Expanding U.S. Uranium Enrichment: Ending global dependence on Russian nuclear fuel and paving the way for deep decarbonization

Shovel-ready solutions with bipartisan backing could support domestic energy independence while advancing progress against global climate change

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GHS CLIMATE

Executive Summary

Expansion of nuclear energy is essential for achieving U.S. and European energy independence and decarbonizing the global economy to protect our planet. Yet nearly half of the world's uranium enrichment capacity, an essential ingredient in powering most nuclear power plants, exists in Russia. The United States, the world's largest producer of electricity from nuclear power, is highly dependent on Russia for the uranium enrichment capacity to power its nuclear power plants. In 2022, a rough equivalent of one out of every twenty American homes and businesses were powered by electricity produced by nuclear fuel enriched in Russia. As a result, each year, America sends an estimated US$1 billion to Rosatom—the company controlled and owned by the Russian government that controls its uranium enrichment facilities and nuclear weapons.

A robust policy response is urgently needed to counter the threat that Russia will hold nuclear power hostage—and with it, a vital source of electric power for the United States and the world, as well as the chance to combat catastrophic climate change. Researchers at the U.S. Department of Energy estimate that achieving 2050 decarbonization goals will likely require more than doubling U.S. nuclear power capacity, with the need for U.S. uranium enrichment capacity increasing by approximately eight times over present capacity to meet these needs while maintaining energy independence. Even more drastic increases in nuclear power generation are likely necessary in nations with little existing nuclear capacity.

There are multiple, shovel-ready solutions that U.S. policymakers could pursue to solve the problem of Russian dominance of global uranium enrichment completely and rapidly.

The United States Nuclear Regulatory Capacity (NRC) has already licensed two facilities—the American Centrifuge Plant in Piketon, Ohio and the National Enrichment Facility in Eunice, New Mexico—which, if brought to their full licensed capacites, would eliminate the United States's dependence on Russian nuclear fuel and decrease global dependence on it by over 75%. Scaling these facilities would create thousands of new, well-paying jobs around the U.S., namely in Ohio, New Mexico, West Virginia, and Tennessee.

Importantly, this would not only bolster U.S. energy security: it would help other countries lessen their dependence on Russia for uranium enrichment. South Africa, Switzerland, Finland, and the United Arab Emirates rely on Russian enrichment services for more than half of their nuclear fuel. Ukraine, Mexico, and India are completely dependent on Russian uranium enrichment services for their enriched fuel needs, as are NATO members Slovakia, Hungary, Bulgaria, and the Czech Republic (Czechia).

By bringing the American Centrifuge Plant online and expanding the National Enrichment Facility to its maximum licensed capacity, the United States will free up non-Russian enrichment capacity all over the world, ensuring that other countries have options when looking for supplies of enriched uranium and mitigating proliferation risk. Critically, scaling uranium enrichment capacity in the United States is also needed to achieve U.S. and global decarbonization goals. There is an urgent need for the U.S. Department of Energy and the U.S. Congress to act to rapidly expand the nation's uranium enrichment capacity.

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1. Background

Understanding the problems and solutions surrounding limited U.S. nuclear fuel enrichment capabilities requires knowledge of the role of nuclear power and how uranium is enriched to create nuclear fuel. This background section explains concepts and terms that will be referred to throughout this report.

1.a Nuclear power is a major source of global energy and must be scaled to achieve deep decarbonization

Today, nuclear power provides approximately 10% of global electricity and 18% of electricity in OECD countries.[1] It is the world's second largest source of low-carbon power (comprising 28% of global low-carbon energy in 2019).[2] In the United States, nuclear energy contributes 19% of electricity generated and is the country's leading source of clean energy, providing more than half of all emissions-free electricity.[3]

According to the Intergovernmental Panel on Climate Change (IPCC), nuclear power has very low emissions of greenhouse gasses per unit of electric power generated, with a median estimate of 12 grams of carbon dioxide equivalent emitted per kilowatt-hour of electric power generated (gCO_2eq/kWh)—the same as wind power. This is lower than solar power, which has a median value of 48 gCO_2eq/kWh for utility scale solar power and 41 gCO_2eq/kWh for rooftop solar. Nuclear power's carbogenicity is dramatically lower than fossil ("natural") gas and coal, which have median values of 490 gCO_2eq/kWh and 820 gCO_2eq/kWh respectively.[4]

Minimizing the worst impacts of climate change and decarbonizing the global economy requires *dramatically increasing* global nuclear power generation alongside an increase in renewables, according to the U.N. Intergovernmental Panel on Climate Change (IPCC)[5] and the International Energy Agency (IEA).[6] Scaling nuclear power generation is essential, according to scientists, because decarbonizing the electrical system will require significant scale-up of 'firm' clean power, or power that can be generated when the sun isn't shining and the wind isn't blowing.[7,8,9,10,11,12] Without firm clean power, societies will remain dependent on fossil fuels when renewables aren't generating electricity—even with large increases in energy storage. Presently, the only proven, scalable source of firm low-carbon power is nuclear power.[13]

Germany's recent decarbonization strategy demonstrates the essential role of clean firm power. Since the early 2000s, Germany spent over €500 billion to decarbonize their electrical power system[14]—tripling solar and doubling wind power capacity. However, they shut down almost all of their nuclear plants simultaneously, leaving their grid without a major source of *clean* firm power.

Despite their enormous investment in electrical grid decarbonization, carbon emissions from the German grid remain among the highest in Europe. In 2021, the German grid emitted 402 grams of carbon dioxide-equivalent (CO_2-eq) of greenhouse gasses per kilowatt hour (kWh) of electricity generated.[15]

As shown in *Figure 1*, in comparison, France, which relied on a mixture of nuclear energy and renewables to decarbonize their power grid, emitted only 67 grams of CO_2-eq per kWh in 2021[16]—***six times* less than Germany**—while being dramatically cheaper (**electricity prices are 40% lower in France than in Germany**).[17] Remarking on the experience of settings like Germany, the UN Economic Commission for Europe stated unequivocally that **"international climate objectives will not be met if nuclear power is excluded"** from future efforts to decarbonize.[18]

In brief, threats to nuclear power generation, such as nuclear fuel shortages, represent potential energy security *and* decarbonization crises.

1.b From uranium ore to nuclear fuel: the front end of the nuclear fuel cycle

The nuclear fuel cycle begins with mining uranium ore. Presently, three-fourths of the world's uranium ore comes from Kazakhstan (45%), Namibia (12%), Canada (10%), and

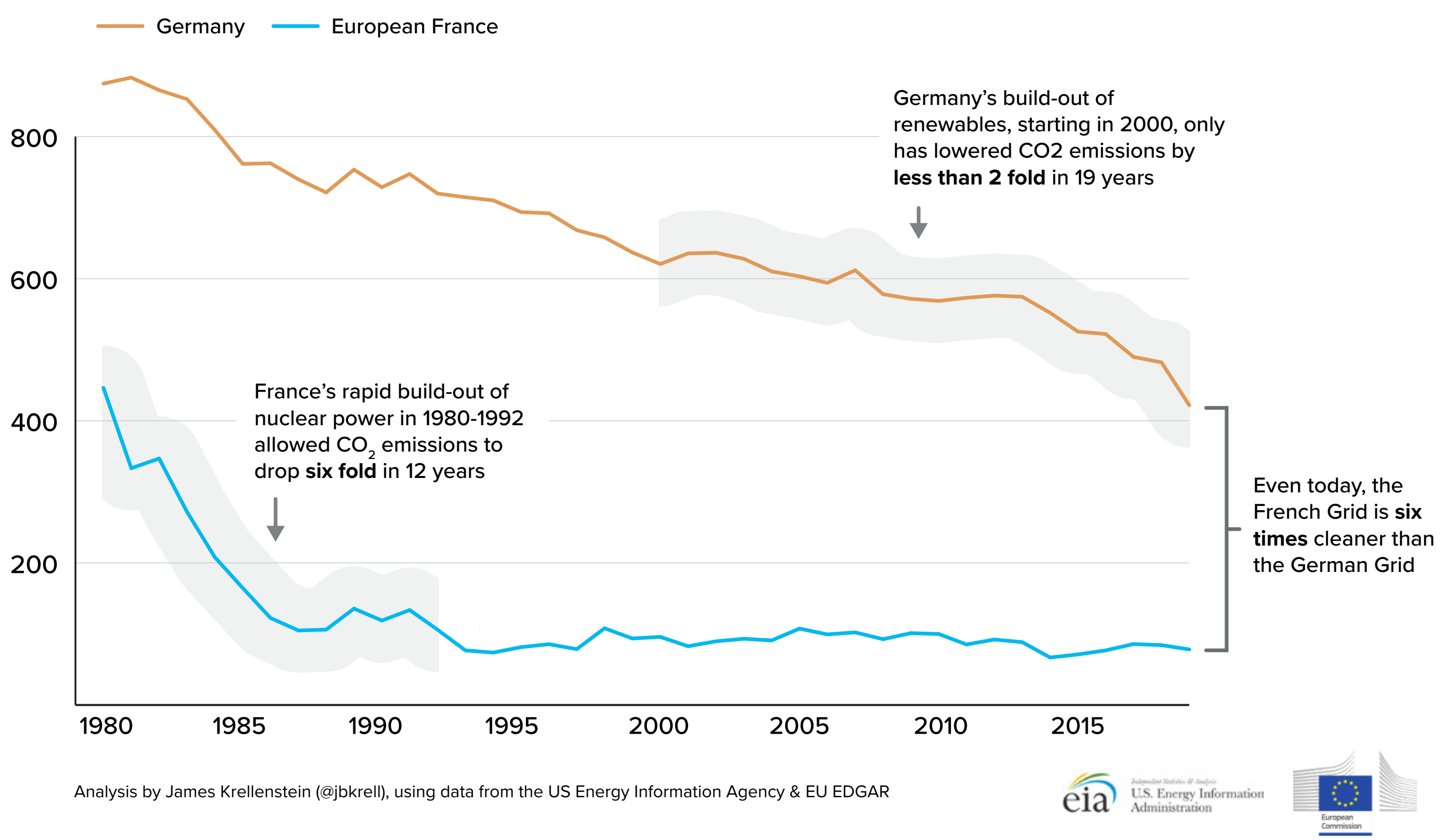

Figure 1: Carbon Emissions (g CO2-Eq per kWh) generated by electric power generation in France & Germany (1980-2019)

Australia (9%).[19] Uranium ore is *milled,* then *converted* into uranium hexafluoride gas and shipped to enrichment facilities for *enrichment*. Following the enrichment process, the enriched uranium hexafluoride gas is shipped to nuclear fuel fabrication facilities, where it is *deconverted* back to solid uranium. The solid uranium is then fabricated into fuel pellets, placed into fuel rods, and bundled up into fuel assemblies. Fuel assemblies are the finished product to be placed in a nuclear reactor. The focus of this report is on the *enrichment* step of the nuclear fuel cycle.

1.c Almost all nuclear power reactors are fueled by uranium enriched via gas centrifugation

Almost all currently operating nuclear power reactors and most future nuclear power reactor designs require *enriched* uranium to operate. In nature, uranium primarily consists of two isotopes: uranium-235 (0.71%) and uranium-238 (99.28%). Generally, only uranium-235 (U-235) can undergo nuclear *fission*—the process of splitting atoms that powers nuclear reactors. The process of increasing the relative concentration of U-235 is called *uranium enrichment.* Because different isotopes of the same element have identical chemical properties, uranium enrichment technologies exploit the small difference in mass between the two isotopes to separate them from one another. The exception to this is laser enrichment, which uses slight differences in the spectroscopic properties of the isotopes.

There are three relevant methods of uranium enrichment: gas centrifugation, gaseous diffusion, and laser isotope enrichment. Almost all operating enrichment capacity today utilizes gas centrifugation. Gaseous diffusion is no longer used because of its high energy requirements (around 20 to 50 times more energy per unit of enrichment than gas centrifugation).[20] Laser enrichment offers much potential, but has yet to be developed commercially at scale.[21] However, as we will explain in Section 7, U.S. development of laser enrichment technology is essential to ensure that U.S. enrichment capacity remains competitive on the global market.

1.d Three essential terms: low enriched uranium (LEU), high assay-low enriched uranium (HALEU), and separative work units (SWU)

Two distinct forms of enriched uranium are used in civilian nuclear power reactors: low enriched uranium (LEU), which a has a maximum concentration of 5% U-235, and high assay-low enriched uranium (HALEU, pronounced "*HEY LOU*"), which has a concentration of between 5% and 20% U-235. HALEU is made by increasing the concentration of U-235 from LEU feedstock.

The work needed to enrich uranium is measured in "separative work units," or SWU (pronounced "*SWOO*"). Making a single kilogram of LEU (at 4.95% U-235) requires 9.813 kg of natural uranium and approximately 8.2 SWU. As shown in *Figure 2,* making a single kilogram of HALEU requires 42 SWU: 35 SWU to convert 31kg of natural uranium into 4.5 kg of LEU, and a further 6 SWU to convert 4.5 kg of LEU into 1 kg of HALEU.

Almost all of the world's current power reactors, including all 93 operational U.S. power reactors, utilize LEU. It is LEU fuel that today powers 1 in 5 American homes and businesses and produces 10% of the world's electricity. Many next generation ("Generation IV") reactors require HALEU. As Generation IV power reactors are developed and constructed in the U.S. and globally in the coming years, the need for HALEU will increase significantly.

1.e The U.S. is dependent on other nations for nuclear fuel enrichment

The existing global fleet of nuclear power reactors require 50.205 million separative work units (SWU) of enrichment capacity each year.[22] The U.S.'s 92 power reactors require approximately 15 million SWU each year.[23] The United States' annual enrichment capacity is merely 5.4 million SWU (at Urenco's facility in New Mexico), meaning that at minimum, the U.S. is dependent on foreign enrichment capacity for roughly two-thirds of its nuclear fuel.[24] In 2021, the U.S. imported nearly 80% of the enrichment services needed for low enriched uranium for commercial power reactors.[25]

The U.S.'s limited fuel enrichment capacity poses two urgent problems: 1) the U.S. and the world depend on Russia to fuel *today's* fleet of power reactors; and 2) the U.S. and the world lack the *increased* uranium enrichment capacity needed to dramatically scale nuclear power generation and achieve 2050 decarbonization goals.

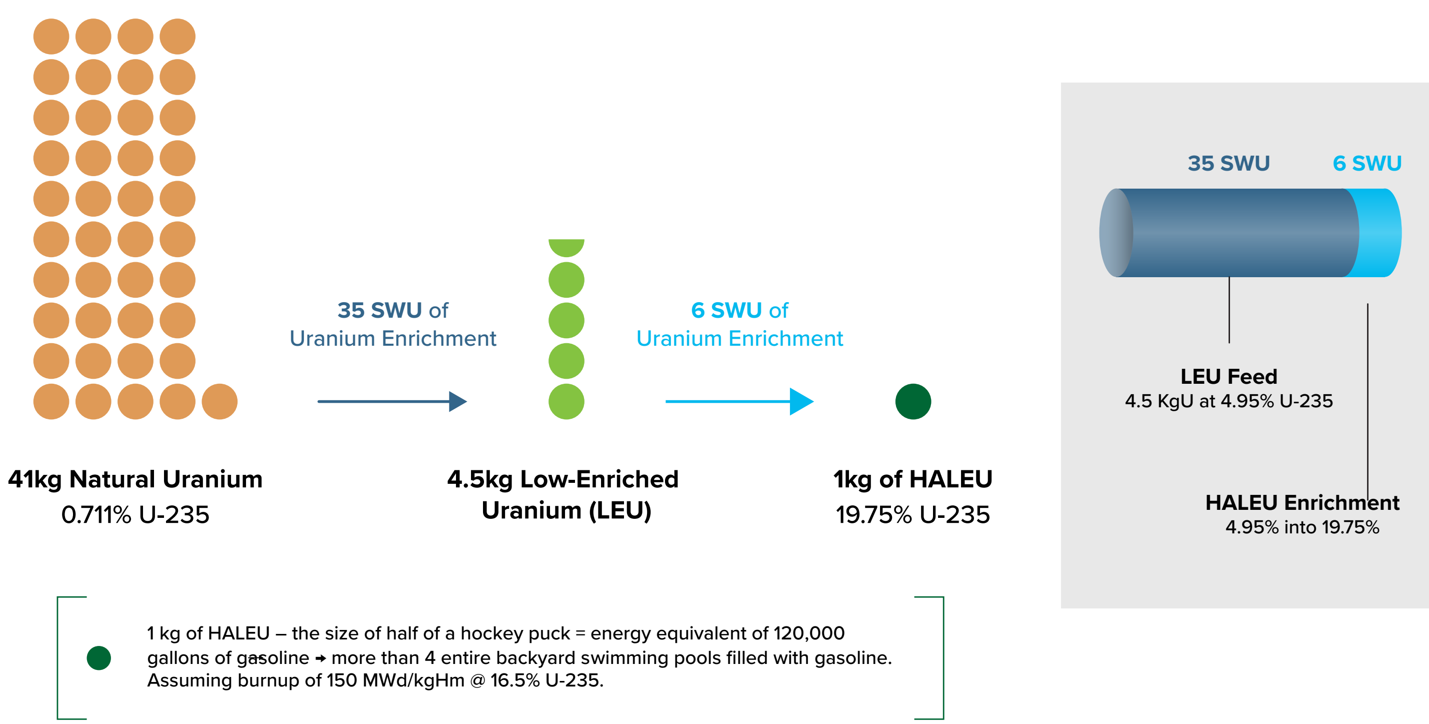

Figure 2: How to make a kilogram of High Assay-Low Enriched Uranium (HALEU)

2. Russia dominates the global uranium enrichment market

2.a Russia controls nearly half of the world's enrichment capacity

Russia has an enrichment capacity of 27.7 million SWU per year, comprising 46% of the world's enrichment capacity (*Figure 3*).[26] Russia's domination of the global uranium enrichment sector is a product primarily of two factors: the legacy of an enormous and efficient gas centrifuge-based uranium enrichment program built by the Soviet Union prior to its dissolution in 1991, and the decision of the Russian President, Vladimir V. Putin, to nationalize and invest tens of billions of dollars to subsidize the Russian nuclear industry, including its uranium enrichment capacity, starting in the mid-2000s.[27]

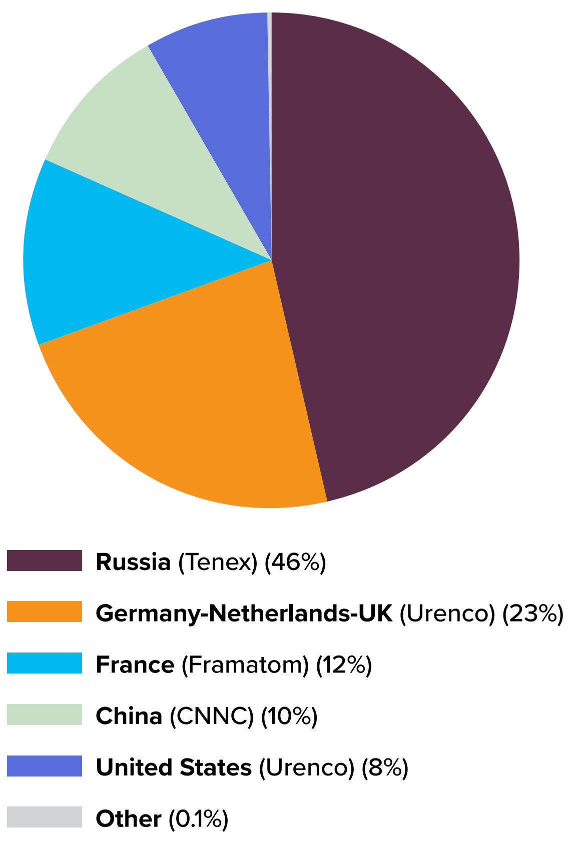

Chart: James Krellenstein • Source: World Nuclear Association

Figure 3: Global uranium enrichment capacity (2020) •
Total Global Capacity is 60.166 million SWU

2.b The world depends on Russia for LEU and HALEU based nuclear fuels

The world is highly dependent on Russia for uranium enrichment capacity, and thus the ability to maintain energy independence and support further decarbonization efforts. If Russia cut off access to its uranium enrichment services, half of the world's nuclear power generation capacity would be at risk of being unable to refuel. Currently, South Africa,[28] Switzerland,[29] Finland,[30] and the United Arab Emirates[31] rely on Russian enrichment services for more than half of their nuclear fuel. Ukraine,[32] Mexico,[33] and India[34] are completely dependent on Russian uranium enrichment services for their enriched fuel needs, as are NATO members Slovakia,[35] Hungary,[36] Bulgaria,[37] and the Czech Republic (Czechia).[38]

2.c The U.S. depends on Russia for its nuclear fuel

Today, the U.S. uses foreign enrichment services for over 80% of its nuclear fuel, with Russia being the leading provider, supplying 28% of the U.S.'s fuel enrichment services in 2021 (*Figure 4*).[39] In 2022, a rough equivalent of one out of every 20 American homes and businesses were powered by electricity produced by nuclear fuel enriched in Russia.[40] Each year, upwards of US$1 billion of America's utilities bills are sent directly to Rosatom—the company owned by Vladmir Putin's government that controls Russia's uranium enrichment facilities and the production of its nuclear weapons.[41]

Additionally, Russia is the only country in the world that currently possesses the ability to produce high assay low enriched uranium (HALEU) commercially, which most advanced (Generation IV) power reactors require.[42] The U.S. Department of Energy projects that 40 metric tons of HALEU will be needed in the U.S. by 2030. TerraPower has announced that they have delayed the construction of their Natrium reactor for two years due to the fact that no non-Russian sources of HALEU exist to fuel the reactor when it comes online.[43]

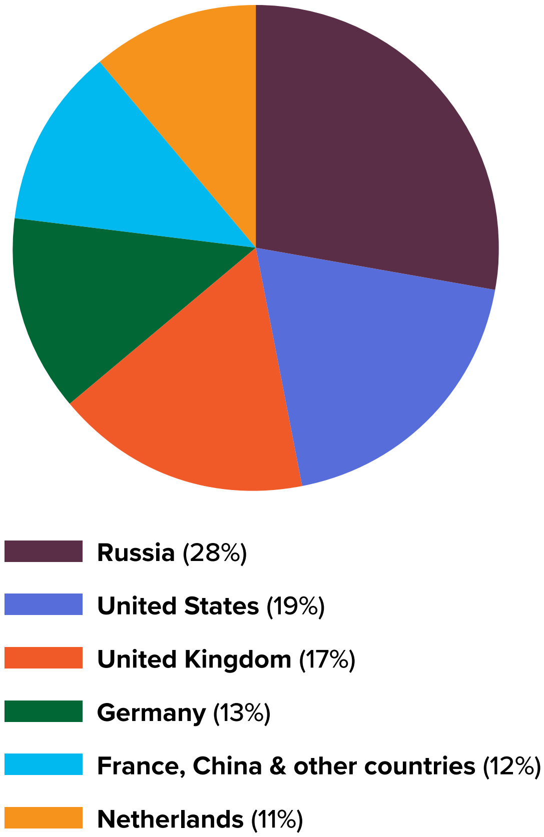

Chart: James Krellenstein • Source: US Energy Information Agency

Figure 4: Sources of Uranium Enrichment for the U.S. (2021) 14.217 million SWU used

U.S. dependence on Russia for fuel enrichment is recognized as an urgent problem by the nuclear power industry, bipartisan U.S. Congressional leadership,[44] international nuclear agencies,[45] and the U.S. Department of Energy.[46]

2.d "Overfeeding" is unable to end U.S. dependency on foreign enrichment services

As markets and geopolitical conditions change, enrichers and uranium purchasers can adjust the amount of enrichment work needed (i.e. increase or decrease the amount of SWU needed) and the amount of uranium needed to manufacture a given quantity of enriched uranium at a given enrichment level.

In conditions where uranium enrichment services are in short supply or expensive, enrichers can "overfeed" their enrichment cascades: meaning that the quantity of unenriched uranium needed to make a given quantity of enriched uranium is *higher* and the amount of enrichment capacity (i.e. SWU per kg end uranium product) is *lower*.

Conversely, in conditions where uranium enrichment services are abundant or cheap relative to the cost of natural uranium, enrichers can "underfeed" their enrichment cascades, meaning that the quantity of natural uranium needed to make a given quantity of enriched uranium is *lower* and the amount of enrichment capacity is higher.

Hypothetically, if the need to reduce or eliminate the use of foreign enrichment services arose, enrichers in the U.S. could "overfeed" their domestic enrichment capacity to increase the quantity of LEU produced without increasing the capacity (measured in SWU) of U.S. enrichment facilities. However, the current U.S. enrichment capacity at Urenco's National Enrichment Facility in Eunice, New Mexico is so limited that it would be impossible to rely on "overfeeding" alone to end U.S. dependence on foreign enrichment services over the long term.

At the U.S.'s present enrichment capacity of 5.4 million SWU, using "overfeeding" to end the U.S.'s annual dependence on Russia for 4.2 million SWU would require over 47,000 metric tons of unenriched uranium.[47] This is four times the amount of uranium required without overfeeding and nearly equivalent to the entire mass of uranium mined worldwide in 2021.[48] In brief, significantly increased enrichment capacity is required if the U.S. is to end its dependence on foreign enrichment services.

2.e The world needs an additional 11.2 million SWU in enrichment capacity to end dependence on Russia and China for nuclear fuel

The world needs an annual enrichment capacity of 37.4 million SWU to fuel the current fleet of nuclear power reactors outside of Russia and China. Presently, there exists just 26.2 million SWU in enrichment capacity outside of Russia and China (see *Figure 3*). Installing new annual enrichment capacity of 11.2 million SWU would end dependence on Russia and China for nuclear fuel outside of these countries. Additionally, this is approximately the increase in enrichment capacity the U.S. needs to end reliance on other nations for its nuclear fuel needs. There are shovel-ready solutions in the U.S. to expeditiously scale fuel enrichment capacity to nearly this level.

3. Scaling U.S. uranium enrichment capacity will aid in global decarbonization and decrease nuclear proliferation risk

3.a Uranium enrichment capacity must increase to achieve global decarbonization goals

Research from Idaho National Laboratory estimates that a fully decarbonized U.S. economy by 2050 will require, cumulatively, 5,350 metric tons of HALEU and 78,000 metric tons of LEU.[49] Producing this volume of LEU and HALEU will require approximately 32 million SWU per year on average between 2023 and 2050.[50] A 2023 DOE report estimates a near tripling of nuclear power generation (from approximately 100GW to 300GW) will be required to meet 2050 decarbonization goals. This level of capacity will require ~30 million additional SWU per year (six times current U.S. capacity), and ~40 million SWU per year to achieve energy independence.[51] Not scaling enrichment capacity to meet the needs of the growing fleet of U.S. power reactors will delay progress on decarbonization. A case in point is Terrapower's January 2023 announcement that they would delay by two years the construction of their Natrium reactor in Wyoming due to an inability to acquire non-Russian HALEU fuel.[52]

Meeting global decarbonization goals will require an enormous expansion of uranium enrichment capacity. Many decarbonization modeling scenarios reviewed by the Intergovernmental Panel on Climate Change (IPCC) and the International Energy Agency (IEA) rely on dramatic increases in global nuclear power generation.[53,54]

3.b Increasing U.S. uranium enrichment capacity can decrease global nuclear proliferation risk

Given that the U.S. has committed to being a leading global partner to low- and middle-income countries in decarbonizing their economies while avoiding proliferation risk, the U.S. will need to expand uranium enrichment capacity several times greater than the capacity needed to serve domestic needs. If the U.S. can ensure an abundant global supply of enriched uranium, other nations will be less likely to feel the need to build their own uranium enrichment facilities.

An example of this concept in practice is the International Atomic Energy Agency (IAEA) LEU bank. The IAEA LEU bank, located in Kazakhstan, is a physical stock of 90 metric tons of uranium hexafluoride, suitable to make fuel for nuclear power reactors. The LEU bank is designed to be used to prevent individual countries from developing their own nuclear fuel enrichment capabilities. In the event of supply disruption of enriched uranium to a civilian commercial nuclear power plant, an IAEA member state can access the enriched uranium in the bank if they are not able to procure LEU on the global market. The LEU bank decreases proliferation risk by providing countries interested in peaceful nuclear energy with supply assurances and more options for their energy programs, without having to develop their own uranium enrichment capabilities.[55] By dramatically increasing the supply of enriched uranium not controlled by a single country (i.e. Russia), the U.S. could create a new LEU and HALEU bank, operated by the U.S., the IAEA or another multilateral agency, which would decrease the probability of global supply disruptions.

4. How we got here: a brief history of uranium enrichment in the Soviet Union and the United States

Following the end of World War II, Soviet special forces kidnapped a team of German physicists and mechanical engineers who had worked on isotope separation techniques for the Nazis. While in a specialized prison camp in the Soviet Union, the German scientists, led by physicist Max Steenbock and engineer Gernot Zippe, developed a successful design for a gas centrifuge for uranium enrichment.[56] Unlike the primary method of uranium enrichment used then in Western Europe and the United States—gaseous diffusion—the gas centrifuge based uranium enrichment approached developed by Steenbock and Zippe was extremely energy efficient, requiring less than one *twentieth* of the energy of gaseous diffusion to do an equivalent amount of enrichment.[57]

The development of Steenbock and Zippe's while imprisoned in the Soviet Union gave the USSR a key advantage over the US and Western Europe in terms of uranium enrichment. The USSR began commercial scale development of the gas centrifuge for uranium enrichment in 1951, decades before other countries.[58] In the USSR, the massive expansion of uranium enrichment capacity in the 1960s and 1970s used gas centrifuges—whereas the US and France invested in building massive plants using the far less efficient gaseous diffusion process during the same period.

It would not be until the death of Soviet leader Joseph Stalin that Gernot Zippe would be allowed to leave the USSR. In 1957, Zi ppe began working with American scientists to develop gas centrifuge technology based on his memory of the Soviet designs,[59] but it was too late. Western Europe's and the United States' first gas centrifuge plants would come online decades after the Soviet Union's first commercial plant began operation in 1962.

On the eve of its dissolution in 1991, the USSR had 20 million SWU of uranium enrichment capacity, all based at facilities within Russia. This was equal to the amount of enrichment capacity the United States had in 1991—the two uranium enrichment facilities in Paducah, Kentucky and Piketon, Ohio had a combined capacity of 19.6 million SWU. [60] Unlike the USSR's facilities however—which were almost exclusively based on gas centrifuge technology—the United State's capacity was entirely based on the dramatically less efficient gaseous diffusion technology.

Following the collapse of the USSR, all nuclear enrichment capacity previously operated by USSR's Ministry of Atomic Energy and Industry was transferred to the control of the Russian company TVEL (Russian: <<ТВЭЛ>>, an abbreviation of <<тепловыделяющий элемент>>, lit. "heat producing element" or fuel rod.).

The massive advantage that the Soviet Union had over the United States meant the U.S.'s gaseous diffusion based enrichment industry could not compete with TVEL's vastly more efficient gas centrifugation based enrichment capacity located in what became the Russian Federation. In 1992, the US Department of Commerce (DOC) initiated an antidumping investigation on uranium from Russia, alleging that it was sold below its fair market value and harmed the US uranium enrichment industry. The Department of Commerce and Russia's Ministry for Atomic Energy (MINATOM)—now Rosatom—signed an agreement to suspend the investigation and limit the volume of Russian uranium exports to the US market by special quotas (More on this in Section 5.a).

The first U.S. facility to completely shut down was the Portsmouth Gaseous Diffusion Plant in Piketon, Ohio in 2001 (8.3 million SWU per year). In 2013, the Paducah Gaseous Diffusion plant near Paducah, Kentucky closed permanently (11.3 million SWU per year). The United States unfortunately did not replace the 19.6 million SWU of shut down gaseous diffusion capacity. Russian and U.S. uranium enrichment capacity since 1960 is shown in *Figure 5.*

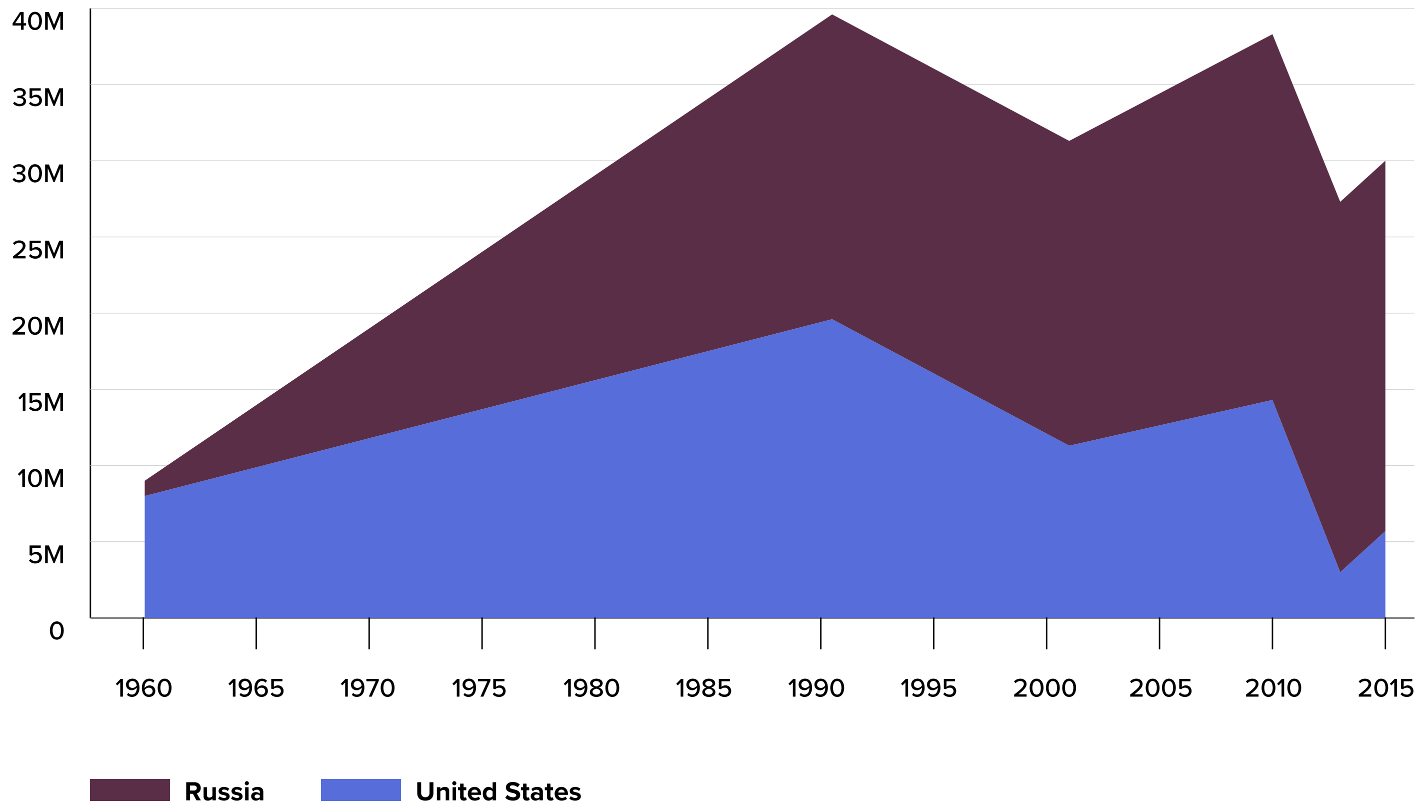

Figure 5 Russia vs U.S. uranium enrichment capacity since 1960

5. What is being done today to address the problem of limited U.S. uranium enrichment capacity?

5.a The continuation of the Russian Uranium Suspension Agreement

In mid-1991, months before the dissolution of the USSR, U.S.-based uranium companies asked the Department of Commerce to investigate Russian uranium enrichers and suppliers for possible ‘dumping’, wherein goods are sold at a lower than market price at harm to the U.S. uranium industry. Prior to the conclusion of that investigation, the U.S. and Russian governments reached an anti-dumping agreement: the Russian Uranium Suspension Agreement of 1992. This agreement has been amended multiple times, most recently in 2020.[61] While the agreement has had some impact in preventing complete U.S. dependence on Russian uranium and enrichment services, the agreement—which was a matter of trade policy rather than national security policy—is insufficient to *end* U.S. dependence on Russia for nuclear fuel. The agreement still anticipates large-scale importation of Russian-enriched uranium through 2040. This agreement, while powerful, is not capable of supporting the present U.S. policy of ending dependence on all Russian sources of energy completely.

5.b Congressional appropriations and U.S. Department of Energy support for HALEU production

The U.S. Department of Energy and the U.S. Congress have taken initial steps toward ending dependence on Russian uranium enrichment services, namely via the Inflation Reduction Act of 2022 and in regular, annual appropriations in recent years. However, these efforts have focused specifically on scaling enrichment capacity to produce HALEU, the grade of enriched uranium that is required by many next generation reactors, but is not currently used in the United States’ fleet of operating power reactors.

As part of the Inflation Reduction Act, the U.S. Department of Energy allocated $700 million through 2026 to begin pilot production of HALEU, aiming to produce 25 metric tons per year in the near term. However, the initial allocation of $150 million will only produce 900 kg per year when it reaches full capacity in 2024. The DoE has yet to explain how the remaining $550 million will enable production to scale by 25-fold. Furthermore, the DoE has stated that the continuance of this entire project is dependent on annual Congressional appropriations.[62]

This policy response to date does not approach the scale of the critical, urgent problem of U.S. dependence on Russian enrichment services. The DoE’s publicly announced goals to date—although more may be forthcoming—of scaling HALEU production to 900 kg per year by 2024 entails supporting an increase of approximately 5,600 SWU in enrichment capacity: just *one tenth of one percent* of the 4.2 million SWU the U.S. imports from Russia each year.[63] While meeting the HALEU fuel needs of advanced reactors is important, the magnitude of the LEU supply problem is far greater, given that LEU is needed both to fuel existing reactors and to manufacture HALEU (with 1kg of HALEU requiring slightly more than 4kg of LEU to manufacture).

Fortunately, as the next section explains, the U.S. can rapidly scale its domestic enrichment capacity if it embraces the shovel-ready solutions it has at its disposal.

6. Shovel-ready solutions to scale U.S. uranium enrichment capability

The U.S. Nuclear Regulatory Commission (NRC) has already licensed two facilities for a combined 13.8 million SWU—a net increase of 8.5 million SWU over existing U.S. enrichment capacity. If brought to their full capacities, these facilities would end the United States's dependence on Russian nuclear fuel enrichment completely *and* decrease global dependence on Russian fuel enrichment by over 75%.[64]

Urenco's National Enrichment Facility in Eunice, New Mexico is NRC licensed for up to 10 million SWU: 4.6 million SWU beyond its current operating capacity. Additionally, the American Centrifuge Plant in Ohio was granted a combined construction and operating license (COL) by the NRC in 2007 for up to 3.8 million SWU of enrichment capacity. While its construction was demobilized in 2009, its NRC license is still valid. If proper support is provided, this facility could be brought online with minimal regulatory barriers. Thousands of jobs would be created in the process of scaling these facilities, according to the NRC.[65,66]

Regulatory approval is a costly and lengthy process for any US commercial nuclear power project. The NRC licenses for the Eunice and Piketon facilities represent years of work by both companies and the regulators, analyzing in detail the safeguards at each facility for worker safety, public health, and the environment. The environmental impact assessments alone issued by the Nuclear Regulatory Commission and the Army Corps of Engineers total approximately one thousand pages for each facility. Each facility took approximately 2.5 years to secure their licenses.[67,68]

6.a The American Centrifuge Plant in Piketon, Ohio

Located on U.S. Department of Energy land at the site of the former Portsmouth Gaseous Diffusion Plant, the American Centrifuge Plant in Piketon, Ohio was granted a combined construction and operating license (COL) by the NRC in 2007 for up to 3.8 million SWU of enrichment capacity. While its construction was demobilized in 2009, its NRC license is still valid.[69]

By 2009, the owner of the facility, the United States Enrichment Corporation, or USEC (today named the Centrus Energy Corporation), invested $1.5 billion (approximately $2.13 billion 2023 dollars) in its construction.[70] Completion of the construction project was dependent on a $2 billion USD loan guarantee from the U.S. Department of Energy (DOE). The DOE denied the loan guarantee request in 2009. Despite the large investment that had already been made, the lack of a DOE loan guarantee resulted in the demobilization of the construction of the 3.8 million SWU facility.[71] Instead, in 2012, the DOE provided a $280 million research, development and deployment grant that allowed USEC to build a full production-scale cascade of 120 machines, which achieved all three milestones of reliability assurance, including 20 machine-years of operations at commercial plant specifications.[72] Unfortunately, for reasons that are unclear, after the DOE funding for this facility ran out, most of the components of this cascade were buried in the desert of the Western United States in the following years.[73]

As shown in the photos below, the large complex of buildings needed to house plant operations have already been constructed. In total, these process buildings total 1.7 million square feet under roof (approximately 30 American football fields) and can house 3,800 AC100M gas centrifuges (the largest gas centrifuges ever to be deployed in commercial uranium enrichment).[74] The facility's equipment, including the gas centrifuges themselves, have been extensively tested and shown to have excellent performance, with more than 1.25 million hours of combined machine runtime already completed.[75]

According to the environmental impact statement written by the Nuclear Regulatory Commission, bringing this facility to its fully licensed capacity would create 600 full time jobs at the facility itself, and 900 indirect jobs in surrounding communities. Construction of the facility will create 3,662 jobs for four years. Construction of the centrifuges for this facility will occur in facilities outside of Ohio, and at peak will create the following numbers of jobs, by state: Tennessee (~1,900), South Carolina (~750), Utah (~480), Alabama (~380), Pennsylvania (~380), Indiana (~120).[76]

Presently, the planned mobilization of the plant is limited to a HALEU demonstration program, which will entail only 16 centrifuges, and less than 6,000 SWU, to create 900 kg of HALEU by the end of 2024.[77]

Image 1 The American Centrifuge Plant in Piketon, Ohio [86]

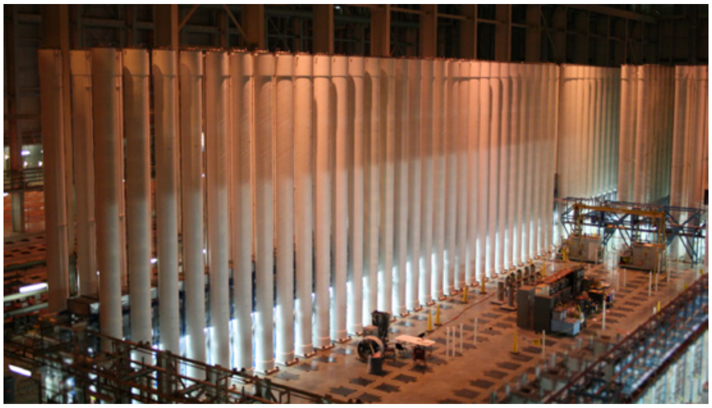

Image 2 Gas centrifuges inside the American Centrifuge Plant [87]

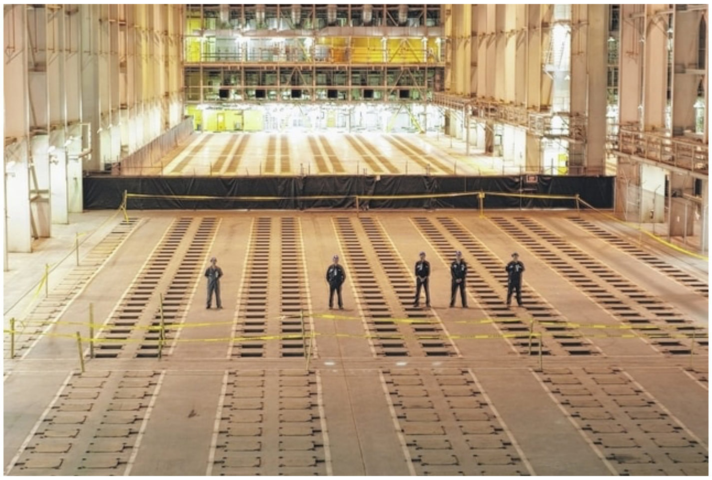

Image 3 American Centrifuge Plant workers standing inside the facility process hall [88]

6.b The National Enrichment Facility in Eunice, New Mexico

Located in Eunice, New Mexico, the National Enrichment Facility is NRC licensed for up to 10 million SWU, and presently operates at 5.4 million SWU per year. The National Enrichment Facility is owned and operated by Urenco, a company created by the Treaty of Almelo that is owned by the British government, the Dutch government, and two German Utilities.[78] The National Enrichment Facility is presently the only source of enrichment capacity for the United States.

The NRC estimated in 2015 that scaling the National Enrichment Facility from 3 million to 10 million SWU per year would create 800 construction jobs in the first five years of construction, 400 jobs in years six and seven, and 300 jobs in years eight and nine.[79]

The cost of construction of the National Enrichment Facility to its current operation capacity of 5.4 million SWU was estimated to cost $3 billion.[80]

6.c Radiological impacts of the American Centrifuge Plant

For every new nuclear project, as part of its environmental impact assessment, the NRC uses state of the art modeling to simulate all potential avenues for radiological exposure to the public, however infinitesimal. Unlike previous gaseous diffusion enrichment technology, the gas centrifuge enrichment technology releases extremely small amounts of uranium to the atmosphere. This is because the gas centrifuges themselves spin in a vacuum, so any leakage is captured by the vacuum and air handling systems of the plant.

For the American Centrifuge Plant, extensive computer modeling was done with the Environmental Protection Agency's modeling simulation code, CAP88, which uses a highly sophisticated Gaussian plume model to simulate all potential air-based radiological impacts of the facility. The CAP88 radiological simulation for the American Centrifuge Plant used years of highly detailed meteorological observations that were captured directly on the site. Importantly, these estimates are likely a dramatic overestimation of radiation exposure, as the simulation included not just direct atmospheric exposure, but indirect exposure through ingestion of locally produced foods and agricultural goods. The simulation assumed a very high percentage of food consumption was from local sources (within 50 miles of the plant), representing the upper bound of possible radiation exposure from food.

The NRC simulated exposures for multiple locations in Piketon, Ohio.[81] The first is the location on the site boundary, where no one lives, which is associated with the highest possible radiation exposure attributable to the American Centrifuge Plant operating at fully licensed capacity. The maximum estimated excess radiation dose at this location over an *entire year* is 0.0021 millisieverts (mSv)—*three thousand* times lower than the radiation dose received by the public from natural background radiation (6.2 mSv/yr)[82]—equivalent to the radiation dose a person would experience over 53 minutes on an airplane.[83] The second location simulated is the business nearest the facility, the Ohio Valley Electric Cooperative, which is approximately 1.5 kilometers from the site boundary. Assuming a person lived in this office for the entire year, the maximum estimated radiation dose is 0.0016 mSv, equivalent to the radiation dose a person would experience over 37 minutes on an airplane.

6.d Radiological impacts of the National Enrichment Facility

The NRC undertook a similar process to estimate exposures for multiple locations in Eunice, New Mexico attributable to the Nation Enrichment Facility operating at fully licensed capacity.[84] The first location is the site boundary. The maximum estimated excess radiation dose at this location over an entire year is 0.000177 millisieverts (mSv), equivalent to the radiation dose a person would experience over 5 minutes on an airplane. The second location simulated is the nearest residence, which is 2.6 miles from the site boundary. At this location, the maximum estimated radiation dose over one year is 0.0000433 mSv, equivalent to the radiation dose a person would experience over 66 seconds on an airplane.

7. Recommendations

Recommendation 1: Scale the American Centrifuge Plant (Piketon) and the National Enrichment Facility (Eunice) up to their fully licensed capacities

There are multiple policy options that could potentially enable the scaling of these facilities to their licensed capacity. These include offtake agreements (a commitment to purchase enrichment services from these facilities), the creation of a new nuclear fuel bank, sanctions on Russian uranium enrichment services, loan guarantees for the companies that own the facilities, or direct subsidies for these facilities.

The White House and the Department of Energy should assess available policy options and release a plan for the scale-up of these two NRC-licensed sites to their fully licensed capacity. Additionally, the White House should request from the U.S. Congress any necessary support needed to enact this plan.

Recommendation 2: Support further development and possible commercialization of laser enrichment technology.

As we previously discussed, the historical circumstances allowing the Soviet Union to surpass the United States gas centrifuge development during the Cold War allowed the US—and the rest of the world—to become highly dependent on Russia for uranium enrichment capacity. If the U.S. is to avoid a similar error, the US must ensure that it remains on the technical cutting edge for uranium enrichment technology.

Laser enrichment offers tremendous promise but has yet to be commercially developed anywhere in the world. In 2015, the US Nuclear Regulatory Commission granted Global Laser Enrichment (GLE) a license to build and operate a laser enrichment enrichment facility with 6 million SWU of capacity. Alas, this license was terminated at the request of GLE in January 2021.[85]

The U.S. Department of Energy should explore policy options to facilitate commercialization of laser enrichment technology. Additionally, the NRC should clarify what steps would be required to reactivate the Global Laser Enrichment license.

Endnotes

1 IEA (2021), Electricity Information: Overview, IEA, Paris https://www.iea.org/reeports/electricity-information-overview, License: CC BY 4.0

2 Our World in Data (2023), Which sources does our global energy come from? How much is low carbon? URL: https://ourworldindata.org/sources-global-energy

3 IEA (2022), Electricity generation, capacity, and sales in the United States. URL: https://www.eia.gov/energyexplained/electricity/electricity-in-the-us-generation-capacity-and-sales.php

4 "IPCC Working Group III – Mitigation of Climate Change, Annex III: Technology - specific cost and performance parameters - Table A.III.2 (Emissions of selected electricity supply technologies (gCO 2eq/kWh))" (PDF). IPCC. 2014. p. 1335. URL: https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_full.pdf

5 IPCC, 2018: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development,and efforts to eradicate poverty* [Masson-Delmotte,V.,P.Zhai,H.-O. Pörtner,D.Roberts,J.Skea,P.R.Shukla,A.Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, 616 pp. https://doi.org/10.1017/9781009157940.

6 International Energy Agency (IEA), 2021. Net Zero by 2050: A Roadmap for the Global Energy Sector URL:https://www.iea.org/reports/net-zero-by-2050

7 Jenkins, Jesse D., Max Luke, and Samuel Thernstrom. "Getting to zero carbon emissions in the electric power sector." *Joule* 2.12 (2018): 2498-2510.

8 Loftus, Peter J., et al. "A critical review of global decarbonization scenarios: what do they tell us about feasibility?." *Wiley Interdisciplinary Reviews: Climate Change* 6.1 (2015): 93-112.

9 Sepulveda, NA, et al. "The role of firm low-carbon electricity resources in deep decarbonization of power generation." *Joule* 2.11 (2018): 2403-2420.

10 Bistline, JET, and Blanford GH. "Value of technology in the US electric power sector: impacts of full portfolios and technological change on the costs of meeting decarbonization goals." *Energy Economics* 86 (2020): 104694

11 Buongiorno, Jacopo, et al. "Nuclear energy in a carbon-constrained world: Big challenges and big opportunities." *IEEE Power and Energy* 17.2 (2019): 69-77.

12 Shaner, MR, et al. "Geophysical constraints on the reliability of solar and wind power in the United States." *Energy & Environmental Science* 11.4 (2018): 914-925.

13 Other proven sources of low carbon power are hydropower and geothermal power; however, these sources of power are highly dependent on geography and are thus not scalable like nuclear power.

14 Unnerstall, Thomas. *How expensive is an energy transition? A lesson from the German Energiewende. Energy, Sustainability and Society* 7.1 (2017): 1-5.

15 European Environment Agency, 2022. G*reenhouse gas emission intensity of electricity generation in Europe — National emissions reported to the UNFCCC and to the EU Greenhouse Gas Monitoring Mechanism*. URL: https://www.eea.europa.eu/ims/greenhouse-gas-emission-intensity-of-1

16 *Ibid.*

17 Eurostat, 2022. *Electricity prices by type of user — data set TEN00117*. URL: https://ec.europa.eu/eurostat/databrowser/view/ten00117/default/table?lang=en

18 UNECE, 2021. International climate objectives will not be met if nuclear power is excluded. URL: https://unece.org/climate-change/press/international-climate-objectives-will-not-be-met-if-nuclear-power-excluded

19 World Nuclear Association, 2022. World Uranium Mining Production. URL: https://world-nuclear.org/information-library/nuclear-fuel-cycle/mining-of-uranium/world-uranium-mining-production.aspx

20 Federation of American Scientists, 2023. Uranium Production. URL: https://fas.org/issues/nonproliferation-counterproliferation/nuclear-fuel-cycle/uranium-enrichment-gas-centrifuge-technology/uranium-production/

21 Nuclear Engineering International, 2022. Testing completed for Silex laser enrichment module. URL: https://www.neimagazine.com/news/newstesting-completed-for-silex-laser-enrichment-module-9980983

22 World Nuclear Association, 2022. World Uranium Mining Production. URL: https://world-nuclear.org/information-library/nuclear-fuel-cycle/mining-of-uranium/world-uranium-mining-production.aspx

23 Energy Resources International, Inc., 2017. The U.S. Nuclear Fuel Cycle: Looking Forward to 2025. URL: https://www.nrc.gov/docs/ML1716/ML17166A334.pdf

24 World Nuclear Association, 2021. U.S. Nuclear Fuel Cycle. URL: https://world-nuclear.org/information-library/country-profiles/countries-t-z/usa-nuclear-fuel-cycle.aspx

25 US Energy Information Agency (EIA), US Department of Energy. *2021 Uranium Marketing Annual Report* (Table 16). URL: https://www.eia.gov/uranium/marketing/table16.php

26 World Nuclear Association, 2021. Russia's Nuclear Fuel Cycle. URL: https://world-nuclear.org/information-library/country-profiles/countries-o-s/russia-nuclear-fuel-cycle.aspx

27 Mukhatzhanova, G., 2007. Russian Nuclear Industry Reforms: Consolidation and Expansion. URL: https://nonproliferation.org/russian-nuclear-industry-reforms-consolidation-and-expansion/

28 World Nuclear Association. Nuclear Power in South Africa (Fuel Cycle). URL: https://world-nuclear.org/information-library/country-profiles/countries-o-s/south-africa.aspx

29 Swiss Broadcasting Corporation. "Use of Russian uranium for Swiss nuclear power under scrutiny" (31 March 2022) URL: https://www.swissinfo.ch/eng/business/use-of-russian-uranium-for-swiss-nuclear-power-under-scrutiny/47479722

30 International Atomic Energy Agency (IAEA). *Country Nuclear Power Profiles — 2022 Edition. (Finland).* URL: https://cnpp.iaea.org/countryprofiles/Finland/Finland.htm

31 World Nuclear Association. Nuclear Power in the United Arab Emirates (Fuel Cycle). URL: https://world-nuclear.org/information-library/country-profiles/countries-o-s/south-africa.aspx

32 It is unclear now that Ukraine has abandoned its fuel supply agreement with TVEL, post invasion, where it is going to source enriched uranium. However, prior to the invasion, Ukraine sourced almost all of its uranium enrichment capacity from TVEL. A small amount is (60,000 SWU / year) sourced from the International Uranium Enrichment Center based in Angarsk, Russia. URL: https://www.iaea.org/topics/international-uranium-enrichment-centre

33 International Atomic Energy Agency (IAEA). *Country Nuclear Power Profiles — 2022 Edition. (Mexico).* URL: https://cnpp.iaea.org/countryprofiles/Mexico/Mexico.htm

34 World Nuclear Association. "Nuclear Power in India". URL: https://www.world-nuclear.org/information-library/country-profiles/countries-g-n/india.aspx

35 World Nuclear Association. Nuclear Power in Slovakia. URL: https://world-nuclear.org/information-library/country-profiles/countries-o-s/slovakia.aspx

36 World Nuclear Association. Nuclear Power in Hungry URL: Nuclear Power in Hungary | Hungarian Nuclear Energy - World Nuclear Association (world-nuclear.org)

37 World Nuclear Association. Nuclear Power in Bulgaria. URL: https://world-nuclear.org/information-library/country-profiles/countries-a-f/bulgaria.aspx

38 World Nuclear Association. Nuclear Power in the Czech Republic. URL: https://www.world-nuclear.org/information-library/country-profiles/countries-a-f/czech-republic.aspx

39 US Energy Information Agency (EIA), US Department of Energy. *2021 Uranium Marketing Annual Report* (Table 16). URL: https://www.eia.gov/uranium/marketing/table16.php

40 From 2017 to 2021, operators of US civilian nuclear power reactors purchased 16.645 million separative work units (SWU) of uranium enrichment services from Russia versus total purchases of 69.532 million SWU — representing 24% of total purchased SWU. *Ibid.* In 2021, nuclear power generated 778 terawatt-hours (TWh) of electricity — approximately 20% of the electric power used in the United States (3,930 TWh). Assuming equal burn up of Russian SWU, uranium enriched in Russian generated the equivalent of 186.42 TWh of electrical power — 5% of US total consumption.

41 U.S. Senate Committee on Energy and Natural Resources, Full Committee Hearing on Opportunities and Challenges Facing Domestic Critical Mineral Mining, Processing, Refining, and Reprocessing (31 March 2022). *Sworn Testimony of S. Melbye* (President, Uranium Producers of America). URL: https://www.energy.senate.gov/services/files/4139EE30-5A5E-4FA4-814B-2CDD6486725E

42 Reuters, 2022. America's new nuclear power industry has a Russian problem. URL: https://www.reuters.com/business/energy/americas-new-nuclear-power-industry-has-russian-problem-2022-10-20/

43 Geekwire, 2022. TerraPower warns of 2-year minimum delay for launch of demo reactor due to Russia-Ukraine war. URL: https://www.geekwire.com/2022/bill-gates-backed-terrapower-warns-of-2-year-minimum-delay-for-launch-of-demo-reactor/

44 Representative Brad Wenstrup, 2022. Reps. Wenstrup, Gonzalez, Johnson, and Luria, Sens. Portman, Brown Voice Concerns Over Supply Chain for Advanced Nuclear Fuels. URL: https://wenstrup.house.gov/updates/documentsingle.aspx?DocumentID=405463

45 Bloomberg, 2022. Russia's Nuclear Power Swagger Unruffled by War as Summit Nears. URL: https://www.bloomberg.com/news/articles/2022-08-02/russia-s-nuclear-power-swagger-unruffled-by-war-as-summit-nears?sref=gb4hj5Ze

46 Bloomberg, 2022. US Redoubles Efforts to End Dependence on Russian Nuclear Fuel. URL: https://www.bloomberg.com/news/articles/2022-09-29/us-redoubles-efforts-to-end-dependence-on-russian-nuclear-fuel?sref=gb4hj5Ze

47 In order to use 5.4 million SWU to produce the equivalent of 1,380 metric tons of low enriched uranium (LEU) produced by Russia at a product assay of 4.4% U-235, we need to increase the tails assay from 0.23% U-235 to *0.6*% U-235, assuming the feed assay is 0.711% U-235. This increases the feed quantity to 47,442 metric tons of uranium.

48 World Nuclear Association, 2022. Uranium Production Figures, 2012-2021. URL: https://world-nuclear.org/information-li-

brary/facts-and-figures/uranium-production-figures.aspx

49 Dixon, Brent W, Kim, Son H., Feng, Bo, Kim, Taek, Richards, Scott, and Bae, Jin Whan, 2022. Estimated HALEU Requirements for Advanced Reactors to Support a Net-Zero Emissions Economy by 2050. United States. https://doi.org/10.2172/1838156. URL: https://www.osti.gov/servlets/purl/1838156.

50 We assume an average of 198 metric tons of HALEU (19.75% U-235) and 2,889 metric tons of LEU (4.95% U-235) will be required on average each year. To make the LEU, assuming a feed assay of 0.711% U-235 and a tails assay of 0.23% U-235, we need 8,155 SWU per metric ton of LEU. (~23.6 million SWU / yr for LEU production). For HALEU, we need 4.5 metric tons of LEU for each metric ton of HALEU. Thus, we need to manufacture an additional 892 metric tons of LEU for HALEU feed (7.3 million SWU per year for LEU feed). To convert the LEU feed (4.95% U-235) to HALEU (19.75% U-235) — assuming a tails assay of 0.7% U-235 — we need 5,927 SWU per metric ton of HALEU. (1.17 million SWU per year).

51 DOE (2023) Pathways to Commercial Liftoff: Advanced Nuclear. p. 32. URL: https://liftoff.energy.gov/wp-content/uploads/2023/03/20230320-Liftoff-Advanced-Nuclear-vPUB.pdf

52 Wyoming Public Radio, 2022. The opening of TerraPower's nuclear plant in Kemmerer will be delayed by two years. URL: https://www.wyomingpublicmedia.org/natural-resources-energy/2022-12-14/the-opening-of-terrapowers-nuclear-plant-in-kemmerer-will-be-delayed-by-two-years

53 IPCC, 2018: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development,and efforts to eradicate poverty* [Masson-Delmotte,V.,P.Zhai,H.-O. Pörtner,D.Roberts,J.Skea,P.R.Shukla,A.Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, 616 pp. https://doi.org/10.1017/9781009157940.

54 International Energy Agency (IEA), 2021. Net Zero by 2050: A Roadmap for the Global Energy Sector URL:https://www.iea.org/reports/net-zero-by-2050

55 Nuclear Threat Initiative, 2017. International IAEA LEU Bank. URL: https://www.nti.org/about/programs-projects/project/international-nuclear-fuel-bank/

56 Bukharin, Oleg, 2004. Understanding Russia's Uranium Enrichment Complex. Science and Global Security, 12:193–218, 2004. URL: https://scienceandglobalsecurity.org/archive/sgs-12bukharin.pdf

57 U.S. Nuclear Regulatory Commission Technical Training Center, No Date. Module 4.0 Gas Centrifuge. URL: https://www.nrc.gov/docs/ML1204/ML12045A055.pdf

58 Abbakumov, E. I., et al., 1989. "Development and industrial use of gas centrifuges for uranium enrichment in the Soviet Union." *Soviet Atomic Energy* 67.4 (1989): 739-741.

59 KEMP, R. Scott, 2009. Gas Centrifuge Theory and Development: A Review of U.S. Programs, Science & Global Security, 17:1, 1-19, DOI: 10.1080/08929880802335816

60 Cochran, Thomas B.; Arkin, William M.; Norris, Robert S.; Hoening, Milton M. (1987). *Nuclear Weapons Databook, Vol. III: U.S. Nuclear Warhead Facility Profiles*. Natural Resources Defense Council. pp. 127–128. ISBN 0-88730-146-0.

61 2020 Amendment to the Agreement Suspending the Antidumping Investigation on Uranium From the Russian Federation, 2020. Federal Register. URL: https://www.federalregister.gov/documents/2020/10/09/2020-22431/2020-amendment-to-the-agreement-suspending-the-antidumping-investigation-on-uranium-from-the-russian

62 DOE Announces Cost-Shared Award for First-Ever Domestic Production of HALEU for Advanced Nuclear Reactors, 2022. U.S. Department of Energy. URL:https://www.energy.gov/articles/doe-announces-cost-shared-award-first-ever-domestic-production-haleu-advanced-nuclear

63 U.S. ramps up advanced fuel production capabilities, 2022. Reuters. URL: https://www.reuters.com/business/energy/us-ramps-up-advanced-fuel-production-capabilities-2023-02-16/

64 *See Appendix* I.

65 U.S. Nuclear Regulatory Commission, Office of Nuclear Material Safety and Safeguard. *NUREG-1834, Environmental Impact Statement for the Proposed American Centrifuge Plant in Piketon, Ohio*. (Volume 1, Page 4-34). URL: https://www.nrc.gov/docs/ML0612/ML061250131.pdf

66 U.S. Nuclear Regulatory Commission, Office of Nuclear Material Safety and Safeguard. Environmental Assessment for the Proposed Louisiana Energy Services, Urenco USA Uranium Enrichment Facility Capacity Expansion in Lea County, New Mexico. URL: https://www.nrc.gov/docs/ML1507/ML15072A016.pdf

67 Urenco's licensing took 2.5 years (application submitted Dec 12 2003; license issued June 2006) See: https://www.nrc.gov/docs/ML1707/ML17076A061.pdf

68 The American Centrifuge Plant's licensing took 2.5 years (application submitted August 2004; license issued April 2007). See: https://www.nrc.gov/materials/fuel-cycle-fac/new-fac-licensing.html

69 *Centrus Energy Corp./American Centrifuge Operating, LLC (formerly USEC Inc.) Gas Centrifuge Enrichment*, 2023. U.S. Nuclear Regulatory Commission. URL: https://www.nrc.gov/materials/fuel-cycle-fac/usecfacility.html

70 Centrus Corp. "Department of Energy Denies USEC's Loan

Guarantee Application" URL: https://investors.centrusenergy.com/static-files/2249d6ed-473e-484d-9ebe-af481254031d

71 'Crunch time' at troubled nuclear fuel plant, 2012. The Washington Post. URL: https://www.washingtonpost.com/business/economy/crunch-time-at-troubled-nuclear-fuel-plant/2011/12/20/gIQAIpUJwP_story.html

72 USEC to Restructure, Seek Bankruptcy to Stimulate American Centrifuge Project, 2013. Power Magazine. URL: https://www.powermag.com/usec-to-restructure-seek-bankruptcy-to-stimulate-american-centrifuge-project/

73 Announcement breathes life into American Centrifuge, 2019. Chillicothe Gazette. URL: https://www.chillicothegazette.com/story/news/local/2019/01/07/piketon-announcement-breathes-life-into-american-centrifuge-rob-portman/2499934002/

74 Eby, Robert, 2013. Nuclear Fuel Cycle Overview. Presentation to the Institute of Nuclear Materials Management, p. 15. URL: https://cdn.ymaws.com/inmm.org/resource/resmgr/docs/chapters/central/2-fuel_cycle_presentation_in.pdf

75 Eby, Robert, 2013. Nuclear Fuel Cycle Overview. Presentation to the Institute of Nuclear Materials Management, p. 23. https://cdn.ymaws.com/inmm.org/resource/resmgr/docs/chapters/central/2-fuel_cycle_presentation_in.pdf

76 American centrifuge overview, 2011. U.S. Enrichment Corporation, p. 9 URL: https://energywv.org/assets/files/Energy-Summit-Presentations/2011/JamesHowe_USEC.pdf.

77 USEC Form 8-K, exhibit 99.1. U.S. Securities and Exchange Commission, 2022. URL: https://investors.centrusenergy.com/static-files/62c85f9f-4b49-4ba3-a501-6256dc8f0945

78 Bannink, Dirk, 2020. "Urenco 1970-2020: From Treaty of Almelo to Atom Ausstieg." Laka Foundation. URL: https://www.laka.org/docu/boeken/pdf/1-01-8-30-69.pdf#page=2.

79 U.S. Nuclear Regulatory Commission, Office of Nuclear Material Safety and Safeguard. Environmental Assessment for the Proposed Louisiana Energy Services, Urenco USA Uranium Enrichment Facility Capacity Expansion in Lea County, New Mexico, p. 88. URL: https://www.nrc.gov/docs/ML1507/ML15072A016.pdf

80 *The National Enrichment Facility.* Projects That Matter, [no date available]. URL: http://www.projectsthatmatter.com/projects/progressdetails/the_national_enrichment_facility/

81 U.S. Nuclear Regulatory Commission, Office of Nuclear Material Safety and Safeguard. *NUREG-1834, Environmental Impact Statement for the Proposed American Centrifuge Plant in Piketon, Ohio*. (Volume 1, Table-4-20). URL: https://www.nrc.gov/docs/ML0612/ML061250131.pdf

82 U.S. Environmental Protection Agency. "Radiation Sources and Doses." URL: https://www.epa.gov/radiation/radiation-sources-and-doses

83 An average flight has a radiation exposure rate of 0.0024 mSv per hour. *See* Feng YJ et al. Estimated cosmic radiation doses for flight personnel. *Space Med Med Eng.* 15(4):265–269; 2002.

84 U.S. Nuclear Regulatory Commission, Office of Nuclear Material Safety and Safeguard. Environmental Assessment for the Proposed Louisiana Energy Services, Urenco USA Uranium Enrichment Facility Capacity Expansion in Lea County, New Mexico. URL: https://www.nrc.gov/docs/ML1507/ML15072A016.pdf

85 *TERMINATION OF SPECIAL NUCLEAR MATERIALS LICENSE NUMBER SNM-2019 FOR THE GE-HITACHI GLOBAL LASER ENRICHMENT FACILITY.* U.S. NRC, 2021. URL: ML20293A175.pdf (nrc.gov)

86 American centrifuge overview, 2011. U.S. Enrichment Corporation, p. 11. URL: https://energywv.org/assets/files/Energy-Summit-Presentations/2011/JamesHowe_USEC.pdf.

87 World Nuclear News, 2010. Deal for American Centrifuge. (Image: USEC) URL: https://www.world-nuclear-news.org/C_Deal_for_American_Centrifuge_2505101.html

88 Eby, Robert, 2013. Nuclear Fuel Cycle Overview. Presentation to the Institute of Nuclear Materials Management, p. 23. https://cdn.ymaws.com/inmm.org/resource/resmgr/docs/chapters/central/2-fuel_cycle_presentation_in.pdf