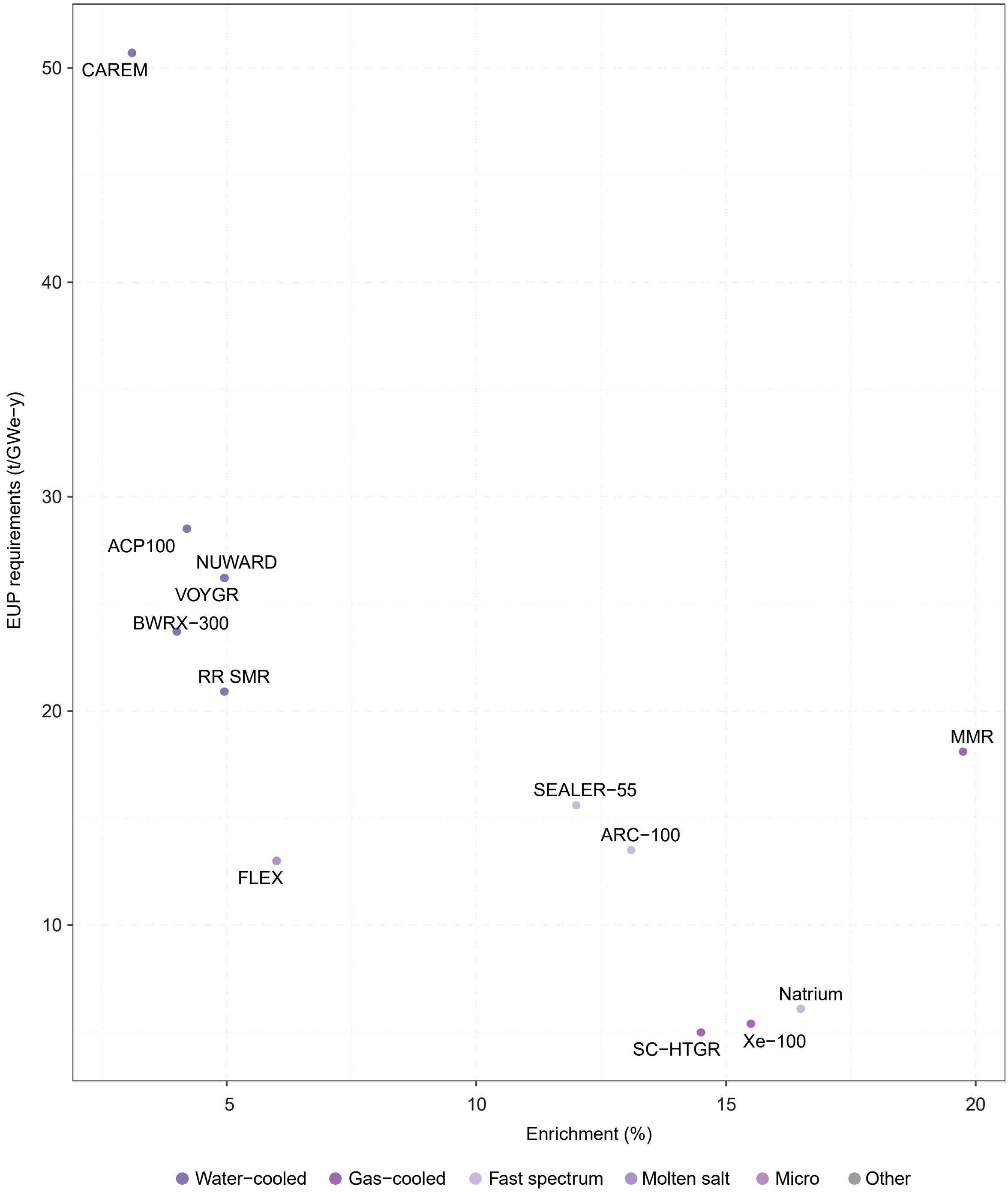


Figure 4.5 shows the average quantity of enriched uranium product (EUP) needed by each of the SMR designs, per unit energy produced. This also corresponds to the average value of mass of fuel that is discharged per unit energy and can be used as an estimator of resulting mass of spent fuel produced, per unit energy.

Figure 4.6: **Separative work units (SWU) needed per electrical unit energy produced, as a function of enrichment levels, across a selection of SMR concepts**

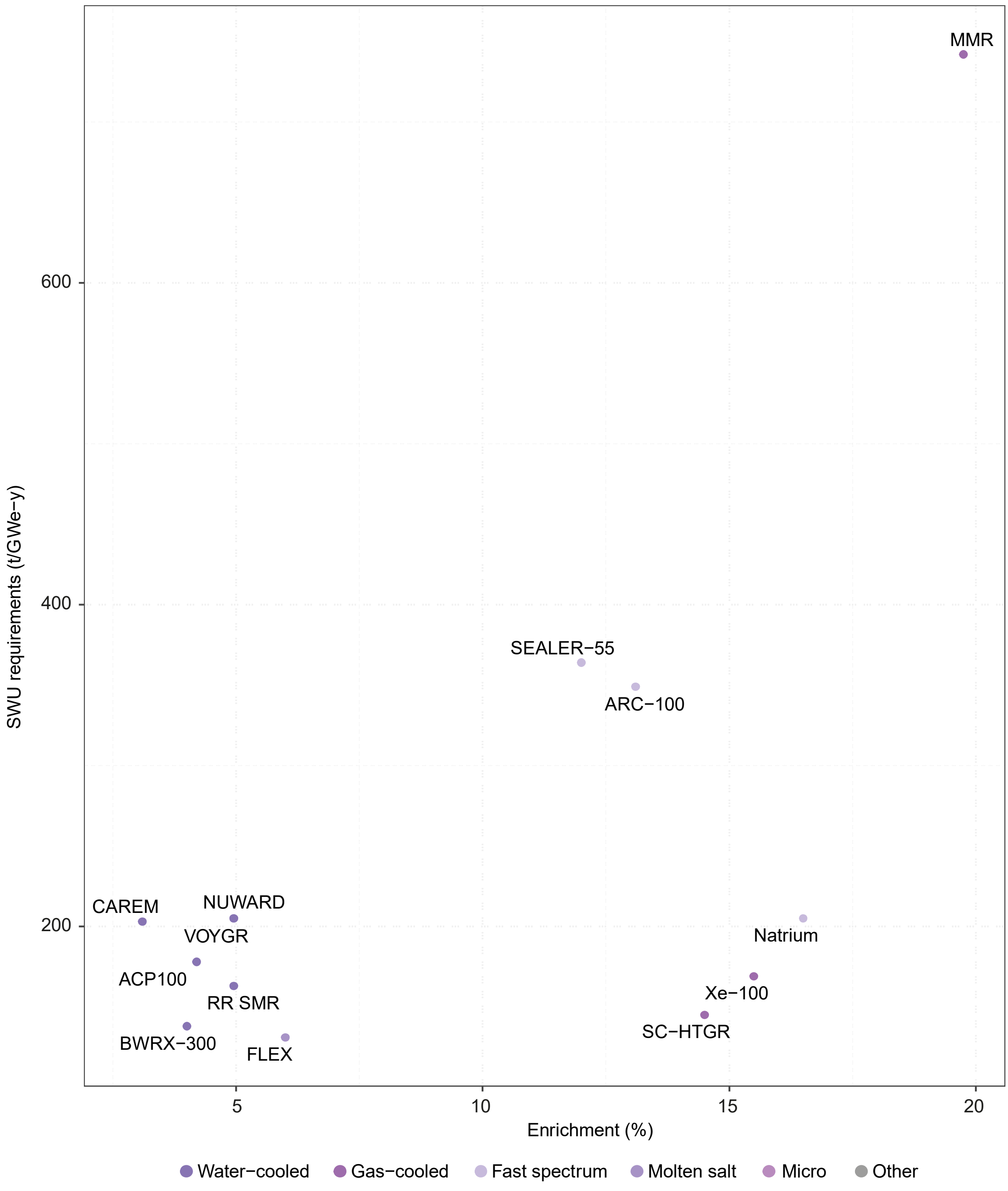


Figure 4.6 shows the amount of enrichment capacities (SWU) needed per SMR concept. As these figures are normalised per unit energy produced, SMRs with similar enrichment but very different fuel burn-up (a measure of the overall energy that is extracted per mass of fuel) will show very different SWU requirements per unit energy. The same is true for all the other quantities shown previously.

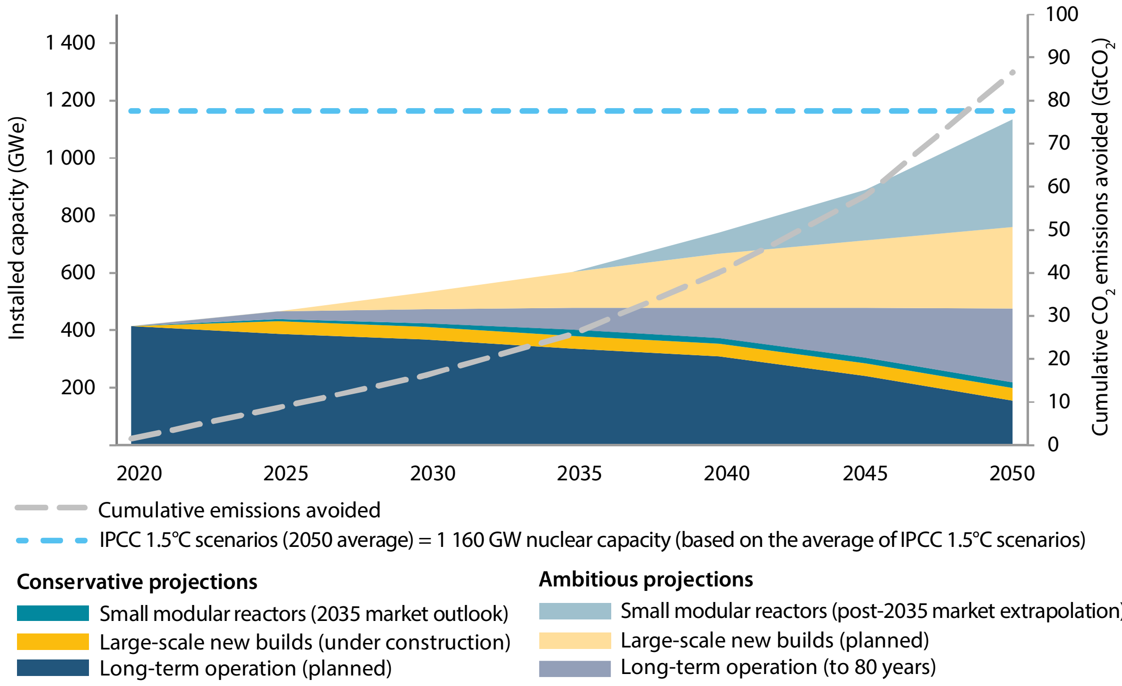
In the following section, an exercise is presented that aims at quantifying the impact that these fuel cycle parameters would have at a macroscopic, global level under a net zero deployment scenario that considers both the deployment of large LWRs and SMRs.

Application to net zero transition scenarios

The preceding sections presented the impacts of enrichment and burn-up levels on key parameters of interest for a selection of SMR concepts. This section will consider the impacts of these fuel cycle requirements at the macro level. The aim is to understand the implications in particular of significant expansion of global installed nuclear capacity, up to a tripling of global nuclear energy by 2050. Specifically, this section presents preliminary analysis about the impacts of HALEU-fuelled SMRs on the demand for uranium and the front end of the nuclear fuel cycle.

For the purposes of this analysis, a scenario is considered where HALEU-fuelled SMRs contribute significantly to the overall tripling of the current global installed power by 2050. This scenario is based on the NEA net zero scenario (NEA, 2022) which is shown in Figure 4.7.

Figure 4.7: **NEA net zero scenario showing a need for tripling global installed nuclear capacities by 2050**



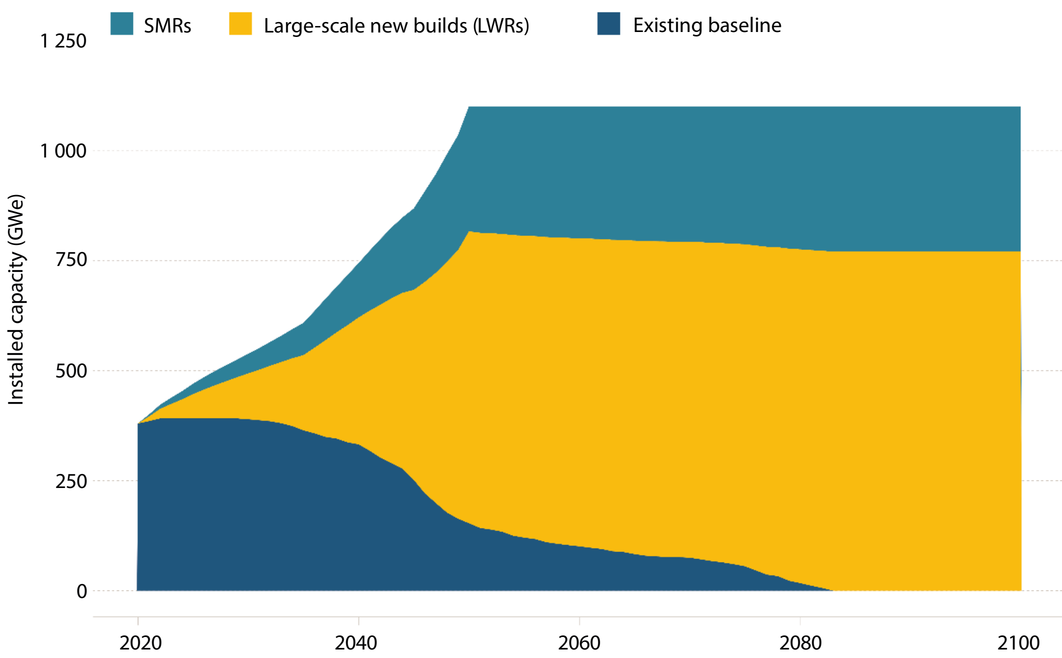
Source: NEA, 2022.

Building on the NEA's 2022 study, a Reference Scenario is outlined here where global nuclear capacity could effectively triple and reach 1 100 gigawatts by 2050, maintaining this output throughout the century. This projection, based on nuclear energy output remaining steady from 2050 until 2100, seeks to grasp the operational scope needed for tripling nuclear capacity, using a rather conservative hypothesis post-2050. It does not aim to pinpoint exact numbers.

Figure 4.8 presents the Reference Scenario. It considers three distinct global fleets under a simplifying assumption that all reactors, whether large or small, operate for a total lifespan of 60 years. The three fleets considered are:

- the existing baseline of currently operating reactors, which will be phased out after completing their operational life;
- a fleet of light water reactor (LWR) new builds;
- a fleet of small modular reactors (SMRs).

Figure 4.8: **"Reference Scenario": Global installed nuclear capacity triples by 2050 then remains constant to 2100**



For this exercise, the tripling of the global installed nuclear capacity is reached in 2050 and maintained constant until 2100. The proportion of the SMR fleet to the total of new builds reaches 30% and is maintained until 2100.

This analysis considers the contributions of different reactor fleets, based on necessary assumptions that align with contemporary nuclear energy practices. A strong, key assumption is the continued dependence on open fuel cycles throughout this transition. The analysis aims at revealing the implications of keeping once-through fuel cycles as the default choice. This approach, which avoids reprocessing or recycling spent nuclear fuel, demands significant natural uranium resources and enrichment capacities. The impact on uranium enrichment capabilities is assessed and these requirements are measured against the backdrop of current global production capacities and natural resource availability.

Having defined the Reference Scenario in terms of expected electrical installed capacity (GWe) throughout 2100, it is possible to use the previously calculated SMR fuel cycle requirements (given in Table 4.3 and normalised per GWe.y) to directly obtain yearly requirements at the global scale.

Yearly requirements associated with the Reference Scenario

For the purpose of this exercise, the calculated fuel cycle parameters representing the SMR fleet are taken from a hypothetical SMR design using HALEU fuel at 16.5% enrichment, and an average discharge burn-up of 146 gigawatt-days-per-ton (GWd/t). Different SMR designs would naturally have different requirements. For the large LWR fleet (existing and new builds), average conventional values are taken[1].

Figure 4.9 provides an overview of the resulting fuel cycle annual requirements for both types of reactor fleets: conventional LWR plants (existing baseline and new builds, aggregated) and SMR requirements, presented separately. These are the annual requirements necessary to achieve and maintain a total capacity of 1 100 GWe by 2050, and to keep that level until 2100. Figure 4.9 gives these requirements in terms of:

(A) global installed nuclear capacity, based on the Reference Scenario;

(B) resulting average annual natural uranium requirements needed to sustain capacity in once-through fuel cycles;

(C) resulting average annual amount of enriched uranium product (EUP) required in once-through fuel cycles;

(D) resulting average annual enrichment capacities required to produce the necessary EUP (in SWU/y) in once-through fuel cycles.

The values above represent only the order of magnitude of yearly requirements of these reactor fleets at equilibrium. Notably, requirements for the first load (start-up inventory of each reactor), which are always initially higher than equilibrium requirements, have not been considered.

Finally, natural uranium production yearly requirements should be compared for reference to the current world and OECD uranium production capacities, which are of roughly 60 000 and 20 000 t/y, respectively (NEA, 2023c).

Figure 4.10 shows the total annual requirements for uranium production and enrichment capacities to provide for global LWRs and SMRs in the Reference Scenario.

Total natural uranium production required is in excess of 200 000 tonnes by 2050, in comparison to present day world uranium production capacities of around 50 000 tonnes given by the latest official data representing 2021 capacities (NEA, 2022). For enrichment capacities, total requirements surpass 170 million SWU by 2050, in comparison to present day capacities of around 60 million SWU. Unsurprisingly, these values are, as could be expected, comparable with an effective tripling of the world uranium production and enrichment capacities.

To give a larger perspective of these magnitudes as far as natural uranium production is concerned, Figure 4.11 illustrates the history of world uranium production and requirement levels, showing the all-time high of uranium production in the world at around 70 000 tonnes in the 1980s.

1. Which are around 17 t of EUP per GWe.y; 187 t of NU/GWe.y; and 132 000 SWU/GWe.

Figure 4.9: **Fuel cycle annual requirements for tripling global installed nuclear capacity (based on the Reference Scenario)**

Figure 4.10: **Annual requirements for natural uranium and enrichment capacities (based on the Reference Scenario)**

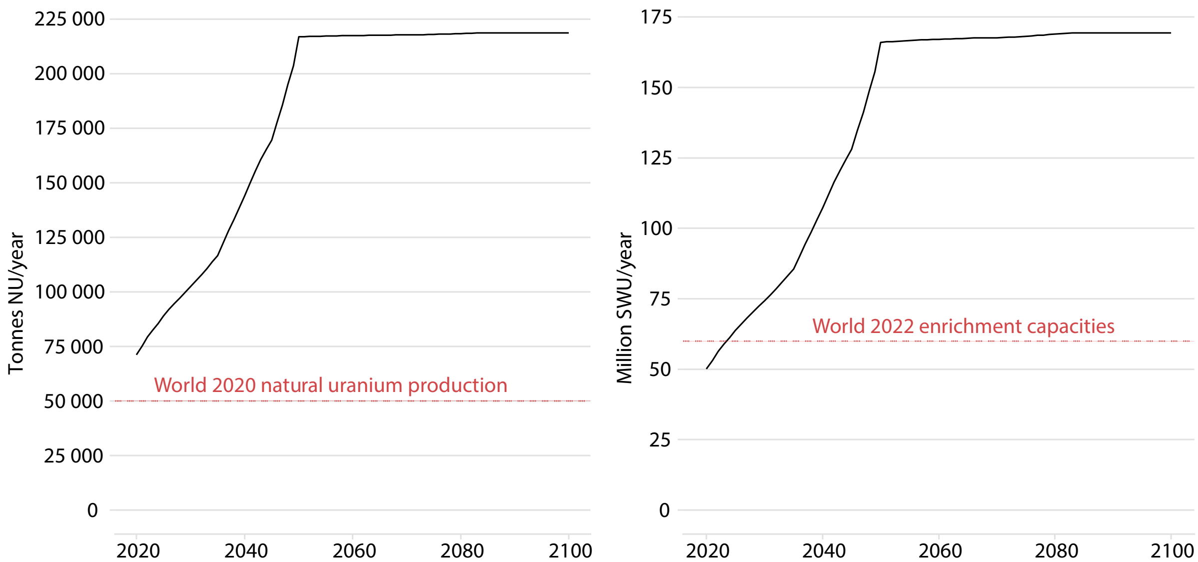
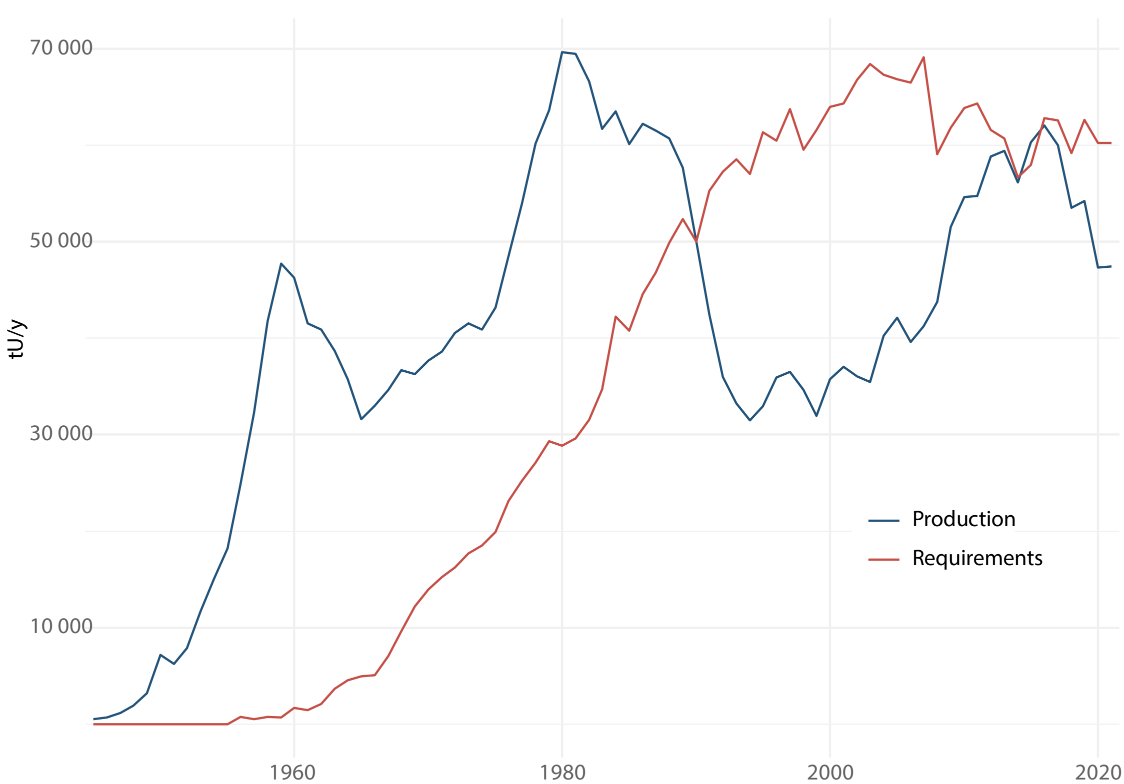


Figure 4.11: **World uranium total production and requirements from 1950 to 2020**



Source: *Uranium 2022: Resources, Production and Demand* (NEA, 2023c).

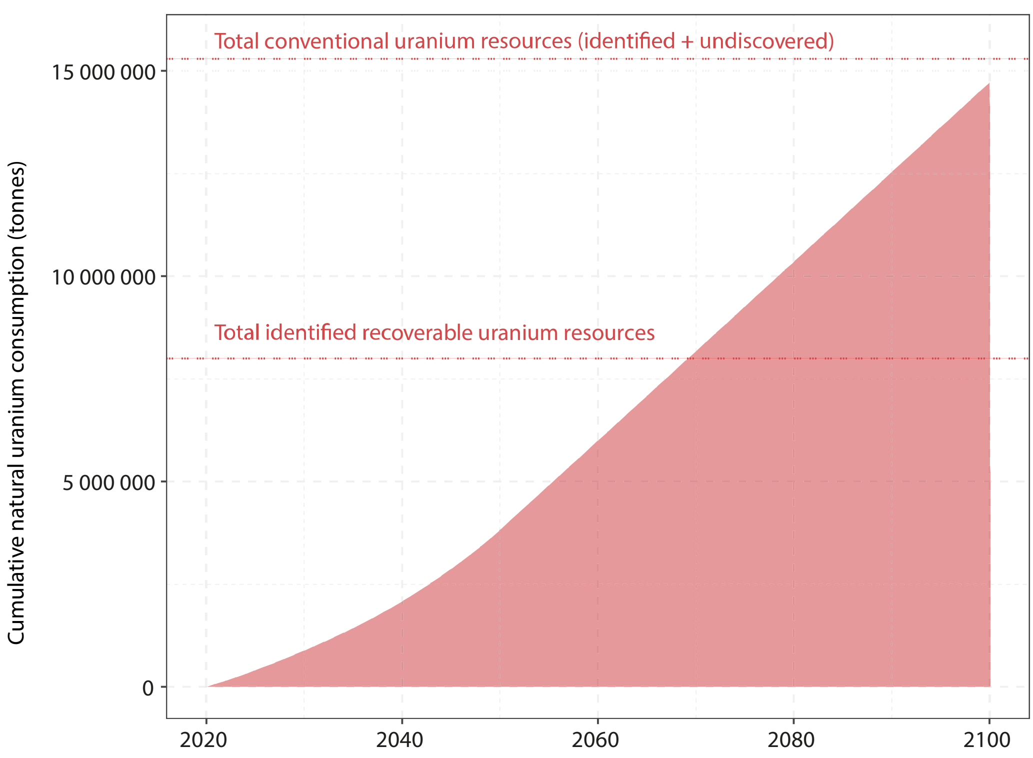
The following section discusses the implications concerning demand for natural uranium resources.

Cumulative consumption of natural uranium

An essential consideration is the availability of natural uranium resources. The joint NEA-IAEA *Uranium Resources, Production and Demand,* commonly known as the "Red Book" and published every two years by the NEA, is the authoritative reference on world uranium resources. The latest (2022) figures on known uranium resources (which are given in different cost and geological confidence categories) can be summarised as follows: There are around 8 million tonnes of presently identified "recoverable" uranium resources, for which there is a high degree of confidence that these resources exist in the ground and can be put into production if proper investments are put in place. To this figure of 8 million tonnes (Mt), one could add another 7.3 Mt, which are presently considered "undiscovered, conventional" uranium resources for which geological confidence is lower and for which further exploration would be required to increase confidence. Considering both would give a total of around 15.3 Mt of "total conventional uranium resources" presently known, albeit with different degrees of confidence.

Figure 4.12 gives, from the start of the Reference Scenario, the cumulative, forward-looking consumption of natural uranium that would ensue were this scenario to be realised. It follows that, in this simplified model, the totality of presently known conventional uranium resources (as per the categories used in the Red Book), would be practically depleted by the year 2100. This exercise has considered only presently known conventional uranium resources. It shows the magnitude of the uranium exploration and production effort needed to sustain a tripling of nuclear energy using only once-through fuel cycles, and the importance of strategic, long-term fuel cycle choices to ensure the viability of plans to triple global installed nuclear capacity.

Figure 4.12: **Cumulative consumption of natural uranium, from 2020 to 2100 based on the Reference Scenario**



Criticality safety considerations

The use of HALEU has significant implications and challenges for the nuclear fuel cycle's front end, particularly with regard to criticality considerations that concern the production, handling and storage of an enriched uranium product above 5%.

The 5% enrichment level has long shaped the design and approved procedures for all aspects and facilities of the front end of the nuclear fuel cycle that handles enriched uranium products. The 5% level is therefore implicitly embedded in these infrastructures by design.

Subcriticality margins would need to be rigorously reassessed across all these stages and facilities: enrichment and deconversion facilities, fuel fabrication facilities, storage at nuclear power plants, fuel transport, fuel storage facilities, spent fuel storage and spent fuel reprocessing facilities, as well as facilities dedicated to radioactive waste processing and disposal. The reconsideration and quantification of all associated safety margins could potentially result in the need for re-dimensioning these facilities (e.g. spacing between spent fuel assemblies in pools, dimensioning of fuel fabrication equipment).

Transport solutions for HALEU fuels will need to be developed. For example, industry canisters commonly used for UF_6 transport and certification standards must be adapted and requalified for enrichments higher than 5% (NEI, 2018).

Current back-end fuel cycle facilities were originally designed to handle spent fuel with an initial enrichment level below 5%. Despite existing safety and design margins, managing spent fuel from fuel with an initial enrichment exceeding 5% requires additional measures. In some cases, the experimental data needed to support optimised safety assessments must be developed.

In all cases, there is the need for compliance with the authoritative IAEA Safety Standards at all uranium enrichment levels. The reference "Light Water Reactor Fuel Enrichment Beyond the Five Per Cent Limit: Perspectives and Challenges" (IAEA, 2020b) provides a detailed overview of the challenges associated with HALEU in LWR infrastructures. It is evident that departing from the existing LWR validation platform would present several challenges.

Validation of data, codes and methods for HALEU systems

There is an international need for high-quality experimental data in the field of nuclear criticality safety, fuel performance and reactor system analysis for accurately representing HALEU-based systems in all their diversity. These data are essential to establish a robust foundation for codes and methods validation for HALEU-based systems to support their future design and licensing. Regulators demand that modelling approaches, which include simulation codes and methods, be rigorously validated against carefully evaluated experimental data to demonstrate their applicability.

Appendix B further expounds on these issues considering existing international collections of experimental data.

Back-end implications of HALEU fuels

The innovative features of SMRs in general, and HALEU-fuelled advanced reactors in particular, whether large or small, directly impact the waste streams and spent fuel characteristics of these systems. While these features enable many benefits in terms of fuel economy, economics and safety behaviours, their effect on the volume and type of radioactive waste produced must also be considered.

There are a variety of Generation IV systems that plan to use HALEU fuel, including molten salt reactors (MSRs), high-temperature gas-cooled reactors (HTGRs), and lead- or sodium-cooled fast reactors (LFRs or SFRs). These advanced systems may also use advanced HALEU fuel types such as liquid fuel, sodium-bonded fuel, TRISO pebbles or accident-tolerant fuel (ATF). Differences in fuel structure, moderator, or coolant material, lead to waste with different chemical, physical and radioactive properties compared with current LWR waste streams. Even waste streams from SMR designs based on LWR technologies may not be entirely similar due to changes in reactor size, operating regime and fuel type.

Regardless of the advanced reactor or SMR design, it is evident that the waste generated by HALEU fuel in the next generation of innovative reactor concepts will differ significantly from the waste of conventional LWR technologies. To establish a long-term, consistent portfolio of sustainable waste management solutions these differences must first be comprehended, evaluated and anticipated. The introduction of any novel fuel cycle, HALEU or otherwise, necessitates this type of analysis.

HALEU waste characterisation challenges

While there is much ongoing research into the front end and the operational behaviour of advanced systems and fuels, there is much less certainty concerning the back end of their fuel cycles. Research at US National Laboratories has identified some potential considerations for accepting spent fuel and waste from these designs in existing waste management solutions, and further work is necessary.

Fuel composition and burn-up

Most waste management considerations regarding HALEU-fuelled systems arise from the higher enrichment and burn-up of the spent fuel. This generally leads to more short-lived heat-producing fission products (e.g. strontium-90 and caesium-137) present in each spent fuel package, increasing the decay emission rate, notably neutron emission, and thermal load on storage, transportation and eventual disposal facilities. Care must be taken to ensure subcriticality margins are maintained and adequate thermal and shielding protection is in place during storage and transportation. Increased thermal loads from waste containers will also impact deep geological repository (DGR) design features such as the size and spacing of waste packages, the size of the repository footprint and engineering designs, thereby impacting the cost of repository construction. These changes in decay heat characteristics and thermal behaviour have not yet been thoroughly investigated and there is also a need for validation of codes and data for decay heat calculations.

Chemical properties

Characterisation of spent fuel chemical properties will also be necessary to identify possible materials issues regarding the stability and durability of waste. While in some cases advanced technologies may exhibit improvements in these areas, such as better containment of radionuclides within the multiple barrier layers in a TRISO fuel pebble, these benefits should be confirmed experimentally before being incorporated into a waste management strategy. In other cases, such as the sodium-bonded HALEU fuel planned for use in SFRs, the chemical properties of the fuel introduce back-end considerations. Sodium-bonded fuel must first be treated to remove the sodium as sodium-bonded spent fuel is not suitable for direct disposal due to the possibility for exothermic, caustic reactions between the sodium and air or water. These chemical reactivity issues are also a consideration with certain nitride and carbide fuels common in ATF technologies.

Waste types and volumes

The lack of experience and commercial-scale technical maturity for these treatment processes is also an issue with the management of other types of waste produced by advanced reactor systems. SFRs and LFRs will produce large quantities of activated liquid metal coolant waste, requiring further investigation to identify suitable treatment and disposal strategies. Combined liquid fuel-coolant MSRs introduce additional considerations for the treatment, packaging and recycling of fissile material, as well as the management of salt mixtures. HTGRs and many other advanced reactors use graphite as moderators or reflectors. The disposal of irradiated graphite waste introduces additional considerations. Furthermore, while direct disposal of TRISO pebbles may provide additional barriers to radionuclide release, the volume of this waste has been shown to be significant compared with an equivalent LWR and other advanced reactor designs. Although LWR-based SMR technologies may address most of these considerations, their smaller size may impact the compatibility of their spent fuel assemblies with existing casks for storage, transportation and eventual disposal.

By considering the logistics and constraints of future waste streams from HALEU-fuelled systems during the design phase and operational planning of SMRs, waste management requirements can actively shape decisions related to technology designs and fuel cycle options. An early and enhanced understanding of waste characteristics and behaviours makes it possible to assess compatibility with existing waste management solutions. In cases where new technologies or processes are required, early identification provides more time for development, testing and regulatory acceptance.

The WISARD Joint Project

An NEA Joint Project on Waste Integration for Small and Advanced Reactor Designs (WISARD) was in development phase during 2023-24 with the work phase due to begin in the first quarter of 2025. WISARD will focus on back-end management aspects for advanced reactors and SMRs. WISARD is designed to bring together advanced reactor developers, government bodies, nuclear fuel companies and waste management facilities to explore how front-end and design phase decisions impact back-end strategies to support sustainable future nuclear systems. While the detailed scope of WISARD will be developed throughout 2024, the impact of HALEU fuels on the back end of the fuel cycle is one possible topic of interest to project participants.

WISARD would focus on four waste management topics:

1. *Disposal*, including deep geological repositories (DGRs) and borehole options;
2. *Transportation*, including different cask designs and options for SMRs in remote locations;
3. *Treatment and recycling*, including new processing methods and closed fuel cycles; and
4. *Storage*, including spent fuel pools and dry casks.

Performance assessments of SMR and advanced reactor waste would be carried out for each of these areas to assess their compatibility with existing waste management systems and to identify future issues requiring innovative solutions. More information on WISARD is available at www.oecd-nea.org/wisard.

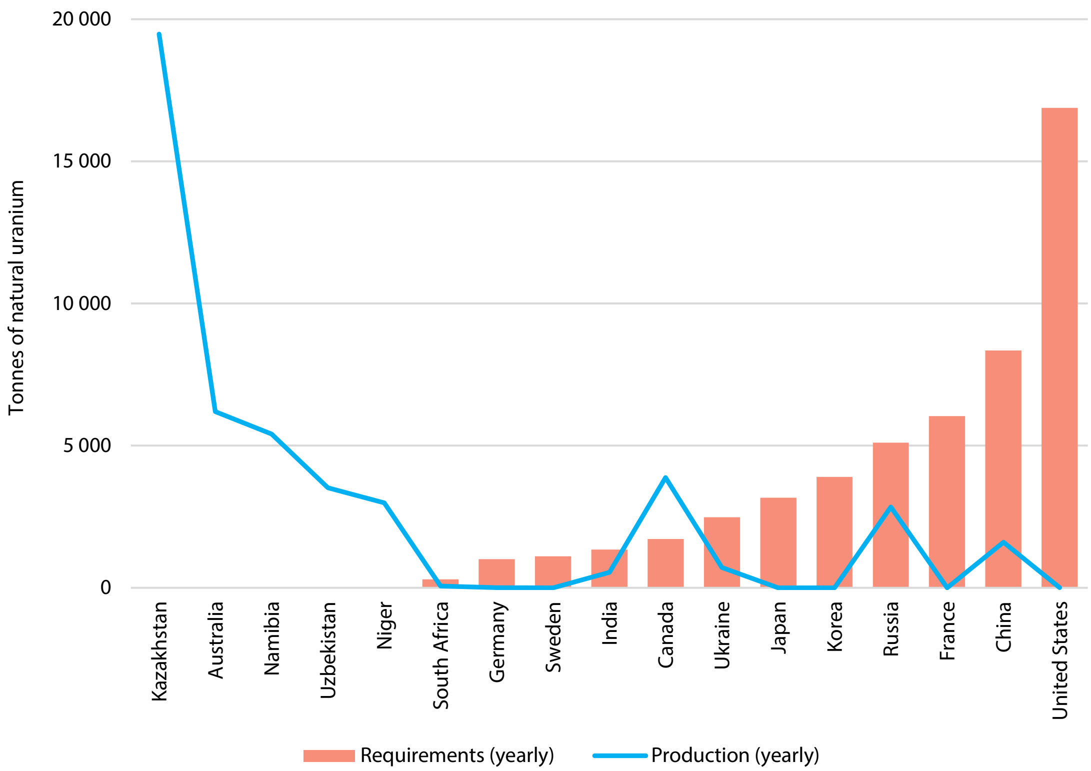
Chapter 5. **Strategic considerations**

Main uranium-producing countries

In 2021, uranium was produced in 17 countries, with total global production amounting to around 47 000 tonnes[1] (NEA, 2023c).

The top six uranium-producing countries in 2021 (Kazakhstan, Namibia, Canada, Australia, Uzbekistan and Russia, by order of production) accounted for 88% of world production, while 99% of world uranium production took place in ten countries, with the addition of Niger, China (the People's Republic of), India and Ukraine to the previous list. Among countries with installed nuclear generating capacity, only Canada produced sufficient uranium to meet its own domestic requirements in 2021.

Figure 5.1: **Natural uranium production and reactor-related natural uranium requirements for major producing and consuming countries in 2021**



Source: Data from NEA, 2023c.

1 These figures are lower than in previous years due to the impact of COVID, leading major producers to suspend uranium operations and temporarily close their mines.

With the potential exception of only one country (Canada), all nations with nuclear power must rely on imported natural uranium for their energy operations. As Figure 5.1 shows, there is a clear distinction between major uranium producing and consuming countries. Figure 5.1 also highlights how, notably, most major uranium producers do not rely on nuclear energy. This establishes a fundamental geographical reality where production of uranium is, in general, located in different locations far from where it will be consumed.

Consequently, the international trade of uranium is an essential dimension of the uranium market. International shipping requirements and transfers to international ports are, for this reason, also consistently a matter of strategic interest.

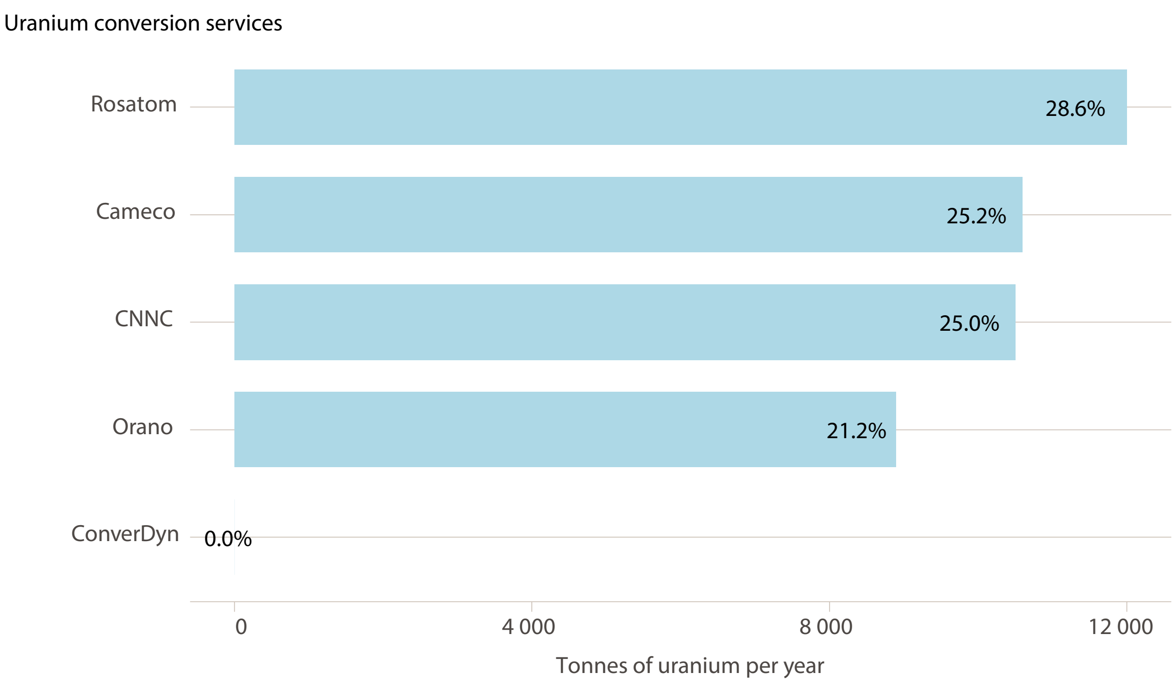
Main uranium conversion and enrichment providers in the world

The uranium conversion and enrichment market worldwide is dominated by only a handful of providers.

For conversion services of UF_6 production (see Figure 5.2), five international companies play a significant role. They are, in order of installed capacities: Rosatom (Russia), Cameco (Canada), CNNC (China), and Orano (France). The reopening of the ConverDyn facility in the United States will enhance supply diversification, adding 7 000 tonnes/year in licensed capacity and ranking it as the fifth-largest globally (WNA, 2023).

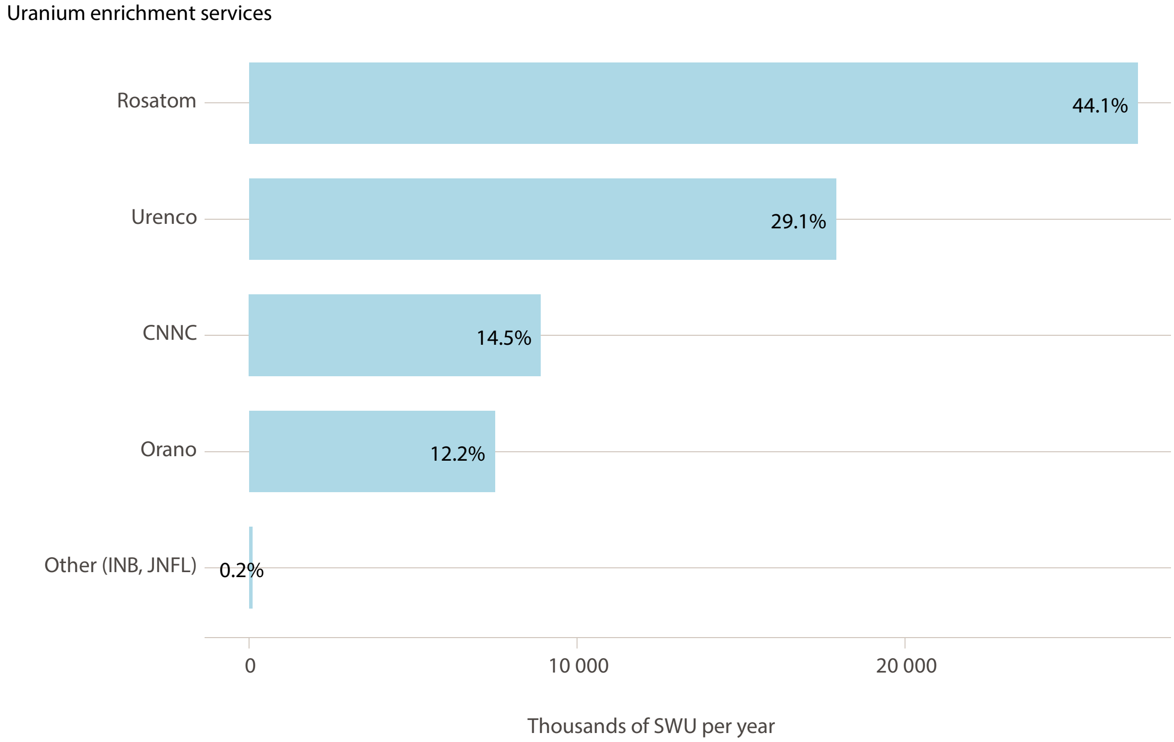
In terms of enrichment services (see Figure 5.3), the key players, in order of capacity, are Rosatom/Tenex (Russia), Urenco (British-German-Dutch), CNNC, and Orano. Only one among them, Tenex, is currently licensed to produce HALEU (WNA, 2023). Notably in 2022, Rosatom – via its subsidiary Tenex – supplied 30% of European utilities and 24% of US utilities (ESA, 2024).

Figure 5.2: **Main providers of uranium conversion services in 2022**



Source: Data from WNA, 2023.

Figure 5.3: **Main providers of uranium enrichment services in 2022**



Source: Data from WNA, 2023.

A changing landscape for strategic partnerships

The preceding figures indicate a significant dependence by OECD and NEA member countries on external supply. Equally important is the extent to which certain electricity utilities in OECD and NEA countries remain dependent on a single supplier for their fuel needs. With a cutoff or supply interruption, these utilities could encounter substantial operational vulnerabilities within a short time frame due to a lack of alternative suppliers in a tightening global market. This has elevated the development of fuel cycle infrastructures to a central and strategic priority for some OECD and NEA countries, prompting increased government spending on these priorities.

Expanding conversion and enrichment capacities will be a time-consuming process, ranging from several years to a decade or more for greenfield projects. Governments may need to take measures to build the confidence of investors in nuclear fuel cycle services and products in OECD and NEA countries – from mining and milling, to conversion, enrichment, and deconversion. In particular, investors may seek assurances that they will not face unfair competition.

Short-term HALEU supply for demonstration projects

Supplies of HALEU will be needed before the end of this decade to enable first-of-a-kind HALEU-fuelled SMR demonstration projects.

Up to and including 2023, there was no commercial supply of HALEU from providers in OECD or NEA countries. Some limited commercial supply is expected to begin in 2024. The other short-term method for producing HALEU fuels for western designs is down-blending existing HEU stocks in those countries where those would be available.

Strategic partnerships in OECD and NEA countries could be started in the short term with the objective of securing initial HALEU start-up inventories to kick-start advanced reactor demonstration programmes in these partner countries (ESA, 2019).

SMR investors need confidence in the availability and long-term security of supply of HALEU fuels.

Chapter 6. **Areas for future consideration**

Areas for future consideration		**Governments**	**Regulators**	**Industry**	**National labs**	**Int. organisations**
1.	**Develop better understanding of the impact of tripling global nuclear energy capacity by 2050**					
1.1.	Assess the impacts of tripling global nuclear energy on global uranium supply in quantitative detail, contributing to the development of a comprehensive global view and understanding of supply and demand scenarios for uranium production, conversion and enrichment needs.					
1.2.	Assess demand-side projections, including granular analysis across different scenarios, taking into consideration which applications specifically require HALEU.					
1.3.	Ensure technology selection processes are fully informed with complete understanding of fuel cycle alternatives and long-term implications, including policy implications.					
2.	**Invest in infrastructure and supply chains**					
2.1.	Invest in the uranium mining sector, including exploration for uranium resources and production capacity building, sufficiently anticipating timelines. Identify potential sources of uranium supply and production capabilities for various fuel options to mitigate supply chain disruptions and ensure continuous availability of fuel in the short, medium and long term.					
2.2.	Invest in capacity building in the conversion sector, sufficiently anticipating timelines.					
2.3.	Invest in capacity building in the enrichment sector, sufficiently anticipating timelines.					
2.4.	Invest in fuel cycle infrastructure, including transportation solutions for new HALEU fuel cycles.					
2.5.	Evaluate options and policy implications vis-à-vis open fuel cycles vs. closed fuel cycles, taking into consideration competing priorities: security of fuel supply and long-term availability of fissile resources; safeguards and non-proliferation; and economic competitiveness, among others.					
3.	**Prepare for different forms of HALEU fuel and ensure appropriate policies**					
3.1.	Undertake further analysis and official clarification as needed on domestic and international policy and regulatory and legal frameworks for different categories of enriched uranium fuels (e.g. 0-5%, 5-10%, 10-20%), taking into consideration IAEA safeguard categories and limits, and economic competitiveness considerations. This could include:					
	a) Identifying relevant customer segments with specific needs and preferences enabling producers to target their offerings effectively and capture niche opportunities.					
	b) Strengthening public and private sector understanding of the diversity of fuel types and forms to help identify opportunities for cost reductions, process optimisation, and value chain integrations, ensuring that the fuel supply chain remains economically sustainable in the long term.					
	c) Understanding and implementing safeguards requirements for HALEU production and use to ensure alignment with international safeguards standards and regulatory frameworks.					

Areas for future consideration		Governments	Regulators	Industry	National labs	Int. organisations
4.	**Invest in R&D infrastructure and capacities**					
4.1.	Anticipate and support the development of experimental data, and codes and methods appropriate for emerging HALEU-fuelled SMR technologies, needed in particular for validation.					
4.2.	Support the development of adequate research infrastructure needed to produce high-quality data appropriate for HALEU application validation, in particular back-end applications.					
4.3.	Ensure the role of HALEU in the production of medical radioisotopes is recognised in policy decisions pertaining to research reactors and HALEU infrastructures.					
5.	**Conduct waste characterisation analyses to inform SMR technology choices**					
5.1.	Develop an enhanced understanding of HALEU waste characteristics and behaviours (e.g. volumes, radiotoxicity, heat) on a case-by-case basis to assess compatibility with existing waste management solutions.					
5.2.	Consider the logistics and constraints of future waste streams from HALEU-fuelled systems alongside the design phase and operational planning.					
6.	**International co-operation**					
6.1.	Periodically convene small meetings of public and private sector decision makers from those OECD and NEA countries concerned to discuss public-private solutions to unlock investments in additional uranium conversion and enrichment capacities, as well as to send clear market signals of OECD member country commitment to nuclear fuel diversification.					
6.2.	Co-ordinate joint analyses to map nuclear fuel supply chain cycle gaps and investment opportunities across OECD and NEA countries concerned.					
6.3.	Engage in early outreach activities to potential first movers for SMR industrial applications. Share information on demand-side projections for nuclear fuel consumption.					

Chapter 7. Conclusions

The challenge of achieving net zero by mid-century has reasserted the importance of nuclear energy in global energy and climate discussions as a key contributor to a decarbonised energy mix. Many nations are now calling for global installed nuclear capacity to triple by 2050. The widespread deployment of small modular reactors (SMRs) is increasingly seen as a game-changing opportunity for various power and non-power applications in support of net zero objectives.

In this context, high-assay low-enriched uranium (HALEU) fuels are likely to play a significant role. The higher-enrichment levels associated with HALEU enable advanced technology applications, particularly in the realm of SMRs. These applications include providing high-temperature process heat for industrial production, microreactors for off-grid applications, and propulsion in the transport sector, ranging from marine to space technologies.

Most SMR designs based on fast reactor concepts require initial fissile concentrations in fuel above 10% using a starting inventory of plutonium or HALEU. Widespread deployment of SMRs and microreactors using plutonium-based fuels could present policy questions in respect to nuclear security. HALEU offers an alternative for countries that make technology choices favouring LEU or prohibit the use of plutonium-based fuels or reprocessing.

HALEU as a fuel comes with its own policy and technology implications. Commercial HALEU production within OECD countries remains limited. Current geopolitical uncertainties continue to pose HALEU supply questions amid the possibility of future disruptions to international nuclear fuel supply chains. Certain OECD and NEA countries are now looking for diversification opportunities to ensure the security of energy supply. Developing both additional LEU and HALEU conversion, deconversion and enrichment capacities in the near term represents a strategic interest for those nations seeking to preserve an independent, leading role in advanced nuclear technology markets.

The nuclear industry has historically operated with commercial enrichments of up to 5%, with the associated industrial supply chain and legal and regulatory frameworks designed accordingly. Moving to higher than 5% enrichment will have implications along the full fuel cycle. These implications are even more pronounced if the enrichment levels are above 10%.

Additional work will be needed to better understand the potential impacts on the full fuel cycle – from the quantity of uranium supply necessary to characterising the waste produced at the back end of the fuel cycle.

There could be significant implications for uranium mining, conversion and enrichment markets, as well as fuel cycle strategies to prepare for HALEU-ready fuel cycle infrastructures. The analysis in this document shows that the use of HALEU-based SMRs may not necessarily translate to more efficient use of uranium resources to produce energy. Depending on the specific enrichment levels and burn-up rates of SMRs to be deployed some HALEU-based SMRs could require higher quantities of natural uranium in addition to higher-enrichment capacities compared to existing LEU based fuels.

In the analysis of the Reference Scenario, which is based on a tripling of installed global nuclear capacity by 2050 and includes significant deployment of HALEU-fuelled SMRs, this document shows that demand for natural uranium would exceed 200 000 tonnes per year by 2050. This would necessitate significant investment in exploration for new uranium resources, optimal use of secondary resources of uranium, as well as consideration of fuel recycle options.

Building out additional enrichment capacity for HALEU production will take time, from several years to more for greenfield projects. Furthermore, meeting the diverse fuel needs of advanced nuclear reactor designs currently under consideration will require the establishment of novel uranium enrichment capacities, chemical conversion and deconversion services and fuel fabrication solutions. Likewise, suitable transportation packages that meet the necessary criticality safety requirements for the new HALEU-based materials will need to be developed at all relevant stages of their transport in a cost-effective manner.

With many SMR and advanced reactor vendors hoping to commercialise their systems internationally, and with renewed interest in nuclear energy for decarbonisation and energy security, the range of potential stakeholders in nuclear projects has never been higher.

In contrast to large LWRs, which represent mature, well-understood technologies with established and experienced industry leaders, developers of SMRs and advanced reactors using HALEU fuels form a diverse field marked by an active start-up culture closely collaborating with academia and independent research organisations worldwide.

While these new entrants into the nuclear energy landscape bring much-needed flexibility and innovation, it is crucial to ensure that the lessons learnt over decades of design, operation, transport, safeguards and waste management experience are also considered for these emerging technologies. This will require new and strengthened strategic partnerships along the length of the supply chain, across industrial sectors and internationally.

It is essential to involve all parties and stakeholders from the beginning to minimise expensive and avoidable disconnects between the supply chain, reactor design, fuel operation, safeguards and decommissioning phases.

Although not exhaustive, the following conclusions could help guide decision making and co-operative activities as part of a “big-tent” approach to stakeholder engagement.

Understanding the impact of tripling nuclear capacity by 2050

For nuclear innovation to help meet net zero targets, the global uranium supply industry must guarantee sufficient uranium production and enrichment and conversion capacities. This requirement is driven by the overall development of nuclear energy at all levels and is not exclusive to HALEU-fuelled SMRs.

For some SMR designs, HALEU introduces added complexity due to the diversification of fuel forms, and higher-enrichment requirements per unit energy compared to traditional LEU fuels. In addition, certain SMR designs, including certain HALEU-fuelled SMRs, could require more natural uranium per unit of energy produced than currently deployed nuclear technologies.

Fuel cycle options, particularly the potential introduction of fuel recycle options, will be crucial determinants of the overall impact of a substantial increase in nuclear energy worldwide. This impact extends beyond natural uranium consumption and front-end capacities to encompass back-end volumes of waste streams that will require processing and disposal. This effort should be undertaken as early as possible and in collaboration with the leading SMR technology developers, who will be the credible first movers before 2030.

Preparing HALEU-ready fuel cycle infrastructures

The nuclear industry has historically operated with commercial enrichments of up to 5%, with the associated industrial supply chain and legal and regulatory frameworks designed accordingly. Moving to higher than 5% enrichment will have implications along the full fuel cycle. These implications are even more pronounced if the enrichment levels are above 10%.

Meeting the diverse fuel needs of advanced nuclear reactor designs currently under consideration will require the establishment of new infrastructure, encompassing uranium enrichment capacities, chemical conversion and deconversion services and fuel fabrication solutions. Likewise, suitable transportation packages that meet the necessary criticality safety requirements for the new HALEU-based materials will need to be developed.

Leveraging the benefits of international co-operation

Government-to-government, public-private and business-to-business co-operation will likely prove important to maximise the cost benefits of shared supply chains and to maximise the benefits of productive competition. Suppliers of nuclear fuel cycle services and products based in certain OECD and NEA countries will also require assurances from governments that new investments in fuel fabrication capacity will be protected from unfair competition from non-market activities such as price discrimination in the future. Co-ordinated efforts to create markets, ensure fair competition, harmonise regulatory frameworks and share best practices can help create the right enabling conditions for a diverse and secure supply chain for HALEU fuel.

Preparing for different forms of HALEU fuels

There is a diversity of SMR concepts under development, which propose to use a variety of fuel types and fuel forms. Even among concepts that propose to use HALEU fuels, there are various HALEU fuel types and fuel forms proposed. An important challenge lies in achieving a flexible and reliable fuel supply chains that can supply a range of custom HALEU fuel forms and enrichment needs, all while remaining economical and cost-effective. Appropriate fuel cycle infrastructures and certifications will be required for novel fuels, which will need to align with safeguards associated with the special nuclear material definitions.

Considering back end and waste management

The back end of the fuel cycle will require careful assessment on a case-by-case basis for all the HALEU-based SMRs moving towards commercial deployment. Characterising and dimensioning volumes and activity of waste streams from SMRs using HALEU will be a key factor in evaluating the technological feasibility, scalability, long-term sustainability of these innovative concepts.

The cost and time needed to develop the necessary experimental qualification platform and evaluated benchmark initiatives, currently lacking for HALEU-based systems, should not be underestimated. These components are essential for the required verification, validation and uncertainty quantification applications of all HALEU-based advanced reactors and are a necessary step in their future licensing.

Conducting waste characterisation analyses to inform SMR technology choices

There is currently a unique window of opportunity to strategically consider fuel cycle, safeguards and waste management. In particular, the long-term viability of nuclear energy in terms of the needed fissile resources, and how these are managed and optimised, will be driven by fuel cycle considerations and its back end.

By considering the logistics and constraints of future waste streams from HALEU-fuelled systems during the design phase and operational planning of SMRs, waste management concerns can actively shape decisions related to technology deployment and fuel cycle options. In cases where new technologies or processes are required, early identification provides more time for development, testing and regulatory acceptance.

This approach could ensure that SMRs follow the correct path towards licensibility, enhancing their prospects in the international market and sending the necessary credible signals to the fuel cycle industry to prepare for their emergence.

References

DeHart, M.D., J.D. Bess and G. Ilas (2023), "A review of candidates for a validation data set for high-assay low-enrichment uranium fuels", *Journal of Nuclear Engineering*, Vol. 4(3), pp. 602-624, https://doi.org/10.3390/jne4030038.

ESA (2019), "Securing the European Supply of 19.75% Enriched Uranium Fuel", Euratom Supply Agency, https://euratom-supply.ec.europa.eu/publications/other-esa-publications_en.

ESA (2024), *Euratom Supply Agency Annual Report 2022*, https://euratom-supply.ec.europa.eu/publications/esa-annual-reports_en.

Geelhood, K. J. (2019), "Fuel Performance Considerations and Data Needs for Burnup Above 62 GWd/MTU", Pacific Northwest National Laboratory, Richland, www.nrc.gov/docs/ML1931/ML19317D098.pdf.

Glaser, A. (2006) "On the proliferation potential of uranium fuel for research reactors at various enrichment levels", *Science and Global Security*, Vol. 14, Issue 1, pp. 1-24, https://doi.org/10.1080/08929880600620542.

IAEA (2001), *Safeguards Glossary – 2001 Edition,* International Atomic Energy Agency, Vienna, www.iaea.org/publications/6663/iaea-safeguards-glossary.

IAEA (2011) "Nuclear Security Recommendations on Physical Protection of Nuclear Material and Nuclear Facilities (INFCIRC/225/Revision 5)", *IAEA Nuclear Security Series*, No. 13, IAEA, Vienna (2011), www.iaea.org/publications/8629.

IAEA (2013), "Online Database, Advanced Reactors Information System (ARIS)", website of the International Atomic Energy Agency, https://aris.iaea.org.

IAEA (2020a), *Advances in Small Modular Reactor Technology Developments, a Supplement to: IAEA Advances Reactors Information System (ARIS)*, International Atomic Energy Agency, Vienna, https://inis.iaea.org/search/search.aspx?orig_q=RN:51111609.

IAEA (2020b), *Light Water Reactor Fuel Enrichment Beyond the Five Per Cent Limit: Perspectives and Challenges*, International Atomic Energy Agency, Vienna, IAEA-TECDOC-1918, www.iaea.org/publications/14697.

IAEA (2022), *Advances in Small Modular Reactor Technology Developments, a Supplement to: IAEA Advances Reactors Information System (ARIS)*, Atomic Energy Agency, Vienna, www.iaea.org/publications/14697.

Michel-Sendis, F. et al. (2017), "SFCOMPO-2.0: An OECD NEA Database of Spent Nuclear Fuel Isotopic Assays, Reactor Design Specifications and Operating Data", *Annals of Nuclear Energy*, Vol. 110, pp. 779-788, Elsevier, https:doi.org/10.1016/j.anucene.2017.07.022.

NEA (2006), *Very High Burn-ups in Light Water Reactors*, OECD Publishing, Paris, www.oecd-nea.org/jcms/pl_14246.

NEA (2018), *State-of-the-Art Report on Light Water Reactor Accident-Tolerant Fuels*, OECD Publishing, Paris, www.oecd-nea.org/jcms/pl_15020.

NEA (2021), *Small Modular Reactors: Challenges and Opportunities*, OECD Publishing, Paris, www.oecd-nea.org/jcms/pl_57979.

NEA (2022), *Meeting Climate Change Targets: The Role of Nuclear Energy,* OECD Publishing, Paris, www.oecd-nea.org/jcms/pl_69396.

NEA (2023a), *The NEA Small Modular Reactor Dashboard*, OECD Publishing, Paris, www.oecd-nea.org/jcms/pl_78743.

NEA (2023b), *The NEA Small Modular Reactor Dashboard: Volume II*, OECD Publishing, Paris, www.oecd-nea.org/jcms/pl_83555.

NEA (2023c), *Uranium 2022: Resources, Production and Demand,* OECD Publishing, Paris, www.oecd-nea.org/jcms/pl_79960.

NEA (2023d), *International Criticality Safety Benchmark Evaluation Project Handbook: 2021*, OECD Publishing, Paris, https://doi.org/10.1787/0235eb97-en.

NEA (2024), *The NEA Small Modular Reactor Dashboard: Second Edition*, OECD Publishing, Paris, www.oecd-nea.org/jcms/pl_90816.

NEA (2024b), *International Reactor Physics Evaluation Project Handbook: 2021,* https://doi.org/10.1787/a1dd6d99-en.

NEI (2018), "Addressing the Challenges with Establishing the Infrastructure for the Front-End of the Fuel Cycle for Advanced Reactors", Nuclear Energy Institute, Washington, www.nrc.gov/docs/ML1810/ML18103A250.pdf.

Kim, T.K., et al. (2023), "Pros and Cons Analysis of HALEU Utilization in Example Fuel Cycles", Argonne National Laboratory, Argonne, https://doi.org/10.2172/1985692.

WNA (2023), *The Nuclear Fuel Report: Global Scenarios for Demand and Supply Availability 2023-2040,* World Nuclear Association, UK, https://world-nuclear.org/shop/products/the-nuclear-fuel-report-global-scenarios-for.

Appendix A. Fuel cycle quantities as a function of reactor parameters

Definitions and key reactor parameters: Enrichment, burn-up, thermal efficiency

The enrichment level E refers to the relative proportion of the fissile isotope U-235 in uranium and is expressed in terms of weight percentage of U-235 mass in uranium metal.

The fuel burn-up B refers to an estimated value giving the total energy extracted from a specific amount of fresh fuel. Fuel burn-up is expressed in units of thermal energy per mass of heavy metal initial (HMI)[1] present in the fresh fuel, and often given as an average at discharge of fuel. For uranium-based fuels, fuel burn-up is commonly given in units of GWd/tU (gigawatt-days per tonnes of uranium *in the fuel*).

For a once-through fuel cycle, the enrichment level E, of the fuel, its average discharge burn-up B, together with the thermal efficiency of the system, ξ, determines four quantities of interest:

- mass of HALEU needed;
- SWU needed;
- NU needed; and
- resulting DU, per electrical energy unit produced.

Required HALEU mass per unit energy produced

The mass of HALEU needed per unit energy produced varies based on the chosen reactor technology and fuel cycle options. As an initial approximation, for once-through fuel cycles, the required mass of HALEU at equilibrium per unit energy produced for a given reactor concept varies as the inverse of its average fuel discharge burn-up.

Given B, the average discharge burn-up in energy per ton of HMI of enriched uranium fuel (HALEU in our case), it possible to express M_H, the corresponding mass of HALEU required to produce one unit energy of thermal power. Considering ξ, the thermal conversion efficiency, and the proper time unit conversion ($\frac{d}{y}$; which is simply switching day units to years), gives:

$$M_H = \frac{1}{B} \times \frac{1}{\xi} \times \frac{d}{y}$$

Where:

- M_H is expressed in tonnes of HALEU per GWe.y;
- B, is the average discharge burn-up expressed in GW.d per ton of Heavy Metal Initial;
- ξ, the thermal conversion efficiency, a dimensionless quantity (ratio of electrical output to thermal output);
- d/y is a unit conversion factor that allows to convert to GWd to GWy (d/y=365).

1 When dealing with fuel mixes containing a combination of uranium, plutonium or even potentially thorium in the fresh fuel, fuel burn-up is given in units of GWd per tonnes of heavy metal initial (tHMI).

This provides a direct estimation of the mass of HALEU fuel needed, regardless of its enrichment level.

Required separative work units per unit energy produced

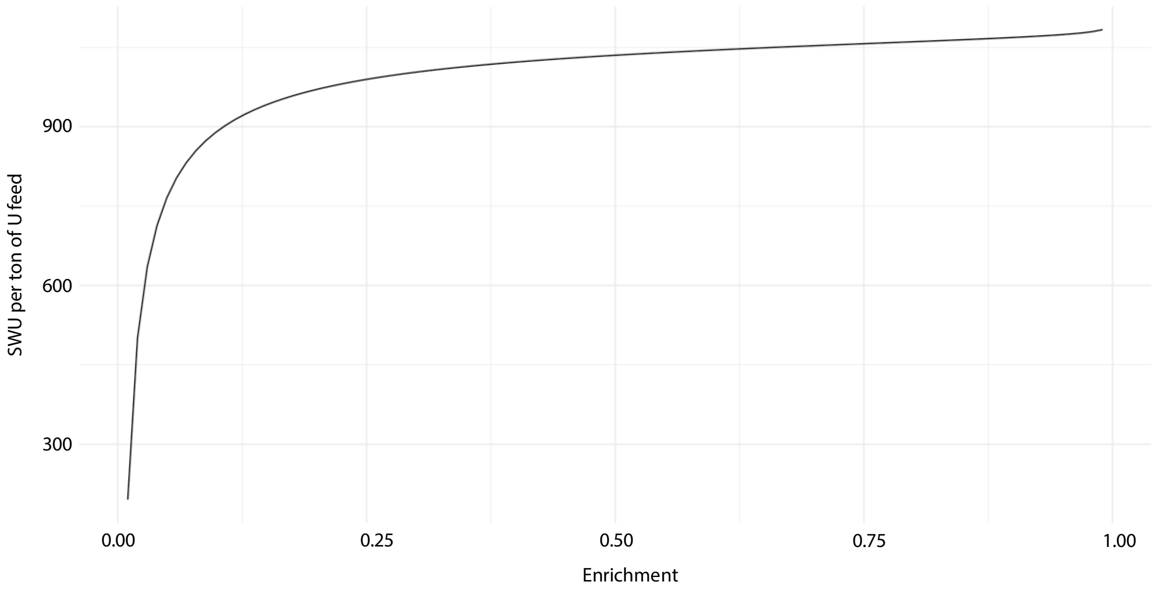
Knowing the mass of HALEU needed per unit energy produced and the enrichment level allows us to calculate the amount of separative work units (SWU) per year, providing an estimation of the required enrichment capacities.

The magnitude of the effort of the separation task in the enrichment phase is expressed in terms of the separative work units (SWUs). The units of this measure of work are mass units. SWUs are expressed as a complex function S, of the different assays in the three streams (one feed, two outputs: enriched and tails) of the enrichment process.

For our general analysis purposes, it is sufficient to know that S is a function of the enrichment level and that it can be easily calculated (Appendix C gives the detailed expression of S). The S function can be used to calculate the enrichment capacities needed by different HALEU-fuelled concepts.

Figure A1 illustrates the function S, the separative work units (SWU) needed per ton of natural uranium feed, as a function of enrichment. It represents the effort required to enrich a given input mass of natural uranium to a specified percentage, resulting in a final enriched uranium product (EUP).

Figure A1: **Separative work units (SWU) needed per ton of natural uranium feed, as a function of enrichment**



Natural uranium consumption per unit energy produced

The natural uranium (NU) consumption per energy produced throughout the lifespan of nuclear fuel is an important quantity in the evaluation of the long-term sustainability of nuclear power, especially in high nuclear capacity growth scenarios, where once-through (open) fuel cycles are considered. In these scenarios, the continuous extraction of mineral resources is inherently necessary.

The quantity of NU needed per GWe.y increases linearly with E and is inversely proportional to B, and can be expressed a product of two terms, one which depends on reactor design, the other on fuel cycle parameters:

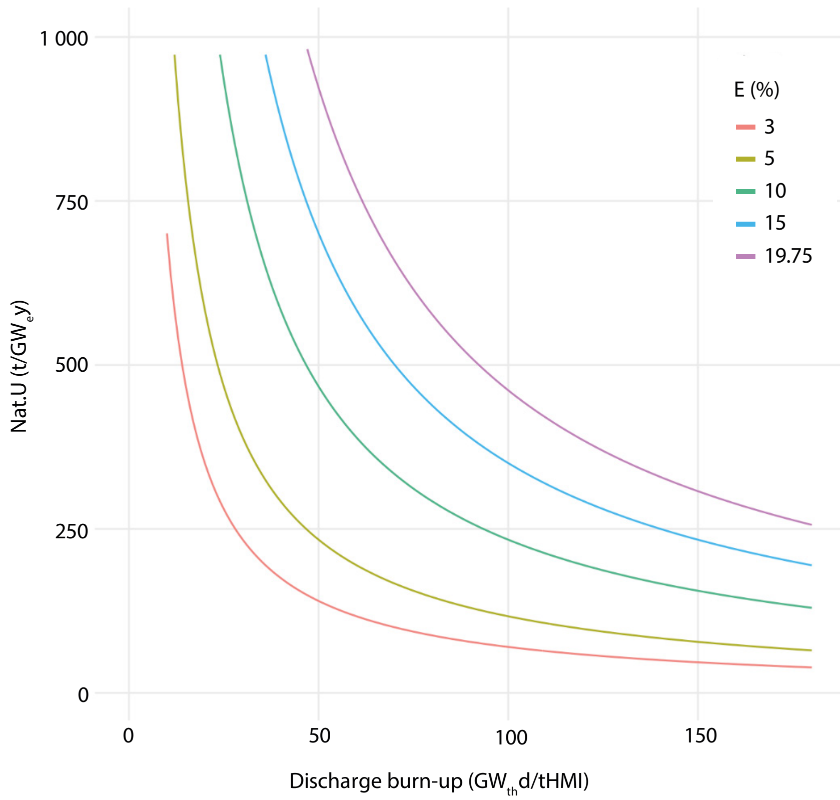
$$M_{NU} = \underbrace{\frac{E}{B.\xi}}_{reactor} \times \underbrace{\frac{1}{(\epsilon_f - \epsilon_t)(1-l)}}_{fuel\ cycle} \times \underbrace{(d/y)}_{unit\ conversion}$$

Where:

- M_{NU} is the mass of NU needed per GWe.y;
- ϵ_f are the assays of the feed;
- ϵ_t are the assays of the tails;
- l are the overall losses of the process.

Figure A2 illustrates the relationship between natural uranium consumption per unit energy produced, fuel burn-up, and enrichment.

Figure A2: **Relationship between natural uranium (NU) consumption per unit energy produced, as a function of fuel burn-up (B), and enrichment (E)**



Note: Thermal efficiency conversion is set to 35%.

Depleted uranium production per unit energy produced

Depleted uranium, often referred to as “tails”, is a by-product derived from the enrichment process and typically consists of approximately 0.25% U-235, a measure known as the “tails assay”.

The rate of depleted uranium production is directly linked to the quantity of separative work units (SWUs) applied during the enrichment process.

If we neglect losses on the enrichment process, the conservation of mass allows us to establish that:

$$M_{DU} = M_{NU} - M_{EUP}$$

Where:

- M_{DU} is the resulting mass of depleted uranium.
- M_{EUP} is the resulting mass of enriched uranium product.
- M_{NU} is the necessary mass of natural uranium in the feed process.

Depleted uranium production is an important quantity to consider in the nuclear fuel cycle, especially in the event of the eventual reclassification of DU as waste in some countries. This reclassification would prompt the development of necessary management solutions, including storage methods, storage scenarios, safety requirements, all with associated costs, to be consistent with other low-level, long-lived waste management strategies.

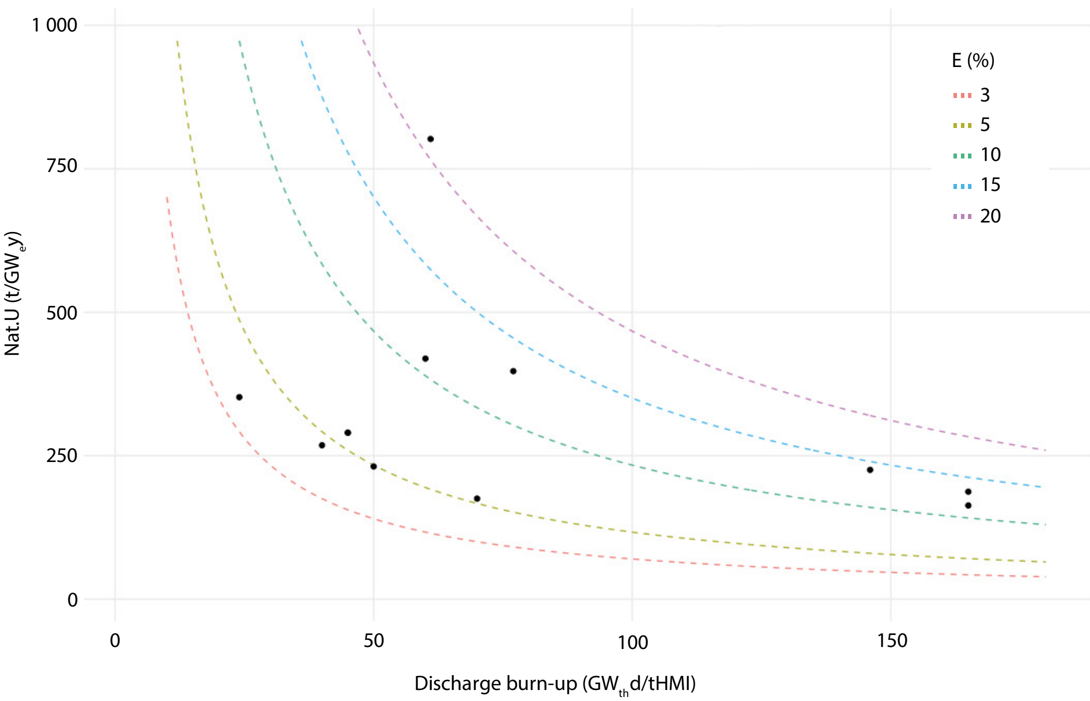
Appendix B. Sensitivity analysis of fuel cycle quantities as a function of reactor parameters

In this appendix the focus is on verifying that the fuel cycle parameters calculated in Chapter 4 behave as expected according to their dependence on the three key variables: enrichment, burn-up and thermal conversion efficiency. A direct sensitivity analysis is conducted by examining how the fuel cycle parameters (NU, EUP and SWU) fluctuate when the three variables are varied within their realistically considered ranges. This makes it possible to delineate the different "envelopes" of expected values, and then to verify that the SMR data points fall within these envelopes as expected. Figures B1 through B4 below illustrate these envelopes.

Figure B2 displays the same data and information as Figure B1, but this time considering a range of thermal conversion efficiencies (from 30% to 45%, which is the range observed in most designs).

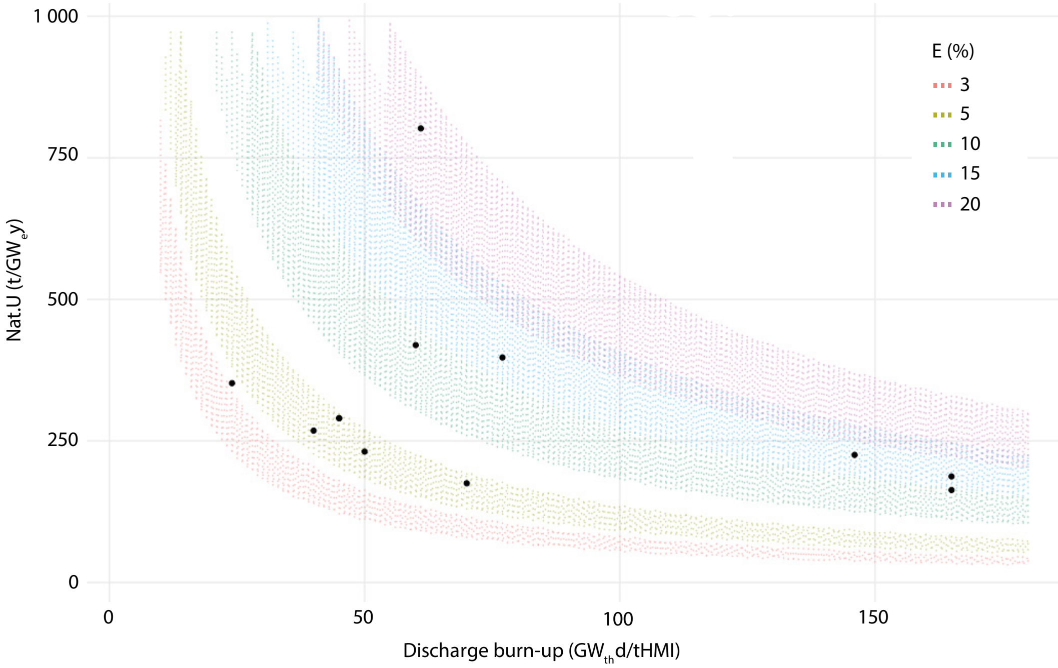
Figure B3 and B4 follow the same visual representation logic and give this view for the other two fuel cycle quantities, EUP and SWU. From them it is possible to conclude that the calculated SMR fuel cycle requirements, which may seem disparate at first glance, do follow the expected behaviour once it is considered how the three variables that define them in the model fluctuate.

Figure B1: **Relationship between natural uranium (NU) consumption per unit energy produced, as a function of fuel discharge burn-up (B), and enrichment (E), for a single fixed value of thermal conversion efficiency (35%)**



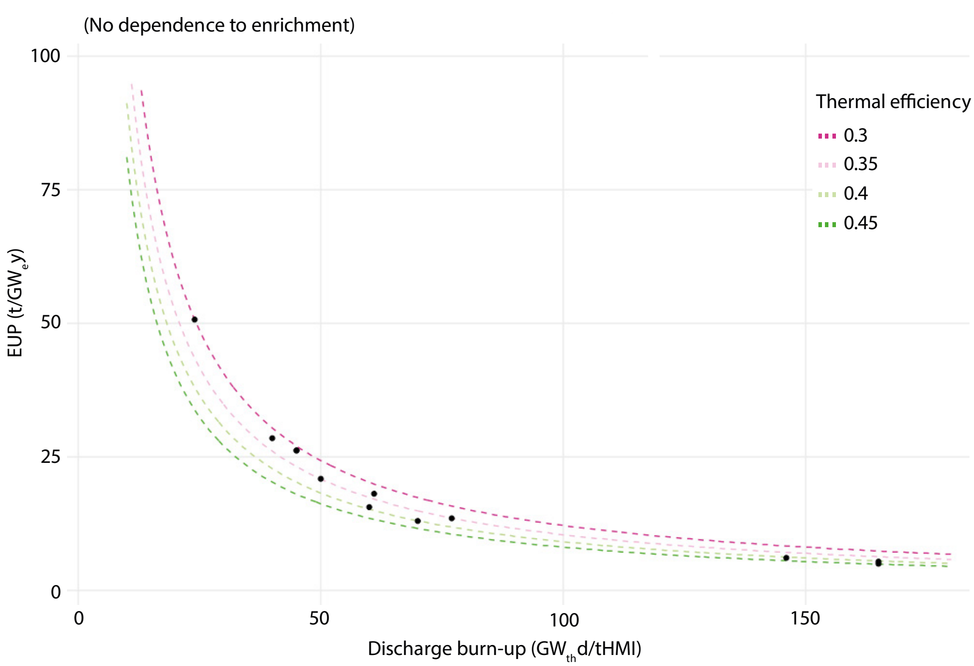
Note: SMR calculated fuel cycle requirement points considered in this report are in black.

Figure B2: **Relationship between natural uranium (NU) consumption per unit energy produced, as a function of fuel burn-up (B), and enrichment (E), for varying values of thermal conversion efficiencies (from 30% to 45% range)**



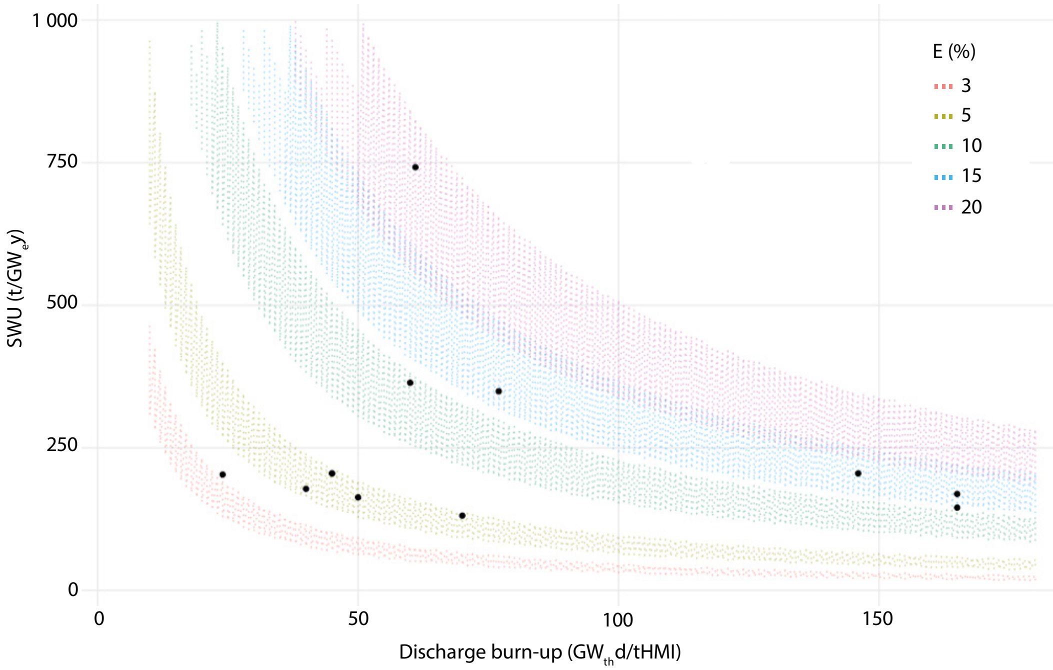
Note: SMR calculated fuel cycle requirement points considered in this report are in black.

Figure B3: **Relationship between Enriched Uranium Product (EUP) needed per unit energy produced, as a function of fuel burn-up (B), for varying values of thermal conversion efficiencies (from 30% to 45% range)**



Note: SMR calculated fuel cycle requirement points considered in this report are in black.

Figure B4: **Relationship between natural Separative Work Units (SWU) per unit energy produced, as a function of fuel burn-up (B), and enrichment (E) for varying values of thermal conversion efficiencies (from 30% to 45% range)**



Note: SMR calculated fuel cycle requirement points considered in this report are in black.

Propagation to SMR capacity deployment in the Reference Scenario

Chapter 4 set out the fuel cycle parameters of a hypothetical SMR design using HALEU fuel at 16.5% enrichment and an average discharge burn-up of 146 gigawatt-days-per-ton (GWd/t). This sensitivity analysis seeks to determine how the conclusions would change if a different hypothetical SMR with different enrichment requirements, burn-up rates or thermal conversion efficiencies is chosen. This report's answer is in the form of a distribution that illustrates the dispersion of fuel cycle yearly requirements for each of the SMR concepts for which data were available during this analysis.

For this purpose, the focus is solely on the isolated SMR installed capacity projections of the Reference Scenario (reaching a total of 330 GWe in 2100; as shown in Figure B5) and the yearly fuel cycle requirements for the four previously introduced quantities, for all SMR concepts, are calculated separately.

Figure B6 illustrates the impact of selecting a different SMR concept in the Reference Scenario for the natural uranium quantities needed per unit energy, by displaying them for each SMR, always making the working hypothesis that each SMR concept would represent 100% of the SMR electrical capacity scenario being deployed. It should be clear that this is done only as an exercise: realistic projections would not choose a single SMR concept but rather a mix of them, with different power levels targeting various end-use applications. However, makes it possible to address the question of how the overall estimates provided by the Reference Scenario would change by examining the dispersion of these results through a statistical approach.

Figure B5: **SMR electrical capacity growth in the Reference Scenario**

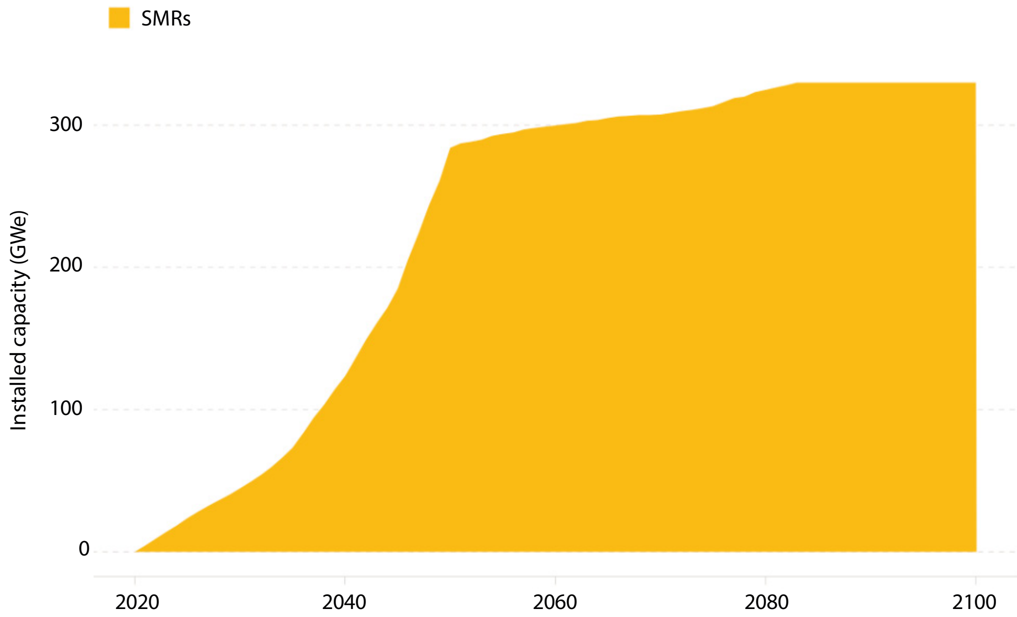
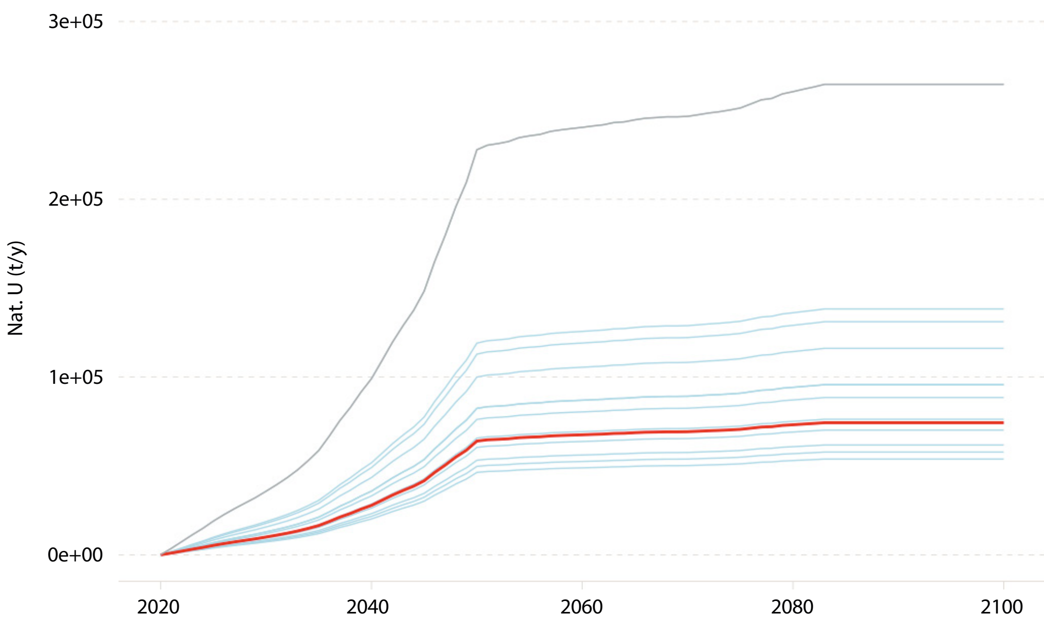


Figure B6: **Natural uranium requirements calculated for the different SMRs in the Reference Scenario**



Note: Each line represents a different SMR choice. Shown in red is the value representing the SMR concept used for the calculations presented in Chapter 4.

Figures B7 through B9 give this spread of values for NU, EUP and SWU requirements in boxplot representations, showing outliers.

Figure B7: **Boxplot representation of natural uranium requirements calculated for the different SMRs in the Reference Scenario**

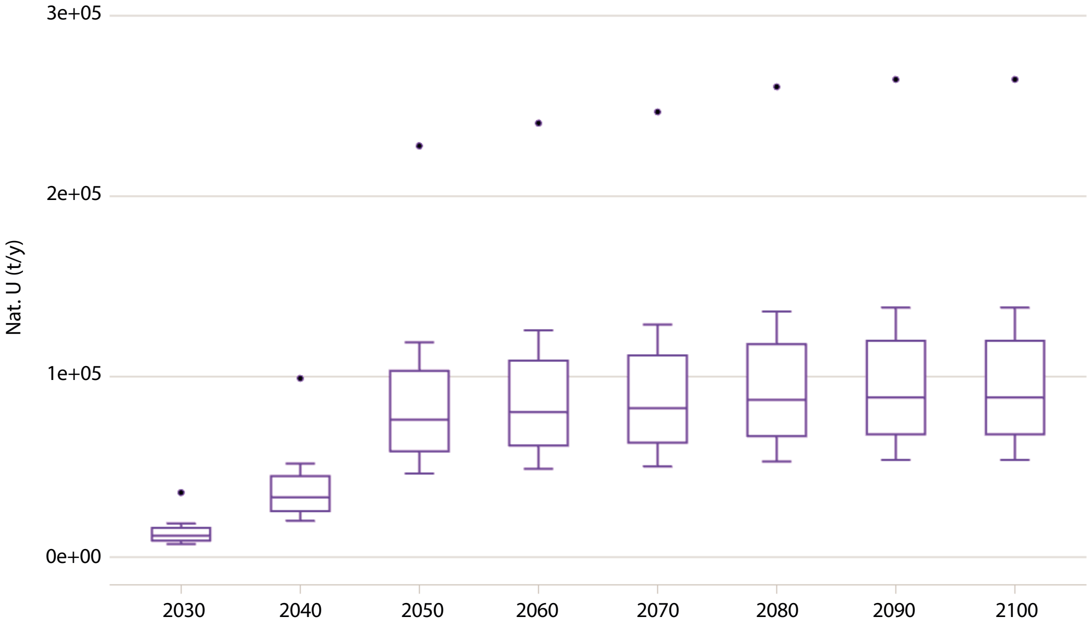


Figure B8: **Boxplot representation of enriched uranium product requirements calculated for the different SMRs in the Reference Scenario**

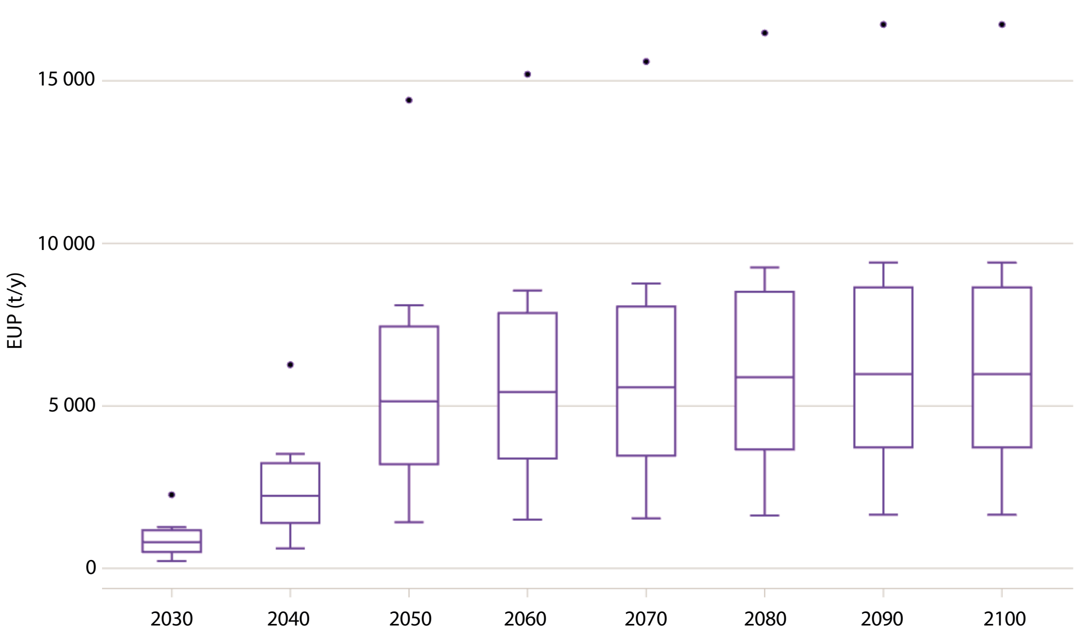
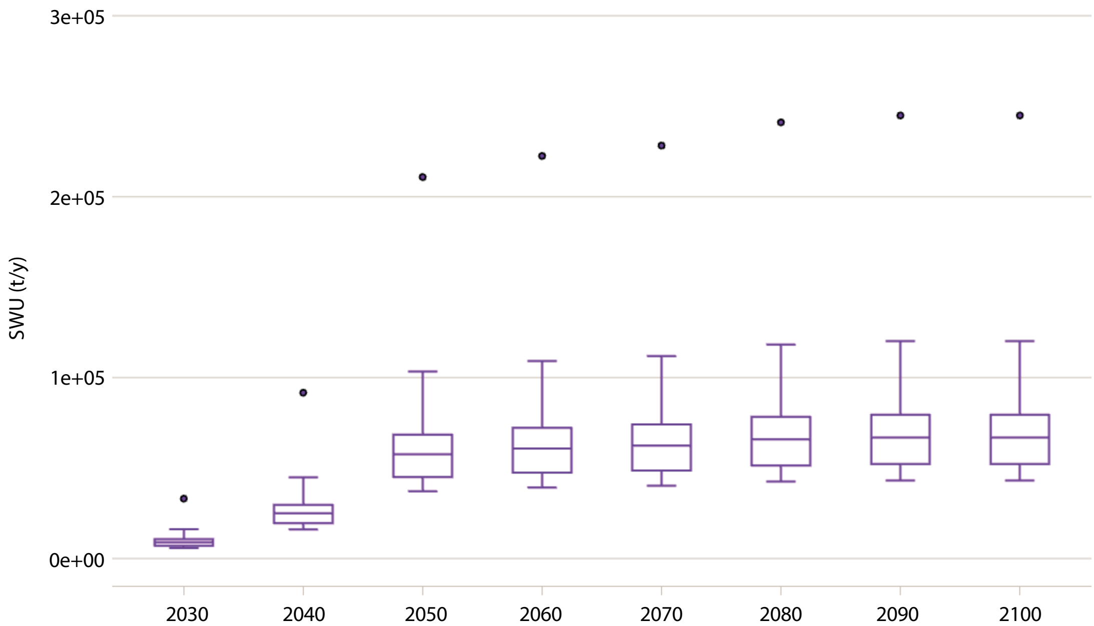


Figure B9: **Boxplot representation of Separative Work Units requirements calculated for the different SMRs in the Reference Scenario**



Conclusions of the sensitivity analysis

This sensitivity analysis revealed that a 50% variation in natural uranium requirements (a variability which is compatible with the dispersion of values observed around the median, excluding outliers) for SMRs in the Reference Scenario would result in around a 16% fluctuation in global yearly natural uranium requirements. Given the nascent stage of SMR technology deployment, it is too soon to predict which SMR designs, fuels and fuel cycles will achieve widespread commercial deployment in the coming decades. Nevertheless, this sensitivity analysis confirms that the broad strokes of the conclusions presented in Chapter 4 of the report are robust.

Appendix C. Further considerations on HALEU data, codes and methods needs

International need for HALEU validation data

Because there is little historical operating experience for HALEU-fuelled commercial reactors, whether in an LWR or advanced reactor concept, the regulator will require the validation of simulation codes and methods (in particular, criticality and fuel depletion methods) using HALEU data.

There is an international need for high-quality experimental data in the field of nuclear criticality safety, fuel performance and reactor system analysis for accurately representing HALEU-based systems in all their diversity. These data are essential to establish a robust foundation for code and methods validation for HALEU-based nuclear systems to support their future design and licensing. Regulators demand that modelling approaches, which include simulation codes and methods, be rigorously validated against carefully evaluated experimental data to demonstrate their applicability.

The codes and methods presently employed to model the performance of existing fuel designs with conventional enrichments might not be adequate for modelling HALEU fuels. Ensuring safety and design requirements are met requires proper validation of these codes and methods specifically for the modelling of innovative fuel designs.

Advanced Generation IV, HALEU-fuelled nuclear reactor designs, whether SMRs or larger systems, depart from conventional low-enriched fuelled light water reactor designs currently in operation worldwide and consequently, a priori also from their validation platforms.

From a regulatory standpoint, commercial reactors are presently limited to using fuels with U-235 enrichment levels below 5%. Among factors limiting the use of fuels with U-235 enrichment beyond 5% is the scarcity of data and experience concerning fuels enriched beyond 5%, particularly closer to the 20% cutoff.

Concerning fuel performance codes and methods, a recent review undertaken by the Committee on Nuclear Safety Installations (CSNI) Working Group on Fuel Safety (WGFS) (NEA, forthcoming) concluded there is useful experimental data for fuel enriched between 5% and 8% from research and test reactors that could be used to validate fuel performance codes and methods. The WGFS members note in the report that as enrichment is increased, so to would, in some cases, the use of burnable poisons such as gadolinia. Fuel performance codes will require validation using a range of enrichment and burnable poison scenarios.

International reference evaluated benchmark handbooks in these domains are hosted and co-ordinated by the NEA. They are the *International Criticality Safety Benchmarks Evaluation Project* (ICSBEP), and the *International Reactor Physics Experiments Evaluation Project* (IRPhE), which each produce handbooks of experimental benchmarks (NEA 2023d, 2023e). Depending on the system developed and design margins, these data may lack sufficient and relevant experiments with appropriate similarity to the full spectrum of HALEU systems and enrichments that will be necessary for the design and deployment of advanced nuclear systems.

There are several reactor physics benchmarks based on fresh HALEU fuel that will help support the validation of criticality calculations for core designs, but experimental benchmarks that can validate the prediction of the evolving fuel isotopic composition during operation do not exist (DeHart, 2023). For instance, none of the data in Spent Fuel Isotopic Composition database

(SFCOMPO) of the NEA (Michel-Sendis, 2017) are HALEU fuel[1]. Qualified benchmark data relevant for validating both criticality and depletion calculations will be essential (NEA, 2006) to satisfy regulatory review for both the front and back end of the fuel. Additionally, there is a need of appropriate experimental data to provide best estimate predictions of decay heat – a key metric for the safe and economical handling of irradiated HALEU.

1. The SFCOMPO database, the world's largest resource of radio chemical assays (RCA) experimental data for spent nuclear fuel, includes data for 750 samples selected from fuel irradiated in 44 reactors, including UOX and MOX fuel, for more than 90 isotopes important to a large variety of spent fuel applications.

NEA PUBLICATIONS AND INFORMATION

The full catalogue of publications is available online at www.oecd-nea.org/pub.

In addition to basic information on the Agency and its work programme, the NEA website offers free downloads of hundreds of technical and policy-oriented reports. The professional journal of the Agency, *NEA News* – featuring articles on the latest nuclear energy issues – is available online at www.oecd-nea.org/nea-news.

An NEA monthly electronic bulletin is distributed free of charge to subscribers, providing updates of new results, events and publications. Sign up at www.oecd-nea.org/tools/mailing list/register.

Visit us on LinkedIn at www.linkedin.com/company/oecd-nuclear-energy-agency or follow us on X (formerly known as Twitter) @OECD_NEA.

OECD/NEA PUBLISHING, 2 rue André-Pascal, 75775 PARIS CEDEX 16

High-Assay Low-Enriched Uranium: Drivers, Implications and Security of Supply

The potential deployment of small modular reactors (SMRs) is viewed by many countries as a transformative opportunity to support net zero objectives through various power and non-power applications. In this context, high-assay low-enriched uranium (HALEU) fuels, with enrichment levels between 5% and 20%, are expected to play a crucial role. However, commercial HALEU production in OECD countries is limited, and geopolitical uncertainties raise concerns about HALEU supply and potential disruptions to nuclear fuel supply chains. Historically, the nuclear energy industry has operated with enrichment levels up to 5%, with the associated supply chain, legal, and regulatory frameworks designed accordingly.

This report aims to support policymakers in NEA member countries with evidence-based analysis on HALEU adoption. It explores the driving forces and implications of HALEU use, fosters a strategic vision for its role in achieving energy goals, optimising nuclear power operations, ensuring safety and security, and addressing natural resource utilisation. The report also provides considerations for developing a HALEU-based or HALEU-ready fuel cycle.

Nuclear Energy Agency (NEA)
46, quai Alphonse Le Gallo
92100 Boulogne-Billancourt, France
Tel.: +33 (0)1 73 21 28 19
nea@oecd-nea.org www.oecd-nea.org

NEA No. 7685