Fuel Supply for Nuclear Energy Production

Stephen S. Greene
Nonresident Senior Fellow, Atlantic Council
Senior Fellow, Nuclear Innovation Alliance
StephenSGreene@outlook.com

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900 17th Street NW, Suite 1100, Washington, DC 20006

About the Author

Stephen S. Greene

Stephen S. Greene is a Nonresident Senior Fellow with the Atlantic Council's Global Energy Center, a Senior Fellow with the Nuclear Innovation Alliance, and a former energy and finance executive with extensive experience in commercial and policy issues related to energy. Most recently, he served in senior finance roles, including as chief financial officer for Centrus Energy, a public company engaged in the sale of nuclear fuel and the development of nuclear enrichment technology. He led strategy for Progress Energy, an investor-owned electric utility, and served as practice-area leader for the consultant Pace Global Energy focused on energy markets and risk management. He arranged project financing for PG&E National Energy Group (US Generating Company), a leading independent-power developer and energy trader, and subsequently developed the company's power market outlook to support project development. Early in his career, he worked at the US Environmental Protection Agency on air-pollution rules. He holds a masters in public policy from the Harvard Kennedy School and a BA in physics from Princeton University.

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Executive Summary

Firm sources of carbon-free energy such as nuclear energy will be essential as the decarbonization of energy systems continues. Nuclear power can also provide much greater energy security than fossil fuels. Thus, nuclear energy is receiving renewed interest to address both decarbonization and energy security objectives.

However, the fuel supply situation for nuclear power is challenged by several factors. First, while natural uranium is widely available, the processing for nuclear reactor fuel is highly concentrated, and for historical reasons, today's processing capacity in Russia is needed to produce sufficient volumes of fuel for nuclear reactors in other parts of the world, including the US. The shortfall in fuel production capacity outside Russia also colors the potential for the expansion of nuclear energy to support decarbonization objectives. Second, new and potentially valuable approaches to nuclear energy production rely on a more energy-dense form of nuclear fuel that requires new facilities (but not new technology) to produce. However, there currently is a mismatch between the commitments that potential producers require to construct those new facilities and the commitments potential purchasers are able to make.

Eliminating the dependence on Russian low-enriched uranium (LEU), and making high-assay, low-enriched uranium (HALEU) available for advanced reactors, can both be achieved with thoughtful capital investment. However, there are barriers to capital investment in each case. In the case of LEU, the barrier is a lack of long-term protection for potential producers from the availability of Russian enrichment that could undermine investment recovery once the war is over. In the case of HALEU, it is a lack of confidence in the long-term market for the product, since the reactor technologies are unproven and the market for the reactors themselves is uncertain.

There appears to be strong Congressional interest in supporting efforts to address the issues surrounding both LEU and HALEU, but legislators are still searching for effective approaches. There are two potential approaches to driving Russian fuel out of non-Russian markets. The first is for cooperating countries to ban imports of Russian fuel, over a timeline that is consistent with the feasible expansion of non-Russian supply, as has been proposed in US legislative attempts. This approach is straightforward (if there is support for restrictions in enough relevant countries), but producers would have to be confident that the restrictions would last long enough to recover their investments – on the order of ten years, perhaps more. A second potential approach would be to require all nuclear plant operators to establish long-term, internationally verifiable contracts with non-Russian producers.

The challenge to make HALEU available in advance of demand from an established advanced-reactor market is, in contrast, somewhat straightforward. It requires government funding to act in place of market demand until the advanced reactor technologies develop some traction. The available funds must be sufficient to enable HALEU producers to build capacity at a reasonable scale and obtain a return on their investment even if the market does not develop further. Department of Energy (DOE) has released an RFP to implement an approach of this type using funding provided in the Inflation Reduction Act (IRA), but the funding does not appear to be sufficient. In the expected case, government investment in HALEU would be returned through operator purchases. However, funding must anticipate that there is a potential downside scenario where the market does not develop. The impact of such a downside scenario may be mitigated by other uses for the HALEU and by structuring the program to reduce the commitment in that scenario.

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Introduction

Firm sources of carbon-free energy such as nuclear energy (unlike renewables, which are variable depending on natural conditions) will be essential as the decarbonization of energy systems continues.[1] Nuclear power plants use much less fuel per unit of energy output than fossil-fueled generation, and nuclear power plants operate for over a year, and in some cases many years, without refueling, so nuclear power can provide much greater energy security than fossil fuels. Thus, nuclear energy is receiving renewed interest to address both decarbonization and energy security objectives.

However, the fuel supply situation for nuclear power is being challenged by several factors. First, while natural uranium is widely available, the processing for nuclear reactor fuel is highly concentrated, and for historical reasons, today's processing capacity in Russia is needed to produce sufficient volumes of fuel for nuclear reactors in other parts of the world, including the US. The shortfall in fuel production capacity outside Russia also colors the potential for the expansion of nuclear energy to support decarbonization objectives. The dependence on Russia may be increasingly tenuous given growing interest, both in the U.S. and Europe, in weaning nuclear plant operators off Russian supply as a reaction to Russia's repeated efforts to weaponize energy supply. Second, new and potentially valuable approaches to nuclear energy production (such as some types of advanced reactors, sometimes called "Generation IV" reactors) rely on a more energy-dense form of nuclear fuel that requires new facilities (but not new technology) to produce. However, there currently is a mismatch between the commitments that potential producers require to construct those new facilities and the commitments potential purchasers are able to make.

The following discussion explores these issues and seeks to identify U.S. strategies for nuclear fuel that will support the continued operation and future expansion of nuclear energy to help achieve decarbonization and energy security goals.

Evolution of Nuclear Fuel Supply and its Effects on US Nuclear Industry

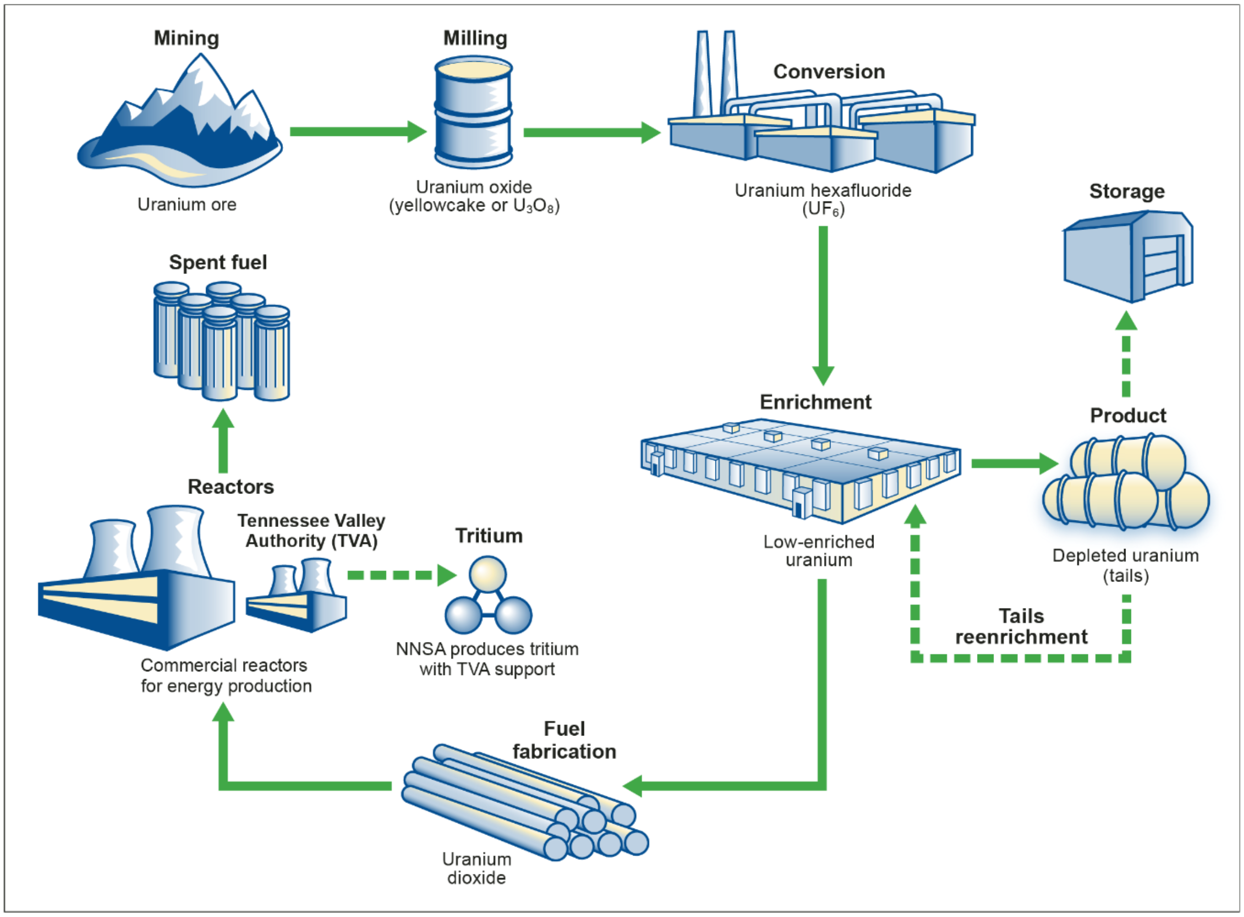
The U.S. built its nuclear fuel capabilities during and after the Second World War. Several reactor types were initially considered for civil nuclear energy, but ultimately the reactor technology chosen for use by the U.S. Navy became the basis for most of the civilian nuclear reactors worldwide. These designs required the uranium enrichment capabilities that the U.S. had built substantially during the Cold War. The fuel for civil nuclear power plants worldwide (outside of Russia) was predominantly produced by U.S. government facilities through the 1960s.[2] However, the U.S. role in nuclear fuel supply (both in the government and private sector) has declined dramatically since that time, due to a series of policy decisions by the U.S. and European governments as well as events in world energy markets. To understand that evolution, it is helpful to have as a framework an understanding of the supply chain for nuclear fuel.

The Nuclear Fuel Value Chain

This supply chain involves four fundamental steps[3]:

1. Mining and milling: uranium is mined, milled, and concentrated into uranium oxide (U_3O_8)
2. Conversion: the uranium oxide is chemically processed into uranium hexafluoride (UF_6), which becomes a gas when moderately heated, enabling uranium enrichment to be performed
3. Enrichment: most nuclear energy reactors in common operation require uranium to have a higher concentration of the U-235 isotope than occurs in nature; “enrichment” processes the UF_6 gas through a series of gas centrifuges to achieve that concentration
4. Fabrication: the UF_6 is “deconverted” to remove the fluorine, and the uranium is formed into ceramic pellets that are sealed into metal fuel assemblies; fabrication of the fuel assemblies is an engineering process generally performed by affiliates of the designers of the reactors

Figure 1: Nuclear Fuel Cycle[4]



Sources: GAO analysis of International Atomic Energy Agency , Nuclear Regulatory Commission, Congressional Research Service, Department of Energy, and Tennessee Valley Authority documents. | GAO-21-28

Sources of mined uranium are driven by economics. Mining production shifts frequently as a function of world demand, relative economics, and factors such as government policy (a large proportion of mining capacity is government owned), natural disasters affecting mines, and mine-specific incremental expansion opportunities. U.S. uranium mining has been a minor portion of world supply since the 1980s, when production began to be dominated by more economically attractive (based primarily on the quality of resource) sources in Canada and Australia.[5,a] Kazakhstan became a major producer prior to 2010. In 2022, Kazakhstan (43%), Canada (15%), Namibia (11%), and Australia (8%) were the major producers. Australia holds by far the greatest proportion of identified recoverable uranium reserves (28%); the US holds about one percent.[6]

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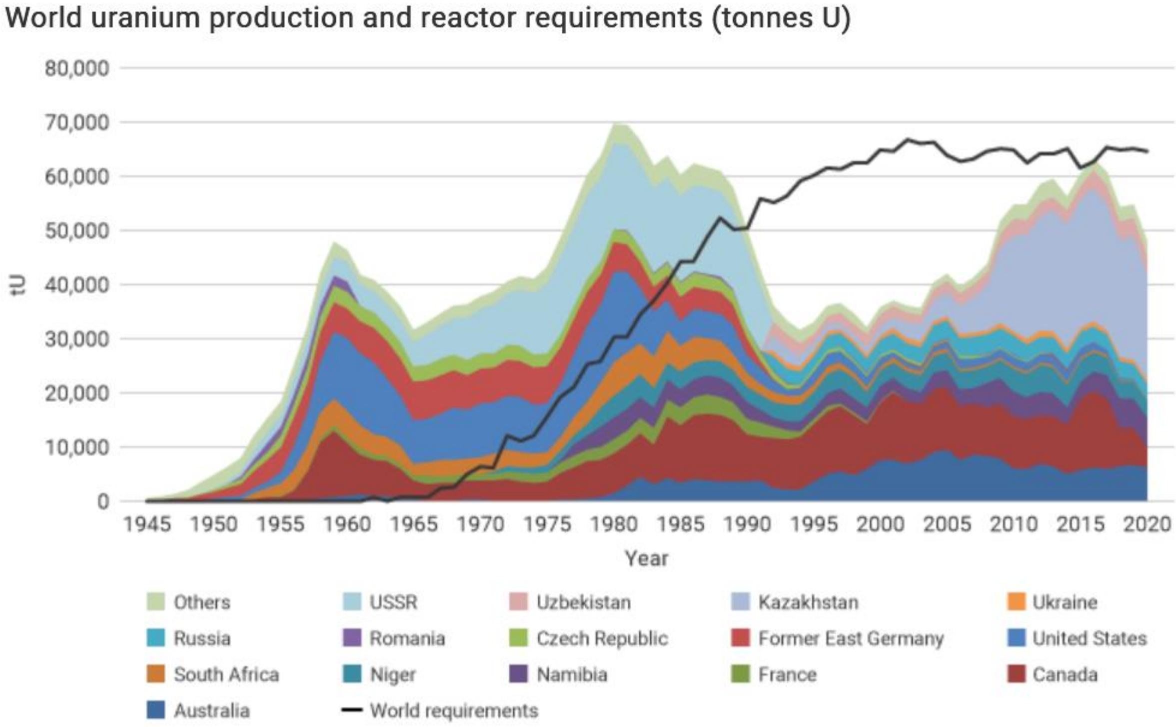
[a] For example, the highest-grade ore in the US averages less than 1 percent uranium, whereas some Canadian ore is more than 15% uranium.

Figure 2: World uranium production[7]



Source: World Nuclear Association, August 2023

Conversion and enrichment are industrial processes that have been highly concentrated in the development of the nuclear fuel supply chain because of economies of scale as well as government control of technology. Conversion is a chemical process that changes mined uranium into uranium hexafluoride (UF_6), which becomes a gas when heated, facilitating the enrichment process. Conversion represents a relatively smaller component of the cost of finished fuel than either mined uranium or enrichment; however, the available conversion capacity can become limiting if uranium hexafluoride “feed” for enrichment is in demand. For example, conversion represented about 10 percent of the cost of “natural” (or unenriched) uranium hexafluoride in late 2021, but over 20 percent of the cost in late 2022 when the limited availability of non-Russian conversion had become recognized.[8]

Uranium conversion capacity is located in Canada, China, France, Russia, and the US.[9] The only facility in the U.S. is the Honeywell Metropolis Works facility in Illinois (output marketed by Converdyn), which was built in 1958, and was idled in 2018 due to forecasts of a worldwide oversupply of UF_6. In 2021, Converdyn announced that the facility would resume production in 2023, following receipt of a 40-year operating license extension from the US Nuclear Regulatory Commission (NRC), and after considering recent and anticipated changes in demand (note this decision was made prior to the Ukraine war).[10,11] The facility is initially expected to restart with half of its licensed capacity of 15,000 metric tons per year of UF_6. [12,13]

By far the most common nuclear reactors used for energy production (including all of those in the US) are "light-water" reactors (LWR).[14,b] These reactors require uranium fuel that has been "enriched," so that the fissile isotope of uranium (U-235) represents about five percent of the fuel, compared to the concentration in naturally occurring uranium of 0.7 percent. The product is known as "low-enriched" uranium or LEU. The technology and infrastructure to enrich uranium is closely guarded because the same technology used to enrich uranium to the levels required for power production can also be used (with production modifications) to achieve the significantly greater enrichment required for use in nuclear weapons (greater than 90 percent). There are only a few large uranium enrichment producers in the world, see Table 1.

Box 1: Fueling a Nuclear Power Plant

As Figure 1 explains, fueling a nuclear power plant with LEU requires uranium, conversion (to make UF_6, which can be processed as a gas by an enrichment facility), enrichment, and fabrication. The enrichment production is measured in Separative Work Units (SWU, pronounced "swoo").[15,c] It is possible to produce LEU using a range of UF_6 and SWU – the more enrichment (SWU) used, the less uranium (UF_6) is required. To fuel a typical 1000 MW reactor for a year requires about 140,000 SWU and 170 metric tons of uranium (MTU)[d] (in UF_6 form) at a typical ratio for current market conditions.[16] However, the same fuel could be produced using only about 120,000 SWU and 200 MTU, or 165,000 SWU and 150 MTU.

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[b] Other reactors, such as most of those deployed to date in Canada, use deuterium or "heavy" water, in which the hydrogen contains a neutron in addition to the typical single proton. Deuterium is present in all water at low concentrations. Heavy-water reactors use unenriched uranium.

[c] SWU is a measurement specific to uranium enrichment, and measures the effort expended to separate a mass of uranium feed into a mass of enriched product and a mass of depleted material ("tails").

[d] A metric ton (MT) is 1,000 kg, or about 2,200 pounds. May be expressed as metric tons of uranium or MTU, in which case only the weight of the uranium is being measured (i.e., the weight of other elements in a molecule, such as fluorine or oxygen, are ignored).

Table 1: World Enrichment Capacity (2020)[17]

Company	Location	Capacity (Thousand SWU/y)
Orano	France	7,500
Rosatom	Russia	27,700
Urenco	Germany, Netherlands, UK	13,700
	US[e]	4,900
	Urenco total	18,600
China National Nuclear Corporation (CNNC)	China	6,300
Other or government	Argentina, Brazil, India, Pakistan, Iran	66
Total		**60,166**

Data from: World Nuclear Association, 2020

Factors Shaping U.S. and Global Enrichment Capacity and Economics

While there is a modest amount of enrichment capacity physically located in the U.S., it is owned and operated by Urenco, a company whose shareholders are the governments of Netherlands and the United Kingdom and two German utilities, and uses technology controlled by a treaty among the German, Netherlands, and UK governments.[18,19,f,20] Orano, Rosatom, and Chinese enrichment producers are also entirely or substantially government owned, as opposed to U.S. enrichment production, which has been privatized.[g] The challenges of U.S. private-sector nuclear fuel competition with state-owned enterprises has become apparent.[21,22]

The U.S. provided most of the world's enrichment (outside Russia) through the 1950s and 1960s, but the last operating enrichment production using U.S. technology was retired in 2013. The U.S. government enrichment production capability was privatized in the 1990s: the U.S. Enrichment Corporation was created as a government corporation in 1992 and became a public company in 1998 (the parent company was originally USEC, Inc. and became Centrus Energy Corp. in 2014).[h,23,24] U.S. Enrichment Corporation originally leased two legacy

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[e] While this facility is in the U.S., it incorporates European technology.

[f] A subsequent agreement governs the deployment of the technology in the US.

[g] Enrichment capacity developed in China is almost entirely dedicated to internally to fuel the rapidly growing Chinese nuclear power sector; little is currently exported.

[h] United States Enrichment Corporation was created as a government corporation in 1992 under the Energy Policy Act of 1992 (42 U.S.C. 2297 et seq.). It was privatized in 1998 through the creation of a parent company, USEC, Inc., under the USEC Privatization Act (42 U.S.C. §2297h (1) – (13)). The company was reorganized as Centrus Energy Corp. in 2014.

1950s-era enrichment facilities from the Department of Energy, located in Portsmouth, Ohio and Paducah, Kentucky. These facilities used the reliable but very energy-intensive gaseous diffusion technology originally developed by the U.S. government during World War II (by the time of their retirement in 2013, energy costs represented 80 percent of the operating costs for the gaseous diffusion plants).[25] Centrifuge enrichment technology, which is far less energy-intensive (energy is about five percent of the cost of operation), was developed in Russia after World War II (based on German research) and in Europe during the 1960s (the origin of the technology used by Urenco and Orano).[26]

U.S. Enrichment Corporation's gaseous-diffusion enrichment capacity was ultimately the victim of increases in foreign centrifuge-based production, declining demand, and high energy costs. The competition from foreign production was in part driven by U.S. government action. In the 1970s, when nuclear generation was expected to grow rapidly in both the U.S. and Europe, the U.S. government raised concerns that it could not support all the growing western demand for enrichment. European governments, concerned about their fuel security (especially after the oil crisis), expanded enrichment capacity at Urenco and the predecessor to Orano.[27] European supply has been further supported by market protection through an unpublished policy, known as the Corfu Declaration, that limits nuclear fuel imports to 20% of the European market.[28]

U.S. Enrichment Corporation retired the Portsmouth capacity in 2001 due to surplus world supply, and ultimately retired the Paducah capacity in 2013 due to high operating costs and insufficient demand.[29] The U.S. government had begun a program to develop its own centrifuge technology, but that was halted in the mid-1980s due to the prospect of laser-based enrichment, which was anticipated to be even more efficient. [i,j,30,31] The U.S. laser technology was later abandoned due to expectations that it would be technically challenging to deploy commercially. One laser enrichment approach, using technology developed by an Australian firm, continues to be pursued by Global Laser Enrichment.[k,32] USEC, Inc. developed an improved centrifuge technology, based on the earlier government efforts, which the company demonstrated under contract to the Department of Energy (DOE), but was unable to finance

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[i] The Gas Centrifuge Enrichment Plant (GCEP) began construction at the Portsmouth enrichment site in 1979 and ceased operation in 1985.

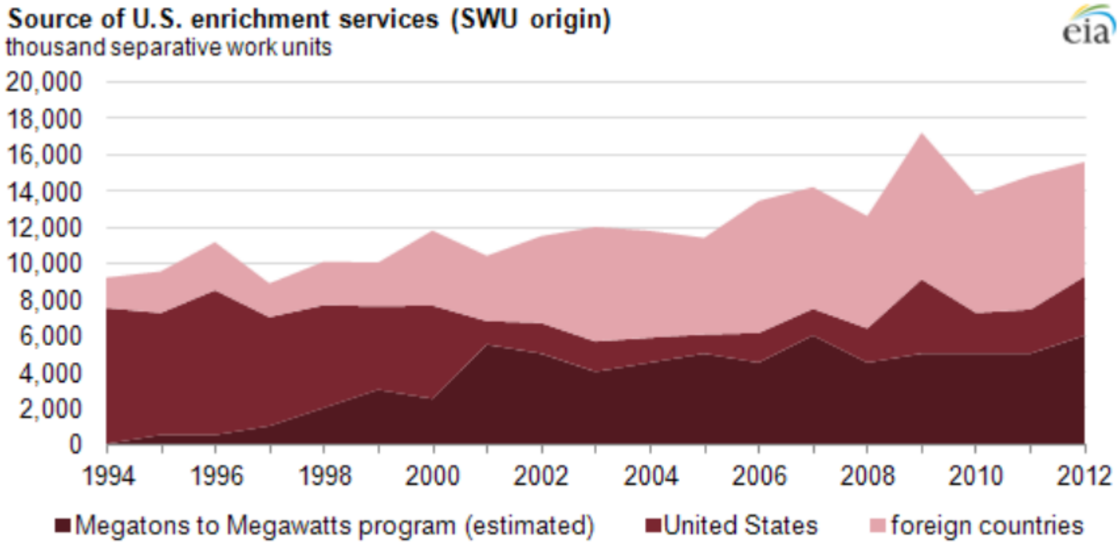
[j] The US program was Advanced Vapor Laser Isotope Separation (AVLIS).

[k] The technology is SILEX.

deployment at a commercial scale. The effort was effectively ended after the Fukushima plant failure led to a further decline in demand for nuclear fuel, although some ongoing demonstrations continued through 2016.[33]

The current world nuclear fuel infrastructure bears the imprint of three significant events. First, following the collapse of the Soviet Union, the U.S. and the new Russian government negotiated an agreement under which the U.S. would purchase uranium from the Russian government that had been downblended from Russian nuclear weapons stockpiles to commercially useable enrichment levels. This program, which became known as “Megatons to Megawatts,” provided about one third of the enrichment (and effectively, the conversion services) required to fuel U.S. nuclear power plants between the first fuel delivery in 1995 and its end in 2013 (the agreement was signed in 1993).[34] While the program is recognized as having effectively kept the former Soviet nuclear stockpile from becoming a nuclear proliferation risk, and having provided hard currency to Russia to aid in its transition from the Soviet Union, the program dampened demand for commercial enrichment and conversion capacity.[35,36] That reduction in demand contributed to the retirement of US capacity, and to the failure to replace it.

Figure 3: Source of US enrichment services[37]



Source: Energy Information Administration, 2013

Second, the development of low-priced natural gas production from shale formations in the U.S. changed the complexion of U.S. power markets. Significant capacity to produce electricity from natural gas had been added in the early 2000s, but the production of shale gas caused natural gas prices to drop dramatically, from almost $9 per million BTU (MMBtu) in 2008 to $4/MMBtu in 2009, and to average around $3/MMBtu or below for most of 2012-2020. [38,39] These low gas prices greatly reduced the cost of power generation from gas-fired capacity, displacing other generation including nuclear power, especially in portions of the US with competitive wholesale power markets, where a substantial portion of US nuclear capacity operates. This dramatic change in the economics of power supply has led a substantial number of US nuclear generating units to retire prematurely.[l,40]

Third, the Fukushima nuclear plant failure in 2011, one consequence of the devastating Great East Japan Earthquake and tsunami, led to the immediate shutdown of all of Japan's nuclear generation, which is only slowly being reversed, and the eventual retirement of a substantial portion. In addition, the Fukushima event led to the acceleration of nuclear power plant retirements in Germany and elsewhere in Europe. The result was a substantial reduction in nuclear generation and therefore fuel demand (see Figure 4).

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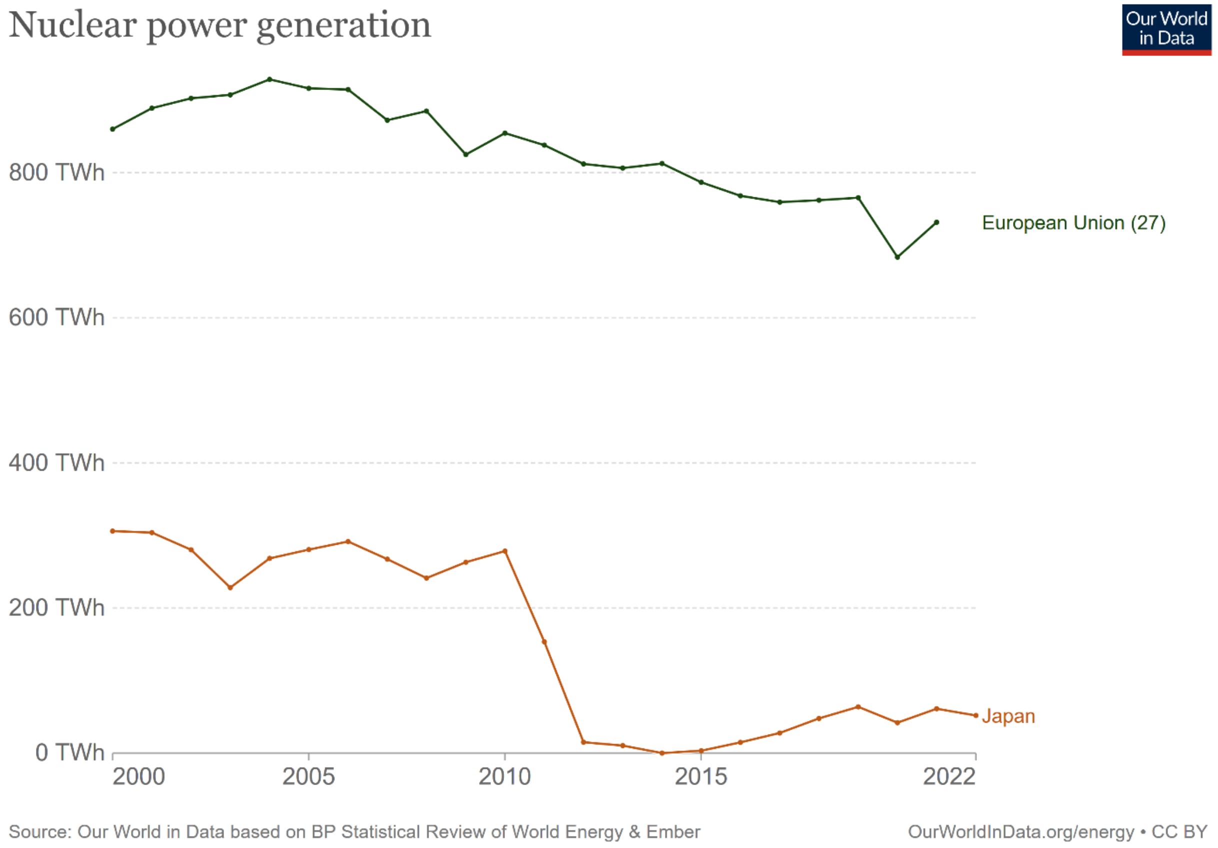
[l] More than 8,400 megawatts of nuclear generation have retired prematurely since 2013.
Note that US natural gas prices have now rebounded due to exports driven by the Ukraine war and may remain higher in the long-term due to post-pandemic changes in the investment dynamics in shale production.

Figure 4: Reduction of nuclear power generation in the European Union and Japan has led to a reduction in demand for fuel[41]



Source: Our World in Data, 2023

The cumulative result of the changes in the nuclear power and fuel markets is that today, world enrichment requirements are ***oversupplied*** – annual world enrichment requirements are about 50 million SWU, while capacity is over 60 million SWU, as shown in Table 1.[42] However, the world outside Russia depends on Russian enrichment and conversion exports to meet demand.[m,43] For example, in 2022, 73 percent of the enrichment required in the U.S. was imported, with the remainder provided by Urenco's U.S. enrichment plant. About one-third of the imports (i.e., about 24% of total requirements) were from Russia.[44]

If Russian exports were to become unavailable, due either to sanctions on nuclear fuel imports or a cessation of exports, nuclear plant operators outside of Russia would face a shortage of LEU. A leading nuclear fuel consultant recently estimated the enrichment gap between supply

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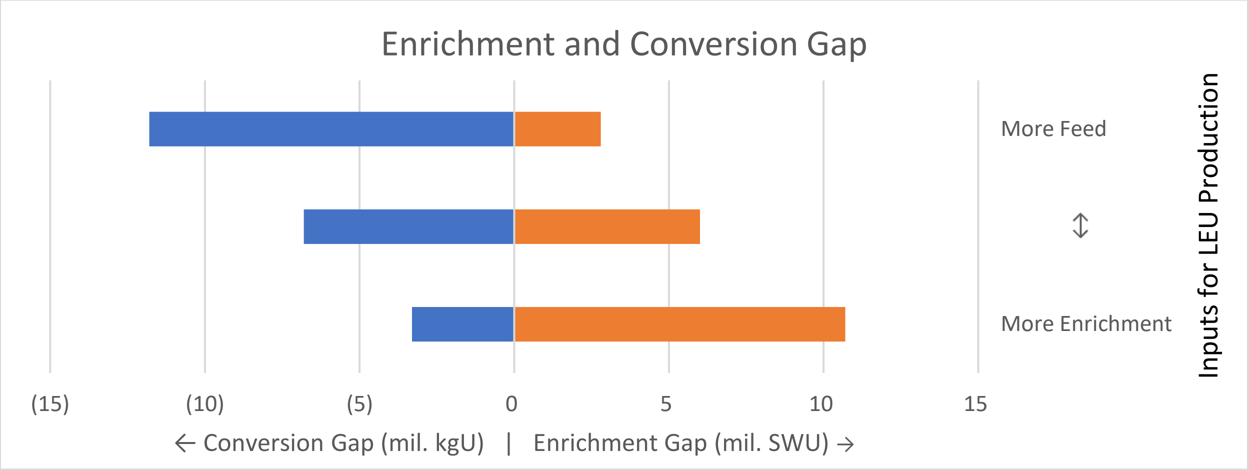
[m] Russian enrichment requirements are estimated at 5.1 million SWU/year compared to enrichment capacity of 27.7 million SWU/year as shown in Table 1.

and demand outside Russia, China, and a handful of countries considered captive to those fuel suppliers, at 3 to 11 million SWU/year.[45] Some estimates of the gap are larger, for example, Constellation estimated a “potential gap” of up to 15 million SWU/year.[46] The range is a function of how much uranium hexafluoride feed could be used to offset the enrichment deficit. To a limited extent, additional uranium hexafluoride can be used to reduce the amount of enrichment required to produce LEU (refer to Box 1). But the amount of uranium hexafluoride available is subject both to mining production and to conversion capacity, which is also in deficit without relying on Russian supply (See Figure 5).

Figure 5: Enrichment and Conversion Gap without Russian Supply[47]



Data from: UxC, 2023

Current Nuclear Fuel Supply Perspectives and Challenges

Two key factors have now brought greater attention to the nuclear fuel supply chain. First, in part due to a focus on climate-change mitigation, greater attention is now being paid to nuclear generation in general, and especially to potential new approaches to nuclear generation. Many nations, power companies, and energy users have committed to rapidly decarbonize their energy systems or supplies. That process will involve electrifying much power and heating demand (including industrial heat and space heating) that is now served directly by fossil fuels, resulting in an increased demand for power. In addition, carbon-free sources will need to be found for energy uses that are not easily electrified, such as for industrial processes.

While much of the future zero-carbon power supply may be provided by renewable sources such as wind and solar power, there is a recognized need for “firm” zero-carbon power that is not weather dependent and can be produced whenever it is needed.[48,49] DOE projects that U.S. nuclear power generation will need to triple by 2050 to meet decarbonization objectives, and the International Energy Agency (IEA) projects that world nuclear power will need to double in that timeframe.[50,51] Nuclear energy can provide heat as well as electricity, so it may be crucial to decarbonizing industrial energy requirements, and valuable in producing hydrogen and supporting desalination (a potentially growing need as water supplies become more challenging in a warming world). There is growing attention to potential constraints on the speed with which renewable energy can be developed due to limits on transmission, interconnection to the grid, and community resistance.[52,53,54] Nuclear power can mitigate some of the risk of those constraints, because nuclear generation can be placed at the site of retiring coal plants, use existing transmission, have less of an impact on the visual environment than renewables, and preserve jobs in energy communities.[55]

Second, the war in Ukraine, and Russia’s leveraging of fossil fuel supply to weaken support for Ukraine in the war, has dramatically renewed worldwide focus on the security of energy supplies and the vulnerability of those supplies to use as leverage for geopolitical objectives.

Nuclear energy improves energy security because nuclear fuel cycles are long and less vulnerable to short-term disruption than fossil fuels, and nuclear energy can potentially be developed in a wide range of locations without regard to renewable resources.[n]

The worldwide reliance on nuclear enrichment and conversion capacity in Russia, however, has become a concern in the context of the war in Ukraine, which has again highlighted concerns regarding energy security broadly, as well as specifically regarding Russia. In an April 2023 statement on civil nuclear fuel cooperation, the U.S., Canada, France, Japan, and the United Kingdom described their "collective intent" to "achieve reduced dependence on Russian supply chains," and in December 2023 those countries announced plans for a collective $4.2 billion "in government-led investments to develop a secure, reliable global nuclear energy supply chain" (note these countries represent over 60 percent of enrichment requirements outside Russia and China; see Figure 6).[56,57] The total revenue attributable to Russia's enrichment exports is roughly half a percent of Russia's oil export revenues, even with sanctions on oil in place (and without considering natural gas revenues), but any value transfer to Russia deserves attention in the context of the war.[o,58] The U.S. government, including Congress, has become increasingly sensitive to the geopolitical vulnerability of reliance on Russian nuclear fuel.[59] The potential for Russian disruption of nuclear fuel exports is also a concern, though such an action could significantly cripple Russia's potential for exports in the long term, since part of the perceived value proposition for nuclear fuel producers is reliability. While the current focus is on Russia, well before the Ukraine war, concerns had been raised regarding the growing influence of both Russia and China in nuclear energy projects and nuclear fuel.[60]

Nuclear plant operators have sought to secure fuel to ensure operations even if Russian contracts are disrupted.[61] The price of enriched uranium (LEU) rose almost 50 percent between November 2021 and October 2022.[62] Urenco has already announced a limited expansion at its U.S. enrichment plant (an increase of about 15% of that plant's output to 5.6 million SWU), to be completed in 2027, and Orano has approved an expansion of its

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[n] Light-water fuel cycles are typically 18 months, and advanced fuel cycles have the potential to last decades.

[o] The estimate uses the midpoint of the UxC estimated enrichment gap, 7 million SWU (roughly double US operators' purchases from Russia), at the average value paid for enrichment by US companies in 2022 per EIA ($101), compared to the March 2023 estimate of Russian oil export revenues ($12.7 billion annualized to $152 billion). Note that the relative value of enrichment would be far less if gas exports were also included.

enrichment capacity by more than 30%, with production expected to start by 2028, in response to “requirements expressed by our customers to strengthen their security of supply.” [63,64] Increases in conversion production are also contemplated through production improvements.[p,65] However, a sizeable gap between LEU demand and supply outside Russia will still exist as noted in Figure 5 (as noted earlier, the constraints to non-Russian supply of LEU are enrichment and conversion, not mined uranium). This gap threatens not only existing nuclear operations, but also the potential expansion of nuclear energy to help support decarbonization.

Fuel for Advanced Reactors

Another dimension to the security of nuclear fuel relates to an emerging need for fuels with higher levels of enrichment. Over the past several years several companies have pursued alternative approaches to reactor design to simplify reactor construction and operation and make it more efficient, enabling nuclear energy to play a greater role in decarbonizing energy production. Some of the new approaches are variants on light-water technologies that incorporate modular construction and redesigned approaches to safety that use natural or passive features to simplify construction.

Other approaches are based on alternatives to the light-water design, many of which were initially researched early in the development of nuclear energy but set aside in favor of the now-common standard. These alternatives use materials other than water to remove heat from the reactor (and use the energy) and different approaches to protect against overheating. For example, some use liquid metals (sodium or lead), molten salts, or inert gases to remove heat from the reactor. These coolants can enable the reactors to operate at higher temperatures than traditional reactors, increasing their efficiency, and are more resilient, simplifying the safety requirements. These alternative designs are “non-LWR” reactors, sometimes referred to as “Generation IV” reactors.[q] Most of the non-LWR reactors are designed to use fuel that has been enriched to a greater level than is used today in light-water reactors, typically 15-20 percent compared to the five percent used in LWRs. This fuel is

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[p] Cameco is working to increase the annual production from its conversion facility, Converdyn is in the process of restoring a portion of its conversion capacity, and Orano has just begun to bring its new conversion facility up to target capacity.

[q] A full discussion of reactor technologies is beyond the scope of this paper. A thorough discussion of the technologies can be found in https://www.nuclearinnovationalliance.org/advanced-nuclear-reactor-technology-primer and https://www.oecd-nea.org/jcms/pl_78743/the-nea-small-modular-reactor-dashboard.

known as “high-assay low-enriched uranium,” or HALEU.[r] Using HALEU allows the reactors to be smaller, use alternative, more resilient fuel designs, and to use coolants other than water.

Producing HALEU, while not technically much more challenging than producing LEU, requires a facility built to safely handle and store the product, and there currently are no commercial facilities capable of producing HALEU outside of Russia. This is a rapidly escalating challenge– there are many advanced reactor designs that require HALEU that are in or about to enter the licensing process, with expectations to begin construction in the next few years, including several receiving funding by the Department of Energy.[66,67,68] Many of these projects anticipated that they would obtain HALEU for their initial requirements from Russia before US supplies became available, but have had to abandon those plans in the face of the war. There is only a small amount of HALEU potentially available in the US, derivable from past research efforts, without constructing new HALEU enrichment facilities – not even enough to test most of the new designs. The lack of HALEU or any clear prospect for HALEU supply to become available has become a major challenge for non-LWR reactor developers to gain traction with potential future customers.

The quantities of HALEU that may be required depend substantially on assumptions regarding the market traction achieved by advanced reactors. DOE estimates that more than 40 metric tons (MT) of HALEU (in total) will be needed by 2030, based primarily on initial reactor demonstrations and the demands of research reactors, and that annual demand would be 8-12 MT and growing. [69,70] Other studies arrive at larger quantities; for example, a study by Idaho National Laboratories concluded that over 100 MT would be needed by 2036, and an industry survey of technology developers concluded that the annual demand could exceed 100 MT before 2030. [71,72]

The timing of this demand, and the development of production capacity, is critical. The initial advanced reactor projects require fuel in the next few years to maintain their deployment schedules. One DOE awardee has already announced a project delay due to the lack of fuel.[73] Centrus Energy has licensed and begun production from a demonstration-scale facility under

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[r] Commonly pronounced “hey loo.”

contract to DOE, and has said a 6 MT/year facility could be constructed within 42 months of funding (with subsequent increases in capacity on a faster schedule).[74] Urenco, which would have to construct a new facility meeting "Category II" standards and obtain a license for that facility in order to produce HALEU, estimates that it could license and bring a HALEU production facility into operation within six to seven years of initiating a project to do so.[s,75,76]

In addition to demand from advanced reactors, demand for uranium enriched above five percent will come from advanced fuel for existing reactors. Westinghouse and Framatome have both developed advanced fuels designed to provide greater protection against the release of radioactive gases in an accident scenario (through changes to the chemical or physical properties of the fuel), and to extend fueling cycles and improve cycle economics. These fuels are designed for enrichment between 5-10%.[77],[78] Urenco is preparing to produce fuels in this range, which has become known as "LEU+," in its US and/or UK facilities; doing so will require some modifications and an amendment to the facilities' existing licenses.[79,80]

Lightbridge Corporation is developing a metallic-uranium fuel for LWRs, including existing reactors, to be used in place of currently used uranium oxide (ceramic) fuels. This fuel is intended to provide economic, safety, and non-proliferation improvements. Lightbridge's fuel would require HALEU.[81] Lightbridge has estimated that large-scale deployment of its fuel could result in a HALEU demand of over 100 MT per year by the mid-2030s.[82]

The potential for downblending HALEU from stocks of HEU is often raised in the context of resolving the HALEU supply challenge.[83] Declassified information regarding the US HEU inventory is limited – the most recent information is from 2013 – making an assessment of the available HEU challenging.[t,84] According to at least one source, the HEU that was characterized as available in the 2013 information has already been downblended to LEU.[85] BWX Technologies was recently awarded a contract to downblend "scrap material containing enriched uranium" into HALEU. The project will produce 2 MT of HALEU over the course of five years, at a total cost of $116.5 million, or $58 million per MT (for context, the Centrus

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[s] Urenco estimates this work would cost $250-$400 million but did not specify the size of facility that could be constructed for that cost. Production of HALEU requires a "Category II" license, which involves more extensive requirements for handling the product, compared to the "Category III" license required for LEU or LEU+. Production of highly enriched uranium (HEU) (see the discussion "National Security and the Nuclear Fuel Cycle" below) requires a Category I license with the most extensive handling and security requirements.

[t] This inventory data was declassified in 2016.

demonstration facility produces 0.9 MT per year).[86,87] Other than scrap material, HEU represents a national security asset that cannot currently be replenished, since there is no existing means by which the U.S. can produce HEU for national security purposes (please refer to Box 2). Furthermore, any additional capital required for a more expanded downblending program would have little to no value once the excess HEU is gone or HALEU enrichment is available.

Conceptualizing Paths Forward

Eliminating the dependence on Russian LEU, and making HALEU available for advanced reactors, can both be achieved with thoughtful capital investment. However, the barriers to capital investment for the two purposes are slightly different.

In the case of LEU, the barrier is a lack of long-term protection for potential producers from the availability of Russian enrichment that could undermine investment recovery once the war is over, assuming diplomatic relations with Russia ultimately recover.[u] In the case of HALEU, it is a lack of confidence in the long-term market for the product, since the reactor technologies are unproven and the market for the reactors themselves is uncertain. The technology developers do not have the capital to make fuel purchase commitments of the volume and length needed to support capital investment in fuel production infrastructure. The sponsors and customers for the initial demonstration projects will only commit to fuel for those projects, and even then, only after the projects themselves have matured enough to be ready for construction. The potential fuel suppliers will not risk the capital, because the prospects of sufficient demand are uncertain (and for the most part they have a perfectly fine existing business producing LEU). If there were customers who would commit to projects beyond the initial demonstrations, that might be sufficient to encourage fuel suppliers to invest in production – but the potential reactor customers will not do so if they can’t be confident that fuel for the projects will be available. Many observers have characterized this as a “chicken and egg” problem.

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[u] Note the Russian economic advantage is primarily the result of fully depreciated capital, though arguably there are also labor costs advantages and cross-subsidies that provide an advantage in operating and maintenance cost.

Policy and Legislative Initiatives

The “chicken and egg” problem facing HALEU production has been a growing concern for policymakers for several years. The Energy Act of 2020, which became law as part of the Consolidated Appropriations Act, 2021, included a requirement that DOE establish a program to support the availability of HALEU, but precluded DOE’s acquisition of HALEU without subsequent appropriations.[88] The IRA appropriated $700 million to support HALEU availability, of which $500 million was specifically targeted at acquiring HALEU for advanced reactors (the remaining $200 million is for programs to support HALEU availability and to design and license transportation systems for HALEU).[89] An additional $2.72 billion of funding was appropriated by the Consolidated Appropriations Act, 2024 (with conditions, described more fully below), greatly facilitating the DOE’s efforts.[90]

Recent legislative initiatives have sought to address both the exposure to Russian LEU imports and the recognition that HALEU production will require more resources than were provided by the IRA. Initiatives focused on LEU have been driven have been driven by the twin objectives of reducing Russian nuclear fuel imports in light of the war in Ukraine and addressing the national security risk represented by the nuclear fuel gap. Even before the war, there was a recognition that the lack of U.S. nuclear fuel infrastructure had implications for national security. For example, in 2020, DOE published “Restoring America’s Competitive Nuclear Energy Advantage” to highlight the shortfall in U.S. fuel-cycle infrastructure as well as the value of supporting US nuclear technology exports.[91]

Box 2: National Security and the Nuclear Fuel Cycle

The U.S. government uses highly-enriched uranium (HEU) – enriched substantially above HALEU levels – to fuel the nuclear navy, as well as LEU for weapons programs (used to produce tritium, a component of nuclear weapons that must be periodically replenished). A stockpile of HEU built during the Cold War still holds substantial quantities, but it will eventually need to be supplemented (in 2015, DOE estimated that its supply of naval reactor fuel would be adequate until 2060, and that enriched uranium for other national security requirements could be needed earlier).[92] For both purposes, enriched uranium produced in an enrichment facility using U.S.-origin technology is required (enriched uranium meeting the required conditions is sometimes referenced as "unobligated" since it is not restricted by treaty obligations).[93,94] In addition, HALEU that would be required for potential future U.S. military mobile power generation ("Project Pele") would require U.S.-origin enrichment.[95] The Centrus HALEU demonstration plant incorporates U.S.-origin technology, but the Urenco commercial enrichment plant in the U.S. uses European technology. In addition, DOE (through Oak Ridge National Laboratory) has been developing a centrifuge design and issued a Request for Information from companies interested in building and operating a pilot plant using this centrifuge design to produce unobligated LEU, with the potential to produce HEU in the future.[96] One aspect of the policy questions surrounding support for additional enrichment capacity is to what extent some portion of any funding should be directed specifically towards U.S.-origin technology to address U.S. national security requirements.

Legislation that has been introduced to address the LEU gap focuses on reducing U.S. imports of LEU produced in Russia. Such imports are already restricted by a trade agreement between the U.S. and the Russian state corporation Rosatom. This agreement, commonly known as the Russian Suspension Agreement (RSA), was originally established in 1992 as part of an anti-dumping investigation and was most recently amended in 2020.[97] The RSA, as amended, restricts imports of Russian LEU to 20 percent of estimated US enrichment requirements from 2024-27 and 15 percent beginning in 2028 (with varying restrictions prior to 2024 that range from 20-24 percent). The RSA technically ends in 2040, at which point the anti-dumping complaint that has been "suspended" by the RSA would resume; however, the agreement requires that the Department of Commerce and Rosatom consult in good faith regarding an extension.

Legislation that has been introduced to address the LEU gap includes the Prohibiting Russian Uranium Imports Act (H.R. 1042), which would immediately require waivers from the Secretary of Energy (in consultation with the Secretaries of State and Commerce) to import LEU produced in Russia and would ban Russian imports completely starting in 2028. To provide a waiver the Secretary of Energy must determine that "no alternative viable source of low-enriched uranium is available to sustain the continued operation of a nuclear reactor or a United States nuclear energy company [or that] importation of low-enriched uranium that is produced in the Russian Federation or by a Russian entity is in the national interest."[v] Even if waivers are provided, the total Russian imports cannot exceed those established in the RSA (as amended in 2020).[98]

The Nuclear Fuel Security Act of 2023 ("NFSA"), which became law as part of the National Defense Authorization Act for Fiscal Year 2024, seeks to address both LEU and HALEU supply.[99] It establishes a "Nuclear Fuel Security Program" under which DOE is directed to enter into at least two contracts to begin acquiring 20 MT per year of HALEU by 2027 (or the earliest practical date thereafter). Under the program, DOE is also directed, if determined to be necessary or appropriate based on a market evaluation, to "take actions, including cost-shared financial agreements, milestone-based payments, or other mechanisms, to support commercial availability of LEU and to promote diversity of supply in domestic uranium mining, conversion, enrichment, and deconversion capacity and technologies, including new capacity, among U.S. nuclear energy companies." The NFSA also establishes a revolving fund, so proceeds from sales of the DOE's acquired fuel can subsequently be used to purchase additional fuel once the programs are under way. The NFSA explicitly precluded the commitment of funds for the fuel purchases until they were specifically appropriated. The funds provided in the Consolidated Appropriations Act would resolve that restriction; however, the Act precluded access to those funds "until a law is enacted or administrative action is taken to prohibit or limit importation of LEU and HALEU from the Russian Federation or by a Russian entity into the United States," thus tying together the two nuclear fuel issues.

After much anticipation, DOE issued a request for proposals (RFP) for HALEU in January 2024, with responses due in March 2024.[100] The contracts established under the RFP will be Indefinite Delivery, Indefinite Quantity (IDIQ), with the work conducted under task orders for an extensive set of separate potential tasks. HALEU enrichment contracts will have a maximum duration of ten years but have a minimum order value of $2 million. The IDIQ structure gives DOE flexibility on the pacing and approach to pursue HALEU production, but the additional funds potentially available through the 2024 appropriations are needed to

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[v] For context, as described earlier, even the earliest modest expansions of enrichment capacity will not be completed until 2027.

provide confidence to HALEU producers that they will continue to be exposed to significant risk that they would be unable to recover their capital investments.

The additional appropriations are critical to supporting the scale of investment required for HALEU production. Producing HALEU starts with LEU, the same fuel that's used for light-water reactors, then it is further enriched. Using the anticipated ratio of LEU to enrichment anticipated for HALEU production, around 4.5 kilograms (kg) of LEU are required to make one kilogram of HALEU. It is possible to use somewhat less, but then more enrichment is required, and the enrichment capacity, which must be constructed anew to meet the requirements for enrichment above LEU levels, is the limiting factor. As of May 2023, the cost of LEU was over $2,900/kg – at the high end of historical prices, due to the dynamics around the Ukraine war. Thus, the LEU feedstock alone will cost about $13,000 per kg of HALEU produced. The capital recovery for the new HALEU enrichment facilities, and the cost of operating those facilities, must be added to the cost of the LEU to estimate the total HALEU cost. Furthermore, due to the "chicken and egg" risk, potential enrichers will likely seek to recover much of their total capital investment over the short delivery window established by the RFP.

Given the cost of the LEU feedstock, the operating costs, and the potentially accelerated capital recovery that might be sought for an enrichment plant under a contract of limited length, the full cost of HALEU production could easily reach $20,000 per kg (i.e., $20 million/MT) or more.[101] Thus, if limited to the available $500 million appropriations (until the restrictions on the 2024 appropriations are resolved), the RFP might only yield a total of 25 MT – well below DOE's estimate of the cumulative demand by 2030. Furthermore, the annual production capacity supported by such an RFP would be too small to support a commercially viable production facility.

The revolving fund permitted by the NFSA certainly improves the funding picture; however, there likely will be a time delay between production and operator purchases, so the funding could still be constrained. More important, the revolving fund does not mitigate a downside scenario in which advanced reactor requirements don't grow as quickly as expected, and the HALEU needs to be held for a long period.

The IDIQ and task-order approach outlined in the RFP seems intended to enable DOE to manage the funding as it evolves by limiting the initial task orders to preparatory activities until full funding is available. However, the key requirement for supporting HALEU enrichment is to provide clarity to enrichers regarding a long-term commitment to HALEU purchases to support capital investment, so it is essential that the restrictions on the 2024 funding be resolved.

Principles of Action to Address Nuclear Fuel Issues

LEU

There continues to be strong Congressional interest in supporting efforts to address the issues surrounding both LEU and HALEU, but legislators are still searching for effective approaches. Regarding LEU, there is a clear desire on the part of both policymakers and operators to phase out reliance on Russian nuclear fuel, while also avoiding any future reliance on fuel from China, which has also used nuclear energy as a geopolitical tool. [102,103,w,x,] The strategy to address the LEU gap must be durable and resilient, regardless of the timing and outcome of the Ukraine war. The size of the gap, and the need to build new capacity to close it, requires that policies provide for a phased transition that avoids disrupting plant operations. To create adequate motivation for suppliers, any policies need to be constructed so that investments in new supply capacity can be recovered before protections are relaxed. For example, in considering further expansion, Orano's board of directors sought a committed order book for the next 10 to 15 years.[104]

Most critically, approaches to improve U.S. nuclear energy security and address reliance on Russian LEU need to recognize that nuclear fuel is a global business, and that policies require broad international coordination. The U.S. represents less than 40 percent of the market for enriched uranium outside Russia and China. More than 25 countries represent another 40+ percent of that market, including many that have close relationships with Russia due to geography, history, or recent politics, including some in Europe. (See Figure 6.) An increase in enrichment supply outside Russia (and avoiding increased dependence on China) will require agreement from most of these other importers to exclude Russian LEU, even as Russian supply may become very attractive economically, as Russian oil has become in the face of sanctions (and also to exclude increases in imports from China, which could be offset

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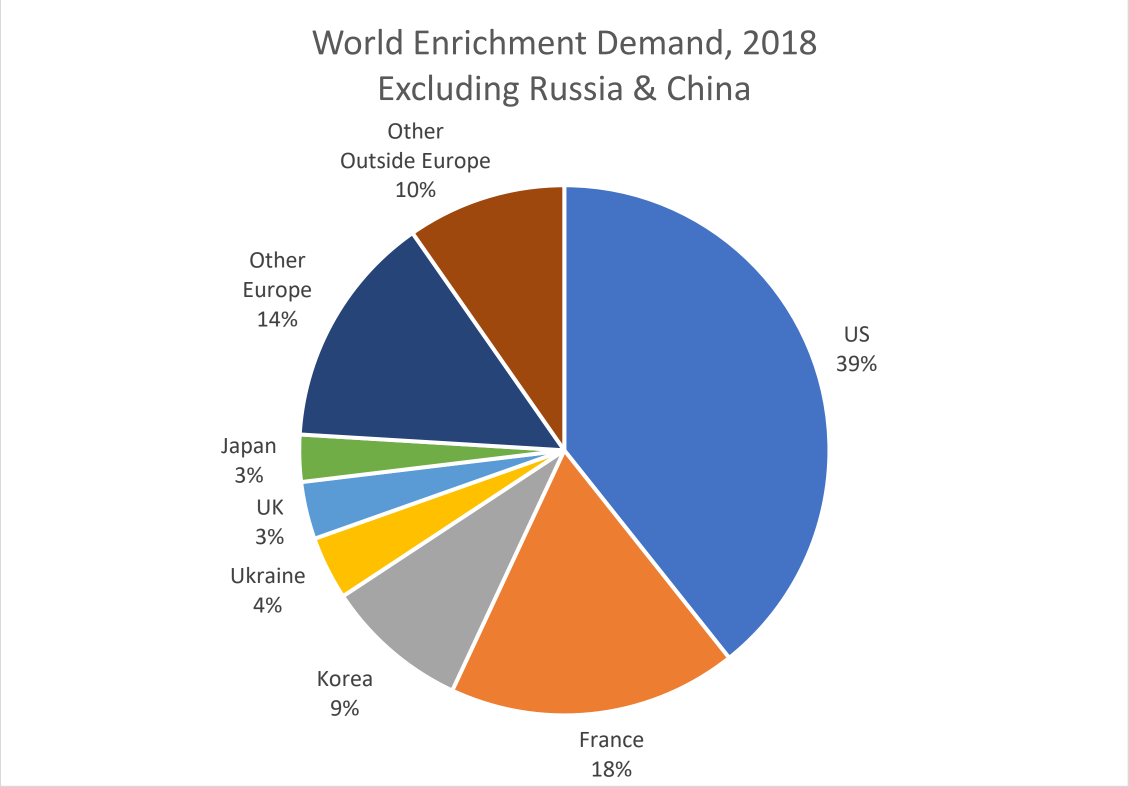
[w] For example, Joseph Dominguez, the CEO of Constellation Energy, testified in early 2023 that Constellation was "in discussion with multiple enrichment providers about signing long-term contracts to support new domestic capacity."
[x] For example, the concern over the potential threat from China's influence in nuclear energy is extensively covered in "Restoring America's Competitive Nuclear Energy Advantage"

by Chinese imports of Russian fuel, and in any case could create a geopolitical risk in the future). Otherwise, Russian supply will simply be redirected from U.S. and other countries that cooperate with the restrictions to countries that do not cooperate. To appreciate the scope of the challenge, note that the two "other" categories in Figure 6 represent more than 20 countries and almost 10 million SWU per year.

Figure 6: World Enrichment Demand in 2018, Excluding Russia and China[y]



Source: World Nuclear Association, 2019

Any policies to phase out reliance on Russian LEU need to recognize that Russia could retaliate by cutting off supply of LEU before new supplies are in place, creating a temporary shortage of LEU and threatening disruption of nuclear plant operations. Some nuclear plant operators have prepared for this contingency, but others have not.[105,106] Given the gap between requirements in countries outside Russia and non-Russian supply, advance preparation for a Russian cutoff could be challenging, though there is always some buffer of fuel in the nuclear fuel pipeline due to the lengthy production process and the natural

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[y] World Nuclear Association 2019 Fuel Market Report, Table IV. Adjusted for subsequent retirements in Germany.

conservatism of nuclear plant operators, for whom fuel cost is relatively small compared to the opportunity cost of being unable to operate a reactor. In addition, the shutdown of reactors in Japan created an unintended reserve of nuclear fuel for which Japanese operators had committed contractually but have not used, which could be made available to other operators in the event of Russian retaliation. However, the amount of fuel available may be small, since some of those commitments may have been resolved contractually rather than through production placed in storage, and some of the stored fuel may already have been delivered to other operators through private agreements about which there is limited transparency. It is also possible that U.S. operators may have acted more urgently to obtain non-Russian supply than operators in other parts of the world, who may not view the risk that they would be cut off from Russian supply to be as severe.

Finally, any path to rebuild non-Russian capacity will require capital investment and therefore drive up U.S. fuel costs. In the absence of a price on carbon emissions, for which there is no near-term prospect, nuclear plants will become less competitive compared to existing carbon-emitting generation, and existing nuclear plants will become more likely to retire. If we value the zero-carbon, always-available energy from nuclear power, it is imperative that the increased cost of fuel resulting from fuel security efforts be counteracted by other policies to preserve existing nuclear generation (the IRA created a tax credit of up to $15/MWh for power from existing reactors, but that was to make nuclear power more competitive with carbon-emitting generation *before* the recent increases in nuclear fuel costs).[107]

HALEU

The “chicken and egg” challenge to make HALEU available in advance of demand from an established advanced-reactor market is, in contrast, somewhat straightforward. It requires the commitment of funds to act in place of market demand until the advanced reactor technologies develop some traction. The available funds must be sufficient to enable HALEU producers to build capacity at a reasonable scale and obtain a return on their investment even if the market does not develop further, which as noted earlier, is still in question despite the DOE’s RFP. Such a program should support the entry of multiple producers to result in a robust supply chain, although if policy intervention is successful and results in growing advanced reactor sales, producers that are not in the initial program are all capable of developing new capacity once the market is visible and can support financial investment. Recent legislation, including the NFSA and the subsequent 2024 appropriations, if the restrictions are resolved, appears adequate to this challenge, if it is effectively deployed.

In the expected case, government investment in HALEU would eventually be returned, since once the market develops, users of the fuel would purchase it from the government-funded supply. However, appropriation of the funds must anticipate that there is a potential downside scenario where the market does not develop and the funds will be used, but the government will own HALEU. The impact of such a downside scenario may be mitigated if there are other uses for the HALEU or the program can be structured to reduce the commitment in that scenario (approaches to mitigation are discussed more extensively below).

Domestic Supply vs. Reliance on Allies

Some discussions regarding how to address nuclear fuel supply have focused entirely or primarily on the U.S. domestic nuclear fuel supply chain. While some U.S. domestic infrastructure in all facets of the supply chain is necessary to support national security requirements (e.g., for uses such as Project Pele, and to ensure supply of nuclear fuel for the Navy over the long term), the fuel supply chain for civil nuclear power is fundamentally global, with the most economic uranium mining outside the U.S., important infrastructure for LEU production in Canada and Europe, and fuel fabricated and shipped worldwide. It would be impractical, and counterproductive, to overbuild infrastructure in the US. Energy security demands that we ensure adequate capacity exists in countries that will not use fuel supply as a weapon in geopolitics, but not that it strictly be controlled domestically. Furthermore, greater national concentration of nuclear fuel infrastructure could be counterproductive to non-proliferation objectives. A key principle behind non-proliferation policy is for countries with nuclear power plants to be confident that nuclear fuel will be available without having to control their own fuel infrastructure (in particular, enrichment). A return to a nationalistic approach to such infrastructure would contradict that principle.

Policy Recommendations

LEU

If the U.S. and its allies choose to address the reliance of the global enrichment market on Russian-produced fuel, then the key requirements are (1) to provide assurance that Russian fuel will be excluded from markets long enough for conversion and enrichment providers to recover investments in new (or restored) capacity, and (2) to achieve global coverage, so Russian fuel is not simply redirected to other markets without increasing the demand for non-Russian supplies.

There are two potential approaches to driving Russian fuel out of non-Russian markets. The first is for cooperating countries to ban imports of Russian fuel, over a timeline that is consistent with the feasible expansion of non-Russian supply, as has been proposed in U.S. legislative attempts (but only for the U.S.). This approach is straightforward (if there is support for legislation in enough relevant countries), but producers would have to be confident that the sanctions would last long enough to recover their investments – on the order of ten years, perhaps more. Sanctions would also need to guard against displacement, i.e., increased purchases of fuel from a country that has commercial enrichment (e.g., China) that is made possible by that country importing Russian fuel.

A second potential approach would be to require all nuclear plant operators to establish long-term contracts with non-Russian producers. Such agreements would need to be internationally verifiable, but the advantage to a contractual approach would be that even if the political will relaxed, the contractual commitments would continue to be binding, providing producers with confidence that their investments could be recovered. However, displacement could still be a concern, and such long-term contracts would inevitably include the opportunity to adjust quantities (e.g., intended for operational uncertainties such as reactor outages) that could be abused to allow less-expensive Russian fuel to be substituted for contractual purchases.

The challenge to both approaches is achieving the global commitment required. As is apparent from the breadth of countries involved, achieving an adequate increase in non-Russian supply will require commitments to exclude Russian supply from almost every importer of nuclear fuel other than those captive in Russian or Chinese spheres, long enough to support capital investment and recovery, with strong provisions to preclude displacement or leakage. The multilateral statement in April 2023 is a start to such commitments, but the effort will need to become more concrete and much broader to be effective.[z,108] Only with that level of commitment can potential suppliers have adequate confidence that investments in new capacity could be recovered. While some suppliers have begun preparations for expansion, if the current apparent commitment to non-Russian supply wanes, the impetus for those projects can be lost and the preparations abandoned.

If adequate protections against Russian supplies entering the market can be put in place, it may not be necessary to commit government funding to achieve the objectives for an adequate LEU supply, since normal market mechanisms would respond if there were a clear commitment to excluding Russian supply for an adequate length of time. However, such funding could be warranted to offset the additional cost that would be imposed on operators of nuclear generation as the costs of new supply are passed through from producers, to avoid potential financial stress on nuclear generation and the threat of further retirements of carbon-free nuclear generation.[aa,109] While the cost of competing generation based on fossil fuels rose briefly as a result of the Ukraine war, natural gas prices have returned to prevailing post-2008 levels.[110]

Embarking on a global plan to exclude Russian fuel entails the risk that the Russian government could cut off supplies of UF_6 or LEU before new capacity can be ready. There are limited options to prepare for such an action other than acquiring adequate reserves to bridge the timing gap (perhaps five years) between a commitment to new capacity and when it can begin production.[111] Acquiring reserves is not necessarily or even appropriately a government action; operators can acquire the reserves if they are physically available and the operators are willing to pay the current prices to hedge the risk (and in the case of price-

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[z] As noted earlier, the statement was issued by the US, Canada, France, Japan, and the United Kingdom.

[aa] Fuel cost represents only about 20 percent of annual plant costs, so the impact on total cost of even a substantial increase in fuel cost is limited.

regulated utilities, able to recover the extra cost). Some operators have already acquired reserves,[112] but others likely remain exposed. The rush to acquire non-Russian supply is reflected in the recent increase in enrichment prices, and in the reported sales volumes of non-Russian enrichers (Urenco reported a 24 percent increase in their order book in 2022 and an 11 percent increase in the first half of 2023).[113,114] As noted earlier, the gap between non-Russian demand and non-Russian supply precludes near-term requirements from being covered globally, but US operators may view the risk of a cutoff as being greater than those in other parts of the world. Continued restoration and expansion of non-Russian conversion capacity could also lessen a near-term supply shortage by enabling a shift in the LEU production inputs to use more UF_6 feed and less enrichment.

HALEU

The first, and most straightforward policy action to support production infrastructure for HALEU is to continue to operate the existing demonstration facility. The investment in that facility has already been made, so the government only needs to continue to cover operating costs and pay for LEU feed to continue to acquire a modest amount (approximately 0.9 MT/year) of HALEU.[115] Given all the potential uses, it seems unlikely that the government will not be able to resell that quantity of material and cover more than its ongoing costs.

The DOE RFP for HALEU supply, if it proceeds to ultimately acquire HALEU, could be the start of a potential HALEU “bank.” A bank would acquire fuel in advance, then resell it later to satisfy future demand; this distinguishes a bank from a “reserve,” which would hold the fuel for unusual events. The RFP represents the first step, acquiring the HALEU. A process to make the fuel available to subsequent purchasers (operators of advanced nuclear energy projects) has not yet been described but would presumably occur through the HALEU Consortium that was established by DOE in December 2022.[116] A fuel bank of this nature serves two purposes: (1) to be a market intermediary, creating a market large enough to support production facilities when only a small market (the near-term demonstrations) is currently visible, and (2) to be a credit intermediary, making credit-worthy commitments to buy the fuel before future buyers have sufficient credit, or are willing to deploy it (e.g., potential advanced-reactor customers who have not yet committed to the reactors or the fuel).

The concept of such a bank has been suggested as a potential solution to the “chicken and egg” problem in the past and it is fundamentally sound.[117,118] The challenge, as noted earlier, is that the currently available funding is likely insufficient to support a workable supply chain. Responses to the RFP may provide DOE with a view of the minimum purchase commitment required for a bank to be successful, though that information may not become public. Assuming the minimum practical size for a single facility is 12.5 MT per year – roughly half what DOE suggested in October 2022 that it would seek in total purchases (and what Centrus has said it could build over 48 months), that a bank must support six to ten years of production to give producers confidence that their investment can be recovered, and that the cost of HALEU is roughly $20 million per MT, a practical bank would likely require on the order of $1.5-2.5 billion to support one facility and $3-5 billion for two facilities.[119,120,bb, cc]

Proposing to fund a large bank, on the order of 75-250 MT, leads naturally to the question of how to mitigate the risk if future demand from advanced reactors does not materialize sufficiently to absorb all the production to which the bank has committed.[dd] One approach would be to incorporate a termination option into the bank’s purchase agreements. Given the current price of LEU, which is likely to continue while new non-Russian LEU production is being developed, it is reasonable to expect that the LEU feed will represent half or more of the cost of HALEU. If demand for HALEU does not develop sufficiently to use the anticipated contents of a bank (and therefore to assure recovery of the funds spent to purchase HALEU), a termination option would allow the bank to save the cost of procuring the LEU feed, while a termination payment could be used to compensate producers for capital recovery embedded in foregone purchases. For example, if the bank were established to support ten years of purchases, and the LEU feed represents 13/20 of the cost of the HALEU, then a termination option after the fifth year of production would save about a third of the anticipated outlays of the bank, even after making a termination payment to cover the capital recovery in foregone

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[bb] As noted, Urenco has not publicly specified the size of the facility they could seek to construct.

[cc] Calculation: 12.5 MT/y * $20m/MT = $250m/year per facility; $1.5 billion for 6 years or $2.5 billion for 10 years; double for a second facility. The rough assumption of $20m/MT is based on the discussion in the earlier section “Policy and Legislative Initiatives.”

[dd] I.e., six years of 12.5 MT/y production to ten years of 25 MT/y.

purchases.[ee,ff] Incorporating a termination option could be achieved by simply requiring that respondents include the options they would accept as part of their RFP response. The IDIQ structure in the DOE RFP provides another type of mechanism that could be used to manage production uncertainty, but it may be challenging to address both volume uncertainty and assurance of capital recovery in that mechanism.

Producers would certainly be averse to potential termination, especially since no producer wants to contemplate stopping and potentially restarting operating centrifuges. However, if a termination payment is provided to offset lost capital recovery, exposure to a potential termination may be a small cost to pay if it enables the establishment of a more appropriately sized bank. In addition, even if the government were to terminate the program, the production assets would be in place and paid for, so HALEU could be provided to other potential customers (e.g., producers of advanced fuel for light-water reactors) at a more attractive price, potentially enabling some production to continue.

Additional protection for an investment in a HALEU bank would come from alternate sources of demand to absorb the product. Advanced fuel for existing and new reactors represents a large potential market, and if HALEU production is in place, more options for advanced fuels that incorporate HALEU could be developed. In addition, there has been an ongoing effort to convert research reactors throughout the world from operating on more highly-enriched fuel – which has risks for weapons proliferation – to operation on HALEU.[121] The US has committed to be one of the suppliers of HALEU for this purpose, and has historically done so through downblending, but the source material for downblending will soon be exhausted. The research reactor requirement is much smaller than the potential demand from advanced reactors for energy production – 3 to 7 MT per year through 2034, and 7 to 9 MT per year after that – but the government's cost to hold HALEU in a bank is also low, and the HALEU would likely eventually find a use.[122]

[ee] Based on the discussion in the earlier section "Policy and Legislative Initiatives."

[ff] In the above example, for each facility the full cost for ten years would be $2.5 billion, but the savings in feed costs available through a termination option after the fifth year would be $13 million/MT * 12.5 MT/y * 5 years or about $0.8 billion of that amount (32 percent). Additional savings could result if the enrichment facility's annual operating costs are also eliminated through termination.

Finally, focusing available funding on the construction of the enrichment infrastructure itself, through a public-private partnership or similar mechanism, is an alternative approach to resolving the key obstacle to HALEU availability – creating the capability to produce HALEU – while potentially requiring less funding than creating a bank of material, especially with the cost of LEU at or near historic highs. Production of the HALEU could then be contingent on receiving orders from project sponsors (who would be required to pay for or deliver the LEU feed, consistent with current commercial practice for enrichment), but at least the sponsors could have confidence that the fuel infrastructure would be available when needed. The DOE RFP's IDIQ structure potentially lends itself to this approach. However, there would still be several issues to resolve in this approach, such as: (a) would it be practical to start enrichment operations with limited orders, when there is a risk that the centrifuges would have to be stopped if additional orders do not materialize, or enrichers would have to purchase LEU feed at their own risk; (b) what ongoing rights would DOE have to allocate enrichment capacity, or to use it for government or national security purposes, in exchange for the funding it provides; (c) what rights would DOE have if enrichers chose to cease HALEU production. To manage some of the uncertainty, in future task orders under the RFP, DOE could seek (and perhaps even offer) options for HALEU offtake in exchange for set payments (and if desired, delivery of a quantity of LEU), rather than specifying firm quantities of production.

Conclusion

The case for a durable strategy to improve U.S. nuclear fuel security, and therefore U.S. energy security, is clear. Similarly, the case for U.S. government action to provide advance support for HALEU, and enable a potential market for advanced nuclear energy, that can accelerate the world's efforts to decarbonize power and industry, is also clear.

The pathways to accomplish both objectives are feasible and are not dependent on new or unproven technologies, only on government action to clear barriers that stand in the way of private investment. For LEU, the requirement is to insulate investors in non-Russian production from being undermined by low-cost Russian fuel, and to do so on a path that is consistent with the feasibility of expanding non-Russian production.

For HALEU, the path is for the government to create a market in advance of the committed demand for fuel. The technology to produce the fuel is known, all that is lacking is adequate confidence in return on private investment in fuel production capacity. The DOE RFP, combined with the NFSA and the funding provided in 2024 (once the restrictions are resolved), is potentially a start on the path to providing that assurance. In exchange for its investment, the government will receive fuel which will have tangible value and a reasonable expectation that it can be sold or used, even if a large market for HALEU fuel for advanced reactors does not develop. It is likely the government can mitigate residual risk from a commitment to HALEU production through using the fuel for research reactors or for future use in advanced fuels for light-water reactors, among other pathways.

Nuclear energy will be needed as part of the solution for decarbonization. Among other estimates, the Department of Energy estimates that the US will need to triple its nuclear power generation capacity by 2050.[123] To meet that need, it is essential to take action to expand preferred sources of supply for LEU and enable the supply of HALEU. Failure to do so risks US and allied energy security, non-proliferation, and decarbonization goals.

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