AVC-VTN-21N04

More than We Need: Projected World Uranium Enrichment Capacity

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Final Technical Report
Under DOS Contract No. 19AQMM19P2400
(09/08/2021-10/26/2021)

Submitted to
U.S. Department of State
2201 C Street, NW
Washington, DC 20520

October 2021

REPORT DOCUMENTATION PAGE			*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*: 26 October 2021

2. REPORT TYPE: Topical Report

3. DATES COVERED *(From - To)*: 9 Sep 2021 - 26 Oct 2021

4. TITLE AND SUBTITLE
More than We Need: Projected World Uranium Enrichment Capacity

5a. CONTRACT NUMBER
DOS 19AQMM19P2400

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Ruaridh Macdonald

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Nonproliferation Policy Education Center, 1600 Wilson Blvd., Suite 640, Arlington, VA 22209

8. PERFORMING ORGANIZATION REPORT NUMBER
NPEC Report No.2106

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Department of State / Bureau of Arms Control, Verification, & Compliance
2201 C Street, NW
Washington, DC 20520

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
AVC-VTN-21-N04

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified//Public Release Authorized

13. SUPPLEMENTARY NOTES
Jointly funded with the MacArthur Foundation, the Scaife Foundation, and the Carnegie Corporation of New York.

14. ABSTRACT
With America's latest offer to facilitate the construction of six to twelve nuclear submarines for Australia, a question has arisen how these boats might be fueled. The attached study on the world's projected uranium enrichment capacity, however, eliminates one concern for sure: We won't need to build additional enrichment plants to keep this project on track. As Ruaridh Macdonald of MIT makes clear in his study, "More than We Need: Projected World Uranium Enrichment Capacity," there currently is an oversupply of global enrichment capacity, which is unlikely to be exhausted anytime soon. There is a worry, however, that despite this oversupply, countries like Saudi Arabia, South Korea, and Turkey, might build enrichment plants that could also support nuclear weapons options. In the upcoming Nuclear Proliferation Treaty Review Conference this February, the United States and other like-minded nations should make it clear that there is no legitimate economic reason for states to go down this path.

15. SUBJECT TERMS
Uranium Enrichment, Enrichment Plants, Oversupply, Saudi Arabia, South Korea, Tyrkey, Nuclear Weapons, Nuclear Proliferation Treaty (NPT)

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Rongsong Jih (COR)
UU	UU	UU	UU	158	19b. TELEPHONE NUMBER *(Include area code)* +1-202-647-8126

OCCASIONAL PAPER 2106

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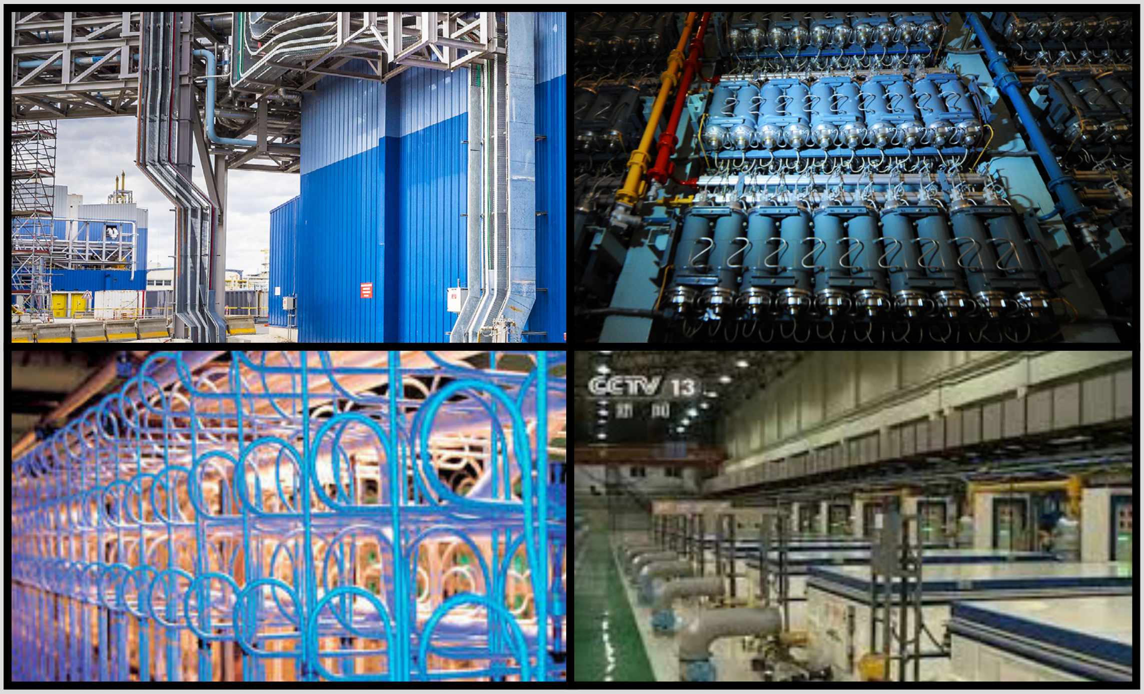

October 2021

NPEC
Nonproliferation Policy Education Center

Nonproliferation Policy Education Center
Arlington, VA 22209
www.npolicy.org

Printed in the United States of America

Cover images, from top left clockwise: 1) Orano's Philippe Coaste Plant where uranium tetrafluoride (UF4) is converted into uranium hexafluoride (UF6) (image: Orano); 2) In the main separation process area of the Ural Electrochemical Integrated Plant (UEIP), owned by the Rosatom State Corporation at Novouralsk, Russia, July 4, 2014 (image: Donat Sorokin/ITAR-TASS/Alamy Live News); 3) Inside the uranium enrichment plant in Lanzhou, China, June 24, 2013 (image: CCTV); 4) A bank of centifuges inside an Urenco enrichment plant (image: Urenco).

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Nonproliferation Policy Education Center
Occasional Paper 2106

October 2021
Series Editor: Henry D. Sokolski

Nonproliferation Policy Education Center

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Editor's Acknowledgements:

This research was supported by generous grants from the MacArthur Foundation, the Sarah Scaife Foundation, the Carnegie Corporation of New York, and the U.S. Department of State's Bureau of Arms Control Verification and Compliance.

Author's Acknowledgements:

The author would like to thank Henry Sokolski for his comments and feedback in writing this paper.

More than We Need: Projected World Uranium Enrichment Capacity

Ruaridh Macdonald

Summary

The global energy system will undergo major changes over the next twenty years to 2040. The extent of nuclear power's role is uncertain, but likely to grow moderately, especially in Asia. Global uranium enrichment demand should remain less than the total available enrichment capacity, but domestic production mandates in China, and potentially the USA, may leave some capacity stranded. Enrichment providers will have to form partnerships with reactor vendors and governments to provide turnkey fission power plants and fuel, in order to avoid being locked out of the market.

Significant overinvestment in enrichment capacity during the 90s and first decade of this century has reduced the price of separative work units (SWU), a measure of enrichment effort and capacity, to less than half its long-term average. This and the fact that many reactors are older and able to purchase fuel from any provider has created a highly competitive global market with four major providers: TVEL (Russia), CNNC (China), Urenco (UK, DE, NL), and Orano (France) together producing 99.5% of the world's SWU.

SWU demand for large reactor fuel will shift towards Asia over the next twenty years. There will be a 10 - 40% net decrease in the number of North American and European large reactors, depending on the success of license-extension efforts and trends in the price of variable renewable energy and energy storage. Globally, this will be more than offset by capacity growth elsewhere in the world, particularly China. However, the Chinese government has set a goal of achieving enrichment self-sufficiency and is building 10-15 reactors-worth of enrichment capacity each year, denying foreign vendors access.

TVEL, Urenco, and Orano will see a net decrease in demand unless they can capture other new business in Asia. Russia and China are offering comprehensive reactor deals, including fuel and financing, to make their exports more appealing. Orano has the capability to do the same in partnership with EDF, but this will depend on securing EPR newbuilds outside of France. Urenco does not have national reactor vendors to cooperate with, and the USA, South Korea, Canada, and Japan reactor vendors do not have domestically-owned SWU providers able to export large volumes of fuel. To avoid being left with excess capacity, Urenco will have to partner with these vendors or make the case to customers to diversify their fuel supply in order to reduce their dependence on China and Russia.

Advanced small and microreactors will be a new source of SWU demand. If small reactors are very successful, total SWU demand may exceed current predictions of global enrichment capacity. Smaller reactors require more SWU per GWd-e output and new exotic fuels, often with higher uranium enrichments than currently used in civilian reactors. While existing facilities are technically capable of producing these fuels, new licenses are required and regulators may prefer separate sites. Urenco and TVEL have the most experience with these new fuels and are currently offering delivery from existing facilities within 24 and 9 months respectively. New reactor vendors in many countries are developing small reactors for export. China has made the largest investment, followed by the USA, and arguably has first-mover advantage. If it successfully captures a large fraction of the small reactor market, TVEL, Urenco, and Orano will again

see a net decrease in SWU demand.

The USA, South Korea, and Saudi Arabia are considering new domestic enrichment facilities to protect their SWU supply, support reactor exports, and possible military purposes. This is very expensive, costing at least $1000/(SWU/yr) for capacity versus $50/SWU on international markets. The three states are moving forward because there are legal and policy disagreements on whether imported uranium can be used for military non-weapon uses, such as naval fuel and tritium production, and they believe domestic SWU supply will also support their broader nuclear industries.

The anticipated changes to global enrichment capacity will create new proliferation pathways and incentives for states, and may challenge the IAEA nuclear safeguards system. The vast majority of new capacity will be in China, which is not subject to full IAEA safeguards because it is a nuclear weapon state. However, if other states fear that China will use this additional capacity to increase its nuclear arsenal, some may be inclined to develop their own nuclear deterrent, leaving the IAEA and international community with a very difficult task. A similar risk exists if Saudi Arabia is allowed to build and operate a large civilian enrichment facility.

New large civilian enrichment capacity in non-nuclear weapon states, such as South Korea, Japan, and Saudi Arabia, will make it possible for them to very quickly repurpose uranium and centrifuges to produce weapon material. Alternatively, they could use their large civilian programme as a cover to procure material and expertise for a covert enrichment programme. Widespread use of 20% enriched civilian fuel would increase this risk, as less material and enrichment capacity would be needed to produce a weapon.

While new enrichment capacity will create the opportunity for states to develop weapons, it is not a foregone conclusion. IAEA powers have been strengthened since the 1970s-90s and the international community has shown that sanctions and diplomacy can have a deterring or stalling effect. In extremis, cyberattacks are an increasingly potent means of disrupting weapons programmes. As the world becomes less unipolar, it will remain critically important that the USA and other major powers provide the assurances and extended deterrence necessary to reduce the appeal of nuclear weapons.

Factors influencing uranium enrichment demand 2020-2040

Demand Source	2020 Demand [MSU/yr]	2040 Demand [MSWU/yr]			Notes
		Low	Mid	High	
Large reactors	51.19	45.24	72.60	84.70	Variation mostly due to different estimates of reactor retirements in North America and Europe. Significant SWU demand growth expected in China, but corresponding enrichment capacity is already under construction in China.
Small & advanced reactors	0.013	0.149	3.285	12.692	Significant variation due to uncertainty in the cost and market-fit of new reactors. USA and China most likely to lead reactor export market; followed by Canada, Russia, UK, South Korea, and Japan. Small reactor sales may reduce large reactor exports and construction, stranding some SWU capacity if vendors also bundle enrichment and other services with reactor sale and exclude third party providers.
Research reactors	0.028	0.038	0.065	0.143	Converting research reactors from weapons-grade uranium to 20% enriched civilian-grade uranium will require some new facilities. Variation is due to the pace of the transition. Mostly presents regulatory challenges, with little further growth potential.
LEU naval reactors	0	0	0.1	0.2	The USA, South Korea, and Brazil have expressed interest in developing military vessels powered by nuclear reactors using civilian-grade fuel. This raises multiple proliferation issues, but the slow pace of development and procurement, and the small overall size, means it will create very little SWU demand by 2040
Switch to domestic enrichment	0	0	0.5	4	There is discussion in the USA about supporting domestic US-owned SWU capacity on energy security grounds and to increase the competitiveness of reactor exports. China, Russia, and European vendors already have domestic enrichment providers. This would be costly and alternatives exist, so the aggregate change to SWU demand is very uncertain. Other states have expressed interest in the same, but domestic enrichment is more contentious for non-nuclear weapon states due to proliferation concerns. If this policy is adopted, it will displace some SWU demand from other categories by forcing it to be met by domestic providers.
Total	51.231	45.427	76.550	100.74	

Enrichment service providers capacity 2020-2040

Provider	2020 Capacity [MSU/yr]	2040 Capacity [MSWU/yr]	Notes
China (CNNC)	7.5	16-37	Constructing SWU capacity to match domestic large reactor demand. Does not appear interested in entering SWU export market, but will add capacity to support reactor exports, if they appear. Hualong One reactor appears promising for exports. Small reactor prototypes are leading the world. Export success in either area, including potentially selling to Europe, would reduce Urenco & TVEL's available market.
Russia (TVEL)	28	>25	Benefits from very cheap energy and labor, as well as state support for exports. SWU capacity scheduled to drop, but has 5-6MSWU/yr excess capacity currently used for tails enrichment and is able to quickly add more. Very successful at reactor exports, but poor international relations may stymie future success. Has limited new reactor designs for future exports. If exports continue it will create new business, otherwise TVEL will rely on being the lowest cost supplier, selling SWU for reactors which do not have an associated national enrichment provider, e.g. Canada, Japan, South Korea. In this role, it benefits from integration with Russian providers in other parts of the fuel cycle and experience with HALEU and other new fuels.
UK, DE, NL (Urenco Europe)	13.7	>10.7	Currently exports to a wide variety of customers, especially reactors which are not limited to fuel from the original vendor. Will see their available market drop significantly if the USA, China, or Russia are very successful with new exports and limit customers to purchasing SWU from domestic suppliers. If vendors from other states succeed, or the USA does not require US-produced SWU, then Urenco may become the first-choice supplier for operators seeking to diversify their SWU purchases, as seen in the UAE.
France (Orano)	7.5	7.5	Exports relatively little of its SWU output, being focused on supplying France. France has delayed its reactor closures and plans new EPRs, which will create demand for Orano to meet. Will support EPR and Nuward exports, though demand is unclear.
USA (Urenco USA, Centrus)	4.8	>4.8	Most uncertain of the large providers. Imports the most SWU/yr, in absolute terms. Previous national SWU facilities were nationalized and closed. Is considering means of supporting domestic nuclear fuel cycle. Recently purchased HALEU fuel from Centrus to make available for R&D. Could use trade barriers or source of origin rules to expand domestic production and support new reactor exports. Has several promising small reactors under development, but competitiveness is unclear.
Japan (JNFL)	0.075	<1.5	Has one facility which is being upgraded with new centrifuges. Reactor exports have not revitalized sufficiently to cover weak domestic demand and reactor construction. While behind China and the USA, it has very promising new small reactors under development. Very unlikely to construct new enrichment facilities to support exports, given previous overruns and low international SWU price.
Argentina, Brazil, DPRK, India, Iran	0.1	<0.5	Multiple states have small enrichment facilities, however none appear interested in expanding their enrichment to meet international demand.
ROK	0	<3.5	The ROK is a growing nuclear exporter and manufacturer, having recently sold and now constructing four large reactors in the UAE. Recently loosened international commitments to not seek domestic enrichment facilities, though it is unclear if it would enrich material for commercial fuel or limited niche and military uses. Very sensitive politically given tensions with North Korea and the proliferation risk of new facilities.
Australia, Argentina, Canada, South Africa, Saudi Arabia, Vietnam	0	0	States with significant or growing participation in the nuclear industry, or who previously developed enrichment technology. None are likely to develop domestic enrichment due to the low SWU price on international market and pressure from other states to deter new enrichment facilities in non-nuclear weapon states.
Total	61.8	>74	

Sources of Demand for Enrichment Services

There will be five principle sources of demand for uranium enrichment services between 2020 - 2040:

- Nuclear fuel for large commercial reactors
- Nuclear fuel for the development and deployment of small and advanced reactors
- Specialist fuel for research and medical isotope reactors
- Civilian-grade nuclear fuel for military naval propulsion
- Mandated domestic production of uranium on energy security grounds, and to increase the competitiveness of strategic exports and influence of nuclear non-proliferation issues

The global energy system is in the midst of a massive transition, precipitated by the falling cost of variable renewable energy (VRE) generation and increased concern about climate change. This makes medium and long-term estimates of uranium enrichment capacity (aka separative work units, or SWU capacity) very uncertain. However, these five sources of demand can serve as indicators of the direction and magnitude of traffic, and we can anticipate where new SWU capacity will be constructed based on the likely responses of current and potential SWU providers to changes in demand.

Large reactor fuel

Today, approximately 51 million SWU (MSWU) are used to provide low enriched uranium (LEU) at 3-5% enrichment for the world's 396GWe of large reactors.[1,2,3] Large reactors will continue to be the largest source of demand to 2040.

Figure 1 and Table 1 show the estimated changes in large nuclear reactor capacity and associated SWU demand between now and 2040. Large reactor capacity is forecast to grow by 30% to 2040, almost entirely due to new reactors in Asia.[4,5] In the most pessimistic forecasts, reactor capacity will fall by 10% due to additional economic pressure from VREs and cheap natural gas, and rejected license extension requests. The most optimistic forecasts see a doubling in capacity, caused by increased government support for emissions reduction and anaemic cost reductions to battery storage and other alternatives.[6] Most high-growth scenarios predict a 42% increase to just under 570GWe.[7,8]

The various models of large reactor require different amounts of SWU per energy output, i.e. SWU/GWd-t, making it challenging to estimate SWU demand from changes in nuclear generating capacity. Modern reactors are slightly more SWU intensive than older ones, because their improved fuel utilization is outweighed by the greater SWU needed to raise the fuel enrichment to 5%. A Gen-III PWR requires 125-

1. "Energy, Electricity and Nuclear Power Estimates for the Period up to 2050," IAEA, 2019.
2. "World Energy Outlook 2020," IEA, 2020.
3. "The Nuclear Fuel Report: Expanded Summary," World Nuclear Association, 2020.
4. "Energy, Electricity and Nuclear Power Estimates for the Period up to 2050," IAEA, 2019.
5. "World Energy Outlook 2020," IEA, 2020.
6. "The Nuclear Fuel Report: Expanded Summary," World Nuclear Association, 2020.
7. "Energy, Electricity and Nuclear Power Estimates for the Period up to 2050," IAEA, 2019.
8. "World Energy Outlook 2020," IEA, 2020.

150SWU/GWd-t, compared to 110-130SWU/GWd-t for an older Gen-II reactor.[9,10,11] Certain designs are very SWU efficient, such as the Canadian and Indian pressurized heavy water reactors, requiring 35SWU/GWd-t or less. However, there are no free lunches and these reactors consume a greater total amount of fuel, albeit at very low enrichment. Comparing reactor designs is complicated further by differences in the capacity factors and operation of specific power plants. Figure 2 shows the SWU intensity of various reactors, and Appendix B discusses the metric in greater detail.

The IEA and IAEA have estimated nuclear power capacity changes by region.[12,13] They foresee a 10-50% reduction in the USA, driven by reactors reaching the end of their 60-year licenses and facing reduced and volatile electricity prices caused by VRE and cheap natural gas. This will result in a 1-6MSWU/yr decrease in annual SWU requirements, from 13.5MSWU/yr currently. Shutdowns could be limited by extending licenses to 80 years where appropriate, and increasing compensation for grid stability services or GHG non-emission. Many European reactors also face retirement before 2040, with a 20-55% reduction in power and SWU demand (from 14MWSU/yr) predicted unless licenses are extended. Russia is replacing older reactors with new VVER 1200s, leading to a net increase of up to 2GWe and 1MSWU/yr of enrichment demand.

This contrasts with eastern and southern Asia, where a 60% net-increase in power capacity is forecast. India and China will add 25-31GWe and 87-113GWe of capacity respectively, contributing to a 25-150% increase in nuclear power capacity in the region overall. The new Chinese reactors will increase SWU demand by 12-16.5MSWU/yr, while the Indian reactors will only require 1MSWU/yr due to their use of very low enriched fuel. These growth predictions are driven by the fact that very few Asian reactors will retire by 2040 and nuclear power is favoured there as a source of low-emission, reliable power. Though China has made significant investments in other generation, particularly VREs, it also lifted a soft moratorium on new reactor licences in the last two years[14] and the 14th Five Year Plan targets 70GWe of capacity by 2025.[15]

The reduction in European and North American nuclear generation and SWU demand, alongside China's plan to meet all of its additional SWU demand itself, means non-Chinese SWU providers face a 3.8-13.7MSWU/yr reduction in large reactor SWU demand. This will be a very large disruption unless matched by increased demand in other sectors.

9. "Advanced Large Water Cooled Reactors," IAEA, 2020.
10. "Advanced Reactor Information System," IAEA, [Online]. Available: https://aris.iaea.org/.
11. "Power Reactor Information System," IAEA, [Online]. Available: https://pris.iaea.org/PRIS/CountryStatistics/CountryStatisticsLandingPage.aspx.
12. "Energy, Electricity and Nuclear Power Estimates for the Period up to 2050," IAEA, 2019.
13. "World Energy Outlook 2020," IEA, 2020.
14. Presentation by Prof Ning Li, 2019.
15. M. Meidan, P. Andews-Speed and Y. Qin, "Key issues for China's 14th Five Year Plan," Oxford Institute for Energy Studies, 2021.

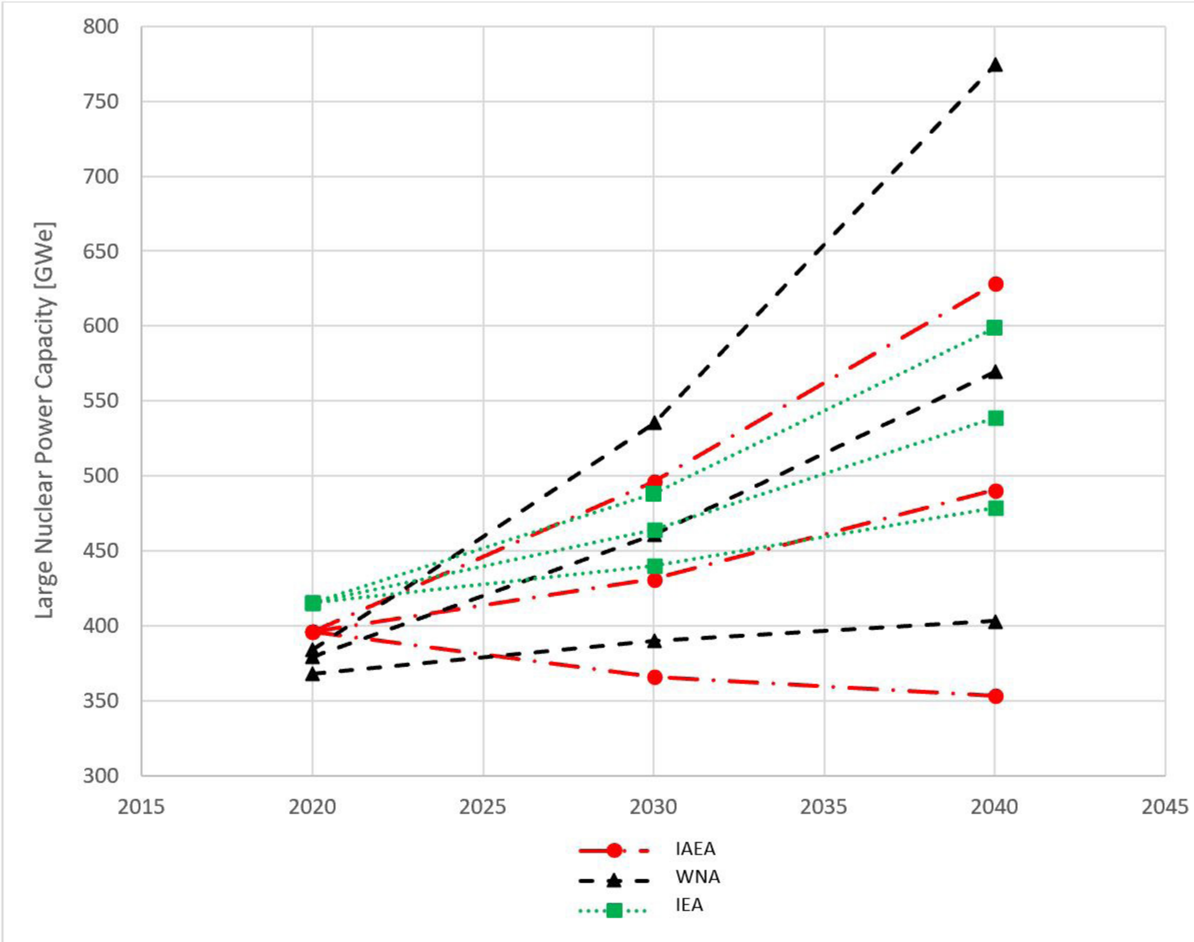

Figure 1. Estimates of global nuclear power plant capacity [GWe] from 2020-2040, by the IAEA, World Nuclear Association, and IEA.[16,17,18] A high, expected, and low estimate is shown for each organization. Differences in the 2020 capacities are due to differences in how reactors which are shutdown for extended periods, but not permanently closed, are accounted for.

16. "Energy, Electricity and Nuclear Power Estimates for the Period up to 2050," IAEA, 2019.
17. "World Energy Outlook 2020," IEA, 2020.
18. "The Nuclear Fuel Report: Expanded Summary," World Nuclear Association, 2020.

	2020			2030			2040		
	Nameplate power [GWe]	SWU intensity [SWU/GWd-t]	Annual SWU demand [MSWU/yr]	Nameplate power [GWe]	SWU intensity [SWU/GWd-t]	Annual SWU demand [MSWU/yr]	Nameplate power [GWe]	SWU intensity [SWU/GWd-t]	Annual SWU demand [MSWU/yr]
Low				365	120	47.18	350	125	45.24
Mid	396	120	51.2	460	120	59.46	540	125	72.60
High				500	125	67.22	630	130	84.70

Table 1. Estimates of global annual SWU requirements in 2030 and 2040, based on estimates of nuclear power plant capacity[19,20,21] and the SWU intensity of nuclear reactors.[22,23,24,25,26,27,28,29,30,31]

Small and advanced reactor fuel

Small and advanced reactors are increasingly seen as the future of the nuclear power industry and their success may require new fuels and additional enrichment facilities around the world. They are most popular in the West, where the business case for large reactors is weakest, but China leads the world in investment and many countries have reactor development programmes.

Much of the focus is on small modular reactors (SMRs) and microreactors. Large advanced reactors offer significant technical improvements, but there is concern that they do not resolve underlying issues with the business case and financial risk of GW-scale reactors. This makes it unlikely that large advanced reactors will create significant enrichment demand by 2040. SMRs and microreactors are 30-300MWe and 1-30MWe respectively, and trade poorer economies of engineering scale (i.e. the amount of concrete required per MWe) for better economies of operational and manufacturing scale (i.e. 100% factory construction and simpler safety). Lower total costs and greater flexibility make them better suited to the changes in energy markets.

SMRs and microreactors are not incorporated into models of future global and country energy systems due to their newness and uncertainty in their costs and capabilities. Bespoke estimates of SMR installed capacity in 2035, by the NEA, UxC, and UK NNL, range over 0.9-85GWe.[32] The NEA and UxC gave middle-case predictions of 21GWe and 22GWe by 2035 and 2040 respectively. All three reports predate the increased interest in microreactors, but it is not clear if microreactors will appeal to new markets or

19. "Energy, Electricity and Nuclear Power Estimates for the Period up to 2050," IAEA, 2019.
20. "World Energy Outlook 2020," IEA, 2020.
21. "The Nuclear Fuel Report: Expanded Summary," World Nuclear Association, 2020
22. "Advanced Large Water Cooled Reactors," IAEA, 2020.
23. "Advanced Reactor Information System," IAEA, [Online]. Available: https://aris.iaea.org/.
24. "Power Reactor Information System," IAEA, [Online]. Available: https://pris.iaea.org/PRIS/CountryStatistics/CountryStatisticsLandingPage.aspx.
25. "Advances in Small Modular Reactors," IAEA, 2018.
26. "Advances in Small Modular Reactor Technology," IAEA, 2020.
27. T. Xin, "Safety Approach and Safety Assessment of Hualong One," Hualong Pressurized Water Reactor Tech Corp, 2018.
28. M. Ding, J. L. Kloosterman, T. Koojiman and R. Linssen, "Design of a U-Battery," Delft, 2011.
29. "Generic Design Assessment Step 2 Assessment of the Fuel & Core Design of the UK HPR1000 Reactor," UK Office of Nuclear Regulation, 2018.
30. B. Shalaby, "AECL and HWR Experience," World Nuclear University, 2010.
31. S. Azeez, P. Dick and J. Hopwood, "The Enhanced CANDU 6TM Reactor," Atomic Energy of Canada Ltd, 2009.
32. "Small Modular Reactors: Nuclear Energy Market Potential for Near-term Deployment," OECD NEA, 2016.

cannibalize the SMR market share, which would affect the net change in SWU required.

SMRs and microreactors are more SWU intensive than large nuclear power plants. Smaller reactors are less fuel-efficient and are designed to refuel every 2-10 years, rather than the 12-18 months typical for a large reactor. These challenges are overcome by increasing the fuel enrichment and/or reducing the overall fuel-utilization (i.e. adding more fuel to the reactor and depleting each assembly less). Both solutions increase the SWU/GWd-t required by the reactor. SMRs will require 135-400SWU/GWd-t, as shown in Figure 2, while microreactors may require as much as 10,000SWU/GWd-t.

Table 2 shows estimated SWU demand for SMR and microreactor fuel across the range of capacity estimates for 2040. This calculation uses an average thermal efficiency and SWU intensity across a fleet of SMRs and microreactors. It suggests SMRs and microreactors will require 0.15-12.7MSWU/yr. The wide range reflects the uncertainty in installed generating capacity.

The NEI surveyed US reactor developers in 2018 and 2020 to estimate national demand for high assay low-enriched (HALEU) fuel for the development and deployments of SMRs and microreactors up to 2032.[33,34] This suggested annual demand will rise to 266.6 tonnes of HALEU in 2032, or 2-9.76MSWU/yr. Figure 3 gives the entire trend. While this is only 13% of present US civilian fuel demand, it is 75% of US SWU demand, due to the greater amount of SWU required to produce HALEU fuel. The survey was made as part of an effort to encourage the US government to invest in new enrichment capability, and only considers US developers. However, it supports 12.7MSWU/yr as an upper estimate for global SMR and microreactor enrichment demand.

In the previous section, we showed that large reactor demand should fall by 3.8-13.7MSWU/yr, which would suggest that spare capacity will be available to meet 0.15-12.7MSWU/yr of SMR and microreactor demand. This will depend on the degree to which small and large reactors compete with one another, uncertainty in the SWU intensity of small reactors, and whether advanced fuels require separate enrichment facilities.

If small and large reactors operate in different market segments then we expect there to be a lower net decrease in large reactor capacity, and more small reactor enrichment demand may need to be met by new enrichment facilities and capacity. If this is not the case or governments and investors choose to pause investments in large reactors while they wait to see the economics of SMRs and microreactors, then small reactor SWU demand will replace large reactor SWU demand to a much greater extent.

33. E. Redmond, "HALEU Needs for Commercial Reactors," NEI, 2020.

34. M. Korsnick, Need for High-Assay Low Enriched Uranium - NEI Letter to Sec Perry, Nuclear Energy Institute, 2018.

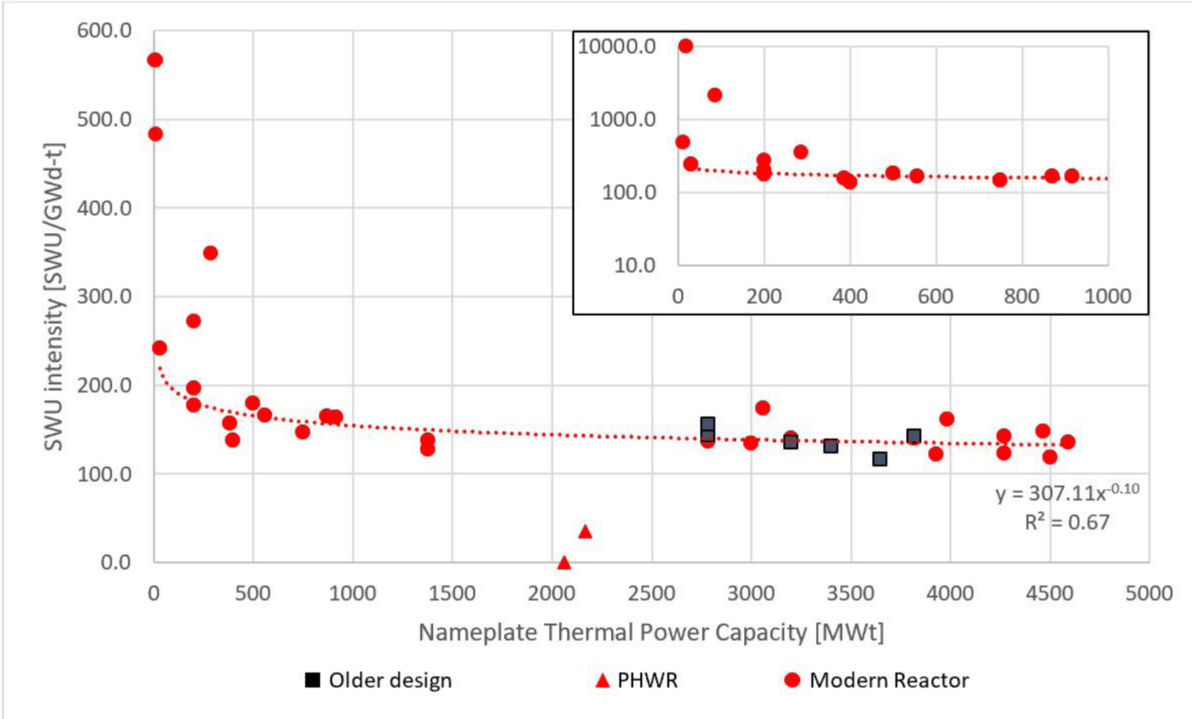

Figure 2. Main: SWU intensity of various constructed and planned reactor types vs their nameplate thermal power capacity. The data is given in Appendix B. The four black squares denote older Gen II reactors, including a US PWR, VVER-1000, older VVER-440, and VVER-440 with modern fuel. The very low triangular datapoints are PHWR designs using 1.1% enriched LEU or natural uranium. The line of best fit does not account for three outliers below 300MWt, in order to improve the fit. **Inset:** The same comparison for small reactors, including some microreactors with very high SWU intensities. It shares the same axes as the main plot.

	Nameplate power [GWe]	Thermal efficiency	Capacity factor	Annual thermal output [GWd-t / yr]	SWU intensity [SWU/GWd-t]	Annual SWU demand [MSWU / yr]	Annual SWU demand per GWe [MSWU / GWe / yr]
Low	1	0.33	0.75	829.5	180	0.149	0.149
Mid	22	0.33	0.75	18250	180	3.285	0.149
High	85	0.33	0.75	70511	180	12.692	0.149

Table 2. Annual SWU demand for a representative fleet of SMRs and microreactors, based on estimates of their installed capacity in 2040.[35,36,37,38,39,40,41,42,43,44]

Small reactor SWU demand will vary significantly depending on the specific reactor designs constructed. Table 3 shows the annual SWU demand for a selection of small reactor designs. More are given in Appendix B. The choice of which reactor to develop first has many factors, and enrichment concerns are not given top consideration. As an example, while NuScale requires more SWU than a Xe-100, it uses the same type of fuel found in existing large reactors, which will make it faster to bring to market. Given the low price of SWU and uranium currently, most investors would prioritize time-to-market and choose NuScale.

Many of the new SMRs and microreactors under development require new fuels types, some of which cannot be produced at existing fuel enrichment and fabrication facilities. Multiple reactor vendors have proposed designs using 19.75% enriched fuel to maximize the performance and/or period between refuelling.[45,46] These HALEU fuels, enriched between 10-20% can be converted more easily into weapon material so are subject to additional regulations and safeguards.[47,48,49]

From a technical point of view, existing gas centrifuge enrichment facilities can be repurposed to produce HALEU.[50,51] The major SWU providers have experience of producing HALEU and keeping those production lines secure and separate from normal low-enriched uranium (LEU) production, at least on small

35. "Advanced Large Water Cooled Reactors," IAEA, 2020.
36. "Advanced Reactor Information System," IAEA, [Online]. Available: https://aris.iaea.org/.
37. "Power Reactor Information System," IAEA, [Online]. Available: https://pris.iaea.org/PRIS/CountryStatistics/CountryStatisticsLandingPage.aspx.
38. "Advances in Small Modular Reactors," IAEA, 2018.
39. "Advances in Small Modular Reactor Technology," IAEA, 2020.
40. T. Xin, "Safety Approach and Safety Assessment of Hualong One," Hualong Pressurized Water Reactor Tech Corp, 2018.
41. M. Ding, J. L. Kloosterman, T. Koojiman and R. Linssen, "Design of a U-Battery," Delft, 2011.
42. "Generic Design Assessment Step 2 Assessment of the Fuel & Core Design of the UK HPR1000 Reactor," UK Office of Nuclear Regulation, 2018.
43. S. Azeez, P. Dick and J. Hopwood, "The Enhanced CANDU 6TM Reactor," Atomic Energy of Canada Ltd, 2009.
44. "Small Modular Reactors: Nuclear Energy Market Potential for Near-term Deployment," OECD NEA, 2016.
45. E. Redmond, "HALEU Needs for Commercial Reactors," NEI, 2020.
46. "Status of Advanced Reactor Demonstration Programs," DOE, 2020.
47. "Analysis of Nuclear Fuel Availability at EU Level from a Security of Supply Perspective," European Supply Agency, 2020.
48. "Securing the European Supply of 19.75% enriched Uranium Fuel," Euratom Supply Agency, 2019.
49. J. McKirgan, "NRC Reviews of HALEU Fuels," NRC, 2020.
50. "Characteristics of the Gas Centrifuge for Uranium Enrichment and Their Relevance for Nuclear Weapon Prolfieration," *Science and Global Security,* vol. 10, pp. 1-25, 2008.
51. H. Wood, A. Glaser and R. Kemp, "The gas centrifuge and nuclear weapons proliferation," in *AIP Conference Proceedings*, 2014.

scales.[52] However, uncertainty remains over whether new sites will be needed, as well as other questions about how material will be transported and stored.[53,54] These issues are under active consideration by Euratom, the US NRC, and other major regulators.

Design	Nameplate power [MWe]	Thermal efficiency	Capacity factor	Annual thermal output [GWd-t / yr]	SWU intensity [SWU/GWd-t]	Annual SWU demand [kSWU / yr]	Annual SWU demand per GWe [MSWU / GWe / yr]
U-Battery	4	0.40	0.75	2.7	483.6	1.324	0.331
NuScale	60	0.30	0.75	54.8	272.0	14.892	0.248
Xe-100	82.5	0.41	0.75	54.8	196.9	10.778	0.131
ACP100	125	0.32	0.75	105.4	157	16.547	0.132
HTR-PM	210	0.42	0.75	136.9	179.5	24.569	0.117
VK-300	250	0.33	0.75	205.3	145.0	29.770	0.119

Table 3. Annual SWU demand for a selection of SMRs and microreactors. The complete data can be found in Appendix B. A 75% capacity factor was chosen to reflect that these reactors may load-follow electricity demand, and is close to the average capacity factor of nuclear plants in France. The annual SWU demand averages multi-year refuelling cycles to a per-year basis. Note, NuScale has published a minimum average discharge burnup value, so it's SWU intensity is an upper estimate.[55,56,57,58,59,60,61,62,63,64]

52. D. Fletcher, "URENCO Next Generation Fuels: Conversion and Enrichment Options," Urenco, 2020.
53. "Analysis of Nuclear Fuel Availability at EU Level from a Security of Supply Perspective," European Supply Agency, 2020.
54. "Securing the European Supply of 19.75% enriched Uranium Fuel," Euratom Supply Agency, 2019.
55. "Advanced Large Water Cooled Reactors," IAEA, 2020.
56. "Advanced Reactor Information System," IAEA, [Online]. Available: https://aris.iaea.org/.
57. "Power Reactor Information System," IAEA, [Online]. Available: https://pris.iaea.org/PRIS/CountryStatistics/CountryStatisticsLandingPage.aspx.
58. "Advances in Small Modular Reactors," IAEA, 2018.
59. "Advances in Small Modular Reactor Technology," IAEA, 2020.
60. T. Xin, "Safety Approach and Safety Assessment of Hualong One," Hualong Pressurized Water Reactor Tech Corp, 2018.
61. M. Ding, J. L. Kloosterman, T. Koojiman and R. Linssen, "Design of a U-Battery," Delft, 2011.
62. "Generic Design Assessment Step 2 Assessment of the Fuel & Core Design of the UK HPR1000 Reactor," UK Office of Nuclear Regulation, 2018.
63. S. Azeez, P. Dick and J. Hopwood, "The Enhanced CANDU 6TM Reactor," Atomic Energy of Canada Ltd, 2009.
64. "Small Modular Reactors: Nuclear Energy Market Potential for Near-term Deployment," OECD NEA, 2016.

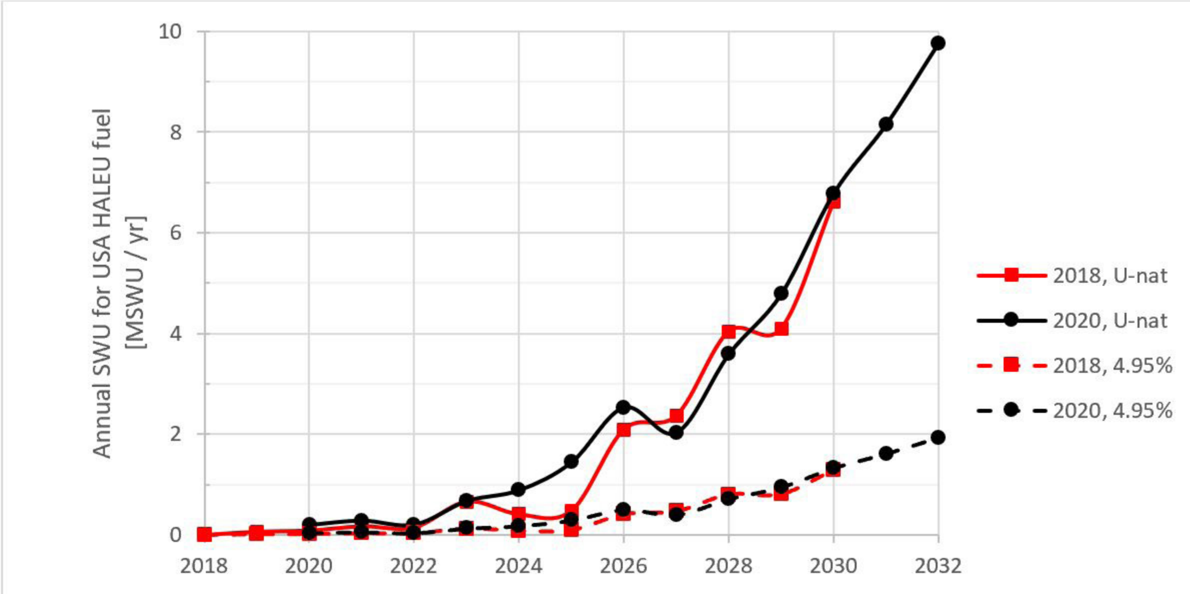

Figure 3. SWU required to meet US HALEU demand up to 2032, as estimated by surveys of US reactor vendors in 2018 (red) and 2020 (black).[65,66] The SWU requirement will also depend on the enrichment feedstock used, either natural uranium (solid line) or existing LEU fuel (dashed line).

Research reactor fuel and medical isotope targets

Nuclear fuel is required for research reactors and medical isotope production, both small but important parts of academia, industry, and healthcare. They utilize a range of exotic and high enrichment fuels to maximize performance as they are not constrained by economics to the same extent as commercial reactors. About half utilize weapons-grade uranium, albeit in small quantities.

There are unlikely to be a significant number of new facilities of this type in the next twenty years, with the few being built in the USA and China. However, all reactors using weapons-grade material have committed to converting to use HALEU fuel instead. This will increase civilian SWU demand, though the timeline has been delayed in the past. Table 4 shows estimates of world demand made by the ESA in 2019.[67]

Even in the high-estimate, demand from research reactors and medical isotope production is not expected to grow beyond 0.15MSWU/yr. This estimate assumes all research reactors are converted to HALEU, so there is not much scope for the demand to be greater.

65. E. Redmond, "HALEU Needs for Commercial Reactors," NEI, 2020.
66. M. Korsnick, *Need for High-Assay Low Enriched Uranium - NEI Letter to Sec Perry,* Nuclear Energy Institute, 2018.
67. "Securing the European Supply of 19.75% enriched Uranium Fuel," Euratom Supply Agency, 2019.

	2030 Estimated 19.75% HALEU annual demand [kg / yr]			2030 Annual SWU demand
	EU	Rest of the world	**Total**	**MSWU / yr**
Low	241	639	880	0.0374
Mid	861	675	1536	0.0653
High	1476	1885	3361	0.1429

Table 4. ESA estimates of the SWU demand from research reactors and medical isotope production. The SWU calculation assumes that 42.517 SWU/kg is required to enrich produce 19.75% HALEU, using natural uranium feed and with 0.23% enriched uranium tails.

Nuclear naval fuel

Nuclear reactors offer tremendous performance to military submarines and surface ships, providing variable power in a compact package and only needing refuelling every few decades. These advantages greatly increase the range of operations they can perform compared to fossil fuel-powered vessels. US submarines and aircraft carrier reactors are fuelled with weapons-grade (93% enriched) highly enriched uranium (HEU). This minimizes the size of the reactor and increases the time between refuelling compared to LEU fuel.[68,69,70]

The USA recognizes that the use of HEU fuel creates direct and indirect threats to its national security, and is exploring using LEU for naval fuel.[71]

There is a direct threat that the several hundred kilograms of HEU in a naval reactor are stolen and used to create a dozen or more nuclear weapons. While this risk is small, it creates additional handling and material accounting costs compared to LEU fuel.

The indirect threat is that the USA's use of HEU naval fuel creates an international norm which other countries follow, allowing them to gather the material required for a nuclear weapon in a legal manner. The Nuclear Non-Proliferation Treaty (NPT) places safeguards on all civilian nuclear facilities and materials in non-nuclear weapon states, to ensure they are not being used towards creating nuclear weapons. However, military facilities and materials are not under safeguards except on a voluntary basis. A non-nuclear weapon state using HEU military naval fuel could legally gather the infrastructure and material to create nuclear weapons, using the USA's example to resist international pressure. Actually creating a weapon is illegal under the NPT, but without safeguards and inspections of the military facilities there would be an erosion of transparency and trust in the non-proliferation regime.

The USA has commissioned multiple studies into whether their naval vessels can be converted or redesigned to use LEU fuel.[72] The present consensus is that it can done without compromising tactical performance, though there are trade-offs with the size of the vessel and/or refuelling schedule. China and France both use LEU naval fuel enriched to less than 10% (possibly 6% or less), reinforcing that it is feasible;

68. B. Hanlon, "Validation of the Use of Low Enriched Uranium as a Replacement for Highly Enriched Uranium in US Submarine Reactors," MIT, 2013.
69. "Low-Enriched Uranium for Potential Naval Nuclear Propulsion Applications," JASON, 2016.
70. C. McCord, "Examination of the Conversion of the U.S. Submarine Fleet from Highly Enriched Uranium to Low Enriched Uranium," MIT, 2014.
71. "Low-Enriched Uranium for Potential Naval Nuclear Propulsion Applications," JASON, 2016.
72. Ibid.

though these reactors are refuelled every ten years compared to 20-40 for US HEU reactors.

The US fleet is estimated to require 2-2.5 tonnes of HEU per year for eighty vessels.[73] The demand for LEU fuel in an equivalent fleet will depend on the trade-offs chosen between reactor size, full-life vs refuelled reactors, uranium loading, and other factors. Figure 4 gives high and low estimates as a function of the ratio of LEU to HEU in the new and existing reactors. Directly replacing 93% HEU with 19.75% HALEU fuel while retaining the same total mass of U-235 would require 0.4-0.5MSWU per year if enriched from natural uranium, but only 0.1MSWU if enriched from purchased 4.95% enriched civilian fuel. A recent MIT study found that reasonable trade-offs with submarine performance could reduce the LEU : HEU ratio to 3.6 : 1, decreasing the upper estimate of enrichment demand to 0.38MSWU/yr.[74,75] A JASON study in 2016 was optimistic about the possibility of converting to LEU without greatly increasing the core volume, but the public document does not report an annual fuel requirement.[76]

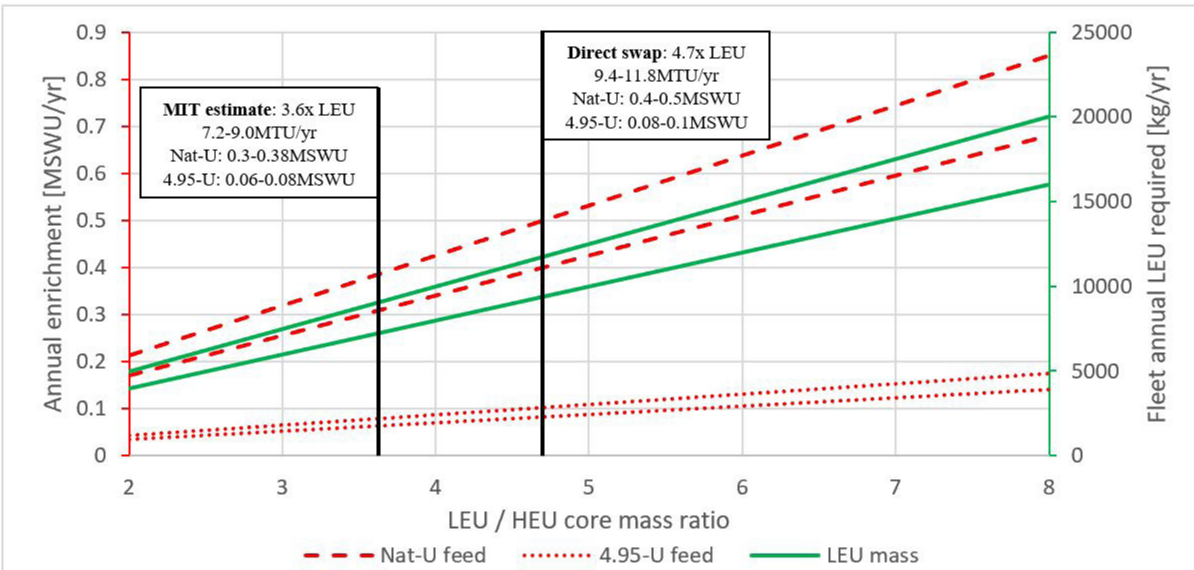

Figure 4. Annual SWU (red) and HALEU fuel (green) required to fuel a US nuclear fleet, of the same size as exists today, if entirely converted to use 19.75% HALEU fuel, as a function of the increase in the reactor uranium mass. The SWU required also depends on the feedstock material used to create the HALEU, either natural uranium (dashed line) or 4.95% LEU fuel (dotted line).

The earliest that a LEU-powered US naval vessel could be launched is the mid-2040s, due to the long lead-times involved in their design and construction.[77,78] The existing and under-construction HEU-powered vessels will not leave service till 2085, with a small number lingering till 2100. These vessels are not designed for refuelling, severely limiting the prospects for converting them to LEU. This means that SWU demand from US nuclear vessels will be limited to testing and demonstration purposes up to 2040, and

73. B. Hanlon, "Validation of the Use of Low Enriched Uranium as a Replacement for Highly Enriched Uranium in US Submarine Reactors," MIT, 2013.
74. Ibid.
75. C. McCord, "Examination of the Conversion of the U.S. Submarine Fleet from Highly Enriched Uranium to Low Enriched Uranium," MIT, 2014.
76. "Low-Enriched Uranium for Potential Naval Nuclear Propulsion Applications," JASON, 2016.
77. B. Hanlon, "Validation of the Use of Low Enriched Uranium as a Replacement for Highly Enriched Uranium in US Submarine Reactors," MIT, 2013.
78. "Low-Enriched Uranium for Potential Naval Nuclear Propulsion Applications," JASON, 2016.

total demand for enrichment services is unlikely to exceed 0.1MSWU/yr; substantially less if HALEU is enriched from surplus 4.95% enriched LEU fuel.

Other nations have also expressed interest in developing LEU-powered submarines, most significantly Brazil and the Republic of Korea (ROK).[79] Both states argue that longer-duration submarines will allow them to better patrol their waters, the ROK in particular wishing to more easily detect North Korean ballistic missile submarines.

Brazil has an ongoing nuclear submarine development programme, including a 9kSWU/yr research facility for this purpose. Its submarine SWU requirement is unlikely to increase by 2040.

The ROK has domestic nuclear reactor vendors but no enrichment service companies. Its LEU-submarine programme has been supported more heavily by the government over the past five years, including making efforts to renegotiate its nuclear cooperation agreement with the USA to allow it to construct domestic enrichment facilities. This is a difficult geopolitical issue, as the USA and its other allies prefer not to allow new states to construct their own enrichment facilities, and an enrichment facility may undermine efforts to shrink North Korea's nuclear infrastructure and weapons programme. In any case, a ROK submarine programme is still likely to be small by 2040, requiring at most 0.1MSWU/yr.

While the quantities of SWU required for USA and ROK naval vessels are relatively modest and could be met using existing global SWU capacity, it is possible that new enrichment facilities will still be required to meet this demand due to legal and safeguards concerns. The bilateral agreements governing international sales of enriched uranium place limitations on how the material can be used, especially for military purposes. This includes material produced in foreign-owned domestic enrichment facilities. While enrichment service providers argue these limits only apply to weapons-use of nuclear material, not all military-use, the issue is still contested.[80] Additionally, the USA has a preference to avoid mixed military-civilian LEU and HALEU enrichment facilities, to avoid setting a precedent which allows other nations to take their civilian nuclear infrastructure out of the international safeguard regime. As such, the USA and ROK naval fuel programmes may require bespoke enrichment facilities, increasing overall SWU demand. However, as detailed earlier in this section, the long development and procurement process of nuclear-powered submarines means any new capacity will be limited to 0.1-0.2MSWU/yr by 2040.

Domestic supply and Strategic Exports

Multiple states are supporting or mandating the development of domestic enrichment service providers, particularly China and the USA, in effect creating duplicate SWU demand which can only be met by those providers. This trend is part of a broader return to industrial planning, including in the EU and USA, and states seeking to bolster their energy security, export strengths, and domestic nuclear skills and industry.

Left undisturbed, the uranium enrichment market tends towards international oligopoly. Fuel costs are dominated by the expense of procuring and enriching uranium, both processes with significant economies of scale and technical barriers to entry. Transport makes up only a fraction of the overall cost, as the vol-

79. F. Von Hippel, "Mitigating the Threat of Nuclear-Weapon Proliferation via Nuclear-Submarine Programs," *Journal for Peace and Nuclear Disarmament,* vol. 2, no. 1, pp. 133-150, 2019.
80. F. von Hippel and S. Weiner, "No Rush to Enrich: Alternatives for Providing Uranium for U.S. National Security Needs," *Arms Control Today,* 2019.

umes of material required annually are small.[81] These factors favor a globalized supply chain with a few large providers, unless disrupted by quotas or other influences.

The fear that foreign powers will limit a state's ability to acquire the resources and equipment necessary to meet their energy needs is not unique to the nuclear power industry, but it is felt more sharply given the relatively small number of vendors, the large output of each power plant, and the link to nuclear weapons. All of the nuclear weapon states developed domestic enrichment capabilities to limit external pressure on their actions. France went furthest after the 1973 Oil Crisis, increasing their nuclear capacity to provide 80% of their electric power, and expanded domestic enrichment and fuel production facilities to minimize foreign influence on their price of energy. China is constructing enrichment capacity as part its goal of a 'self-sufficient' nuclear fuel cycle, announced in 2010, adding 7.5MSWU of capacity so far and likely a further 16MSWU by 2040.[82]

The USA is the largest importer of enrichment services and the most likely to create additional demand by requiring domestic enrichment. The Trump administration argued that the USA must create domestic uranium enrichment capacity in order to protect the country's energy security. The USA imports 8-10MSWU of its 13MSWU annual demand, having privatized and then closed its largest enrichment facilities. The majority of the remaining domestic production is by Urenco USA, a European-owned company. This is seen by some as a strategic weakness, with foreign governments theoretically able to stymie 20% of US electricity production.

Proponents of domestic US enrichment capacity also argue that domestic enrichment would increase the competitiveness of US nuclear exports, and increase US influence on international nuclear safety and non-proliferation norms. Russia, China, France, Japan and South Korea have all created verticalized nuclear consortiums to offer comprehensive nuclear power plant deals; including some or all of financing, construction, fuel delivery, operations, waste disposal, and decommissioning. Each successful sale gives these states a relationship and leverage over their customers for forty or more years. Future SMR sales may not be as impactful as these smaller reactors are shorter-lived, require less fuel, and each make up a smaller fraction of a country's power generation; allowing pressure to be mitigated using minimal fuel stockpiles. However, for both small and large reactors, exporting reactors creates influence by imposing de-facto standards for nuclear safety, security and non-proliferation.

The US does not have an equivalent national consortium of vendors and has not been as successful in exporting large nuclear power plants in the past decade. There is a fear that the US will miss out again in the race to sell SMRs if vendors must operate individually or in ad-hoc collaboration with foreign fuel and enrichment providers. This is especially the case when selling to countries who do not have any large reactors or nuclear experience and may prefer dealing with only one party. The USA is supporting development of new US SMRs for export and recently allowed for projects abroad to receive financing support,[83,84] but explicit calls for a national export consortium have not emerged.

81. "The Nuclear Fuel Report: Expanded Summary," World Nuclear Association, 2020.
82. H. Zhang, "China's Uranium Enrichment and Plutonium Recycling 2020-2040: Current Practices and Projected Capacities," Belfer Center, 2020.
83. "Congress Strengthens National Security by Boosting Nuclear Exports," Nuclear Energy Institute, 19 Dec 2019. [Online]. Available: https://www.nei.org/news/2019/congress-national-security-nuclear-exports.
84. "EXIM Chairman Reed Underscores EXIM's Role in Supporting U.S. Nuclear Energy Industry in the International Marketplace, Highlighting Opportunities for Civil Nuclear Cooperation Between the United States and Japan," Export-Import Bank of the United States, 8 Oct 2020. [Online]. Available: https://www.exim.gov/news/exim-chairman-reed-underscores-exims-role-supporting-nuclear-energy-industry-international.

Requiring domestic enrichment services creates a small number of high-skill jobs. Urenco employs approximately 60 people per MSWU/yr.[85] China and the USA have emphasised the benefits these workers can bring to nuclear operations and the pace of design innovation in their respective nuclear industries and the broader economy. These roles also increase a state's diplomatic weight in nuclear diplomacy, by training experts for advice, inspections and other tasks. Conversely, it will also give a state the experts and facilities required to design a HEU weapon and procure the requisite material. There are multiple means of producing a nuclear weapon[86] but a domestic enrichment facility and gun-type HEU weapon is the most technically straight-forward.

Enrichment Provider Responses up to 2040

The previous section explored the shifts we expect to see in SWU demand over the next twenty years: away from the West towards Asia, and away from large reactors to smaller reactors. This section will review the most likely responses of SWU providers to those changes.

All enrichment service providers, except CNNC in China, are currently expected to reduce or maintain their enrichment capacity between now and 2040, due to the low price of SWU and reductions in demand. Some new demand will be created by future large and small reactors, but it is unclear which vendors and states will benefit. This, as well as external factors which affect the growth of the nuclear power sector more generally, will determine which of the enrichment providers will be able to expand their capacity. Additionally, a few states are considering constructing their first enrichment facilities.

We will consider three categories of enrichment service provider:

- Major providers, which make up 99.5% of nameplate capacity today

  China, France, Russia, USA, Urenco

- Minor providers, with small existing facilities

  Brazil, India, Iran, Japan, North Korea, Pakistan

- States without domestic enrichment service providers but which have expressed interest in or investigated constructing enrichment facilities. These fall into three further categories:

  Heavily involved in the nuclear supply chain or as a reactor vendor

  - Australia, Canada, South Korea

  Formerly had enrichment capacity

  - Argentina, South Africa

  Ambitions for increased nuclear energy and fuel cycle facilities

  - Saudi Arabia, Vietnam

85. "Urenco Global Operations," Urenco, 2021. [Online]. Available: https://www.urenco.com/global-operations.
86. V. Narang, "Strategies of Nuclear Proliferation: How States Pursue the Bomb," *International Security,* vol. 41, no. 3, pp. 110-150, 2017.

Major producers

Russia (Rosatom / TVEL)

From a technical standpoint, Russia is in the best position to respond to any large increases in SWU demand, as it has 5-6MSWU/yr of excess capacity, experience producing HALEU fuel, and the state-owned suppliers have very low costs and face fewer regulatory hurdles. Rosatom, the state conglomerate, is successful at exporting large reactors and nuclear services,[87] with $6.6bn in foreign sales in 2019[88] and $130bn of orders to 2030.[89] Russia has several advanced reactor programmes, including the VVER-300 and KLT-40s[90] SMRs, but broader concerns about Russian influence over domestic energy may limit future reactor and SWU exports.

TVEL, a subsidiary of Rosatom, operates approximately 28MSWU/yr of enrichment capacity, 45% of the global nameplate capacity. 17MSWU/yr of this capacity is exported by TENEX, another subsidiary, with only 3-5MSWU used to produce fuel for civilian nuclear reactors in Russia. Since 2015, Russia has exported an average of 11.4MSWU and 3MSWU per year to the EU and USA respectively,[91,92] with most of the remainder going to former Soviet and other states who operate Russian-designed VVERs. The excess 5.6MSWU/yr of Russian capacity is used for uranium tails enrichment, which produces 'fresh' uranium from the depleted uranium created as a by-product of normal enrichment.

Russia is expected to reduce its enrichment capacity to 25MSWU by 2040 in response to a reduction in exports, mostly through not replacing older centrifuges.[93] Other states are already reducing their reliance on Russian SWU, especially in North America and Europe. For example, Ukraine has worked with the USA and Westinghouse to halve their Russian imports to 1MSWU/yr,[94] the USA lowered caps on Russia SWU imports, and EU imports have fallen from 5MSWU/yr in 2012 to 2.5-3.5MSWU/yr today.[95,96] Domestic Russian demand will only increase by 1MSWU/yr to supply the handful of new VVER-1200s, not enough to cover the export deficit.[97,98]

Despite this poor outlook, Russia appears willing to retain most of its excess capacity and wait-out the market. Rather than shutter more capacity, it recently purchased additional equipment for fuel conversion and tail enrichment from Orano.[99] This decision could be driven by an internal political preference to maintain domestic production and employment, which Rosatom celebrates in media releases.[100] Alter-

87. S. Thomas, "Russia's Nuclear Export Programme," *Energy Policy,* vol. 121, pp. 236-247, 2018.
88. "Rosatom expects foreign business income to double by 2024," World Nuclear News, 10 May 2019. [Online]. Available: https://world-nuclear-news.org/Articles/Rosatom-sees-income-from-foreign-business-doubling.
89. "Rosatom - Projects Overview," Rosatom, [Online]. Available: https://rosatom.ru/en/investors/projects/.
90. "Advanced Reactor Information System," IAEA, [Online]. Available: https://aris.iaea.org/.
91. "2019 Uranium Marketing Annual Report," US EIA, 2020.
92. "Euratom Supply Agency - Annual Report," European Union, 2019.
93. "The Nuclear Fuel Report: Expanded Summary," World Nuclear Association, 2020.
94. "Westinghouse signs VVER-440 fuel agreement with Ukraine," World Nuclear News, 30 Sept 2020. [Online]. Available: https://www.world-nuclear-news.org/Articles/Westinghouse-signs-VVER-440-fuel-agreement-with-Uk.
95. "2019 Uranium Marketing Annual Report," US EIA, 2020.
96. "Euratom Supply Agency - Annual Report," European Union, 2019.
97. "Advanced Reactor Information System," IAEA, [Online]. Available: https://aris.iaea.org/.
98. "Power Reactor Information System," IAEA, [Online]. Available: https://pris.iaea.org/PRIS/CountryStatistics/CountryStatisticsLandingPage.aspx.
99. "Orano to supply second Russian deconversion facility," World Nuclear News, 11 Dec 2019. [Online]. Available: https://www.world-nuclear-news.org/Articles/Orano-to-supply-second-Russian-deconversion-facili.
100. "Rosatom expects foreign business income to double by 2024," World Nuclear News, 10 May 2019. [Online]. Available:

natively, it is a cost-reduction tactic to allow it to wait longer for an uptick in demand or for other SWU providers to reduce their capacity. Russian enrichment costs have been estimated at as little as $27.70/SWU, a third of US costs,[101] so it can probably maintain this position indefinitely, albeit without much profit. The long lead time of nuclear reactor projects, even small ones, means Rosatom can continue to bid for enrichment business and transition facilities back to LEU or HALEU production when necessary.

The primary means for Rosatom to grow its SWU exports, and require more SWU capacity, will be through exporting reactors and fuel together or providing fuel for new Japanese and South Korean reactors, as they do not have a domestic enrichment provider. Rosatom will face significant competition from Chinese reactor vendors who also benefit from low costs and state-support. There has been less interest in Russia's SMR offerings compared to those from China and the USA, though Russia's focus and early demonstration of a floating reactor may prove wise.[102] The design might appeal to smaller or first-time nuclear states who prefer a small reactor which can be moved based on demand, and which can be operated at arm's length and with regulatory assistance.

Secondarily, Rosatom could grow its SWU exports by offering cheap civilian HALEU fuel more quickly than Western providers. It produced HALEU fuel for the icebreaker and floating reactor programmes and already has the licensed sites necessary for production. This could be advantageous if the USA or Europeans require a near-term supplier. Rosatom is advertising deliveries of 19.75% HALEU to the USA within 6-9 months of ordering, in volumes up to several tonnes per year.[103] They claim the fuel can be delivered as uranium dioxide or uranium metal, with uranium-molybdenum and uranium-aluminium alloys possible in the near future. Assuming the HALEU is produced by enriching existing LEU stockpiles, this demand is unlikely to exceed 1MSWU/yr for the USA.

China (CNNC)

China will continue its policy of developing uranium enrichment self-sufficiency, with CNNC, the state enrichment service provider, increasing domestic SWU production from 7.5MSWU/yr today to 16-37MSWU/yr in 2040, principally to meet demand from Chinese large reactors.[104,105] The present pace of construction suggests 5-9GWe will be added each year, requiring an additional 0.75-1.4MSWU/yr annually, though the 14th Five Year Plan only calls for 3.6GWe to be constructed per year.[106] CNNC is estimated to be able to add 1-1.5MSWU of annual capacity each year between now and 2040, based on its manufacturing capability and available space at licensed sites.[107] Additionally, CNNC has approximately 30MSWU stockpiled in the form of enriched uranium, which can be used to accommodate any temporary shortfall in supply.

CNNC could also add SWU capacity to support broader Chinese nuclear exports. Early reports on the

https://world-nuclear-news.org/Articles/Rosatom-sees-income-from-foreign-business-doubling.

101. O. Bukharin, "Understanding Russia's Uranium Enrichment Complex," *Science and Global Security,* vol. 12, pp. 193-218, 2004.

102. "KLT-40S," IAEA - ARIS, [Online]. Available: https://aris.iaea.org/PDF/KLT-40S.pdf.

103. F. Newton and N. Kolsovskaya, "HALEU: Rosatom View," Rosatom - Tenex, 2020.

104. "The Nuclear Fuel Report: Expanded Summary," World Nuclear Association, 2020.

105. H. Zhang, "China's Uranium Enrichment and Plutonium Recycling 2020-2040: Current Practices and Projected Capacities," Belfer Center, 2020.

106. M. Meidan, P. Andews-Speed and Y. Qin, "Key issues for China's 14th Five Year Plan," Oxford Institute for Energy Studies, 2021.

107. H. Zhang, "China's Uranium Enrichment and Plutonium Recycling 2020-2040: Current Practices and Projected Capacities," Belfer Center, 2020.

Chinese self-sufficiency policy mentioned CNNC becoming a general enrichment service provider,[108] but this has been de-emphasized as the SWU market price remained depressed. CNNC only exports 1MSWU/yr currently, compared to 3MSWU/yr of imports. Instead, any future excess capacity is more likely to be bundled into reactor sales. China's first two exported Hulaong One / HPR1000 reactors are under construction in Pakistan and the UK is reviewing the design for use there. Each reactor will require 0.14-0.18MSWU/yr, depending on the capacity factor it can be operated at.

Large reactor and fuel exports under CNNC and CGN, the other Chinese state nuclear vendor, appear economical competitive. Both firms have assembled a cadre of experienced project managers and construction teams, maximizing learnings from domestic construction and helping to reduce costs and timetable overruns.[109] They have ensured they are invited to all nuclear development conversations by financing nuclear construction by other firms, particularly in Europe,[110,111] and by being associated with the broader Belt and Road Initiative.

The main uncertainty for the Chinese large reactor export programme, and SWU exports, is how large the market will be and whether states will ban them from constructing reactors. The IEA predicts 106GWe of nuclear capacity will be constructed outside of North America, India, and China by 2040 (note, this is not net of reactor closures). This assumes no radical improvements in transmission or grid-scale storage technologies which disadvantage large nuclear reactors. Of these new large reactors, 42GWe is in Europe, where governments are becoming wary of Chinese investment in energy and other strategic sectors. Nearer neighbours in Eurasia and Asia-Pacific region are predicted to construct 45GWe new reactors. These states may be more interested in concomitant Chinese investment in other sectors. However, they may also be concerned about excessive Chinese influence, or may be offered alternatives by the US and EU.

Even in an optimistic scenario where CNNC and CGN manage to secure a third to half of this construction, the fuel contracts would only require 4.5 - 7MSWU/yr. Middle estimates of Chinese domestic SWU demand suggest CNNC will only use 24MSU/yr of a maximum 37MSWU/yr capacity.[112] This indicates that large reactor export demand is well within CNNC's capabilities, unless the pace of domestic reactor construction also accelerates significantly.

CNNC is also developing a variety of advanced, small and microreactors; some of which appear more promising than the large Hualong One design. These include the CFR-600 fast reactor, which is fuelled with HALEU and lower assay HEU imported from TVEL in Russia.[113,114] Prototypes of the 210MWe high-temperature gas-cooled HTR-PM reactor and the 125MWe ACP100 PWR are currently under construction, well in advance of their North American and European competition. While the fuel utilization and performance of each is arguably less impressive than those competing designs, more akin to shrunken versions of large reactors, they appear to meet the key market needs and will have first-mover advantage.

108. L. Guanxing, *Status and future of China's front-end of nuclear fuel cycle industry,* 2010.
109. *Presentation by Prof Ning Li,* 2019.
110. "China agrees Hinkley Point nuclear plant deal with UK," BBC, 21 Oct 2015. [Online]. Available: https://www.bbc.com/news/av/uk-34590205.
111. "Bulgaria shortlists GE, others for nuclear plant contract," AP News, 19 Dec 2019. [Online]. Available: https://apnews.com/article/0f87ece6cdcd30e5b9ea6f38f715e7a0.
112. H. Zhang, "China's Uranium Enrichment and Plutonium Recycling 2020-2040: Current Practices and Projected Capacities," Belfer Center, 2020.
113. "Russia to supply HEU fuel for China's CFR-600 fast reactor," International Panel on Fissile Materials, 10 Jan 2019. [Online]. Available: http://fissilematerials.org/blog/2019/01/russia_to_supply_heu_fuel_2.html.
114. "TVEL Fuel Company of ROSATOM will supply nuclear fuel for China's CFR-600 fast-neutron reactor," Rosatom, 2019. [Online]. Available: http://www.rusatom-energy.com/media/rosatom-news/tvel-fuel-company-of-rosatom-will-supply-nuclear-fuel-for-china-s-cfr-600-fast-neutron-reactor/.

In particular, the HTR-PM design, with two reactors feeding one turbine, offers high outlet temperatures and significant operational flexibility, which should appeal to industrial users.

Even if CNNC's first mover advantage allowed it to capture 50% of the small reactor market, this would only create an additional 1.65MSWU/yr demand by 2040; which is feasible for CNNC even with the Hualong One exports discussed above. As discussed in the previous sections, it is still unclear whether these small and advanced reactors will complement or cannibalize large reactor sales. The ACP100 and HTR-PM require 19.9kSWU/yr and 29.5kSWU/yr each, compared to 174kSWU/yr for a 1150MWe Hualong One reactor (assuming 90% capacity factor for each). Directly substituting small reactor exports for Hualong One sales on a GWe basis will require the same or slightly fewer SWU.

United Kingdom, Netherlands, Germany (Urenco Europe)

If a large swing towards domestic enrichment does not occur in the USA and elsewhere, Urenco is well positioned to take advantage of any increases in demand, due to its technical advantages and the relatively benign relationships between potential buyers and the UK, Netherlands, and Germany. While Urenco also operates an enrichment facility in the USA, they are separate subsidiaries and are often considered separate suppliers due to differences in the host governments policies.[115]

Urenco's European facilities have 13.7MSWU/yr capacity. This is expected to diminish to 12-12.5MSWU/yr by 2040 if European demand falls.[116] Urenco serves customers in 19 countries, including seven outside of Europe. In 2019, 40% of its sales were to North America, 40% to Europe, and 20% to the rest of the world.[117] Most of Urenco USA's sales are in North America, so 59% of Urenco's services are sold in North America overall.

While its volume of SWU sold has increased in the past few years, Urenco's annual reports appear uncertain about its medium-term profit, due to the low SWU price and expiry of more profitable multi-year contracts.[118] It has increased its tail enrichment activities, including constructing and commissioning a tails deconversion facility in the UK,[119] presumably to offer a European alternative to Russian services and reduce the net cost of any excess SWU capacity. Urenco also expanded its medical, industrial, and research isotope production in the Netherlands.[120] Finally, Urenco is advertising its experience of producing and delivering exotic and higher enrichment fuels, including HALEU, in the USA and Canada.[121] It has made expanding this a strategic priority[122] so should be well positioned to capture market share.

Unlike CNNC and Rosatom, Urenco Europe does not have a strong domestic reactor export programme to attach itself to. Multiple small and advanced reactor designs are being developed in the UK,[123] but they are not as far along or well-funded as the Chinese and US alternatives.

115. S. Billingham, "2019 Annual Results Presentation," Urenco, 2020.
116. "The Nuclear Fuel Report: Expanded Summary," World Nuclear Association, 2020.
117. S. Billingham, "2019 Annual Results Presentation," Urenco, 2020.
118. "2019 Annual reports and Accounts," Urenco, 2020.
119. S. Billingham, "2019 Annual Results Presentation," Urenco, 2020.
120. Ibid.
121. D. Fletcher, "URENCO Next Generation Fuels: Conversion and Enrichment Options," Urenco, 2020.
122. "2019 Annual reports and Accounts," Urenco, 2020.
123. "Prime Minister confirmed this government's commitment to advancing large, small and advanced reactors as part of our 10 Point Plan for a Green Industrial Revolution," UK Government, Nov 2020. [Online]. Available: https://www.gov.uk/government/publications/advanced-nuclear-technologies/advanced-nuclear-technologies.

Urenco could partner with reactor vendors who lack domestic enrichment providers; such as the USA, Canada, South Korea, and Japan; to provide a reactor, fuel and other services. If the USA introduces requirements for US-based enrichment or fuel production, Urenco could partner with US reactor vendors and fuel manufacturers via Urenco USA.

If CNNC or Rosatom win more market share, reactor customers might purchase SWU from Urenco in order to diversify their supply chain. This is a common practice for current large reactors, though it might not be practical for SMRs if a country constructs only a few, or for microreactors where the fuel and reactor are entirely replaced by the vendor at each refuelling. If this approach is viable, Urenco may find a sustainable position as the reliable second supplier to many states, though they would likely have to wait a decade for the initial fuel contracts to expire.

Altogether, this makes it very difficult to estimate Urenco's SWU capacity in 2040, as the answer is highly contingent on which countries successfully export reactors. Even if Urenco reduces its SWU capacity further, it will be able to ramp-up again in a timely manner. Urenco develops and produces all of the technologies required for enrichment, including centrifuges, and has shown it can install over 0.1MSWU/yr capacity per month in the USA. Additionally, it has enriched and natural uranium stockpiles to meet immediate demand. As long as it retains its sites, it can add or reconfigure centrifuge cascades in less than a year; certainly in time for reactor construction to be completed. Urenco's maximum capacity is unclear, and large expansion may have to take place at its US sites.

France (Orano)

Orano, the French fuel cycle company, has 7.5MSWU of capacity at one site in France. The company is verticalized across the entire fuel cycle, from uranium mining to plutonium recycling and MOX fuel production. Less than 25% of its consolidated revenue comes from enrichment and other front-end services. Like Urenco, it has suffered under the low SWU price, and is expanding its output in more profitable areas, such as isotope production. Its front-end business is focused in Europe, with 43% of its revenue from France and the remainder equally split between the rest of Europe, the Americas, and the Asia-Pacific region.[124]

Orano will have limited SWU capacity available to export up to 2040. The majority of its SWU output is sold to the French reactor operator, EDF, and its order book is full up to 2030.[125] France requires approximately 8MSWU/yr for its nuclear reactors.[126] This is reduced by 0.5-0.7MSWU through the use of MOX fuel for 10% of generation.[127,128,129] Urenco supplies some enrichment services, particularly for recycled uranium. Orano meets at least 3.5MSWU/yr of the French demand, based on earning reports and estimates of its contract long-term SWU price, but this figure is likely to be 5MSWU or more.[130] It also has existing

124. "2019 Annual Activity Report," Orano, 2020.
125. Ibid.
126. "France: Fuel cycle - front end," World Nuclear Association, [Online]. Available: https://www.world-nuclear.org/information-library/country-profiles/countries-a-f/france.aspx.
127. "Uranium production and demand data," Euratom Supply Agency, 2018. [Online]. Available: https://ec.europa.eu/euratom/observatory_data.html.
128. "Mox production and useage," Orano, [Online]. Available: https://www.orano.group/country/china/en/our-stories/mox-recycling-nuclear-energy.
129. "Mox production and useage," Orano, [Online]. Available: https://www.orano.group/country/china/en/our-stories/mox-recycling-nuclear-energy.
130. "2019 Annual Activity Report," Orano, 2020.

export agreements. Until 2030, 0.6MSWU/yr is contracted to Centrus in the USA[131] and 0.4MSWU to the two EPRs operating in China. Once operational, a further 0.6MSWU/yr will be supplied to the EPRs in Finland and the UK.

French SWU demand should hold steady to 2040, and industry commentators do not expect Orano to reduce its SWU capacity till then.[132] The French government has delayed the its closure of 15 older reactors and announced it will replace them with six EPRs.[133] This may change the fleet SWU requirement slightly, depending on the capacity factor of the new reactors and whether MOX will still be used. As the price of enrichment fell, operations at older French reactors were changed to maximize reactor performance at the expense of SWU intensity.[134] This made them more SWU intensive per GWd-t than EPRs. However, the larger EPR reactors are likely to have higher capacity factors, which will balance out the first effect and keep total annual French SWU demand the same.

Altogether, this suggests Orano will be able to export at most 2MSWU each year between now and 2040, but probably less. It can manufacture centrifuges and expand capacity through its ETC partnership with Urenco, feasibly adding 1MSWU/yr, based on the time required to build its current facility, if Urenco is not also adding capacity and the sites have been licensed and approved.

Orano will first look to use any export capacity it has to support French export of the EPR. While technically impressive, the EPR was designed with a pre-VRE market in mind and an emphasis on safety rather than cost and market-fit. A few additional newbuilds are under negotiation in India, and Central Europe, but the reactor has faced significant construction challenges in Europe, which may hamper future exports. France is developing the Nuward SMR, which emphasises a modular approach and lessons from operating France's nuclear fleet. While this design is behind its US, Chinese and Russian counterparts, the integrated French R&D environment could help recover the deficit.

If these exports do not materialize, Orano could find itself as a neutral enrichment provider, much like was described for Urenco. It previously held a license for an enrichment facility in the USA, which it could look to reclaim. Additionally, the France has extensive experience producing HALEU and exotic fuels for research reactors, which could be leveraged to sell fuel to foreign reactor vendors. Finally, Orano could collaborate with foreign vendors to provide bundled front and back-end fuel services, in a similar manner to Rosatom.

USA (Urenco USA, Centrus)

The USA has the most nuclear power capacity of any state, with 100GWe over 94 reactors. This requires 13.5MSWU/yr, on average, of which one third is produced domestically and the remainder imported. The EIA reported 12-13 enrichment service providers selling SWU in the USA each year between 2017 and 2019, including six US providers.[135] The largest domestic provider is Urenco USA, a subsidiary of Uren-

131 "Centrus Signs Long-Term Supply Agreement with Orano," Centrus, 3 May 2018. [Online]. Available: https://www.centrusenergy.com/news/centrus-signs-long-term-supply-agreement-with-orano/.
132. "The Nuclear Fuel Report: Expanded Summary," World Nuclear Association, 2020.
133 "France asks EDF to prepare to build 6 EPR reactors in 15 years -Le Monde," Reuters, 14 Oct 2019. [Online]. Available: https://www.reuters.com/article/us-edf-nuclear-epr/france-asks-edf-to-prepare-to-build-6-epr-reactors-in-15-years-le-monde-idUSKBN1WT27T.
134. N. Waeckel, "Les Gestions des Coeurs et les Perspectives," EDF-SEPTEN, 2009.
135. "2019 Uranium Marketing Annual Report," US EIA, 2020.

co, which operates a 4.8MSWU/yr facility in Ohio.[136,137] The remainder are a variety of power utilities, engineering companies and uranium traders who resell enriched material in lieu of providing enrichment services themselves.

The USA's SWU demand and output between 2020 and 2040 is the most uncertain of all the major suppliers. This uncertainty stems from two questions: how much will new SWU demand from US SMRs and microreactors make up for large reactor closures, and what rules will the US put in place regarding SWU imports and domestic production?

US large reactor capacity is expected to fall 10-50% by 2040,[138] reducing demand by 1-6MSWU/yr. US SMR and microreactor vendors claim they will require almost 10MSWU/yr for HALEU fuel by 2032, for R&D and to fuel reactors.[139] This does not include vendors, such as NuScale, who are using already-available 5% LEU fuel and are much closer to market. Global estimates put small reactor SWU requirements at 3.3-12.7MSWU/yr by 2035, suggesting that the US vendors' HALEU requirement is an upper estimate. All of these estimates are also subject to uncertainty over the USA's electricity demand and VRE and energy storage costs.

The USA will require 8.4-18.6MSWU/yr by 2040, if we assume that US vendors capture half of the global small reactor market and HALEU submarine and research reactors require 0.1MSWU/yr or less. How this demand is met will be heavily influenced by US industrial policy, in particular quotas on foreign imports and how they may be used. The Trump administration and industry groups proposed various supports for US fuel cycle companies,[140] and this discussion appears to be ongoing in the new administration. Three options have been considered:

Few or no import controls – Maintaining the status quo will mean the US continues to import the majority of enrichment services, but reactor operators benefit from the low international SWU price. Given the wafer-thin profit margins of many nuclear-owning utilities in the USA,[141] trade-barriers which raise the SWU price in the USA could exclude nuclear power from the US grid entirely. Fuel expenses are a larger fraction of SMR and microreactor costs, so this would doubly harm their prospects at home and abroad. This policy would leave more room for European and Russian SWU production, even if US advanced reactor exports are very successful, as reactor vendors will have to purchase SWU in the international market, unless the US heavily subsidises domestic production without erecting import barriers.

Choosing this policy still allows for a rebalancing of foreign SWU suppliers. The Trump administration negotiated an amendment to the agreement with Russia governing uranium and SWU import limits. The agreement, which is in force until 2040, caps US SWU imports from Russia to 15% of demand by 2028, down from 22% today.[142] If US demand remains at 2020 levels, this will probably transfer 1MSWU/yr of SWU purchases to Urenco Europe. Similarly, the US government could steer US vendors choice of enrichment service providers by adding source-of-origin requirements to financial support.

136. S. Billingham, "2019 Annual Results Presentation," Urenco, 2020.
137. "2019 Annual reports and Accounts," Urenco, 2020.
138. "Energy, Electricity and Nuclear Power Estimates for the Period up to 2050," IAEA, 2019.
139. E. Redmond, "HALEU Needs for Commercial Reactors," NEI, 2020.
140. "Restoring America's Competitive Nuclear Energy Advantage," DOE, 2020.
141. G. Haratyk, "Nuclear asset shutdown under uncertainty," MIT PhD Thesis, 2017.
142. "2020 Amendment to the Agreement Suspending the Antidumping Investigation on Uranium From the Russian Federation," Federal Register, 9 Oct 2020. [Online]. Available: https://www.federalregister.gov/documents/2020/10/09/2020-22431/2020-amendment-to-the-agreement-suspending-the-antidumping-investigation-on-uranium-from-the-russian.

US-origin SWU – The USA could require that some or all SWU used to fuel US domestic and exported reactors be produced in US-based facilities. Creating this guaranteed demand would encourage private capital to support US enrichment providers, in particular Centrus, while also leaving the door open to foreign firms with their own advanced technology. The domestic price per SWU would likely still increase, due to the higher price of labor and energy in the USA.

Centrus has the IP required to construct new enrichment facilities. Previously known as USEC Inc, it was originally a state-owned company which operated the US enrichment infrastructure and managed certain SWU import agreements and contracts. After being privatized in 1998, it closed the gaseous diffusion-based enrichment facilities it inherited from the DOE, as the technology is at least twice as expensive as centrifuge systems.[143] Centrus has since developed its own AC100(M) centrifuges. They are a very large design, generating 340SWU/yr each, roughly triple that of Urenco and more for TVEL.[144,145] The technology was demonstrated for 60 days of operation at a 40.8kSWU/yr facility for LEU production in a $352m program.[146] While the larger design's economies of scale should help it be more cost-competitive with TVEL and others, it has greater maintenance complexity. Urenco and TVEL centrifuges are cheap enough to produce that they are simply replaced when their performance drops,[147] minimizing plant downtime. The DOE also owns the AC100 IP, as it was developed through a joint DOE-Centrus programme, and is also developing a Urenco-style small centrifuge at ORNL,[148] so could presumably license them to a third party if development or production at Centrus is slow.

Creating a new facility in the USA will be costly and take at least two years. The NNSA estimated that a 0.4MSWUyr facility using the AC100 to produce unobligated HALEU would cost $3.1b-11.3b, and require nine years to be fully operational.[149] Some experts have expressed doubts about the lower estimate provided, saying $5.7b is more realistic.[150,151] Orano previously held a license to construct a 3.3MSWU/yr facility in the USA, which was estimated would cost at least $3.3b.[152] Urenco USA's current facility cost over $4.5b for 4.8MSWU/yr of capacity. It was constructed in three 1.6MSWU/yr stages, each taking 18 months.[153]

This policy choice may suffer from a chicken-and-egg problem. With a SWU spot price hovering around $50/SWU versus a facility cost of at least $1000/(SWU/yr), investors will need to be very confident that any SWU capacity they build will be highly utilized. Given the significant uncertainty in US SWU demand, for both domestic and export reactors, investors may choose to wait and see. This would encourage

143. "Uranium Enrichment Processes - Gas Centrifuge," NRC, [Online]. Available: https://www.nrc.gov/docs/ML1204/ML12045A055.pdf.
144. Ibid.
145. P. Sullivan, "American Centrifuge Demonstration Program - Final Scientific Technical Report," USEC Inc, 2014.
146. Ibid.
147. "Uranium Enrichment Processes - Gas Centrifuge," NRC, [Online]. Available: https://www.nrc.gov/docs/ML1204/ML12045A055.pdf.
148. GAO-18-126, "NNSA Should Clarify Long-Term Uranium Enrichment Mission Needs and Improve Technology Cost Estimates," GAO, 2018.
149. "Tritium and Enriched Uranium Management Plan Through 2060," DOE NNSA, 2015.
150. F. von Hippel and S. Weiner, "No Rush to Enrich: Alternatives for Providing Uranium for U.S. National Security Needs," *Arms Control Today,* 2019.
151. GAO-18-126, "NNSA Should Clarify Long-Term Uranium Enrichment Mission Needs and Improve Technology Cost Estimates," GAO, 2018.
152. "Areva's Eagle Rock gets loan guarantee," Nuclear Engineering International, 21 May 2010. [Online]. Available: https://www.neimagazine.com/news/newsareva-s-eagle-rock-gets-loan-guarantee.
153. "DOE RFI: Excess Uranium Management - Urenco," DOE, 15 Sept 2016. [Online]. Available: https://www.energy.gov/sites/prod/files/2016/10/f33/2016_RFI_URENCO.pdf.

US reactor vendors to secure 10+ year SWU supply contracts with foreign suppliers, disincentivizing investment in a US enrichment facility. The same is true if reactor exports fail to materialize. Therefore, this policy will rely on existing large reactors remaining in operation to provide demand for domestic providers in the meantime, careful coordination between enrichment providers and reactor vendors to time the construction of enrichment facilities and share the cost of temporary SWU stockpiles, and the US government providing financial support. If the policy is successful, it will mostly reduce Urenco Europe and TVEL's business, as CNNC will simply limit its capacity expansions to match demand and Orano has fewer US contracts.

US-owned SWU – The final policy option is to require or support SWU services provided by US-owned and located facilities. This could only be applied to niche SWU uses or limited tranches of commercial demand, given the minimal ability of the US nuclear industry to absorb additional fuel costs. The policy could be pursued through regulation or government purchases of SWU services.

The most likely focus for such a policy is HALEU production. US-based HALEU enrichment and fabrication would accelerate reactor R&D efforts, as access to the material is one of the principle challenges facing these vendors.[154] The DOE has already contracted Centrus to construct a 5.44kSWU HALEU enrichment facility, producing 900kg HALEU/yr from 5% enriched LEU feedstock. The DOE will provide $115m in funding, covering 80% of the costs.[155,156]

US-produced HALEU would also be free of obligations set by other governments in uranium trade agreements. This unobligated material could be used for military purposes, particularly tritium production for nuclear weapons and HALEU fuel for future naval vessels. The USA have said their agreements with the governments of the United Kingdom, Germany, and the Netherlands forbid material produced at Urenco USA from being used for any military purposes.[157] Urenco USA disagrees, arguing the limitation is only on using the material in nuclear weapons themselves.[158]

This legal argument could potentially be side-stepped if the US government purchased a stake in Urenco. E.ON, one of the two German utility owners, has expressed a desire to sell it's 16.7% stake,[159] as has the British government in the past.[160] Urenco was valued at $10b on $1.6b annual revenue in 2017. Its revenue was $1.8b in 2019 but the SWU market is weaker, so that remains a reasonable estimate. This amounts to a cost of $540/(SWU/yr) for pro-rated capacity, versus $1000/(SWU/yr) for a new facility. Clearly, ownership does not imply control of the company or immediately make material unobligated. However, it could help secure the US SWU supply and is worthy of consideration at such a low price.

Urenco USA has begun the process of increasing the enrichment limit at its facility[161] in order to provide military or civilian HALEU. However, even if the USA accepted Urenco uranium as unobligated, the USA seems unlikely to accept this for military use given its long-standing policy not to mix military-civilian nuclear facilities, for the reasons discussed in the Nuclear Naval Fuel section.

154. "Status of Advanced Reactor Demonstration Programs," DOE, 2020.
155. E. Redmond, "HALEU Needs for Commercial Reactors," NEI, 2020.
156. GAO-21-28, "Actions to Mitigate Risks to Domestic Supply Chain Could Be Better Planned and Coordinated," GAO, 2020.
157. Ibid.
158. D. Fletcher, "URENCO Next Generation Fuels: Conversion and Enrichment Options," Urenco, 2020.
159. "E.ON not solely relying on Urenco stake sale in asset disposals," Reuters, 9 May 2017. [Online]. Available: https://www.reuters.com/article/e-on-results-ma/e-on-not-solely-relying-on-urenco-stake-sale-in-asset-disposals-idUKL8N1IB2P2.
160. "Government launches sale of uranium enrichment firm Urenco," Reuters, 22 Apr 2013. [Online]. Available: https://www.reuters.com/article/uk-britain-urenco-idUKBRE93L0B820130422.
161. D. Fletcher, "URENCO Next Generation Fuels: Conversion and Enrichment Options," Urenco, 2020.

The USA has also explored how to meet civilian and military HALEU demand by downblending existing stockpiles of HEU, all of which is unobligated material. DOE has begun producing 1-2 tonnes of HALEU fuel per year for reactor R&D.[162] The USA no longer has a HEU production facility, so these stockpiles are a limited but significant resource. The US Navy has 150 tonnes of 93% HEU for submarines fuel, of which 65 tonnes will be required by the current fleet up to 2040.[163] There also is a 20 tonne civilian stockpile.[164] Additionally, 100 tonnes of weapon HEU could be declared excess without affecting the strategic nuclear deterrent.[165] Each tonne of 93% HEU can be downblended to 4.58 tonnes of 19.75% HALEU. Downblending half of the stockpiles mentioned above would produce 618 tonnes of HALEU. This would be sufficient HALEU to meet US reactor vendor needs to 2030[166] or the NNSA tritium production requirements for 9 years (assuming the 0.4MSWU/yr required equates to 68.6 tonnes of 19.75% HALEU). There are understandable hesitations about depleting the HEU stockpiles, particularly those for Naval fuel, however this would be less of a concern if the USA committed to HALEU-fuelled vessels or reduced the land-based component of the deterrent.

Minor producers

Japan

Even if Japan retakes its position as a major reactor exporter, the low price of SWU and previous cost overruns make it very unlikely to construct complementary domestic enrichment capacity.

Japan has a successful history as a nuclear technology and reactor exporter, particularly of BWRs, with a reputation for operational innovations which reduced costs and ensured on-time delivery of projects. Japanese vendors also sold AP1000s and other reactors through subsidiaries such as Westinghouse Electric Company. These exports, as well as operation of Japanese domestic reactors, were paused after the Fukushima accident in 2011. Both are slowly restarting, but exports of large reactors have not materialized yet. In response, Japanese vendors are developing new SMRs and microreactors with better market-fit and wider pool of potential investors.[167] While these reactors have significant potential, it remains to be seen whether taking more time to understand future changes to the energy system will pay off versus Chinese and US first-move advantage, or the project financing strengths of the state-backed Chinese, Russia, and South Korean exporters.

Japan Nuclear Fuel Limited (JFNL) operates Japan's only enrichment facility, at Rokkasho. It currently produces 75kSWU/yr, which will be expanded to 1.5MSWU/yr by 2022.[168] There is little appetite to expand Japan's SWU capacity further. Domestic demand is still low as reactors are only gradually being

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162. "Government launches sale of uranium enrichment firm Urenco," Reuters, 22 Apr 2013. [Online]. Available: https://www.reuters.com/article/uk-britain-urenco-idUKBRE93L0B820130422.
163. B. Hanlon, "Validation of the Use of Low Enriched Uranium as a Replacement for Highly Enriched Uranium in US Submarine Reactors," MIT, 2013.
164. Ibid.
165. F. von Hippel and S. Weiner, "No Rush to Enrich: Alternatives for Providing Uranium for U.S. National Security Needs," *Arms Control Today,* 2019.
166. E. Redmond, "HALEU Needs for Commercial Reactors," NEI, 2020.
167. J. Buongiorno, "Japan's Next Nuclear Energy System," MIT Canes, 2020.
168. "Operational Status at Uranium Enrichment Plant," JFNL, 31 Jan 2021. [Online]. Available: https://www.jnfl.co.jp/en/business/uran/.

restarted: 1-1.5MSWU/yr versus 4.5MSWU/yr pre-2011. Also, frequent cost overruns when constructing Rokkasho compare unfavourably with the cheap SWU imports available.

Lastly, Japan does not need an enrichment facility as a nuclear weapons hedge. It has 48 tonnes of separated plutonium, enough for many thousands of nuclear weapons.[169]

India

India is expected to construct 25-31GWe of new nuclear reactors in the next twenty years, but its reliance on PHWRs and cheap SWU imports mean it is unlikely to construct new enrichment facilities. These new reactors will require 1MSWU/yr of additional capacity, and can be operated using natural uranium if preferred.

India has domestic enrichment facilities which produce HEU using locally manufactured centrifuges. India has contracts with TVEL to import natural uranium and low-enriched uranium, including for its four existing Russian-built VVERs.[170] This is very affordable and allows greater flexibility in the timing and scale of new reactor construction. Additionally, excess SWU capacity would lose value if India successfully develops thorium-fuelled reactors, which would take advantage of its significant thorium reserves.

Pakistan

Pakistan has no civilian enrichment centres and has not announced plans to construct any. Its two existing enrichment facilities, producing less than <0.1MSWU/yr, are used to produce HEU. Fuel for its four PWRs is imported from CNNC.[171]

Brazil

Brazil has two enrichment facilities: a 9kSWU/yr plant operated by the Navy in Aramar and a commercial plant in Resende.[172] The latter is still under construction, with a multi-stage schedule of installing centrifuge cascades and testing. Once completed in 2022, it will have a 0.2MSWU/yr capacity, to be used to produce fuel for Brazil's domestic reactors.[173]

While Brazil does not have a reactor export programme, there have been some internal proposals for it to export HALEU fuel for research reactors and new reactor testing. Brazil has developed and demonstrated all of the mining and front-end fuel cycle technologies, and the Aramar facility has delivered small quantities of HALEU for domestic research reactors and isotope production.[174] In the future it might also be

169. M. Takubo and F. von Hippel, "An Alternative to the Continued Accumulation of Separated Plutonium in Japan: Dry Cask Storage of Spent Fuel," *Journal for Peace and Nuclear Disarmament,* vol. 1, no. 2, pp. 281-304, 2018.
170. "Euratom Supply Agency - Annual Report," European Union, 2019.
171. M. Hibbs, "China provides nuclear reactors to Pakistan," Jane's Intelligence Review, 2014. [Online]. Available: https://carnegieendowment.org/email/DC_Comms/img/JIR1401%20F3%20ChinaPak.pdf.
172. M. D. Laughter, "Profile of World Uranium Programmes," ORNL NNSA, 2009.
173. "INB Activities: Enrichment," Industrias Nucleares Do Brasil, [Online]. Available: http://www.inb.gov.br/en-us/Our-Activities/Nuclear-Fuel-Cycle/Enrichment.
174. "Brazil Looks to HALEU," Nuclear Engineering International, 24 June 2020. [Online]. Available: https://www.neimagazine.com/features/featurebrazil-looks-to-haleu-7993503/.

used for a nuclear submarine programme.[175,176,177] These proposals are very preliminary, and it is unlikely to affect the global SWU market.

Iran and North Korea

Iran and North Korea both have enrichment facilities capable of producing LEU and HEU. North Korea's output is uncertain, but estimated to be less than 10kSWU/yr. Iran has announced it will increase its capacity in light of the breakdown of the JCPOA, growing from 7.5kSWU/yr today to 250kSWU/yr in the next few years and 1MSWU/yr ultimately. It is unclear if this pace is realistic given the constraints on their manufacturing capabilities.[178]

Neither state will be involved in the global enrichment market or reactor exports by 2040, unless there are radical changes in the international political environment.

Potential producers

Australia

Australia is the world's third largest uranium miner, producing 12% of all primary uranium supplies.[179] The low SWU price and significant public and political opposition to nuclear activities, especially the storage of nuclear waste, have precluded expansion into enrichment. Australia's research reactors are been fuelled with material imported from the USA and UK. Calls for Australian nuclear power have diminished post-Fukushima, further reducing the need for domestic enrichment. The SILEX laser enrichment technology, offering uranium enrichment at very low powers and capital cost, was developed in Australia, but the R&D effort moved to the USA.[180]

Australia has recently announced plans to acquire nuclear-powered submarines for the Royal Australian Navy, in cooperation with the USA and UK, as part of the AUKUS pact.[181] Plans are in an early stage, so it is not clear how enriched the fuel will be or whether it will be produced domestically or by the USA or UK. Importing the fuel would be fastest and carry the least risk of delay, as well as raise the fewest proliferations and safeguards concerns. However, the Australian government might try to construct domestic enrichment facilities or a fuel stockpile in the longer term, to create skilled jobs and ensure they can operate independently.

175. F. Von Hippel, "Mitigating the Threat of Nuclear-Weapon Proliferation via Nuclear-Submarine Programs," *Journal for Peace and Nuclear Disarmament,* vol. 2, no. 1, pp. 133-150, 2019.
176. M. D. Laughter, "Profile of World Uranium Programmes," ORNL NNSA, 2009.
177. S. M. Short, M. R. Weimar, J. Phillips and H. A. Mahy, "Economic and Non-Proliferation Policy Considerations of Uranium Enrichment in Brazil and Argentina," PNNL, 2008.
178. D. Albright and S. Burkhard, "A Technical and Policy Note on Iran's Recent Uranium Enrichment Capacity Claims," Institute for Science and Global Security, 2020.
179. "Uranium 2020: Resources, Production and Demand," OECD-NEA, 2020.
180. "Silex and Cameco agree terms for GLE acquisition," World Nuclear, [Online]. Available: https://www.world-nuclear-news.org/Articles/Silex-and-Cameco-agree-terms-for-GLE-acquisition.
181. "IAEA on Trilateral Effort of Australia, United Kingdom, and United States on Nuclear Naval Propulsion", IAEA, [Online]. Available: https://www.iaea.org/newscenter/pressreleases/iaea-on-trilateral-effort-of-australia-united-kingdom-and-united-states-on-nuclear-naval-propulsion.

Canada

Despite significant nuclear power capacity and fuel cycle companies, including SMR and microreactor vendors, it does not appear that Canada will develop domestic enrichment facilities by 2040.

Canada is the seventh largest user of nuclear power, with 13.5GWe of capacity from 19 PHWRs.[182] It was the largest uranium producer in the world until 2009, and currently sits second to Kazakhstan.[183] Ontario hosts the largest uranium conversion facility in the world, operated by Cameco. Twelve Canadian PHWRs have been exported to various parts of the world, leveraging their ability to be fuelled by natural uranium without the need for (previously expensive) enrichment services. Multiple new reactor vendors developing SMRs and microreactors have located to Canada due to the strong government support and the cooperative and respected nuclear regulator. These vendors hope to export their reactors globally.

Canada's fleet of domestic PHWRs require little to no SWU to operate, so constructing enrichment facilities would be to increase the value of fuel exports or support the sale of new non-PHWR reactors. A 2009 report found that enrichment services make up 90% of the value of export uranium, and that there was a positive economic case for enriching and then exporting 80-85% of the uranium produced in Canada.[184] It suggested inviting an international SWU provider to construct and wholly operate a centrifuge enrichment facility in Canada, to avoid R&D costs and mitigate proliferation concerns. This proposal did not move forward, though Cameco purchased a minority stake in the SILEX laser enrichment technology.[185]

South Korea

South Korea (ROK) generates one quarter of its electricity from 24 nuclear reactors, with over 23GWe of capacity.[186] Nuclear power is an important part of the ROK's energy policy, as it lacks significant fossil fuel reserves, though VREs are an increasingly important generator as well. Four reactors are under construction, amounting to an additional 5.4GWe of capacity. The ROK currently imports the 3.2MSWU/yr required by its reactors through contracts with all of the major enrichment providers, but has signalled its desire to construct domestic enrichment and reprocessing facilities.

Over the past decade, the ROK has loosened its commitments to not enriching or reprocessing uranium. It had previously committed to never doing so, under the terms of a 30-year agreement with the USA, in 1973, which gave it access to civilian nuclear technology.[187] The 2015 follow-on agreement allows the ROK to enrich uranium to 20% and reprocess some spent fuel, in collaboration with the USA.[188]

Allowing the ROK to build enrichment and reprocessing facilities is politically sensitive due to the pro-

182. "Power Reactor Information System," IAEA, [Online]. Available: https://pris.iaea.org/PRIS/CountryStatistics/CountryStatisticsLandingPage.aspx.
183. "Uranium 2020: Resources, Production and Demand," OECD-NEA, 2020.
184. D. Jackson and K. Dormuth, "Uranium Enrichment in Canada," The Center for International Governance Innovation, 2009.
185. "Cameco: Global Laser Enrichment," Cameco, 2021. [Online]. Available: https://www.cameco.com/businesses/fuel-services/enrichment-gle.
186. "Power Reactor Information System," IAEA, [Online]. Available: https://pris.iaea.org/PRIS/CountryStatistics/CountryStatisticsLandingPage.aspx.
187. M. Holt, "U.S. and South Korean Cooperation in the," Congressional Research Service, 2013.
188. "U.S.-Republic of Korea (R.O.K.) Agreement for Peaceful Nuclear Cooperation - Fact Sheet," 2015. [Online]. Available: https://www.state.gov/remarks-and-releases-bureau-of-international-security-and-nonproliferation/u-s-republic-of-korea-r-o-k-agreement-for-peaceful-nuclear-cooperation/.

liferation concerns in the region. The ROK previously explored how to develop its own nuclear weapons when the USA reduced troop deployments there in the 1970s, entering negotiations with France to purchase reprocessing technology for plutonium production.[189] An independent ROK nuclear deterrent is unpopular with the USA and China, though the idea has gained more currency domestically as North Korean nuclear weapon capabilities have increased and the reliability of US extended deterrence has come into question.[190,191]

The ROK argues that both activities are needed to meet its fuel needs, manage its growing nuclear waste stockpile, and potentially to power military naval vessels. The government historically prioritized producing Korean-designed and manufactured reactors, initially focusing on PHWRs before purchasing intellectual property from Westinghouse and Combustion Engineering to produce the APR-1400 and its predecessors.[192] The ROK hopes to capture a significant fraction of the reactor export market and began by selling four APR-1400s to the UAE.[193] It is also developing the SMART SMR, an industrial-power focused reactor, and is in discussions with Saudi Arabia.[194] The fuel for both reactor classes is being produced by a combination of international service providers. Cheaper fuel from domestic enrichment may improve the competitiveness of future reactors, though it is unclear if the ROK can beat TVEL and Urenco's low costs.

The ROK government has expressed interest in developing nuclear-powered submarines to extend their patrol and submarine-hunting capabilities, and that it requires domestic enrichment facility to produce LEU fuel for these reactors.[195,196,197] North Korean advancements in submarine and nuclear weapon delivery technologies have made this more of a priority. As with the US LEU submarine programme, international enrichment providers believe existing agreements allow HALEU or LEU to be sold to the ROK for use as military submarine fuel, just not for constructing nuclear weapons. Importing submarine fuel would avoid the need for a military enrichment facility outside of safeguards. If the ROK does go ahead with domestic enrichment it would likely only require a small amount of HALEU or LEU for testing and development by 2040, 0.1MSWU/yr or less.

Argentina

Argentina previously operated a 20kSWU/yr gas-diffusion enrichment plant at Pilcaniyeu. The facility

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188. E. Lim, "South Korea's Nuclear Dilemmas," Journal for Peace and Nuclear Disarmament, vol. 2, no. 1, pp. 297-318, 2019.
190. Ibid.
191. "South Korea will not develop or possess nuclear weapons, president says," Washington Post, 31 Oct 2017. [Online]. Available: https://www.washingtonpost.com/world/south-korea-will-not-develop-or-possess-nuclear-weapons-president-says/2017/10/31/e440b2da-beaa-11e7-af84-d3e2ee4b2af1_story.html.
192. R. S. Kemp, *Lecture on history of nuclear power industry - MIT,* 2018.
193. "Barakah Nuclear Power Plant - Report," Power Technology, [Online]. Available: https://www.power-technology.com/projects/barakah-nuclear-power-plant-abu-dhabi/.
194. "Korea, Saudi Arabia progress with SMART collaboration," World Nuclear News, 7 Jan 2020. [Online]. Available: https://world-nuclear-news.org/Articles/Korea-Saudi-Arabia-progress-with-SMART-collaborati.
194. F. Von Hippel, "Mitigating the Threat of Nuclear-Weapon Proliferation via Nuclear-Submarine Programs," Journal for Peace and Nuclear Disarmament, vol. 2, no. 1, pp. 133-150, 2019.
196. E. Lim, "South Korea's Nuclear Dilemmas," *Journal for Peace and Nuclear Disarmament,* vol. 2, no. 1, pp. 297-318, 2019.
197. S. W. Kim, J. Kang and F. Von Hippel, "South Korea's risky quest to build nuclear-powered attack submarines," The Bulletin, 18 Nov 2020. [Online]. Available: https://thebulletin.org/2020/11/south-koreas-risky-quest-to-build-nuclear-powered-attack-submarines/.

was restarted in 2015, though it is unclear if production has begun.[198] Argentina's three large commercial reactors are PHWRs and the small enrichment demand for its research reactors is met through imports. An agreement for CNNC to construct a Hualong One reactor appears to have stalled.[199] If it goes ahead, CNNC will supply the fuel, creating little extra impetus to construct new facilities.

South Africa

South Africa operated an enrichment facility at Pelindaba until 1990.[200] It used an aerodynamic separation method. While it operated fuel conversion, enrichment and fabrication facilities in the 1980s and 90s, South Africa now purchases all fuel services for its two reactors from a mixture of providers.

South Africa was very involved in the development of pebble bed reactors and fuel over the past twenty years. Initially a 5-10MSWU/yr enrichment facility was proposed as part of a pebble fuel production complex, in collaboration with one of the major enrichment service providers. After significant spending the reactor programme was cancelled in 2010.[201] Plans for a smaller 1.3MSWU/yr facility were published in 2012 but have not moved forward due to the continued low SWU price and anaemic domestic and foreign SWU demand growth.

Saudi Arabia

Saudi Arabia intends to construct 16 nuclear reactors with 17.6GWe of power by 2040,[202,203] in order to reduce its consumption of fossil fuels as its population and energy consumption grow. It is in discussion with vendors from the USA, China, Russia, South Korea, and France.

Saudi Arabia has expressed interest in developing its own enrichment capability to reduce costs and create high-skilled jobs.[204] It would be unusual for reactor vendors to not include a decade or more of fuel as part any reactor sale, but Saudi Arabia may be able to reduce this obligation by leveraging the scale of their construction programme or simply use that decade to develop their own enrichment facilities. The full complement of 16 reactors would require 1.5-3MSWU/yr.

It seems very unlikely that other states would allow any foreign enrichment provider to construct an enrichment facility in Saudi Arabia, and very challenging for a native programme to produce 3MSWU/yr in the next ten years. States fear that enrichment facilities in Saudi Arabia would be co-opted into producing HEU for nuclear weapons, exacerbating tensions in the region. The Crown Prince of Saudi Arabia has said he would seek to develop a nuclear weapon if Iran did so.[205] Significant assurances from Saudia Arabia

198. "Argentina inaugurates enrichment plant," World Nuclear News, 2 Dec 2015. [Online]. Available: https://www.world-nuclear-news.org/UF-Argentina-inaugurates-enrichment-plant-0212154.html.
199. "Chinese nuclear energy in Argentina is in trouble," SupChina, 3 Sept 2020. [Online]. Available: https://supchina.com/2020/09/03/chinese-nuclear-energy-in-argentina-is-in-trouble/.
200. L. Von Wielligh-Steyn and N. Von Wielligh, "The Bomb: South Africa's Nuclear Weapons Programme," 2015.
201. S. Thomas, "The pebble bed modular reactor: an obituary," *Energy Policy,* pp. 2431-2440, 2011.
202. "Why US wants Saudis to follow UAE's path to nuclear energy," Christian Science Monitor, 3 Sept 2020. [Online]. Available: https://www.csmonitor.com/World/Middle-East/2020/0903/Why-US-wants-Saudis-to-follow-UAE-s-path-to-nuclear-energy.
203. "Saudi plans to build 16 nuclear reactors by 2030," Reuters, 1 June 2011. [Online]. Available: https://www.reuters.com/article/saudi-nuclear-idAFLDE75004Q20110601.
204. C. Carpenter, "Saudi Arabia in talks with 5 vendors to build its first nuclear power reactors," S&P Global, 30 Oct 2019. [Online]. Available: https://www.spglobal.com/platts/en/market-insights/topics/hydrogen.
205. "Saudi Atomic Reactor Progresses with Inspectors Still Frozen Out," 21 May 2020. [Online]. Available: https://www.

would be required both internationally, by agreeing NPT Additional Protocols, and bilaterally with the supplier. Saudi Arabia has almost completed construction of a research reactor, purchased from Argentina. It will need to agree to more international safeguards in order purchase fuel, which may indicate the shape of future agreements.[206]

Vietnam

Vietnam has a rapidly growing population and energy demand, driven by its growing attractiveness as a manufacturing hub. It has explored the possibility of purchasing nuclear reactors to meet some of this need since the 1980s, and currently plans to build 1GWe of nuclear power by 2040 and 5GWe by 2050.[207] The vendor has not been announced. Similar contracts with Russian and Japanese vendors have been cancelled in the past. Despite reports of initial reluctance, Vietnam signed agreements with the USA in 2014 to not seek domestic enrichment or fuel reprocessing technologies, instead relying on international markets.

Safeguard and Proliferation Concerns

Most or all of the increase in SWU capacity will be in China. Urenco and TVEL may increase their capacity if they successfully partner with reactor vendors, but China is set to add at least 9.5MSWU/yr of capacity just to meet domestic demand. That would constitute two thirds of all new enrichment capacity.

As a nuclear weapon state, China is only subject to voluntary safeguards so new enrichment facilities there will not burden the IAEA. However, there is an emerging consensus that China is expanding its nuclear weapons arsenal,[208,209,210] which will be made easier by China's new enrichment facilities, though it may also favour lighter plutonium warheads over HEU.

This build-up may prompt China's neighbours to seek their own nuclear deterrents, unless the USA and other allies can provide suitable assurances of protection and extended deterrence. South Korea, Japan, and Taiwan all have civilian nuclear programmes and experts, and currently or previously have had some form of reprocessing and plutonium production.[211,212,213] Given the scale and sophistication of these nuclear programmes, it is not clear that the IAEA would detect diversion of material in a timely manner,[214,215] put-

bloomberg.com/news/articles/2020-05-21/saudi-atomic-reactor-progresses-with-inspectors-still-frozen-out.

206. "First Images of Saudi Nuclear Reactor Show Plant Nearing Finish," The Japan Times, 4 April 2019. [Online]. Available: https://www.japantimes.co.jp/news/2019/04/04/world/first-images-saudi-nuclear-reactor-show-plant-nearing-finish/.

207. "Vietnam urged to reconsider nuclear power programme," 6 Sept 2020. [Online]. Available: https://www.nst.com.my/world/region/2020/09/622500/vietnam-urged-reconsider-nuclear-power-programme.

208. O. o. t. S. o. Defense, "Military and Security Developments Involving the People's Republic of China 2020," DOD, 2020.

209. J. Lewis, "China Is Radically Expanding Its Nuclear Missile Silos," *Foreign Policy,* 30 June 2021.

210. M. Korda and H. Kristense, "China Is Building A Second Nuclear Missile Silo Field," Federation of American Scientists, 26 July 2021. [Online]. Available: https://fas.org/blogs/security/2021/07/china-is-building-a-second-nuclear-missile-silo-field/.

211. E. Lim, "South Korea's Nuclear Dilemmas," *Journal for Peace and Nuclear Disarmament,* vol. 2, no. 1, pp. 297-318, 2019.

212. D. Albright and C. Gay, "Taiwan: Nuclear nightmare averted," *Bulletin of the Atomic Scientists,* vol. 54, no. 1, pp. 54-60, 2015.

213. F. von Hippel, "How to simplify the plutonium problem," *Nature,* pp. 415-416, July 1998.

214. S. Voss, "Tracking Nuclear Proliferation within a Commercial Power Program," NPEC, 2012.

215. J. Cochran, "Adequacy of IAEA's Safeguards for Achieving Timely Detection," NPEC, 2005.

ting significant pressure on the IAEA and multilateral non-proliferation efforts.

A large enrichment facility in Saudi Arabia would make it easier for them to develop nuclear weapons. Saudi Arabia's leaders have expressed interest in acquiring nuclear weapons, especially in response to Iran doing so,[216] increasing the apparent proliferation risk of any new facility. Concern about Saudi Arabia's breakout capability could prompt its neighbours, including Iran, UAE, and Turkey, to maintain parity by developing their own nuclear weapons. As with China and its neighbours, an arms race in the Middle East would require constant inspections and enforcement action from the IAEA and UN, which they have been reluctant or slow to do in the past.

A Saudi Arabian enrichment facility creates two potential proliferation pathways. Saudi Arabia could attempt to quickly produce weapon material by diverting a large volume of fuel and reconfiguring its civilian centrifuges for HEU production. A 1.5MSWU/yr facility would produce enough HEU for a warhead in less than week, once the facility had been reconfigured. Alternatively, Saudi Arabia could use the large civilian organization as cover to slowly procure material and expertise for a covert HEU facility. Countries have previously taken this approach without the IAEA detecting the activity, at least for a time.[217] A ROK enrichment facility would create the same proliferation pathways, particularly if it was a joint military-civilian facility and so subject to more limited inspections and safeguards.

Beyond enrichment facilities, the wider deployment of nuclear reactors, including to states which have never previously used nuclear power, increases the opportunities for fuel to be diverted gradually or en-masse and enriched in covert facilities. Advanced centrifuges have proved difficult to procure or develop even with very large investments of human and financial capital.[218] The adoption of Additional Protocols and greater Nuclear Suppliers Group controls have likely increased this difficulty further. However, basic centrifuges producing 0.5SWU/yr (versus 100-300SWU/yr for modern devices) can be manufactured easily using unmonitored materials and controllers.[219,220] The UK produced a 1kSWU/yr facility using centrifuges of this type over the course of a year in the 1960s, suggesting a similar facility would be within the technical capability of most states with nuclear power today.[221]

The widespread use of HALEU fuel would exacerbate the proliferation risk of both known and covert enrichment facilities. A would-be proliferator requires only 150kg of 19.75% enriched HALEU fuel and 350SWU to produce a nuclear weapon, compared to 650kg of 5% LEU and 1100SWU.[222] A state could successfully breakout and produce a weapon more quickly using HALEU fuel in either kind of enrichment facility.

New enrichment facilities and reactor deployments certainly increase the potential for nuclear proliferation, but it is by no means a foregone conclusion that new nuclear weapon states will be the result. IAEA and NSG safeguards and inspection powers have been strengthened since the major shortcomings in the 1970-90s. Nuclear weapons programmes require significant coordination across multiple levels of gov-

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216. "Saudi Atomic Reactor Progresses with Inspectors Still Frozen Out," 21 May 2020. [Online]. Available: https://www.bloomberg.com/news/articles/2020-05-21/saudi-atomic-reactor-progresses-with-inspectors-still-frozen-out.
217. S. Voss, "Tracking Nuclear Proliferation within a Commercial Power Program," NPEC, 2012.
218. J. Hymans, Achieving Nuclear Ambitions: Scientists, Politicians, and Proliferation, Cambridge University Press, 2012.
219. "Characteristics of the Gas Centrifuge for Uranium Enrichment and Their Relevance for Nuclear Weapon Prolfieration," *Science and Global Security,* vol. 10, pp. 1-25, 2008.
220. R. S. Kemp, "Centrifuges: A New Era for Nuclear Proliferation," NPEC, 2012.
220. R. S. Kemp, "The nonproliferation emperor has no clothes: the gas centrifuge, supply-side controls, and the future of nuclear proliferation," International Security, vol. 38, no. 4, pp. 39-78, 2014.
222. H. Wood, A. Glaser and R. Kemp, "The gas centrifuge and nuclear weapons proliferation," in *AIP Conference Proceedings*, 2014.

ernment, as and investments in covert enrichment facilities, uranium processing, and warhead delivery vehicles.[223,224] This degree of mobilization makes such efforts more detectable.[225,226] While the UN has sometimes failed to take appropriate actions once programmes have been detected, unilateral and multilateral sanctions have had some effect in Iran and the DPRK. In the most extreme cases, states also have increasing abilities to interfere with R&D and infrastructure through cyber-attacks, as demonstrated by Stuxnet, the Ukrenergo attack, Triton and the Colonial pipeline ransomware attack.

Even when a state has the capability to develop nuclear weapons, history has shown they also require sufficient motivation and a lack of cheaper alternatives to achieve their strategic goals. For example, the ROK and Taiwan have met their safeguard obligations for the past thirty years and adhered to agreements with the USA to not reprocess spent fuel.[227,228] The Nuclear Weapon Ban Treaty movement may also limit states with new civilian nuclear programmes, such as Vietnam, from going on to develop weapons programmes. However, this good behaviour assumes states' security is not seriously threatened, which is not true in some regions. This assumption will be increasingly tested as the world continues to becomes less unipolar, especially if states do not believe they can rely on support and extended deterrence from the USA. All in all, these risks must be balanced against the damage of climate change and the feasibility of meeting emission goals with non-nuclear alternatives.

223. V. Narang, "Strategies of Nuclear Proliferation: How States Pursue the Bomb," *International Security,* vol. 41, no. 3, pp. 110-150, 2017.
224. J. Hymans, Achieving Nuclear Ambitions: Scientists, Politicians, and Proliferation, Cambridge University Press, 2012.
225. Ibid.
226. R. S. Kemp, "The nonproliferation emperor has no clothes: the gas centrifuge, supply-side controls, and the future of nuclear proliferation," *International Security,* vol. 38, no. 4, pp. 39-78, 2014.
227. E. Lim, "South Korea's Nuclear Dilemmas," *Journal for Peace and Nuclear Disarmament,* vol. 2, no. 1, pp. 297-318, 2019.
228. D. Albright and C. Gay, "Taiwan: Nuclear nightmare averted," *Bulletin of the Atomic Scientists,* vol. 54, no. 1, pp. 54-60, 2015.

Appendix

A - What is a SWU?

A separative work unit (SWU) is a measure of the effort exerted during a uranium enrichment process. It is a useful metric to make like-for-like comparisons across various enrichment technologies and facilities, given their wide differences in energy and separation efficiencies.

The SWUs required to enrich material to a given enrichment percentage grows approximately linearly with the enrichment, per kg of product material. However, it only grows logarithmically with the product enrichment for a fixed mass of input, as shown in Figure A-1. This mean that producing 1kg of 10% enriched uranium requires roughly twice as many SWU as producing 1kg of 5% enriched uranium from the same starting stock. However, enriching 1kg of 5% uranium to have 10% enrichment will require fewer SWU than originally producing the 5% stock, though you will be left with less than 1kg of 10% uranium.

The SWU required in a given process is calculated using the following expressions:

$$SWU = M_p f(x_p) + M_t f(x_t) - M_f f(x_f)$$

$$f(x) = (2x - 1) * \ln\left(\frac{x}{1 - x}\right)$$

Where M_p and x_p are the mass and U-235 enrichment of the product material stream, and M_t, x_t and M_f, x_f are the same for the tails and feed material streams.

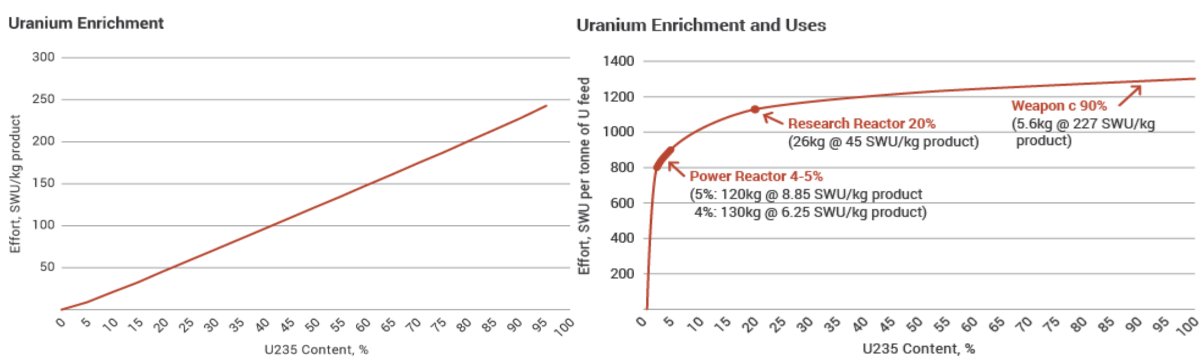

Figure A-1 Left: SWU required to produce uranium of a given U-235 enrichment, per kg of output product uranium. **Right:** SWU required to produce uranium of a given U-235 enrichment, per tonne of natural uranium feed.[229]

B - SWU intensity of various reactors

Nuclear reactor designs require different amounts of fuel, at different enrichments, and make more or less efficient use of it. The SWU intensity, i.e. the SWU required per unit of energy produced or SWU/GWd-

229. "Uranium Enrichment," World Nuclear, [Online]. Available: https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/conversion-enrichment-and-fabrication/uranium-enrichment.aspx.

t, will hence vary between designs. To summarize this, we can divide the SWU required to produce one tonne of fuel, the SWU / tHM, by the average thermal energy a design produces per tonne of fuel, the GWd-t / tHM.

To calculate the annual SWU requirements of a specific reactor, the SWU intensity must be multiplied by the plant-specific annual generation: [SWU / yr] = [SWU / GWd-t] * [GWd-t / yr]

Table B-1 gives the SWU intensity metric for a variety of large reactors, SMRs, and microreactors. The data is also shown in Figure 2 of the main text.

Table B-1 Estimates of SWU intensity per GWd-t output for various nuclear reactor designs[230,231,232,233,234,235,236,237,238,239]

	Name	Country	Type	MWe	MWt	Enrichment	GWd-t/tHM	SWU/tHM	Feed / Output	**SWU/GWd-t**	vs GenII
Large	Gen II PWR	USA	PWR	1194	3645	3.6	45	5250	8.2	**116.7**	100%
	CANDU-6	Canada	PHWR	728	2064	0	7.5	0	0.0	**0.0**	0%
	IPHWR-700	India	PHWR	700	2166	1.1	14	484	1.8	**34.6**	30%
	ESBWR	USA / Japan	BWR	1600	4500	4.2	55	6532	8.3	**118.8**	102%
	ABWR	USA / Japan	BWR	1350	3926	4	50	6102	7.9	**122.0**	105%
	REP 1450 v1	France	PWR	1561	4270	3.4	39	4823	6.6	**123.7**	106%
	VVER-440 v2	Russia	PWR	440	1375	4.25	52	6640	8.4	**127.7**	109%
	AP1000	USA	PWR	1200	3400	4.8	60	7836	9.5	**130.6**	112%
	VVER-1000	Russia	PWR	1000	3000	4.45	52.8	7073	8.8	**134.0**	115%
	EPR	EU	PWR	1770	4590	4.95	60	8164	9.8	**136.1**	117%
	VVER-1200	Russia	PWR	1170	3200	4.95	60	8164	9.8	**136.1**	117%
	REP 900 v1	France	PWR	951	2785	3.25	33	4510	6.3	**136.7**	117%
	VVER-440 v1	Russia	PWR	440	1375	3.82	41.6	5717	7.5	**137.4**	118%
	ACR-1000	Canada	PHWR	1165	3200	2.4	20	2791	4.5	**139.6**	120%
	REP 1300 v1	France	PWR	1362	3817	3.3	33	4614	6.4	**139.8**	120%
	REP 1450 v2	France	PWR	1561	4270	4	43	6102	7.9	**141.9**	122%
	REP 1300 v2	France	PWR	1362	3817	4	43	6102	7.9	**141.9**	122%
	REP 900 v2	France	PWR	951	2785	3.7	38	5455	7.2	**143.6**	123%
	APWR	Japan	PWR	1538	4466	4.95	55	8164	9.8	**148.4**	127%
	REP 900 v3	France	PWR	951	2785	4.2	42	6532	8.3	**155.5**	133%
	APR-1400	S.Korea	PWR	1400	3983	4.65	46.5	7508	9.2	**161.5**	138%
	HPR1000	China	PWR	1150	3060	4.95	47	8164	9.8	**173.7**	149%

230. Advanced Reactor Information System," IAEA, [Online]. Available: https://aris.iaea.org/.
231. "Power Reactor Information System," IAEA, [Online]. Available https://pris.iaea.org/PRIS/CountryStatistics/CountryStatisticsLandingPage.aspx.
232. "Advanced Large Water Cooled Reactors," IAEA, 2020.
233. "Advances in Small Modular Reactors," IAEA, 2018.
234. "Advances in Small Modular Reactor Technology," IAEA, 2020.
235. T. Xin, "Safety Approach and Safety Assessment of Hualong One," Hualong Pressurized Water Reactor Tech Corp, 2018.
236. M. Ding, J. L. Kloosterman, T. Koojiman and R. Linssen, "Design of a U-Battery," Delft, 2011.
237. "Generic Design Assessment Step 2 Assessment of the Fuel & Core Design of the UK HPR1000 Reactor," UK Office of Nuclear Regulation, 2018.
238. B. Shalaby, "AECL and HWR Experience," World Nuclear University, 2010.
239. S. Azeez, P. Dick and J. Hopwood, "The Enhanced CANDU 6TM Reactor," Atomic Energy of Canada Ltd, 2009.

Small	IMSR	Canada	MSR	194	400	3	29	3999	5.8	**137.9**	118%
	VK-300	Russia	BWR	250	750	4	41.4	6102	7.9	**147.4**	126%
	ACP100	China	PWR	125	385	4.95	52	8164	9.8	**157.0**	135%
	VBER-300	Russia	PWR	325	917	4.95	50	8164	9.8	**163.3**	140%
	BWRX-300	USA / Japan	BWR	280	870	4.95	49.5	8164	9.8	**164.9**	141%
	ThorCon	Intl	MSR	250	557	19.7	256	42437	40.6	**165.8**	142%
	Happy200	China	PWR		200	4.45	40	7073	8.8	**176.8**	152%
	HTR-PM	China	HTGR	210	500	8.5	90	16159	17.2	**179.5**	154%
	Xe-100	USA	HTGR	82.5	200	15.5	165	32481	31.8	**196.9**	169%
	HTTR-30	Japan	HTGR		30	14	120	28948	28.7	**241.2**	207%
	NuScale	USA	PWR	60	200	4.95	30	8164	9.8	**272.1**	233%
	ARC-100	Canada	LMFR	100	286	13.1	77	26836	26.8	**348.5**	299%
	U-Battery	UK	HTGR	4	10	19.75	88	42556	40.7	**483.6**	415%
	eVinci-like v1	USA	Heat Pipe	25	85.0	19.6	19.8	42160	40.27	**2129.3**	1825%
	eVinci-like v2	USA	Heat Pipe	5	17	18.6	3.98	39785	38.191	**9996.2**	8568%

Notes:

- Reactors with multiple versions in the table (e.g. the REP 1450) refer to alternative fuel loadings for a given reactor design.
- Some documentation was ambiguous as to whether burnup figures (GWd-t/tHM) were average or maximum values, or gave minimum or maximum values. For example, the NuScale documentation gives the average burnup as >30GWd-t/tHM.
- The "Feed / Output" is the mass of natural uranium, in kg, required to produce one kg of uranium at the relevant enrichment

About the Author

Dr. Ruaridh Macdonald is a postdoctoral researcher in the Department of Nuclear Science and Engineering at MIT. His current research focuses on understanding how nuclear power systems must change in order to succeed in modern energy systems and markets, and developing new designs in response. Prior to that, he developed a framework for comparing nuclear warhead disarmament verification protocols, designed a portable version of MIT's Fluoride Salt-Cooled High-Temperature reactor, and developed a new long-endurance aluminium-water battery. Ruaridh completed his undergraduate degree and Ph.D in Nuclear Science and Engineering at MIT.

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