



ABUNDANT FUEL FOR ABUNDANT REACTORS

SECURING U.S. AND
GLOBAL URANIUM ENRICHMENT

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EXECUTIVE SUMMARY

Without fuel loaded into their cores, nuclear reactors cannot run. Yet as the United States and governments around the world seek to expand nuclear generation, the global nuclear fuel supply chain has descended into crisis. Except for the Russian and Chinese uranium industries, global mining and uranium enrichment industrial capacity has atrophied over recent decades. Today, the global nuclear fleet relies far too heavily on processed uranium from Russia in particular. Without current Russian enrichment capacity, there would not be enough enriched uranium feedstock to supply already operational nuclear power plants in Europe and North America, let alone support global growth of the sector.

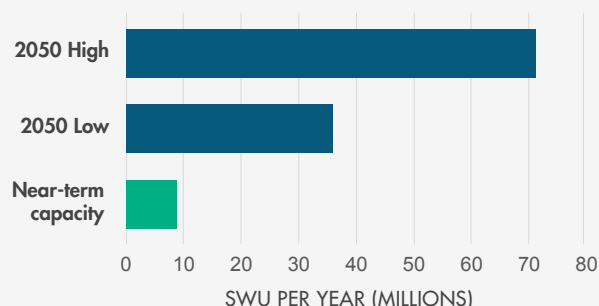
President Trump's executive orders of May 23, 2025, promise to increase both the demand and the supply of reactor fuel,¹ but the total effects and the timing of these efforts are not clear. Fundamentally, any large-scale buildout of new U.S. nuclear projects will fail unless an adequate fuel supply chain is in place. The United States also has a national interest in supporting nuclear energy development in partner countries and combating dependence on Russia and China for uranium or uranium enrichment.

Our analysis found that the U.S. faces a dramatic shortage in enrichment capacity, with current capacity only sufficient to cover 10% to 25% of projected annual needs in 2050 (Figure ES-1). The production of high-assay low-enriched uranium (HALEU) to support the deployment and operation of advanced nuclear reactors could account for the majority of these future enrichment requirements. The U.S. doesn't need to meet all uranium enrichment needs with domestic production and can cooperate with allies to secure supply, but should also seek to minimize general geopolitical risk and ensure energy security. In light of these needs, U.S. policymakers must take urgent and aggressive steps to foster a robust commercial market for enrichment and fuel fabrication, particularly for HALEU.

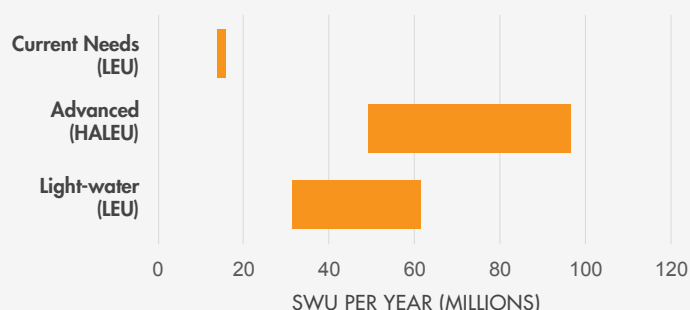
For a global nuclear industry to prosper without fully relying on China and Russia will also require a significant increase in uranium services. Even assuming a world nuclear market that continues to remain weighted heavily toward conventional light-water reactors and low-enriched uranium (LEU) fuel, enrichment needs may more than double while uranium mining may see a nearly fourfold increase.

While policymakers and nuclear advocates want increased investment in uranium services to replace Russian supply, such discussions require quantitative understanding of the magnitude of nuclear fuel supply chain investments required to meet anticipated demand. Our findings highlight the vast gap between commercializing a limited domestic enrichment industry and achieving the scale necessary to support a significant U.S. program of nuclear project construction. To meet anticipated demands, the federal government must provide assurance of both future supply of and demand for nuclear fuel, mobilizing policy efforts to secure access to total enrichment capacity around five to ten times larger than current U.S. capacity. Maximization of energy security will require developing a significant share of this added enrichment capacity in the United States. Successful development of a domestic fuel supply chain may in turn position the U.S. advantageously to assist global nuclear deployment efforts as a competitive fuel services provider.

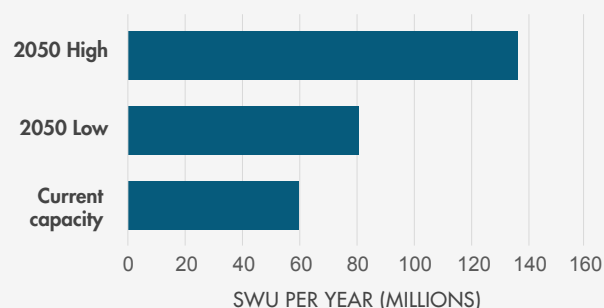
a. Current and Future U.S. HALEU Enrichment Needs



b. U.S. enrichment needs for 250-490 GW of light-water or advanced nuclear by 2050



c. Current and Future Global Enrichment Needs



d. Current and Future Global Uranium Needs

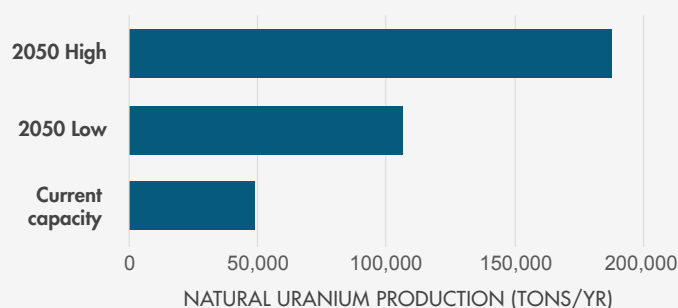


Figure ES-1: (a) Current U.S. uranium enrichment capacity relative to current and future HALEU enrichment needs in 2050, in millions of separative work units (SWU). (b) Bounding low to high range of U.S. low-enriched or high-enriched low-assay uranium enrichment required by 2050, for an operating capacity of 250-490 GW of either light-water or advanced nuclear energy, relative to current needs for 92 GW of light-water nuclear. (c) Current global uranium enrichment capacity relative to future global needs in 2050, in millions of SWU. (d) Current global uranium production relative to future global needs in 2050.

2050 Nuclear Enrichment and Fuel Requirements

- Existing and near-term potentially available U.S.-based enrichment by Centrus and Urenco of ~8.8 million separative work units (SWU) is far short of potential advanced nuclear demand for HALEU by 2050 (36 to 71.2 million SWU).
- To operate 250-490 GW of nuclear capacity by 2050, the U.S. will require a bounding range of 31.4 to 96.5 million SWU, necessitating total geopolitically secure enrichment services five- to tenfold greater than near-term available domestic capacity.
- Current global capacity of ~60 million SWU is insufficient to meet total LEU and HALEU needs in 2050 (81 million to 137 million SWU) as the global nuclear fleet grows.
- Current global uranium mine production of ~49,000 metric tons per year must also increase by two- to fourfold to meet world uranium requirements of 106,500 to 187,400 tons per year by 2050.

Policy Strategies

Building resilient nuclear fuel supply chains for the United States

1. Prioritize targeted federal funding for projects that can credibly grow to deliver full commercial production.
2. Establish a HALEU bank at the Department of Energy to purchase and sell HALEU at commercial scale.
3. Leverage federal electricity procurement in support of U.S. advanced nuclear deployment to build an order book of domestic nuclear projects and establish firm market demand for future fuel.
4. Securely improve cross-government coordination on the availability of stockpiled nuclear materials potentially usable for nuclear fuel production.
5. Resolutely maintain the ban on imported Russian uranium.
6. License new enrichment and fuel manufacturing facilities through the Nuclear Regulatory Commission within 18 months for known designs and facility types.
7. Devote federal research efforts and public sector investment to innovative, more efficient enrichment techniques like laser enrichment.

8. Expand state and federal mapping programs that seek to identify domestic uranium resources.
9. Invest in spent fuel recycling and reprocessing, with appropriate safeguards.
10. Pursue efficiency improvements and new breeder reactor technology that reduce nuclear fuel and enrichment needs.
11. Work with allies and international partners to secure U.S. uranium imports.
12. Update Nuclear Regulatory Commission regulations to create avenues for sourcing uranium for energy sector use from tailings at abandoned uranium mine sites.

Enhancing international nuclear cooperation on securing supplies of nuclear fuel

1. Establish agreements to address current and future uranium needs among a consortium of like-minded nations, based on shared alignment regarding fuel sourcing and supply concerns.
2. Pursue joint research efforts and co-investment focused on new uranium production and innovation opportunities in uranium exploration and mining.
3. Share best practices for efficient and effective regulation and licensing of uranium production and enrichment projects.
4. Revise international and bilateral agreements to improve access to peaceful uses of nuclear technology, particularly technologies used in nuclear fuel production.
5. Develop secure and effective frameworks for spent nuclear fuel management, including spent fuel exchange and take-back between countries.
6. Establish international HALEU banks to create strong market demand signals and secure HALEU supply for new nuclear projects.
7. Expand and facilitate international scholarship in nuclear physics, nuclear engineering, materials science, and related disciplines to foster global development of a robust skilled technical workforce.

INTRODUCTION

Nuclear energy is gaining remarkable momentum across both developed and developing nations. The Russia-Ukraine war has resulted in a swift about-face away from restricting nuclear expansion, as Europe and the broader world have relearned the geostrategic importance of energy security.

The United States has resumed licensing reactor construction after three decades of stagnancy² and is even supporting efforts to bring shuttered reactors back online,^{3,4} marking a new age for American nuclear power. Two advanced reactors that will require HALEU fuel, TerraPower's Natrium project in Kemmerer, Wyoming, and Dow and X-energy's Xe-100 cluster of four small modular reactors, in Seadrift, Texas, have applied to the Nuclear Regulatory Commission for construction permits, and construction crews have already started work on the non-nuclear parts of the TerraPower project. President Trump's executive orders of May 23, 2025, encourage short- and intermediate-term increases in nuclear energy domestically.⁵ Among other provisions, the orders call for ten large new reactors to commence construction by 2030.

Simultaneously, countries such as Poland are building their first nuclear reactors, with plans to expand nuclear capacity further in the future.⁶ Other countries from Argentina to India are expanding nuclear capacity to keep pace with increasing energy demand amidst economic growth. Last year's COP29 conference saw 31 nations endorse the nuclear support agreement—a declaration to triple global nuclear energy capacity by 2050.⁷ But as the world finally comes to appreciate the value of nuclear energy for the energy transition, nuclear fuel supply chains remain unprepared to meet increased demand.

Assessing the magnitude of future demand relative to supply requires a detailed survey of global enrichment capacity. Enrichment, the process that increases the proportion of U-235 atoms in the fuel, is essential for enabling a fast enough rate of fission (atom-splitting) within the reactor to sustain viable operation. Nuclear reactors require enrichment as a necessary fuel treatment to not only operate but to operate efficiently. The nuclear energy sector expresses enrichment capacity in units of separative work units (SWUs), which reflects the effort needed to separate the U-235 and U-238 isotopes using centrifuges or other enrichment technologies.⁸ Low-enriched uranium (LEU), typically enriched between 3% and 5%, powers conventional reactors.⁹ High-assay low-enriched uranium (HALEU), enriched between 5% and 20%, powers advanced reactor designs.^{10,11} More recently, the nuclear sector has begun to test LEU+ fuel enriched to 5-10% U-235, which compensates for added

neutron absorption from coatings that make the fuel accident-tolerant, while allowing higher power output, longer intervals between refueling, and more efficient safety system design.

It takes approximately 140,000 SWU to enrich the annual fuel requirement of a 1000-megawatt (MW) light-water reactor running on LEU.¹² An equivalent 1000 MW of advanced reactors with thermal energy storage (ARTES) running at 90% utilization might require nearly 200,000 SWU annually.¹³

As of 2022, Russia supplied 44% of the global demand for nuclear fuel enrichment services, dominating the global enrichment market.¹⁴ Russia's enrichment provider, Tenex, was the only large-scale commercial producer of HALEU until U.S. fuel services firm Centrus began pilot-scale production in 2023. In 2022, the U.S. imported 12% of its mined uranium supply from Russia,¹⁵ while the European Union (EU) countries imported about 17% of their mined uranium supply from Russia.¹⁶ Russia supplied roughly a quarter (27%)¹⁷ of the enrichment needed by the U.S. reactor fleet.¹⁸

Nuclear fuel exports are not critical to Russia's economy. In 2022, its oil and gas exports were valued at \$272 billion,¹⁹ far exceeding its enriched uranium exports at \$2 billion.²⁰ However, Russian nuclear uranium import dependence poses significant risks to other countries using nuclear energy. U.S. concern over Russia's unreliability as a supplier has proven justified given Moscow's recent decision to restrict nuclear fuel exports to the U.S. in response to U.S. sanctions on Russia.²¹ Curbing nuclear uranium exports won't cripple Russia's economy, but such developments illustrate the critical importance of diversifying the international nuclear fuel supply chain. Currently, nations like the United States and the United Kingdom depend on Russia for their civilian nuclear energy programs and must swiftly and decisively reduce this reliance while expanding their own nuclear capacity in coming years.

In response to these needs, numerous governments have launched initiatives to expand their fuel enrichment capacity. The U.S. Senate, in an amendment to the Emergency National Security Supplemental Appropriations Act, allocated \$2.7 billion to develop domestic enrichment capacity.²² The UK committed £300 million (\$397 million) to its own HALEU production program for future advanced reactors.²³ France's Orano plans to expand its enrichment capacity by more than 30% by 2028, ensuring it is more capable of meeting its own needs while supporting U.S. supply diversification efforts.²⁴ Notably, the U.S., Canada, France, Japan, and the UK have formed the Sapporo 5 partnership, committing to jointly leveraging their civil nuclear capabilities to decrease global dependence on Russian uranium.²⁵ Calling on like-minded countries to join this initiative, the Sapporo 5 members had mobilized \$5.6 billion by September 2024, exceeding the partnership's initial \$4.2 billion three-year investment goal.²⁶

One of President Trump's executive orders of May 23, "Reinvigorating the Nuclear Industrial Base," declares that American reliance on foreign sources of uranium and enrichment "cannot continue."²⁷ New executive orders require the Department of Energy, in cooperation with the Nuclear Regulatory Commission, to increase fuel enrichment and fuel manufacturing capacity and to revive fuel reprocessing as a means of fabricating fresh fuel from spent fuel, calling for a report within 240 days on fuel recycling.

Our analysis aims to help define potential enrichment and fuel capacity goals by quantifying fuel enrichment requirements needed to support future nuclear generation capacity, for both the U.S. and the world at large. Leveraging modeling results from the Breakthrough Institute's *Advancing Nuclear Energy* report, we assessed four scenarios with varying costs and learning rates for 2050 U.S. LEU and HALEU nuclear fuel demand.²⁸ To assess future global needs, we used recent International Atomic Energy Agency (IAEA) 2024 estimates for 2050 global nuclear power capacity to construct 2050 scenarios on global LEU and HALEU fuel demand.²⁹ We found that U.S. enrichment capacity must grow by five to ten times in size by 2050, while global enrichment may need to increase to more than double its current capacity. Our results illustrate the necessary scale that nuclear fuel supply chains must achieve to meet U.S. and global nuclear fuel demand and highlight the urgency of public and private investment required to build such enrichment capacity.

URANIUM CONVERSION AND ENRICHMENT

Making reactor fuel is a multi-step process. Uranium-bearing ore is mined and then sorted to produce an oxide, U_3O_8 , known as "yellowcake," an inert, mildly radioactive yellow powder.

The yellowcake is combined with fluorine to form uranium hexafluoride, UF_6 , which is a gel at room temperature but can be heated into a gas. In this converted form, it can be processed through an enrichment plant, whether centrifuge or laser. In that step, the two dominant isotopes of uranium, U-238 and U-235, are sorted, and the proportion of U-235 is raised from the natural level of 0.7% to 3-5% for use in light-water reactors. Many advanced reactor designs call for enrichment to nearly 20%.

Then the enriched uranium hexafluoride is "de-converted" back to an oxide and incorporated in ceramic pellets, which are loaded into thin-walled tubes that are bundled into fuel assemblies. Some advanced designs use the fuel in different physical forms.

Commercial relationships involving enrichment are complex. A utility can buy ore, pay to have it converted and enriched,³⁰ and then ship it to a fuel fabricator. Or it can buy enriched uranium hexafluoride and continue the process from that point.

Russia is only the sixth-largest uranium producer in the world,³¹ but it can buy uranium from Kazakhstan³² and convert and enrich it for export, earning value in the enrichment step.

At present, bottlenecks exist mostly at the enrichment stage, although conversion has historically also been in short supply at times. Future attention to adequate conversion capacity remains important.

U.S. NUCLEAR FUEL AND ENRICHMENT DEMAND

The U.S. front-end nuclear fuel cycle today

If policymakers intend to establish secure uranium mining, conversion, enrichment, and fuel fabrication capacity sufficient to meet more of the U.S. nuclear power sector's needs, the path forward poses significant challenges. The U.S. relies on imports for the vast majority of its uranium, a pattern entrenched for the past two decades (Figure 1). Russia remains a key trading partner for uranium, ranking fourth for U.S. 2023 uranium imports at roughly 2,300 metric tons of uranium (Figure 2).^{33,34} Now the U.S. is prioritizing expansion of domestic uranium production and enrichment capacity to eliminate this import dependence. But the current circumstances beg the question: How did the U.S. arrive at this vulnerable position in the first place?

U.S. uranium production peaked in 1980 and has rapidly declined since. Under the Megatons to Megawatts agreement, the U.S. agreed to import enriched uranium from Russia for 20 years, with Russia sourcing enriched uranium from decommissioned nuclear warheads and military stockpiles.^{35,36}

This agreement marked a high point in diplomacy and nuclear weapons de-escalation, but depressed U.S. uranium enrichment capacity as an unintended consequence. The Atomic Energy Commission built three huge gaseous diffusion plants. The first, in Oak Ridge, Tennessee, ceased operation in 1985; a sister plant in Portsmouth, Ohio, closed in 2001; and the last one, in Paducah, Kentucky, closed in 2013. These facilities were shut down because they were antiquated and because the Cold War had ended. In 2010, Urenco opened an enrichment facility in New Mexico, the first new facility to enter service in the U.S. in over 30 years.³⁷ Centrus, the second new U.S. enrichment facility to start production in recent history, commenced operations in 2023 with an initial production capacity of only 900 kg of HALEU annually.^{38,39} While Centrus is quickly moving to expand this production, only much more concerted efforts at scale will ensure the U.S. can meet its own nuclear energy deployment targets. Imported Russian enriched uranium still contributed 12% of U.S. supply in 2023. Of all foreign-imported enrichment services in the same year, Russia supplied the largest portion of the U.S. SWU supply at 27%—a level approximately equal to U.S.-origin SWU at 28%.⁴⁰

With nations such as Canada and Kazakhstan acting as reliable suppliers of mined uranium, the U.S. also steadily reduced domestic uranium mining.⁴¹ The decline of U.S. uranium mining since its peak in 1980⁴² largely stems from dynamics of the global uranium ore market, with other countries maintaining sizable uranium mining industries and producing competitively priced uranium from good quality reserves. Considerations of national and economic security aside, overall industry demand for uranium has simply not sufficed to maintain a meaningful U.S. uranium mining sector in recent decades.

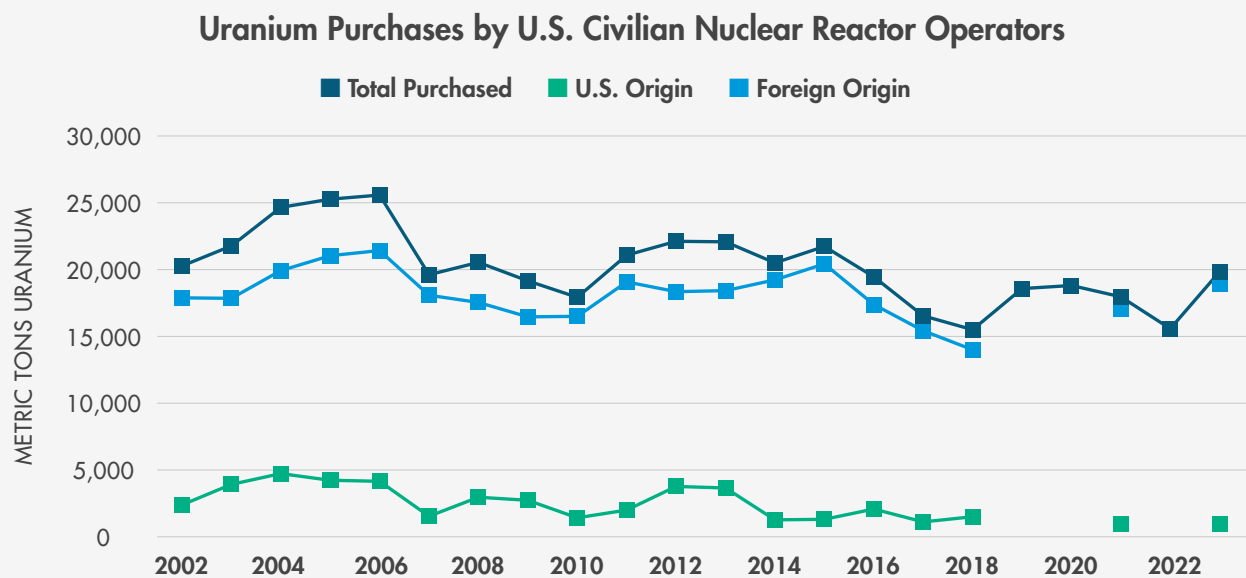


Figure 1: Uranium purchases by civilian power reactor operators from 2002 to 2023, illustrating the import dependency underlying the vast majority of U.S. uranium supply. Data is adapted from the Energy Information Administration (EIA)'s Table S1a.⁴³ The data gap for 2019, 2020, and 2022 represents data withheld by the EIA to protect individual company data.

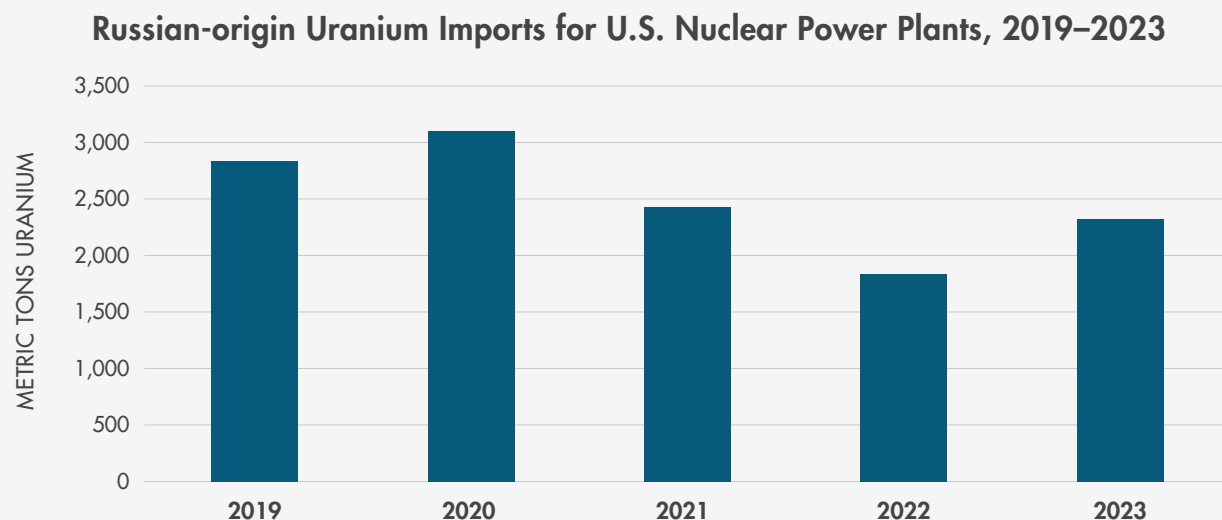


Figure 2: Uranium imported from Russia for U.S. nuclear power sector use from 2019 to 2023. Over this period, Russian uranium imports accounted for ~14% of U.S. annual uranium purchases on average. Data is adapted from the EIA's 2023 uranium marketing annual report, Table 3.⁴⁴

Scenario design

Our team based future operating U.S. reactor generating capacity values on four scenarios presented in the Breakthrough Institute’s *Advancing Nuclear Energy* report.⁴⁵ This estimate includes scenario variations of assumed initial nuclear costs and rates of cost improvement rates (learning rates). Our Low Cost, Low Learning scenario, for example, is an intermediate scenario that assumes lower initial nuclear project costs, but also assumes that nuclear project costs do not improve as rapidly with additional deployment. The Low Cost, High Learning scenario is therefore an upper-bound scenario representing the most optimistic future U.S. nuclear development, while the High Cost, Low Learning scenario is a lower-bound scenario for the most pessimistic future case. The High Cost, High Learning scenario represents another intermediate case.

Table 1 lists conventional and advanced nuclear installed capacities by 2050 for each of the scenarios examined. In terms of deployment, the lower-bound High Cost, Low Learning scenario achieves 250 gigawatts (GW) of total installed nuclear capacity by 2050, whereas the upper-bound Low Cost, High Learning scenario achieves 490 GW by 2050. These scenarios capture an envelope of projections that would include the Trump administration’s recently announced ambition targeting 400 GW of total operating nuclear generation capacity by 2050,⁴⁶ a level of deployment approaching our upper-bound scenario.

Scenario	U.S. Conventional LWR (MW)	U.S. LW SMR (MW)	U.S. ARTES (MW)	U.S. HTGR (MW)
Low Cost, Low Learning	19,748	17,952	252,962	95,301
Low Cost, High Learning (most optimistic)	19,589	53,611	223,414	192,305
High Cost, Low Learning (most pessimistic)	62,322	6,076	178,879	358
High Cost, High Learning	34,067	85,084	221,599	372

Table 1: Projected nationwide advanced and conventional nuclear installed capacities in 2050 under varying capital cost and cost learning rate scenarios, based on modeling in the Breakthrough Institute’s *Advancing Nuclear Energy* report.⁴⁷ LWR = light-water reactor. LW SMR = light-water small modular reactor. ARTES = advanced reactor with thermal energy storage. HTGR = high-temperature gas-cooled reactor.

We consider traditional light-water reactors (LWRs) and light-water small modular reactors (SMRs) using U-235 fuel enriched at 4.8%, while advanced reactor technologies, namely advanced reactors with thermal energy storage (ARTES) and high-temperature gas-cooled reactors (HTGRs), both use HALEU fuel enriched at 19.85%.⁴⁸

This analysis calculated the SWU capacity, uranium fuel, and mined uranium needed to realize each selected nuclear deployment scenario in 2050, based on factors including annual operational capacity, burnup rates, fuel requirement, and SWU requirement for each reactor type. We adopted reactor-specific assumptions using the Idaho National Laboratory's study on advanced nuclear reactor costs.⁴⁹ LEU supply chain SWU and uranium needs were calculated using the light-water reactor capacities under each scenario of our *Advancing Nuclear Energy* report, as outlined in Table 1. HALEU supply chain SWU and uranium needs were calculated in a similar manner, done separately for the ARTES and HTGR reactors. The assumptions for each reactor are listed in Table 2.

Parameters	Conventional LWR and LW SMR	ARTES	HTGR
Average burnup rate (MWd/kg)	50	147.3	165
Net thermal efficiency (%)	33	41	40
Fuel requirements (kg U fuel/MWh)	0.0025	0.00069	0.00063
Total SWU (SWU/kg U fuel)	6.3	36.2	31.3
kg natural (mined) U per kg U fuel	8.6	37.7	33.1

Table 2: Reactor-specific assumptions were adapted from Table 34 of the Idaho National Laboratory's advanced nuclear reactor costs report.⁵⁰ While this table reports both burnup rate and fuel requirements, we note that our calculations used the burnup rates. LWR = light-water reactor. LW SMR = light-water small modular reactor. ARTES = advanced reactor with thermal energy storage. HTGR = high-temperature gas-cooled reactor.

Methodological Approach

To estimate total uranium fuel requirements for the portions of this analysis focusing on future uranium fuel needs for the United States, we first calculated the thermal energy each category of reactor needs as input per MWh produced. We did this using the thermal efficiency (η):

$$\eta = \frac{MWh_e}{MWh_t}$$

Where:

MWh_e : the total electrical power output of all power plants of a given technology category

MWh_t : the thermal power output (heat energy) utilized to produce the electrical power.

Based on the *Advancing Nuclear Energy* report's modeled U.S. operating generation capacity and total annual electricity generation in 2050 for each category of reactors, we calculated total annual thermal power generation, using each reactor's assumed net thermal efficiency. Using each reactor type's assumed average fuel burnup rate per unit of thermal power generation, we derived total fuel use for reactors of each type in service in 2050. This methodology assumes reactors require only the fuel they need to generate their produced electricity and thus underestimates fuel requirements given that reactors refuel on a standard cycle in practice. New reactors in particular require more fuel at startup, given that subsequent refuelings of operational reactors usually replace only one-third of the core.

Multiplying the assumed SWU per kg fuel by the total fuel use for each reactor then yields the SWU requirement to supply fuel for each category of reactors. Finally, multiplying the mass of mined uranium used to make each unit of uranium fuel by the total uranium fuel requirement yields the mined uranium requirement for the modeled quantity of operating reactors.

Assumed nuclear reactor capacity factors differed between technologies and scenarios for our U.S.-only analysis. For these U.S. calculations, we assumed the scenario-specific capacity factor observed in the results of our *Advancing Nuclear Energy* report's energy system modeling. For conventional LWRs, this factor ranged between 71.5% and 79.0%, with a range of scenario-specific values assumed for light-water SMRs (62.8% to 85.7%), ARTES (87.3% to 91.6%), and HTGRs (76.1% to 85.8%).

Both U.S. and global enrichment and fuel requirements are heavily determined by reactor technology characteristics. Figures 3 and 4 compare the SWU requirement and the fuel usage of each reactor type studied, assuming a uniform 90% capacity factor. Advanced reactors have higher SWU requirements per MWh (Figure 3), principally because they use fuel at higher enrichment levels to

enable more densely packed fuel geometries while their smaller cores may result in more neutron “leakage.” Some designs, especially micro-reactors, need higher enrichment levels because they are intended to operate longer between refuelings. Meanwhile, LWRs exhibit the highest uranium use per MWh (Figure 4). This high usage is partly because of their low burn-up rate and thermal efficiency relative to the advanced reactors.

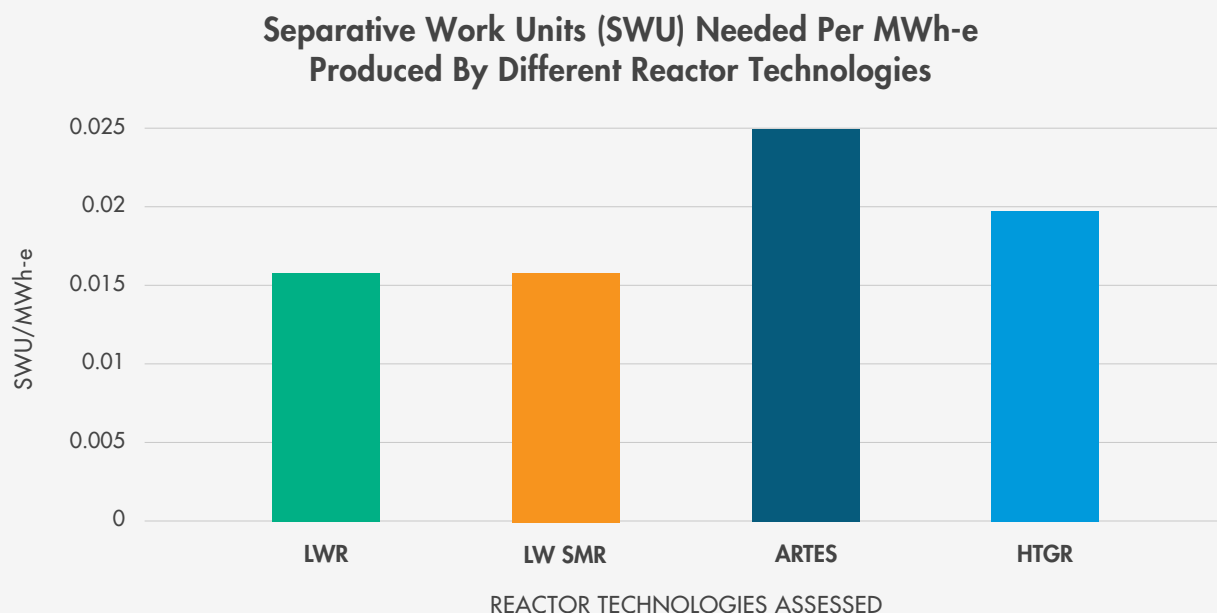


Figure 3: SWU capacity requirement per unit of electricity generation (per megawatt-hour electric) for each assessed reactor technology.

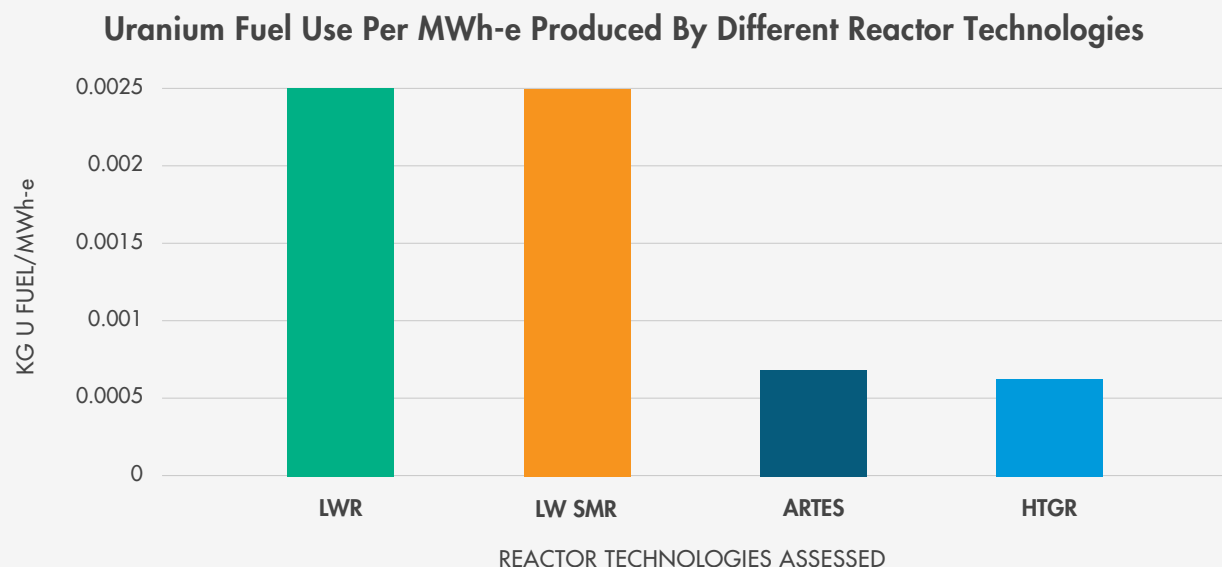


Figure 4: Uranium fuel consumption per unit of electricity generation (per megawatt-hour electric) for each assessed reactor technology.

Results: U.S. Fuel Enrichment Needs

Our resulting calculated U.S. SWU and uranium fuel requirements for 2050 reveal a massive growth in SWU demand driven by advanced reactors, as shown in Figures 5 and 6. Based on these numbers, our results show that annual U.S. SWU needs in 2050 could range from 4,000,000 to 13,000,000 for conventional light water reactors and 36,000,000 to 71,200,000 for advanced reactors. Current SWU demand for the U.S. fleet stands at about 15 million SWU annually.⁵¹

The facility licensed by Centrus, the only operating U.S.-owned enriched fuel company, will have a capacity of 3.8 million SWU annually if planned capacity is fully built.⁵² The Urenco USA facility has a capacity of 4.3 million SWU annually and is in the process of adding another 0.7 million SWU of capacity.⁵³ If solely used for enrichment up to 5%, this combined capacity conceivably available in the near term (8.8 million SWU) would cover less than 60% of current demand from conventional light-water reactors in the U.S. Alternatively, if directed toward enrichment at 19.85%, 8.8 million SWU annually covers only 12-24% of potential future demand for advanced reactors across these scenarios and would also require different facilities licensed to produce the HALEU.

2050 uranium fuel requirements range between 660 and 2,100 metric tons for conventional reactors, while ranging from 987 to 2,090 metric tons for advanced reactors. The corresponding mined uranium requirements range from 5,700 to 17,000 metric tons for LW reactors, while ranging from

37,200 to 74,500 metric tons for advanced reactors as shown in Figure 7. As of 2024, the United States produced a mere 250 metric tons of mined uranium.⁵⁴

The U.S. is beginning strong efforts to support growth of the nuclear industry. But after decades of stalled production, capacity to keep pace with future nuclear deployment will remain far beyond reach unless secure supply chains for both SWU capacity and uranium mining rapidly expand.

The U.S. doesn't need to meet all its SWU and uranium needs using U.S.-based capacity and can turn to allies to replace the Russian supply. But low domestic production will continue to impose import dependence and pose risks to the security of the U.S. nuclear energy supply chain.

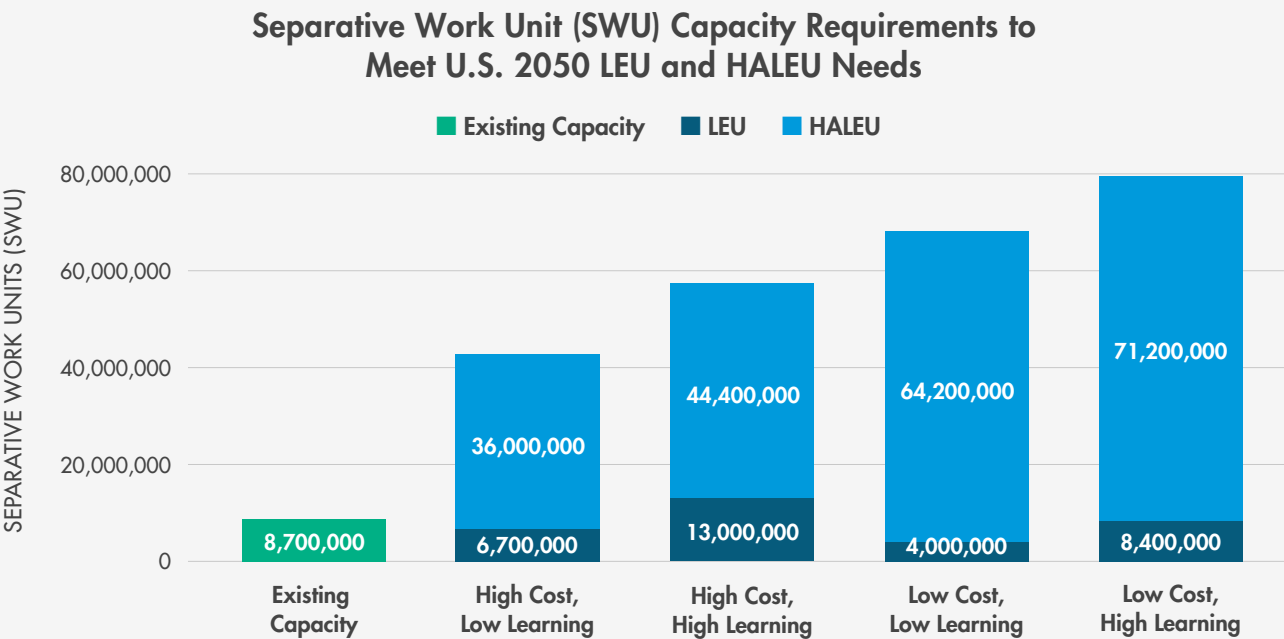


Figure 5: Projected total 2050 U.S. SWU capacity requirements by scenario and enrichment level (LEU: dark blue, HALEU: light blue), shown as stacked bars relative to current operational U.S. capacity. HALEU = high-assay low-enriched uranium. LEU = low-enriched uranium.

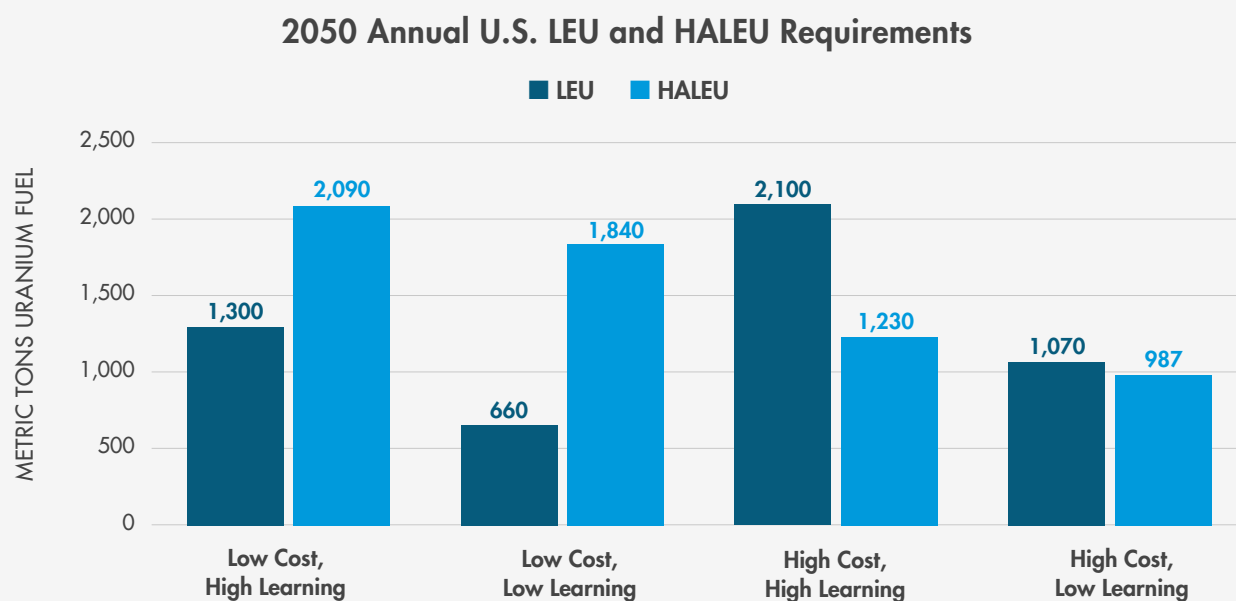


Figure 6: Projected total 2050 U.S. uranium fuel requirements by scenario and enrichment level (LEU: dark blue, HALEU: light blue). HALEU = high-assay low-enriched uranium. LEU = low-enriched uranium.

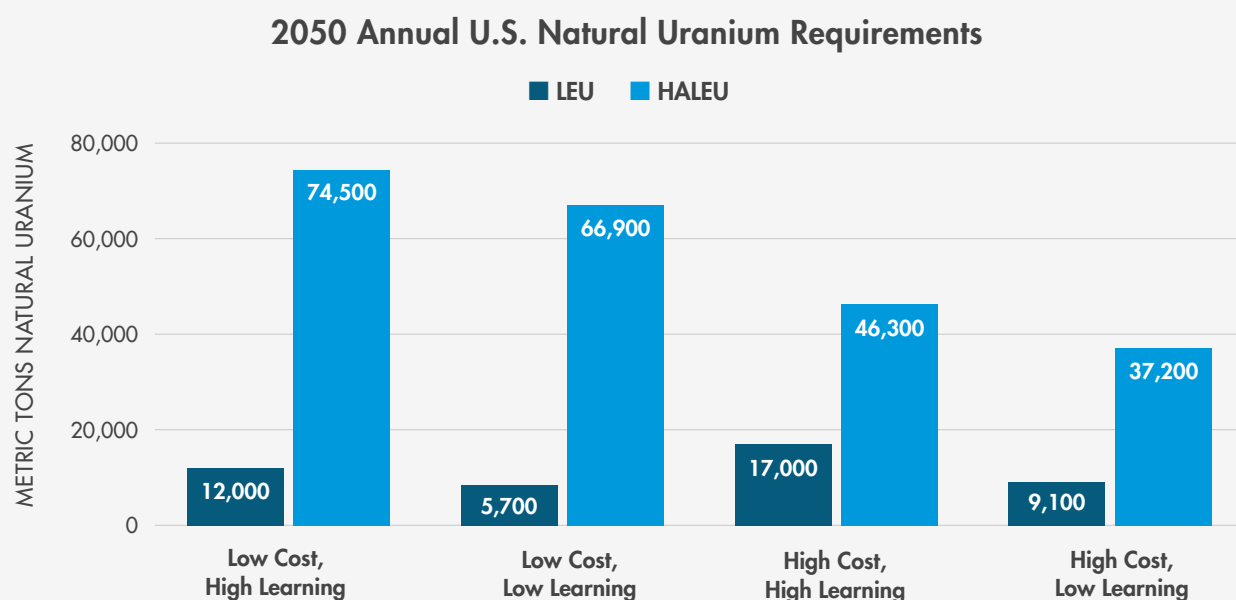


Figure 7: Projected total 2050 U.S. mined uranium input requirements by scenario and enrichment level (LEU: dark blue, HALEU: light blue). HALEU = high-assay low-enriched uranium. LEU = low-enriched uranium.

In these scenarios, fuel supply for advanced reactors poses a significant long-term challenge for the U.S. The U.S. has strong market potential for advanced reactors such as high-temperature gas-cooled reactors (HTGRs) and molten salt reactors (MSRs), yet domestic nuclear fuel enrichment remains minimal and insufficient. SWU capacity must rapidly expand to accommodate the growing need for enrichment.

While conventional light-water reactor capacity decreases significantly in these scenarios from its present 92 GW, this result may no longer be plausible considering a strong recent trend toward relicensing of existing reactors and even recommissioning of decommissioned facilities amid rising U.S. electricity demand forecasts. A larger share of conventional light-water reactors operating in 2050 would decrease SWU requirements relative to our projections. We thus additionally considered a wide bounding analysis in which the United States operates either 250 GW or 490 GW of LEU-fueled light-water reactors or HALEU-fueled advanced reactors (Figure 8). This sensitivity analysis yielded a total range of future U.S. enrichment needs of 31.4 to 96.5 million SWU, around five to ten times greater than the 8.8 million SWU of potentially available U.S. enrichment capacity in the near term.

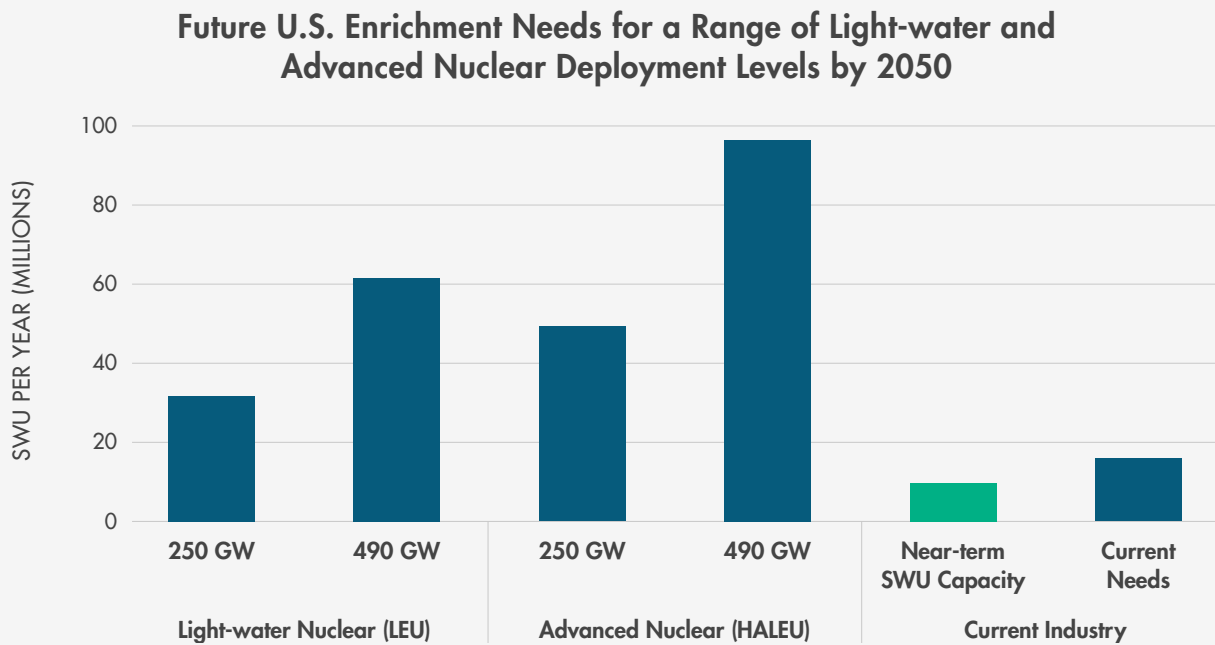


Figure 8: Future U.S. uranium enrichment needs under a range of different light-water and advanced nuclear deployment scenarios by 2050, relative to potentially available U.S. enrichment capacity in the near term and existing enrichment requirements for the currently operating 92 GW of conventional light-water nuclear.

Public efforts are already moving fast to build new reactors to meet needs for flexible, resilient, low-carbon power. The Department of Defense, for instance, recently started construction on the first Project Pele microreactor at the Idaho National Laboratory.⁵⁵ The Trump administration's recently announced ambition to set the U.S. on a path to 400 GW of total operating nuclear generation capacity by 2050 would represent a dramatic scale-up of construction approaching our upper-bound scenarios. Meanwhile in the private sector, there is no shortage of nuclear developers aiming to gain footing in this new nuclear market space. Kairos Power started construction for its Hermes molten-salt advanced reactor demonstration facility this past summer.⁵⁶ TerraPower is now building its Sodium sodium-cooled fast reactor demonstration project in Wyoming.⁵⁷ Overall, without adequate and secure fuel supply chains, the U.S. risks failing to realize its own advanced nuclear market potential and failing to exercise leadership in global nuclear power markets.

Indeed, more emerging economies are constructing nuclear power plants and are partnering with nuclear power technology providers to do so. Russia and China have extended their global nuclear energy leadership, with a growing number of nuclear technology partnerships that have significant geopolitical implications. Conversely, competition in the global market for nuclear engineering, procurement, and construction, alongside a secure and well-resourced nuclear energy supply chain, can strengthen U.S. political and economic influence internationally.

GLOBAL NUCLEAR FUEL AND ENRICHMENT DEMAND

Globally, many countries—particularly those averse to sourcing from Russia or China—must, like the U.S., evaluate their uranium and fuel supply options as they prepare to support growing nuclear energy usage. As both developed and emerging economies deploy more reactors, uranium mining and enrichment capabilities will pose increasingly important constraints. Global uranium requirements have surpassed total production over the past two decades (Figure 9). Global mining levels have caught up with current consumption in recent years, but it is questionable whether this balance will persist in light of shifts in geopolitics and supply chains caused by Russia’s invasion of Ukraine. As the global nuclear industry gains momentum, planners must establish greater certainty that mining and enrichment can keep pace with growing demand, or else risk bottlenecks when the world community’s needs for new nuclear power are greatest.

Global Uranium Production and Demand Trends Over Time

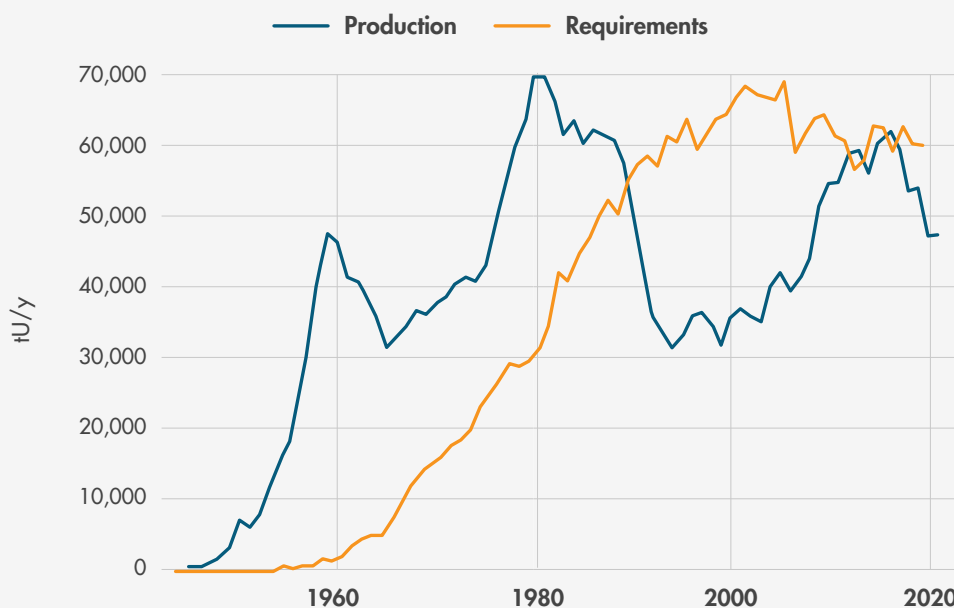


Figure 9: Global uranium production and demand trends over time. Figure is adapted from Figure 4.11 in the Nuclear Energy Agency’s High-Assay Low-Enriched Uranium report.⁵⁸

Scenario design

For our global analysis, we constructed deployment scenarios using the most recent International Energy Agency (IEA) 2025 estimates for 2050 global nuclear power capacity.⁵⁹ We used the Stated Policies Scenario (STEPS), the Announced Pledges Scenario (APS), and the Net Zero Emissions (NZE) scenario. The total installed global capacities for both conventional and advanced nuclear technologies in each scenario are displayed in Table 3. We note that the IEA’s modeled global advanced nuclear deployment is generally more conservative than our modeling for the U.S., with total global IEA advanced nuclear construction of 200 GW in the NZE scenario on par with or well below the capacity built in the U.S. across our range of U.S. scenarios.

Our assumed advanced reactor capacities are based on the IEA’s projected SMR capacities for each scenario in 2050. Our team assumed most SMRs are light-water reactors, with the remaining 20% of advanced nuclear deployment split evenly between HTGRs and ARTES. Our methodology for calculating the global 2050 SWU and uranium requirements is largely identical to the approach for U.S.-only needs.

Given that the IEA does not report its projected capacity factors for these reactor designs, our team assumed a capacity factor of 90% for all reactor technologies for our projections of global fuel and SWU requirements. This assumption may slightly overestimate fuel requirements in some scenarios.

Scenario	Global Conventional LWR (MW)	Global LW SMR (MW)	Global ARTES (MW)	Global HTGR (MW)
STEPS	610,000	32,000	4,000	4,000
APS	750,000	96,000	12,000	12,000
NZE	900,000	160,000	20,000	20,000

Table 3: Projected advanced and conventional nuclear installed capacity worldwide in 2050 under different global IEA modeling scenarios. Data is adapted from the IEA’s most recent estimates.⁶⁰ LWR = light-water reactor. LW SMR = light-water small modular reactor. ARTES = advanced reactor with thermal energy storage. HTGR = high-temperature gas-cooled reactor.

Results: Global Fuel Enrichment Needs

By 2050, global SWU and uranium fuel requirements both will see considerable growth as shown in Figures 10 and 11. In these scenarios, conventional and light-water nuclear power plants play a primary role in expanding global nuclear deployment in the IEA's analysis. This pattern largely reflects nations, especially developing countries, leveraging existing or incrementally improved commercial reactor designs to build initial and subsequent projects. Cost and schedule are better defined for light-water designs. Advanced reactors will still play an important role as developed economies seek to diversify their nuclear technology assets, but advanced nuclear's share of global nuclear capacity may be below the share in the U.S. As more advanced reactor designs are deployed, however, technological learning and cost improvements may alter this calculus over time relative to the IEA's modeling, driving further expansion in global SWU capacity needs.

Taking the IEA scenarios at face value, our results show that global SWU requirements for conventional light-water nuclear technologies could range from 80,000,000 to 130,000,000, compared to a current global SWU capacity of ~60 million annually as of 2022.⁶¹ For advanced reactors, global SWU capacity needs could range from 1,410,000 to 7,050,000.

Future uranium fuel requirements range from 13,000 to 21,000 metric tons for conventional light-water reactors, while ranging from 42 to 208 metric tons for advanced reactors. The corresponding mined uranium requirements range from 105,000 to 180,000 metric tons for light-water reactors, while ranging from 1,500 to 7,400 metric tons for advanced reactors (Figure 12). Globally, uranium mines produced ~49,000 metric tons of uranium in 2022.⁶² Assuming no significant fuel production from reprocessed spent fuel, increased global nuclear capacity will require more than doubling uranium production by 2050 to meet estimated needs in the most conservative scenario.

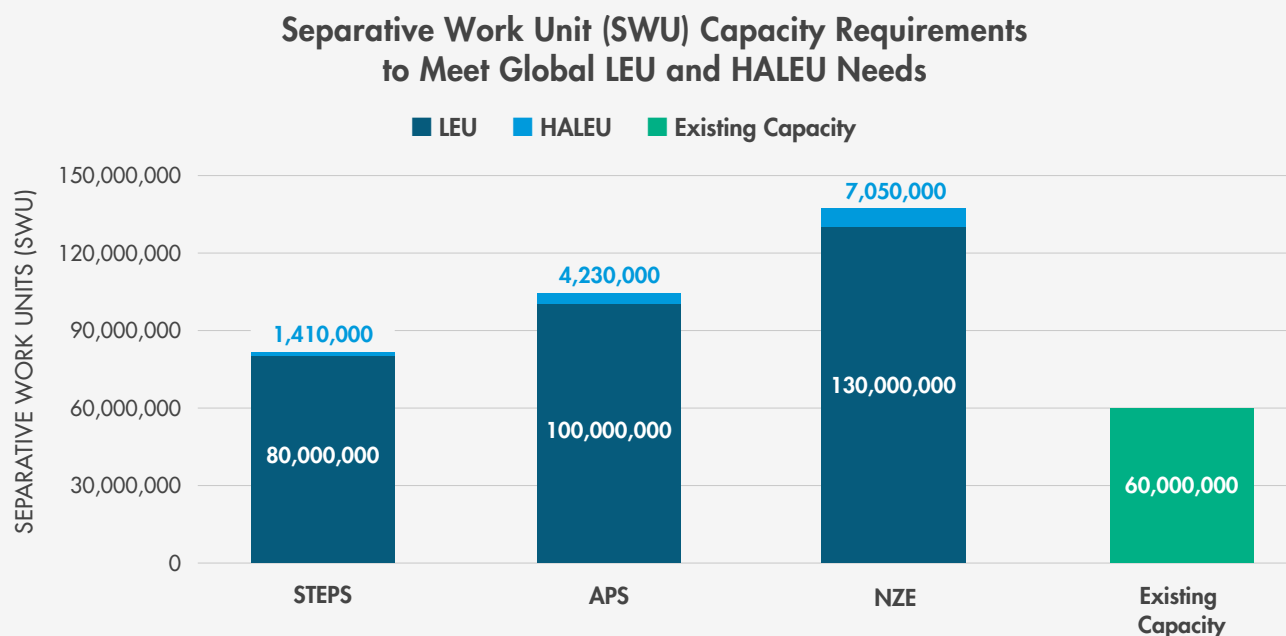


Figure 10: Projected total 2050 global SWU capacity requirements by scenario and enrichment level (LEU: dark blue, HALEU: light blue), shown as stacked bars relative to current operational global capacity.

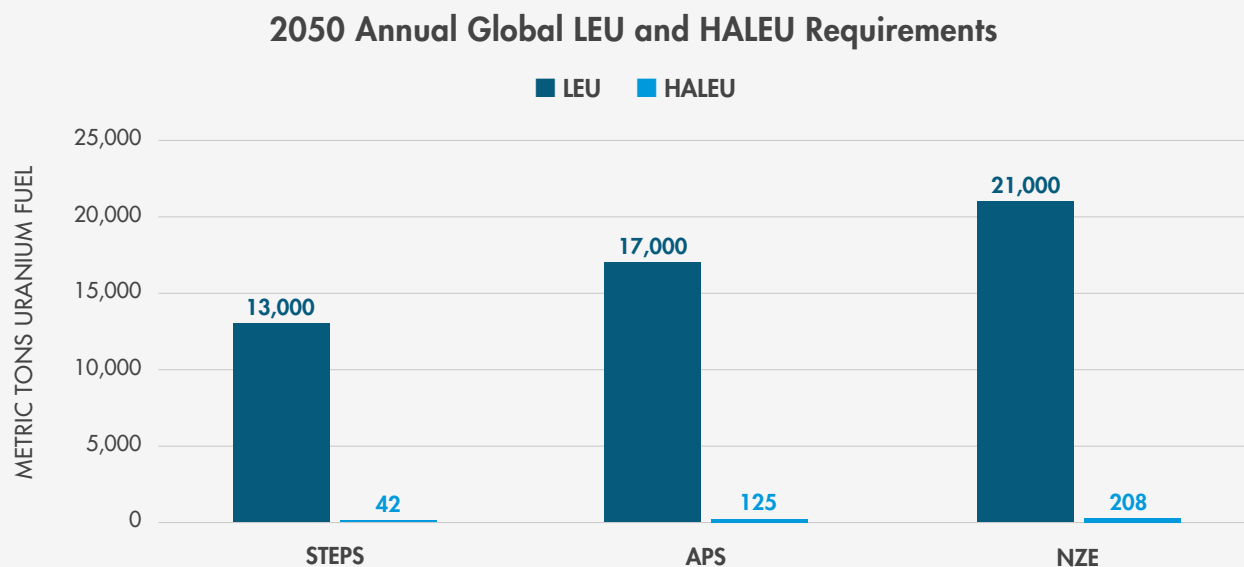


Figure 11: Projected total 2050 global uranium fuel requirements by scenario and enrichment level (LEU: dark blue, HALEU: light blue).

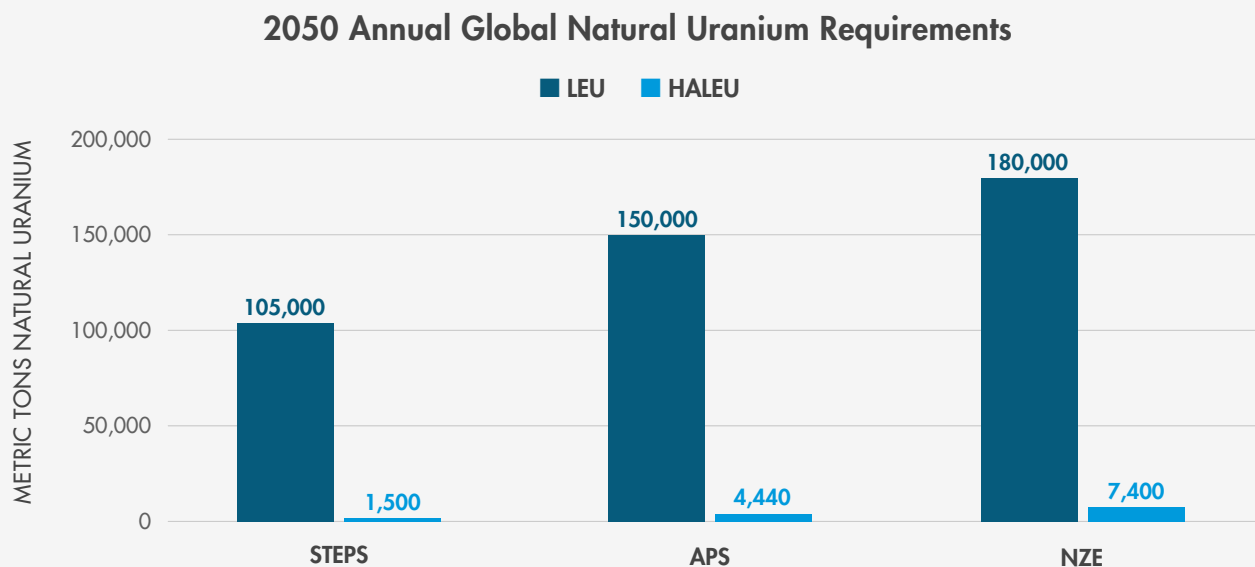


Figure 12: Projected total 2050 global mined uranium requirements by scenario and enrichment level (LEU: dark blue, HALEU: light blue).

At the global scale, SWU capacity must expand to meet projected 2050 requirements. Existing SWU capacity can meet 75% of the most conservative STEPS scenario LEU requirement, but would cover only 45% of the NZE scenario LEU requirement. Yet politics surrounding the distribution of existing SWU capacity further complicate this calculus. Although Russia is one of the smaller producers of mined uranium (about 5% of global uranium mining, ranking sixth for country mine production),⁶³ Russian supply dominates the global enrichment market, providing 44% of global enrichment services. In response to Russia's invasion of Ukraine, developed nations like the U.S.,⁶⁴ Japan,⁶⁵ the EU,⁶⁶ and the UK⁶⁷ are now rapidly working to reduce their dependence on Russian enrichment. On the other hand, emerging economies may hardly share the same urgent aversion to Russian or Chinese enrichment services, let alone possess the luxury of shunning these well-developed supply chains. To discourage reliance on import relationships with Russia and China and mitigate geopolitical and energy security risks to the clean energy transition, the global nuclear supply chain must diversify and offer competitive alternatives.

COMPARISON TO OTHER NUCLEAR FUEL STUDIES

A number of other organizations and researchers have previously sought to estimate both U.S. and global uranium or enrichment needs, providing points for comparison with our own modeling. We briefly summarize here a selection of relevant independent results (Figures 13, 14, and 15) and how they relate to our findings.

U.S. Nuclear Fuel Projections

- The Nuclear Energy Institute's (NEI) 2021 HALEU survey projected a requirement of 215 metric tons of HALEU by 2030.⁶⁸ This requirement increases to 614 metric tons by 2035. With the 15-year gap between 2035 and 2050, these findings are on a trajectory aligned with our team's 2050 projections (987 to 2,090 tons), considering subsequent deployment of advanced reactors after 2035.
- The Idaho National Laboratory's (INL) 2021 projections are less optimistic, estimating a HALEU demand of less than 100 metric tons in 2035, although this demand increases to 520 metric tons in 2050.⁶⁹ This estimate is closest to our most conservative U.S. HALEU scenario of high costs and low learning, which produced an estimated 2050 HALEU demand of 987 metric tons. We note that both this INL study and the NEI study mentioned above were published a few years ago and do not reflect recent Trump administration nuclear deployment executive orders and programs.

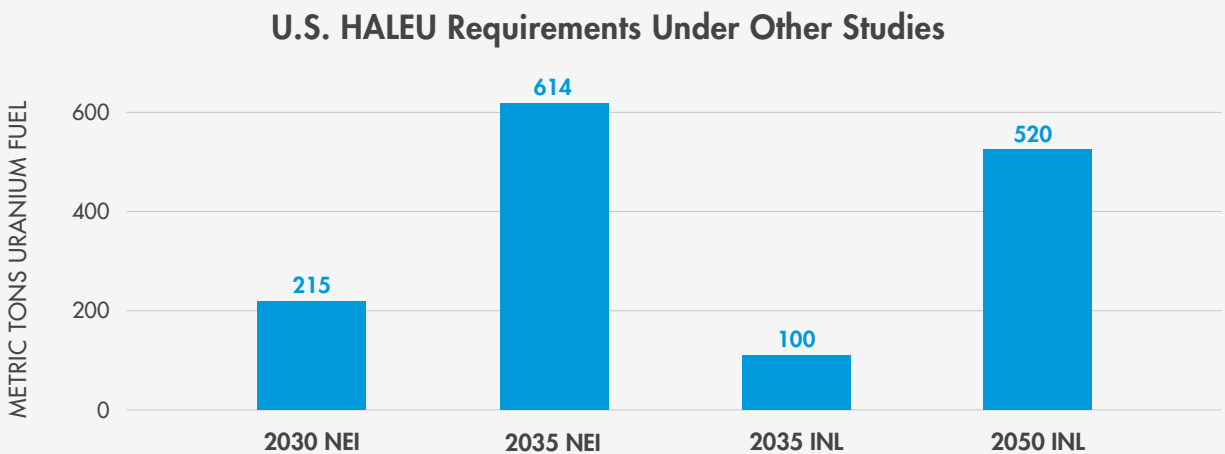


Figure 13: Annual metric tons of HALEU required for the U.S. as estimated in the 2021 Nuclear Energy Institute's (NEI) HALEU survey for 2030 and 2035⁷⁰ and in the 2021 Idaho National Laboratory's (INL) report for 2035 and 2050.⁷¹ For comparison, our study's calculated 2050 HALEU requirements for the U.S. ranged between 987 and 2,090 tons across scenarios.

- A recent independent estimate of future U.S. enrichment requirements for a quadrupling of U.S. installed nuclear capacity to 400 GW arrived at a range of 60 to 70 million SWU per year needed by the year 2050.⁷² This estimate similarly falls within our range of 31 to 97 million SWU per year to support 250 to 490 GW of installed nuclear.

Global Nuclear Fuel Projections

- The Nuclear Energy Agency's (NEA) 2024 HALEU report was based on a scenario in which the global 2050 LWR capacity reaches approximately 800 GW in addition to global deployment of 300 GW of HALEU-fueled SMRs.⁷³ These projections align most closely with the IEA's 2050 NZE scenario with a total nuclear capacity of approximately 1,100 GW. Similarly, the NEA's estimated 2050 LWR SWU requirement, at 105 million SWU per year, is closest to the LWR SWU our study calculated for the IEA's APS scenario at approximately 100 million SWU. The NEA's 2050 SMR SWU requirement is much higher, estimated at approximately 60 million SWU per year compared to our estimate for the IEA's optimistic NZE scenario estimate of roughly 7 million SWU. These differences are likely due to varying assumptions regarding advanced nuclear capacities and the distribution of reactor types, which influence the fuel cycle.

Annual mined uranium requirements follow a similar trend, with the NEA projecting ~155,000 metric tons and ~62,000 metric tons for LWRs and SMRs in 2050, respectively. The LWR uranium requirement most closely aligns with the IEA APS 2050 LEU uranium requirement of about 150,000 metric tons. The NEA's SMR mined uranium requirement is highly optimistic compared to our high IEA NZE scenario at about 7,400 metric tons. These are likely due to the NEA's more optimistic assumptions for global SMR deployment driving uranium requirements, relative to the IEA's scenarios.

- The World Nuclear Association's (WNA) 2023 nuclear fuel report, while not distinguishing between reactor types, projected overall mined uranium requirements significantly higher than our high scenarios, reflecting greater optimism for advanced reactor deployment.⁷⁴ For 2030, the WNA estimated uranium requirements at 84,000 metric tons per year under its reference scenario with a global nuclear capacity of 444 GW, increasing to nearly 130,000 metric tons per year by 2040 with a global nuclear capacity of 686 GW. This estimate can be contrasted with the 2050 mined uranium requirement in the IEA's APS scenario in our analysis: approximately 154,440 metric tons.
- The WNA's 2021 nuclear fuel report presents expectations for global SWU requirements.⁷⁵ The 2040 global SWU requirement for the reference scenario was projected to be 90 million SWU with a global nuclear capacity of 615 GW. This projection is closest to the IEA's conservative 2050 STEPS scenario, which has a total nuclear capacity of 650 GW.

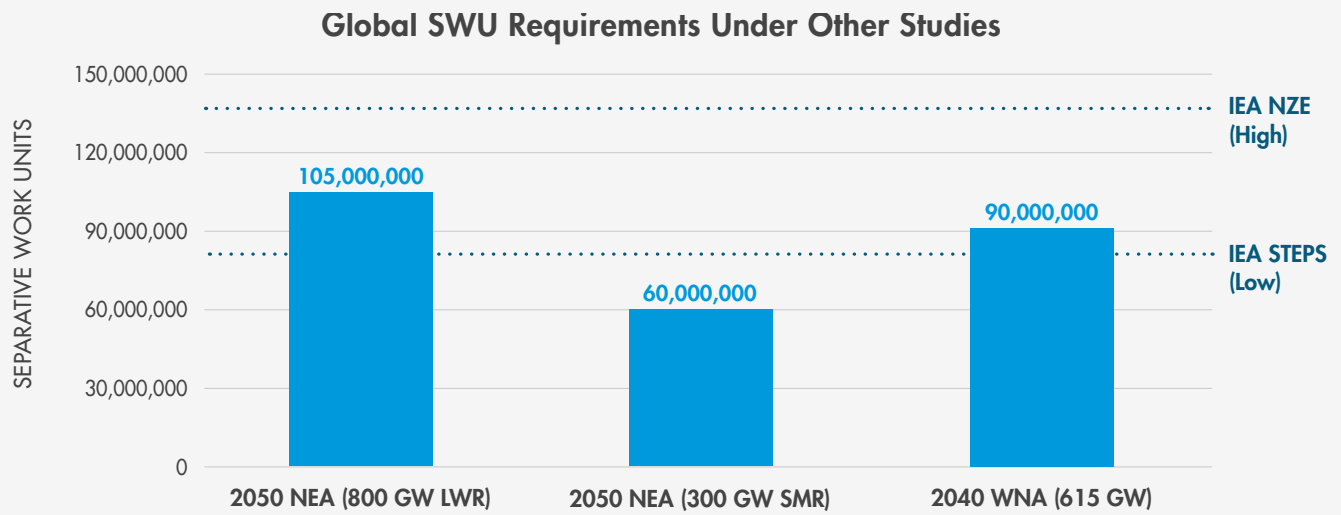


Figure 14: Annual global separative work unit (SWU) requirements estimated under the 2024 Nuclear Energy Agency (NEA) HALEU report for 2050 projected separately for LWR and SMR capacities⁷⁶ and the 2021 World Nuclear Association (WNA) nuclear fuel report for 2040.⁷⁷

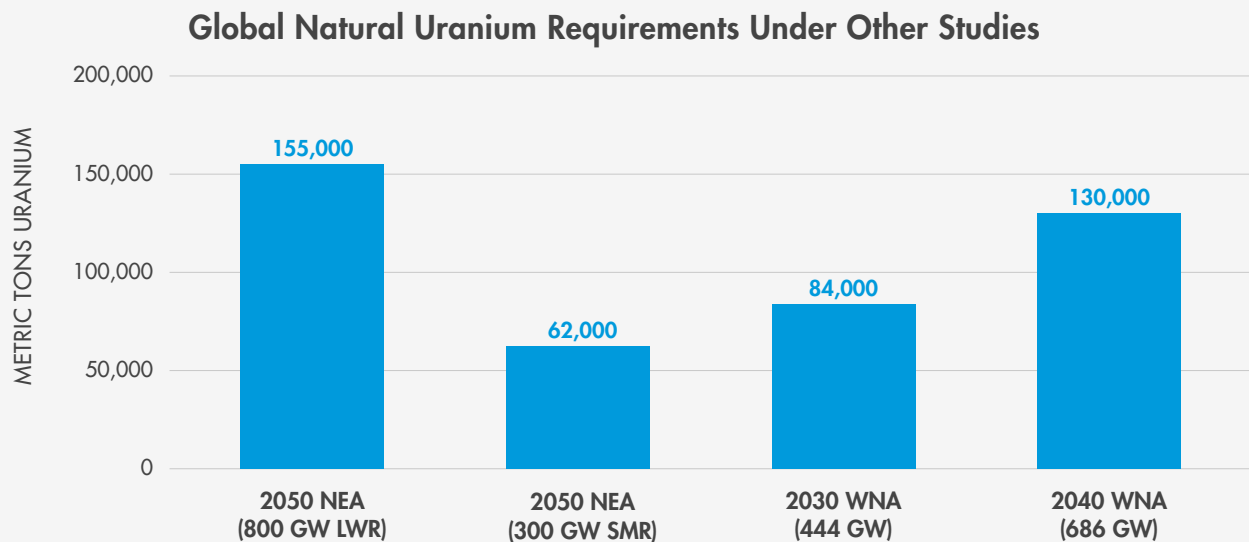


Figure 15: Annual global mined uranium requirements estimated under the 2024 Nuclear Energy Agency (NEA) HALEU report for 2050 projected separately for LWR and SMR capacities⁷⁸ and the 2023 World Nuclear Association (WNA) nuclear fuel report for 2030 and 2040.⁷⁹

**HOW MIGHT
TECHNOLOGICAL
PROGRESS
IMPACT FUEL
SUPPLY CHAIN
ESTIMATES?**

In practice, changes in technology and international politics will significantly influence uranium and enrichment needs relative to this report's estimates. The most obvious uncertainties include the following: increased recycling of plutonium produced in light-water reactors, which can substitute for uranium and enrichment; development of new reactor types that generate more plutonium and other transuranics useful for fuel during operation, whether or not they are breeder designs; and development of new enrichment technologies.

Development of reactor types that generate more plutonium is important because enrichment and uranium ore can substitute for each other. It takes about 15 million SWU to run the U.S. nuclear reactor fleet,⁸⁰ for example, which amounts to roughly 161,000 SWU per reactor. Some reactors in other countries use less, but have to refuel more frequently, thereby reducing their output.

The World Nuclear Association offers this analysis of the trade-off: enriching 1 kilogram of uranium to 5% can be done with 7.9 SWU if the tails are reduced in U-235 content to 0.25% or with 8.9 SWU if the assay is 0.2%.⁸¹ If more SWU are applied, then making the kilogram of enriched product will take only 9.4 kilograms of uranium instead of 10.4 kilograms of uranium.

Centrifuges have an odd mechanical characteristic that further affects the equation: once they reach operating speed, they generally can't be stopped until they are ready to retire, after decades of operation.⁸² So if market forces lower the value of an SWU, enrichers tend to apply more SWU to a reduced amount of uranium feed to minimize their raw material cost, a technique called "underfeeding." When Russia was strong in the international market, those conditions prevailed, and Russian and European enrichers commonly achieved tails assays of 0.2% or lower.⁸³

In the United States, on the other hand, for decades of operations ending in the 1990s, gaseous diffusion plants, which required huge amounts of electricity, processed uranium much less thoroughly, leaving an enormous inventory of tails with assays of 0.3% or 0.4%. These are already in the form of uranium hexafluoride, the compound used in enrichment by gaseous diffusion and centrifuges. The U.S. has an inventory of about 700,000 metric tons of uranium hexafluoride, which is sitting in steel canisters with limited lifetimes. The uranium does not present much health hazard, but the fluorine does.

The U.S. Department of Energy said in 2008 that it had about 75,300 metric tons of depleted uranium with an assay of 0.35% or higher, which is the equivalent of 29,950 metric tons of mined uranium.⁸⁴

Waiting in the wings is a new technology, laser enrichment,⁸⁵ not yet commercialized, that could perform a triple function: scavenge the U-235 from the tails, reduce the volume of waste that the Department of Energy must dispose of, and reduce the need for uranium ore mining and conversion to uranium hexafluoride, at least temporarily.⁸⁶

Laser enrichment uses a beam of light to selectively excite the uranium hexafluoride molecules with U-235, without exciting the ones with the heavier U-238. While closely guarded, the technique appears to suppress the re-condensation of the lighter molecules so they can be separated. Laser processing can handle more material at a time (centrifuges are filled with only a few grams, and centrifuge plants need hundreds or thousands of units) and have lower requirements for energy. Potentially, they have lower requirements for capital. If they achieve commercialization, perhaps by starting with the rich tails in U.S. government hands, they could replace centrifuges just as centrifuges supplanted gaseous diffusion in the 1980s and 1990s. This new technology could result in a smaller demand for uranium ore because of the ease of achieving lower tails assays.

Another variable is wider use of reprocessing. Light-water reactors create plutonium as they operate, when an atom of U-238, which is non-fissile in that kind of reactor, absorbs a neutron from the fission of an atom of U-235. After a brief period, the U-238 is transmuted into Pu-239, which is fissile.

In the course of operations, the reactor will split some of the Pu-239 it has created, as well as Pu-241, which is created as such atoms absorb additional neutrons. The process also creates some non-fissile atoms of plutonium, like Pu-240 and Pu-242.

According to the World Nuclear Association, used reactor fuel is about 1% plutonium, but only about two-thirds of that is fissile.⁸⁷ However, recycling the plutonium from spent fuel, plus the unburned uranium, can increase the energy created by a given quantity of uranium by 22%. That number declines slightly with fuel that is designed to stay in the reactor longer or create more fissions per kilogram of fuel.

In the United States, only one nuclear plant now in operation was licensed for operation with mixed oxide fuel (MOX): Palo Verde, one of the last reactors built in the wave of construction in the 1970s and 1980s. But Palo Verde does not use the material. Other reactors can be modified to do so, and many in Europe already use MOX. Duke Energy once proposed modifying its Catawba and McGuire plants to use MOX,⁸⁸ when the Department of Energy was trying to fabricate MOX fuel using surplus weapons plutonium, but the government later abandoned the idea.⁸⁹

The economics are complex. Reprocessing creates valuable fuel, and it reduces the amount of long-lived isotopes that must be buried, but those are the isotopes that make waste disposal a big challenge. Reprocessing also adds to energy independence, which is hard to quantify in financial terms, but explains why the French⁹⁰ and the Japanese embarked on that path. The United States turned away from reprocessing in the 1970s because it was seen as a proliferation risk and thus would set a poor example for other countries. But reprocessing is intermittently proposed for the

United States, most recently in President Trump's executive orders. The U.S. continues to possess by far the largest accumulation of spent nuclear fuel, warranting serious consideration of reprocessing as a waste and fuel security solution.

A third potential variable involves changes in light-water reactor technology. Russia has announced work on a new kind of light-water reactor that would make far more efficient use of the neutrons liberated in fission. In the designs used today in pressurized water reactors, when the core is new and there is a surplus of neutrons, operators inject the element boron into the cooling water to absorb them. In the new Russian design, those neutrons are absorbed by U-238, the type that makes up more than 99% of natural uranium, and can be transmuted by neutron absorption into Pu-239. The Russians estimate that by harvesting that plutonium and fashioning it into new fuel with a uranium-plutonium mix, they could reduce the need for uranium by about half.⁹¹ This process would reduce enrichment needs by a corresponding amount.

It is too soon to say if this technology, called VVER-S, will succeed or will be widely adopted. But there is another, well-documented technology that could have a similar impact: turning reactors into breeders, by installing additional U-238. In nuclear parlance, nearly all the reactors in service today are “burners,” meaning that they consume more fuel than they make. A “breeder” exhibits the opposite behavior.

There is another form of breeding that could also prove successful: turning thorium, a mildly radioactive, non-fissile element found in abundance in India, the United States, and elsewhere, into U-233. This process is more complicated than breeding plutonium from U-238 and requires enhanced radiation shielding for safety, but it was demonstrated more than half a century ago.

A new factor in the process has been developed for CANDU (Canada deuterium uranium) pressurized heavy-water reactors, which were developed in Canada and are operated in India.⁹² New fuel, now under test at the U.S. Department of Energy's Idaho National Laboratory, combines thorium with higher-assay uranium in a CANDU fuel element, where it is transmuted and then consumed in situ, reducing the volume of waste by a factor of 7 and saving substantial amounts of uranium. The technology's deployment is not certain, with India having articulated intermittent plans to deploy dozens of new reactors using a design derived from CANDU. Deployment would require CANDU-operating countries to develop or contract enrichment services, as existing CANDU reactors currently use natural non-enriched uranium.

STRATEGIES FOR DIVERSIFYING THE NUCLEAR FUEL AND ENRICHMENT SUPPLY CHAIN

U.S. Nuclear Fuel Supply Chain Recommendations

Russia plays a significant role in fulfilling U.S. uranium demand (12% in 2023⁹³) and enrichment demand (27% of U.S. SWU needs in 2023⁹⁴). Ensuring energy security for the current and future U.S. nuclear power sector thus requires significant increases to both secure uranium supply and enrichment capacity.

Across our range of specific scenarios with 250 GW to 490 GW of total installed nuclear capacity by 2050, future U.S. nuclear sector needs surpass 40 million SWU, 987 metric tons per year of HALEU fuel, and 660 metric tons per year of LEU fuel, with needs growing to as high as 84 million SWU, 2,090 metric tons per year of HALEU, and 2,100 metric tons per year of LEU (Table 4). An upper-bound scenario of 490 GW of total operating nuclear capacity by 2050 is comparable to the deployment vision recently articulated in the president’s executive orders of May 23, 2025.

	Fuel Type	U.S. Requirement by 2050	Global Requirement by 2050
SWU	LEU	4,000,000–13,000,000	80,000,000–130,000,000
	HALEU	36,000,000–71,200,000	1,410,000–7,050,000
Uranium Fuel (metric tons U fuel)	LEU	660–2,100	13,000–21,000
	HALEU	987–2,090	42–208
Mined Uranium (metric tons)	LEU	5,700–17,000	105,000–180,000
	HALEU	37,200–74,500	1,500–7,400

Table 4: Estimated annual requirements for separative work units (SWU), uranium fuel, and mined uranium for the U.S. and globally by 2050. The range of values reflects requirements under different scenarios modeled in the Breakthrough Institute’s Advancing Nuclear Energy report for U.S. requirements⁹⁵ and in the International Energy Agency 2025 estimates for global 2050 nuclear power capacity.⁹⁶

Ambitious nuclear deployment will require a decisive strategy to de-risk and stimulate investment in enrichment capacity to diminish overreliance on Russian supply. With anticipated industry growth and the shift away from Russian uranium imports driving uranium prices to a 15-year high,⁹⁷ policymakers must take decisive action to avoid a serious structural supply shortage. The following recommendations articulate public policy and public research priorities that can significantly increase the reliability of U.S. nuclear fuel supplies, while driving technological advancement in enrichment techniques.

1. **Prioritize targeted federal funding for projects that can credibly grow to deliver full commercial production.** Currently, the Department of Energy supervises \$3.7 billion in total funding appropriated by Congress to support expanded enrichment for both HALEU and LEU.⁹⁸ Federal grants and financing support for enrichment and fuel fabrication must consider the magnitude of future U.S. nuclear deployment goals⁹⁹—requiring at least 40 million SWU based on our report’s lower-end scenario of 250 GW of total installed nuclear capacity by 2050. Policymakers should allocate public sector support preferentially toward projects with facilities and planning designed to achieve correspondingly meaningful commercial scale. Awarding too many funds to small-scale pilot projects led by different new producers creates a risk that production will remain a bottleneck to sectoral growth, requiring entirely new facilities and investment to expand production. With the Department of Energy now moving to establish a new Defense Production Act Consortium with nuclear fuel cycle companies to refine U.S. supply strategies,¹⁰⁰ prioritization of large-scale production must guide the federal government’s overall approach.
2. **Establish a HALEU bank at the Department of Energy to purchase and sell HALEU.** To provide early-stage certainty of demand for enrichment providers and ensure HALEU supply for nuclear project developers,¹⁰¹ the Department of Energy should continue robust support for a national HALEU bank to serve as the first purchaser of newly produced HALEU.¹⁰² Acting as a middleman purchaser, this program would buy HALEU from producers on a futures market, then sell HALEU at cost in advance to nuclear power projects under development, without the bank needing to take physical delivery. Such an initiative will resolve the chicken-and-egg problem of nuclear projects and HALEU enrichment waiting for one another to develop first,¹⁰³ while also stabilizing HALEU prices. Through the HALEU Availability Program,¹⁰⁴ the Department of Energy has already committed initial allocations of HALEU to five nuclear developers¹⁰⁵ using funds appropriated in the Nuclear Fuel Security Act Authorizations in the FY24 National Defense Authorization Act.¹⁰⁶ Once a mature enrichment services industry has developed, this HALEU bank program should rapidly transition to functioning as an emergency strategic reserve.
3. **Leverage federal electricity procurement in support of U.S. advanced nuclear deployment to build an order book of domestic nuclear projects and establish firm market demand for future fuel.** President Trump’s executive order “Ordering the Reform of the Nuclear Regulatory Commission” articulates a U.S. policy goal of expanding domestic nuclear capacity from its current 92 GW today to 400 GW by 2050.¹⁰⁷ Our upper-end scenarios (up to 490 GW of domestic nuclear by 2050) suggest a potential for even higher future U.S. nuclear fuel demand, which would require 80 million SWU or more. Reliable power purchasers are necessary to

establish a confidently robust future for the U.S. nuclear power sector and help catalyze sufficient investment in domestic fuel enrichment. To this end, the federal government should mobilize its purchasing power as the largest domestic buyer of electricity to procure at least 20% of its electricity purchases from new nuclear power plants. Such a purchase program will incentivize new nuclear project construction, with purchasing power scaling proportionally with growing federal government electricity demand driven by strategic data and computing needs.

4. **Securely improve cross-government coordination on the availability of stockpiled nuclear materials potentially usable for nuclear fuel production.** President Trump's executive order "Deploying Advanced Nuclear Reactor Technologies for National Security" directs the Department of Defense to cooperate with the Department of Energy to source HALEU fuel for new nuclear demonstration projects.¹⁰⁸ Such coordination has already begun, with recently announced HALEU allocations¹⁰⁹ to companies starting to make use of material from the National Nuclear Security Administration.¹¹⁰ The administration is also now pursuing expansion of highly enriched uranium production for defense purposes.¹¹¹ Recognizing the national security sensitivity of information related to nuclear materials, the Department of Defense and National Security Administration should cooperate closely to clarify to the Department of Energy the overall domestic potential to reprocess and downblend stockpiled material to help support powering of the demonstration projects specified in the executive order.
5. **Resolutely maintain the ban on imported Russian uranium.** Reversal of the Russian uranium ban¹¹² by the White House or Congress would reintroduce sizable uranium supplies from a major geopolitical adversary into the international market, eroding the private investment case into alternative, secure uranium production and enrichment projects and jeopardizing considerable public investments in this sector.¹¹³ Injudicious extension of waivers for the Russian uranium ban could cause similarly detrimental effects. The federal government must consistently enforce a ban on Russian uranium to avoid harming development of a Western nuclear fuel industrial base—a difficult effort currently in its most crucial early commercial stages.
6. **The U.S. Nuclear Regulatory Commission (NRC) should aim to license new enrichment and fuel manufacturing facilities within 18 months.** Considering long construction lead times for enrichment facilities, an efficient licensing process is key for steadily increasing domestic capacity. A target licensing timeline of 18 months for known technology and facility types is a reasonable pace for regulatory review relative to the NRC's licensing of new nuclear reactors in around 18 months. The NRC should modernize and update its regulations and procedures

as needed to ensure timely licensing decisions aligned with this goal. The NRC should similarly seek to license new in-situ recovery uranium production within a comparably prompt timeframe.

7. **Devote federal research efforts and public sector investment to innovative, more efficient enrichment techniques like laser enrichment.** The federal government should invest in research on and commercialization of next-generation enrichment technologies like laser enrichment, which could substantially improve the energy efficiency and economic competitiveness of U.S. enrichment activities,¹¹⁴ while enabling the U.S. nuclear sector to leverage significant volumes of Department of Energy waste materials that still contain large quantities of usable U-235. Using such waste materials could also, at least temporarily, offset or obviate the need for uranium ore mining and conversion to uranium hexafluoride. Overall, commercial-scale adoption of laser diffusion technology could meaningfully accelerate domestic efforts to scale SWU capacity.
8. **Expand state and federal mapping programs that seek to identify domestic uranium resources.** Public sector mapping programs may increase domestic uranium mine production in the long term by encouraging private investment through discovery and assessment of uranium deposits in the U.S. Domestic mapping efforts can identify regions amenable to lower-cost extraction techniques like currently operating in-situ recovery fields in Texas, and can uncover new resources in environmentally benign areas that may simplify project permitting.¹¹⁵ With permitting considerations in mind, mapping campaigns should seek to collect non-geological data as well when characterizing deposits to further expedite environmental reviews. Mineral exploration also furthers geological understanding of different types¹¹⁶ of domestic uranium deposits,¹¹⁷ which can enhance subsequent geological studies and help the private sector better plan operations. All public efforts on this front absorb cost and risk on behalf of the private sector and boost the potential economic competitiveness of U.S. uranium mining. The last national mapping program specifically targeting uranium ended in 1984.¹¹⁸ Policymakers should establish an ongoing mapping program dedicated to uranium and consider expanding the Department of Energy's Uranium Leasing Program,¹¹⁹ which maintains tracts of federal land to safeguard access for uranium development. While the U.S. need not strive for uranium mining self-sufficiency, efforts in this sector remain prudent given import dependence risks, as evidenced by recently announced mine production cuts in Kazakhstan.¹²⁰

- 9. Invest in spent fuel recycling and reprocessing, with appropriate safeguards.** The recent executive order “Reinvigorating the Nuclear Industrial Base” directs new evaluation of spent nuclear fuel reprocessing to facilitate permanent spent fuel management solutions and potentially enable new fuel production from recycled materials.¹²¹ The federal government should indeed support research and development efforts on spent fuel reprocessing technologies under the Department of Energy’s Gateway for Accelerated Innovation in Nuclear (GAIN) and ARPA-E programs. The department’s Loan Programs Office should also clarify the eligibility of spent fuel reprocessing projects for loan guarantees. In addition, the United States should consult with fellow Sapporo 5 alliance members including Japan, France, and the UK¹²² regarding the potential development of U.S. reprocessing, leveraging allies’ experience with commercial fuel reprocessing. Constructing a pilot reprocessing facility can aid in demonstrating technological and operational viability and enabling commercialization. The federal government could eventually award contracts to companies with the capacity to recycle spent fuel into new nuclear fuel. At the same time, fuel reprocessing and recycling should not be imposed as a requirement for nuclear developers.
- 10. Pursue efficiency improvements and new breeder reactor technology that reduce nuclear fuel and enrichment needs.** Research and development efforts to improve the fuel efficiency, thermal efficiency, and fuel material breeding capabilities of next-generation reactors could help alleviate long-term domestic fuel requirements while increasing the technological competitiveness of new U.S. nuclear reactor designs. A new experimental Russian pressurized water reactor, for example, seeks to use U-238 rather than boron as a neutron absorber, with the benefit of breeding plutonium as a product of normal reactor operation.¹²³ With appropriate safeguards, such breeder technologies may reduce national uranium enrichment needs long term, freeing up uranium supply for nuclear fuel production.
- 11. Work with allies and international partners to secure U.S. uranium imports.** Given extremely limited domestic uranium mining particularly in the near term, the United States will depend crucially upon secure supplies of imported uranium from long-standing allies like Canada and Australia to support expansion of domestic nuclear power capacity. The U.S. federal government should prioritize enhanced nuclear technology cooperation and stable trade relations with both Canada and Australia, ensuring long-term, reliable, alternative uranium sourcing while aiding the development and growth of U.S. fuel cycle capabilities. Efforts to minimize trade barriers will also reduce the costs of imported uranium material, improving the economics of U.S. nuclear power generation. Geoscience technical cooperation between the U.S., Canada, and Australia¹²⁴ can also increase long-term uranium mining to support nuclear power development across the U.S. and allied countries.

12. Update Nuclear Regulatory Commission regulations to create avenues for sourcing

uranium for energy sector use from tailings at abandoned uranium mine sites. A promising opportunity exists for policymakers to support regulatory reforms that can simultaneously accelerate remediation efforts at legacy abandoned uranium mine sites in the western U.S., while also establishing new domestic sources of mined uranium. The NRC should adopt updated definitions for uranium milling and byproduct material that exempt remedial actions from regulation under the “byproduct material” approach, so long as such operations significantly remove harmful materials from the site without introducing any additional hazardous materials.¹²⁵ While abandoned mine cleanup efforts are likely to yield relatively small volumes of uranium relative to national requirements, introducing such materials into the market will improve the economics of such advanced remediation approaches and could dramatically accelerate remediation work nationwide.

Global Nuclear Fuel Supply Chain Recommendations

Based on our results, global enrichment capacity can in theory meet low-end projections for future worldwide nuclear deployment, provided that the nuclear industry modestly expands current global enrichment capacity, which totaled ~60 million SWU annually as of 2022.¹²⁶ Based on IEA scenarios with future global nuclear capacity in 2050 ranging from 650 to 1100 GW,¹²⁷ the corresponding enrichment and fuel needs would range from 81 million to 137 million SWU and from 13,000 to 21,000 tons of mainly LEU fuel per year.

In practice, however, many countries are seeking to shift away from Russian SWU capacity because of energy security and geopolitical considerations. At the same time, many governments are also recognizing geopolitical risks associated with a current global nuclear technology landscape where newcomer countries seeking to develop new nuclear power projects have few alternatives other than to partner with Russian or Chinese state nuclear corporations. Currently, in particular, there is no commercial source of HALEU other than Russia. Policymakers who recognize the strategic value of a globally more diversified and competitive nuclear fuel services industry should continue to prioritize efforts to develop viable alternative suppliers of nuclear fuel and nuclear technology more broadly.

The United States doesn't need to meet all its SWU and uranium needs using U.S.-based capacity and can turn to allies to replace Russian supplies. The U.S. should certainly leverage enrichment services and fuel production from its allies where strategic, but should avoid excessive dependence on allied supply. While the U.S. is not competing with allied nations per se, limited domestic capabilities will necessitate fuel purchases from allies to operate U.S. nuclear capacity. In contrast, ambitious efforts

by the United States to move first could establish the U.S. as a supplier for allied countries' nuclear deployment efforts while increasing U.S. investment and energy security.

The following measures can significantly secure and diversify global enriched uranium supplies, while enhancing efforts to establish nuclear energy projects in new countries globally:

- 1. Establish agreements building upon the Sapporo 5 alliance to address current and future nuclear fuel needs among a consortium of like-minded nations, based on shared alignment regarding fuel sourcing and supply concerns.** Global nuclear fuel supply considerations are becoming increasingly scrupulous as governments have reconsidered their willingness to source from Russian SWU providers. Efforts to transition away from Russian supply will proceed more efficiently and successfully if interested nations formally pool their expertise and capabilities, consider supply needs collectively, and pursue opportunities for joint investment. Additional governments can join the promising Sapporo 5 partnership and drive accelerated development of uranium and SWU capacity by coordinating supportive policies, such as by making collective advance procurement commitments for nuclear fuel. Such agreements should prioritize concrete collaborations and projects with clear, quantitative results.
- 2. Pursue joint research efforts and co-investment focused on new uranium production and innovation opportunities in uranium exploration and mining.** Governments should devote particular attention to partnerships that can expand or improve uranium mining, thereby diversifying a uranium supply chain that both currently exhibits excessive overconcentration in Kazakhstan and needs to accommodate substantial future growth in uranium demand. In addition to leading in global mined uranium production, Kazakhstan boasts the largest reserves in the <\$40/kg cost category with 272,000 metric tons (Figure 16).¹²⁸ The only other countries that report potential reserves at this price point are Brazil with 53,000 metric tons, China with 32,000 metric tons, and Spain with 8,000 metric tons. This distribution not only gives Kazakhstan a global cost advantage, but also risks further concentrating production during low price regimes.

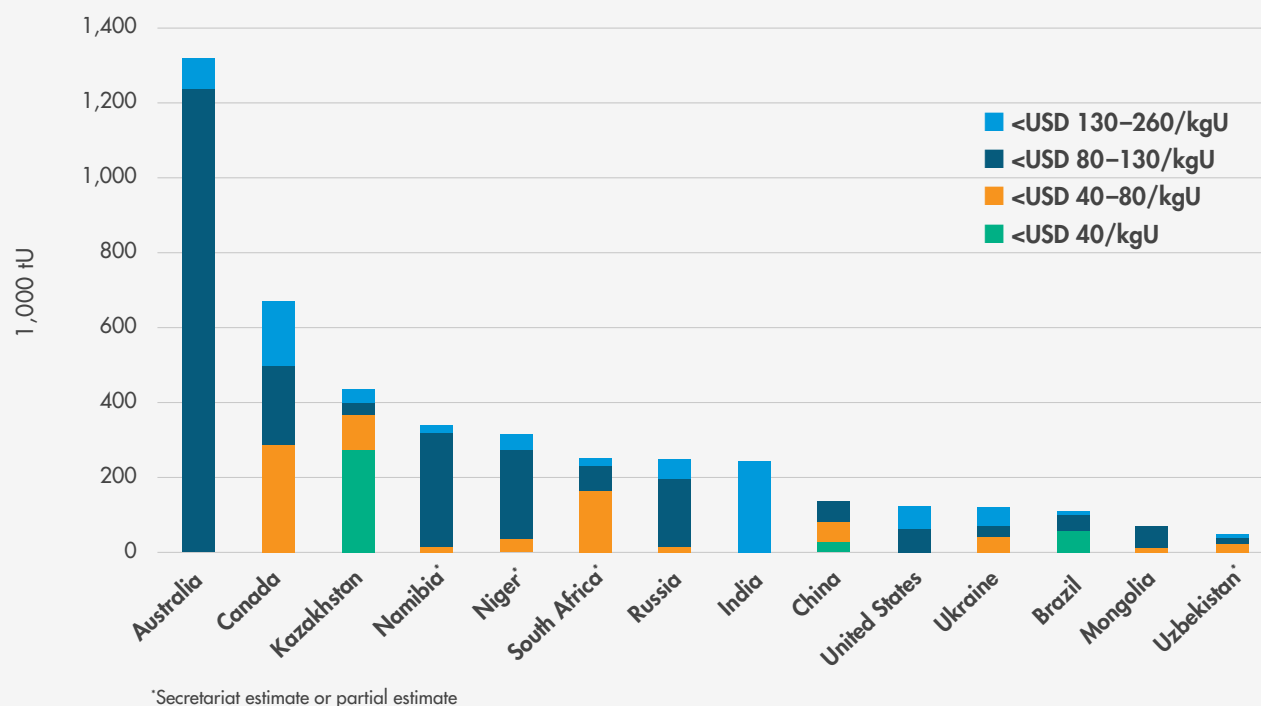


Figure 16: Distribution of reasonably assured recoverable conventional uranium resources among select countries with a significant share of resources. Adapted from Figure 1.2 of NEA's Uranium 2024 report.¹²⁹

A successful international nuclear cooperation consortium must manage risks of uranium supply or trade shocks from certain countries, as exemplified by recent moves by Kazakhstan to reduce its uranium mine production.¹³⁰ Robust reserves exist outside of Kazakhstan albeit at higher price points. Outside of Kazakhstan, countries report combined reserves of 800,000 metric tons at less than \$80/kg, 3.5 million metric tons at less than \$130/kg, and 4.3 million metric tons at less than \$260/kg. Geological surveying may identify more competitive resource deposits, while coordinated research, development, and financing can catalyze new uranium extraction approaches and mine projects.

3. Share best practices for efficient and effective regulation and licensing of fuel cycle projects.

To maximize efficiency in the development of new uranium mining and enrichment capacity, countries should collectively study the range of regulatory approaches in practice around the world and identify lessons learned and best practices to improve their own nuclear sector policies. Such collaborations could save time and avoid duplicated effort in developing new regulatory frameworks, particularly for nuclear newcomer countries.

Where possible, governments should strive to develop and adopt standardized regulatory approaches that could provide greater consistency and simplify compliance for nuclear industry actors that work in multiple national jurisdictions.

4. **Revise international and bilateral agreements to improve access to peaceful uses of nuclear technology, particularly technologies used in nuclear fuel production.** Many policies governing country-to-country nuclear cooperation or international governance of nuclear materials could benefit from targeted changes that reduce technology adoption costs and allow improved industry flexibility for partner nations. Particularly given likely growth across a variety of advanced nuclear technologies that utilize a wider range of fuel materials, it will be important for partnering countries to consider technology cooperation agreements that, with appropriate safeguards and oversight, grant recipient countries more flexibility to move, repackage, or alter nuclear materials. This cooperation is crucial to overcome political barriers to new nuclear deployment often associated with the management of spent nuclear fuel, by enabling all parties to pursue efficient and safe solutions most appropriate for their specific national circumstances. Excessively rigid terms of cooperation that make potential partner countries feel undervalued will increase the risk that those countries select China or Russia as nuclear technology providers. At the same time, cooperation agreements should maintain strict governance limits against transferring nuclear technology to third-party nations beyond the scope of the partnership.
5. **Develop secure and effective frameworks for spent nuclear fuel management, including spent fuel exchange and take-back between countries.** Given that many commercial reactors today conduct refueling operations every 18 months, spent fuel management poses a financial and political challenge for many countries seeking to develop nuclear power projects for the first time. Governments should strive to establish secure programs for transferring or returning spent nuclear fuel across national borders. Domestic progress toward long-term storage facilities and/or reprocessing capabilities will crucially aid development of such frameworks. Policymakers must also proactively work to achieve consensus with citizens and communities who may oppose receipt of spent fuel from overseas.

Such options can enable more rapid scale-up of projects for nuclear newcomer countries, simplify nonproliferation safeguards, and increase the international competitiveness of nuclear technology cooperation efforts relative to Russian contracts that already offer spent nuclear fuel take-back services. Such programs may also play a helpful long-term role in securing nuclear fuel supplies by expanding the production of new nuclear fuel by countries like Japan or France that have developed the capability to reprocess spent fuel. France,

for instance, has produced new nuclear fuel¹³¹ by reprocessing spent fuel imported from other countries for decades.¹³² Trade and take-back of spent nuclear fuel may similarly create opportunities benefiting efforts to establish reprocessing capacity in the United States.

- 6. Establish international HALEU banks to create strong market demand signals and secure HALEU supply for new nuclear projects.** As would be the case for a U.S. HALEU bank, coalitional HALEU banks involving a network of partner countries could similarly help grow enrichment capacity by creating a strong market demand signal for HALEU. Intergovernmental organizations such as the OECD's Nuclear Energy Agency could establish banks for HALEU to ensure greater certainty of supply for international nuclear developers. While the IAEA maintains a limited fuel bank for low-enriched nuclear fuel, this bank specifically exists to provide an emergency response buffer to supply fuel for conventional light-water reactors in the event of fuel supply disruptions. As a neutral international regulator of nuclear energy, the IAEA would not be an appropriate venue for a HALEU bank seeking to de-risk nuclear energy projects and nuclear technology development efforts.
- 7. Expand and facilitate international scholarship in nuclear physics, nuclear engineering, materials science, and related disciplines to foster global development of a robust skilled technical workforce.** Many governments and industry stakeholders have highlighted a shortage of skilled workers relative to growing technical, research, and operational needs in the global nuclear industry. To alleviate potential workforce-related bottlenecks to the development of more robust nuclear fuel supply chains, governments should prioritize increased public educational funding of relevant technical disciplines and assist partner nations in workforce training through executive and student exchange programs. Where programs already exist, countries should seek to strengthen and expand workforce partnerships. Recognizing that engineers and operators require specific training to work in the nuclear sector, policymakers should design training programs to facilitate and standardize workforce development. As a trained workforce is essential for any international consortium to scale up nuclear deployment efforts, the case for workforce capacity growth is clear; such expansion will easily recoup its associated costs through expanded nuclear investment and follow-on economic growth.

FUELING A VIBRANT NUCLEAR FUTURE

The greatest challenge the U.S. and its allies face in building nuclear fuel supply chains capable of meeting their nuclear energy policy goals is one of sheer scale. Without enrichment and fuel services at sufficient scale, a large-scale buildout of new U.S. nuclear power projects categorically will not happen. A chief concern today of many potential customers considering an advanced nuclear project is whether the required HALEU fuel will be available to operate the reactor.

From the starting point of an enrichment industry—outside of Russia—accustomed to stagnant if not decaying market demand, the enrichment sector must now grow at a pace sufficient to support potentially hundreds of gigawatts of new operating nuclear capacity each decade beginning in the 2030s. Failure to achieve the needed scale at this front end of the nuclear fuel cycle will create a supply bottleneck that will in turn directly limit the magnitude of nuclear deployment. Even the short-term objective of transitioning many North American and European countries away from previous reliance on Russian enrichment services will pose difficulties, particularly in the absence of sufficient supporting policy.

The U.S. must rapidly expand secure uranium supplies and secure added domestic enrichment and conversion capacity on the order of 31 to 96 million SWU annually, five to ten times larger than the total capacity of domestic enrichment projects currently operating or starting production within the coming years. Well-designed public policy efforts must chiefly prioritize the development of projects and suppliers with a credible potential to achieve adequate scale. The federal government should also establish strong demand signals to reduce market uncertainty and perceived risk that are slowing development of a domestic enrichment sector, leveraging a Department of Energy HALEU fuel bank¹³³ and firm federal commitments to procure new nuclear-generated electricity. Meanwhile, public research efforts and regulatory reforms can dramatically facilitate a rapid large-scale buildout of new projects. Overall, successfully establishing robust U.S. enrichment capacity will simultaneously wean the U.S. off Russian uranium dependence, bolster overall national energy security, and accelerate advanced nuclear energy development.

As the U.S. prioritizes its nuclear energy future, it must also consider its role in global nuclear technology leadership. Collectively, the U.S. and a consortium of its allies must increase enrichment capabilities to keep pace with newfound momentum in nuclear sector demand worldwide, aiming to adequately fulfill the supply needs created by the shared shift away from Russian state-owned uranium enrichment services. The U.S. faces a number of possible choices in this context, ranging from growing its enrichment capacity to become a service provider for global markets, to achieving self-sufficiency, to remaining a customer dependent on purchasing such services from overseas partners.

By leading the charge in expanding enrichment capabilities and diversifying the nuclear fuel supply chain, the U.S. and its allies can position their new nuclear deployment efforts for success and support a more resilient and sustainable global nuclear industry at a time the world needs it the most.

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