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SUMMARY

The primary purpose of this report is to provide a documented estimate of High-Assay Low-Enriched Uranium (HALEU) needs that may be used in Department of Energy discussions with stakeholders as part of preparations to establish the HALEU Availability Program authorized by the Energy Act of 2020. This report employed a two-step process to estimate HALEU needs for commercial advanced reactors.

First, a scenario analysis was conducted using the Global Change Analysis Model (GCAM) to generate a projection of U.S. electricity generation capacity consistent with achieving net-zero emissions, economy-wide, by 2050. The model allows a carbon tax to be imposed on all carbon emissions sources to progressively limit total annual CO_2 emissions for achieving the net-zero emission goal. A carbon tax of ~\$100/tCO_2 in 2025 and growing to ~\$350/tCO_2 by 2050 was required for a straight-line emissions reduction to net-zero by 2050. This resulted in significant changes in the electricity generation mix, including the addition of carbon capture and sequestration (CCS) to all fossil fuel-based generation, growth in renewable energy including biofuels with CCS, and growth of nuclear energy to ~250 GW installed capacity by 2050. The GCAM analysis did not differentiate among different types of nuclear reactors.

Second, a spreadsheet model was developed that achieved the GCAM projection for nuclear capacity in 2050 using an assumed mix of conventional and advanced nuclear reactors; some of these reactor types require HALEU and others do not. It was assumed that new construction would employ roughly equal capacity shares of four different reactor types:

- A GW-scale Light Water Reactor (LWR) represented by the AP-1000 design
- A small modular LWR represented by the NuScale design
- An advanced sodium-cooled fast reactor represented by the Natrium design
- An advanced high temperature gas-cooled reactor represented by the Xe-100 design.

The model included constraints on reactor deployments based on technology availability and growth rates to produce the deployment schedule. The reactor deployment schedule was then used to calculate the amount of HALEU needed each year to support the initial start-up (first cores) and operation (fuel reloads) of the advanced reactors.

Total cumulative HALEU needed by 2050 for this scenario is ~5,350 MT @ 19.75% ^{235}U with a range of 3,450-7,175 MT depending on the advanced reactor mix. This estimation reflects the impact of down-blending from 19.75% to the target enrichments for each type of non-LWR, which average around 16%. The HALEU is first needed in small amounts for reactor demonstrations starting in 2027, then increases as more reactors are deployed, reaching ~520 MT/yr in 2050, split ~ 2/3rd for reloads and 1/3rd for start-up cores for new reactors.

The above amounts do not include consideration of fuels enriched to slightly over 5% for the LWRs. The analysis included growth in electricity usage that supports electrification and the decarbonization of end-use sectors. Nuclear reactor applications for industrial heat and hydrogen production were not investigated in this analysis.

The HALEU needs may also vary significantly upward or downward if one of the four reactor types does not achieve assumed growth or other electricity generation technologies such as CCS mature differently than assumed.

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ACRONYMS

ALWR	Advanced Light Water Reactor
ARDP	Advanced Reactor Demonstration Program
BECCS	Biomass with CCS
CCS	Carbon Capture and Sequestration
DOE	Department of Energy
EIA AEO	Energy Information Agency Annual Energy Outlook
EOY	end of year
GCAM	Global Change Analysis Model
GHG	greenhouse gas
GW	gigawatt
GWe	gigawatt electric capacity
HALEU	High Assay Low Enriched Uranium (enriched in ^{235}U >5% and <20%)
HTGR	High Temperature Gas-cooled Reactor
LEU	Low Enriched Uranium (enriched in ^{235}U >0.71% and <20%)
LWR	Light Water Reactor
NRC	Nuclear Regulatory Commission
SFR	Sodium-cooled Fast Reactor
TWh	terawatt-hour electricity

Estimated HALEU Requirements for Advanced Reactors to Support a Net-Zero Emissions Economy by 2050

1. INTRODUCTION

The primary purpose of this report is to provide a documented estimate of High-Assay Low-Enriched Uranium (HALEU) needs that may be used in Department of Energy (DOE) discussions with stakeholders as part of preparations to establish the HALEU Availability Program authorized by the Energy Act of 2020.

1.1 Background

The DOE's nuclear energy research is focused on development of advanced nuclear reactors and fuels that are safe, affordable, flexible, and resilient to improve the competitiveness of nuclear energy in the marketplace, especially as a complement to variable wind and solar energy. Several actions were recently taken to help advance this research toward commercial deployment. In October 2020, DOE announced several awards under the Advanced Reactor Demonstration Program (ARDP) in three areas: (1) Demonstration projects to build TerraPower's Natrium reactor and X-energy's Xe-100 reactor that can be operational by 2028, (2) Risk Reduction for Future Demonstration Projects and (3) Advanced Reactor Concepts to assist the progression of advanced reactor designs in their earliest design phases.

Most advanced reactor designs, including the two demonstration projects rely on the use of HALEU to achieve increased power density, longer core life, improved economics, and other desirable design attributes. The Energy Act of 2020, enacted in December 2020, directed establishment of the HALEU Availability Program to provide a source of fuel for advanced reactors, including commercial reactors.

In January 2021, the President established goals for a carbon pollution-free power sector by 2035 and a net-zero emissions economy by 2050[a]. Achieving these goals will require reliable sources of clean energy including nuclear energy, which currently is the largest source of emissions-free electricity. The Infrastructure Investment and Jobs Act of 2021, enacted in November 2021, recognizes the importance of nuclear energy, and supports continued operation of existing nuclear plants[b] and provides full matching funds for construction of the two ARDP demonstration projects.

HALEU needs for R&D, research reactors, and the ARDP demonstration projects are known with reasonable certainty. Estimates of HALEU needs for commercial advanced reactor deployments are less certain. Analyses are required to estimate HALEU needs for advanced reactor deployment to achieve the Administration's new clean energy goals.

1.2 Approach

This report employed a two-step process to establish an estimate for HALEU needs for commercial advanced reactors.

First, a scenario analysis was conducted using the Global Change Analysis Model (GCAM) to generate a projection of U.S. electricity generation capacity consistent with achieving net-zero emissions, economy-wide, by 2050. All clean energy technology options were included in the analysis. Details of this analysis are provided in Section 2.

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[a] Presidential Executive Order EO 14008

[b] The Civil Nuclear Credit Program

Second, a spreadsheet model was developed that achieved the GCAM projection for total nuclear capacity in 2050 by assuming a mix of conventional and advanced nuclear reactor types. The model included constraints on reactor deployments based on technology availability and growth rates to produce a deployment schedule. Details of this analysis are provided in Section 3. The reactor deployment schedule was used to calculate the HALEU needed each year to support the initial start-up (first cores) and operation (fuel reloads) of the advanced reactors. Details of this analysis are provided in Section 4.

Section 5 provides some additional considerations and Section 6 summarizes the findings.

2. ELECTRICITY GENERATION CAPACITY PROJECTION

Assessing the potential of nuclear energy for contributing to deep decarbonization efforts and net-zero emissions by 2050 in the U.S. requires the understanding of the likely evolution of the electricity sector. This study assumes that domestic energy policies going forward will support all available clean energy options. Deep decarbonization policies incentivize the retention of existing nuclear plants and deployment of additional nuclear reactors due to their ability for carbon-free electricity generation. The GCAM model was utilized for assessing the evolution of the U.S. electric power sector and for projecting the potential contribution of advanced nuclear reactors and their deployment schedule for supporting the U.S. net-zero emission goal by 2050.

GCAM is a publicly available, open-source integrated-assessment model from the Pacific Northwest National Laboratory developed for the purposes of exploring the coupled human-Earth system dynamics and the response of this system to global change. GCAM is widely utilized for generating scenarios of energy, agricultural, and greenhouse gas (GHG) emissions projections and the assessment of policy and technology impacts of climate mitigation efforts. GCAM is a global model with 32 regions, including the U.S. as one of the regions. GCAM provides projections in five-year time steps from 2015 to 2100. Although 2020 is a historical year, 2015 is the final historically calibrated period due to lags in data availability. For this analysis, only the U.S. results for the period of 2015 to 2050 were used. Multiple data sources and assumptions are inputs to the model and rebasing of historical calibration is conducted when updated datasets become available. Further documentation on GCAM is available online (http://jgcri.github.io/gcam-doc).

2.1 Capacity Projection Approach

The U.S. Administration's deep decarbonization goal of a net-zero economy by 2050 was imposed in the model in a technology-neutral manner by using a straight-line economy-wide CO_2 emissions reduction constraint from 2020 to net-zero by 2050. Emission reductions were achieved by applying a carbon tax starting in 2025 as a carbon penalty on all carbon emissions sources. The carbon penalty increases the competitiveness of all non- or low-emitting technologies throughout the economy. The carbon penalty also induces greater electrification of end-use sectors (buildings, industry, and transportation) as fossil fuel use is replaced by electricity.

The model assumed that the deployment of clean energy technologies induced by the carbon penalty, including new nuclear and carbon capture and sequestration (CCS) technologies, could begin as early as 2025. A five-year timestep was used in the analysis.

2.2 Results of Capacity Projection

Under deep decarbonization efforts, electricity demand projections are greater relative to a baseline projection without carbon mitigation policies. This is because carbon penalties induce greater electrification of end-use sectors (buildings, industry, and transportation) as energy services with electricity become more competitive than those based on direct fossil fuel use. The resulting GCAM electricity demand growth rate for the U.S. was ~ 2% per year from 2020 to 2050 in the net-zero scenario. This compares to the GCAM baseline growth rate, without net-zero policy, of 1.2% per year for the same time period. For comparison to other model projections, the EIA AEO 2021 Reference scenario electricity demand growth rate for the U.S. is 0.9% per year from 2020 to 2050. Electricity demand projections vary across models due to model structural and technology assumption differences.

The straight-line economy-wide CO_2 emissions reduction constraint is shown in Figure 1, left panel. Projected carbon taxes required to meet the net-zero emissions goal in GCAM are shown in Figure 1, right panel. The projected carbon price is 109 \$/tCO_2 in 2025 and rises to 352 \$/tCO_2 by 2050.

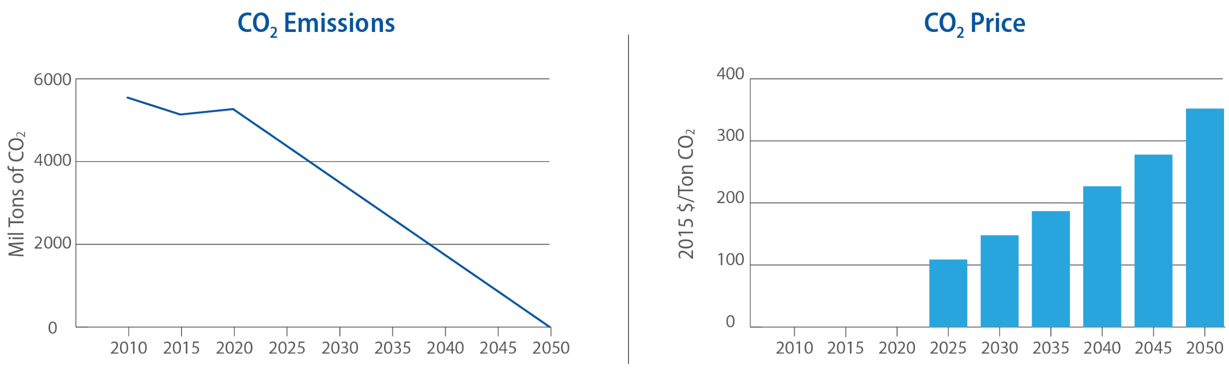

Figure 1. U.S. total economy CO_2 emissions constraint and resulting GCAM carbon taxes.

Total U.S. electricity generation grows to 8,300 TWh by 2050 in the net-zero scenario, which is double the 2015 generation of 4160 TWh (Figure 2). The electric power sector becomes fully decarbonized by 2035. While the total economy reaches net-zero emissions by 2050, the electric power sector reaches net-zero emissions earlier due to the availability of multiple low-cost carbon-free technology options.

Nuclear share of total electricity generation grows from 20% in 2015 to 24% by 2050, with total nuclear electricity generation of 1991 TWh in 2050. Growth of Nuclear Generation from 20% to 24% requires an additional capacity of about 150 GW, based on a capacity factor of 90%.

Renewable energy, including wind, solar, hydro, and geothermal together comprise a share of generation of 12% in 2015 and 24% in 2050, with a combined generation of 1967 TWh in 2050. Biomass with CCS (BECCS) is reported separately from other renewables due to differences in the carbon emissions accounting. BECCS is able to provide net-negative emissions since CO_2 absorbed from biomass growth is captured during power conversion and sequestered. Biomass power generation was less than 1% share of total in 2015. However, power generation from BECCS grows to 14% share and 1191 TWh of generation in 2050 due to its ability to provide net-negative emissions.

The availability of CCS enables continued utilization of fossil power generation with low carbon emissions. Oil, gas, and coal shares in 2015 (without CCS) were 1%, 31% and 35%, respectively. By 2050, there is no fossil power generation without CCS. Gas CCS and coal CCS power generation grows to 26% and 11% share in 2050, with corresponding generation of 2164 TWh and 905 TWh, respectively. Oil CCS does not contribute significantly to power generation with a share of 1% in 2050. CCS technologies played a significant role in this analysis. Long-term leakage rates from geologic carbon storage remain uncertain. At present, there are no commercial deployments of CCS for power generation. Excluding the CCS technology option due to safety, geologic leakage, and other risk factors would result in a greater projected need for nuclear and renewable energy.

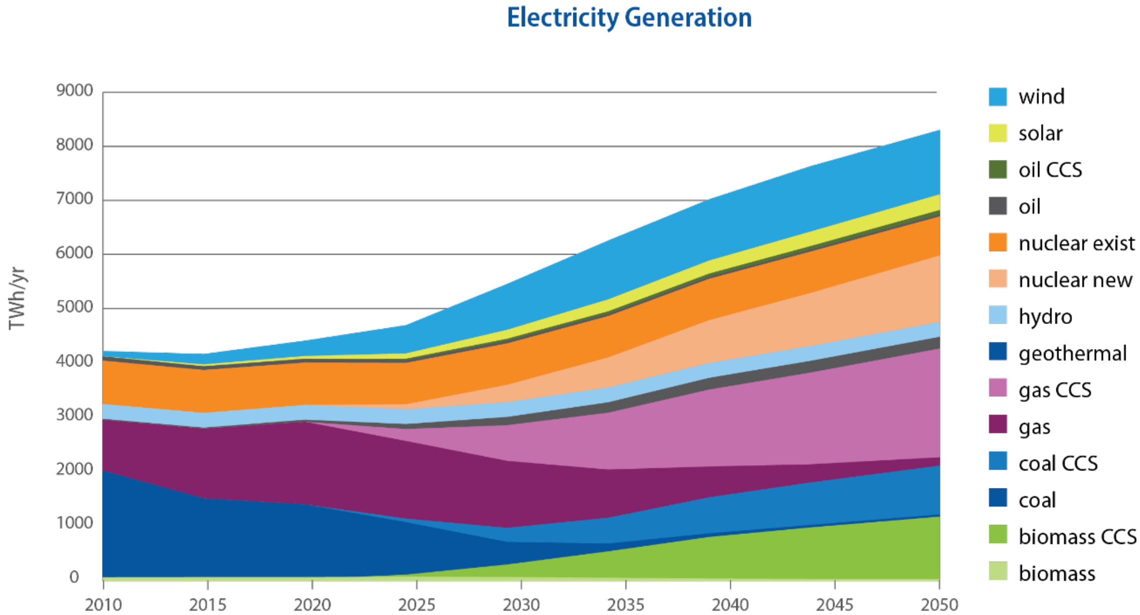

Figure 2. Projected electricity generation by source.

3. NUCLEAR DEPLOYMENT PROJECTION

The capacity analysis with GCAM used a five-year timestep, while estimation of annual HALEU needs was desired. Therefore, a spreadsheet model was developed that utilized a one-year timestep for deployment of new reactors.

3.1 Nuclear Deployment Approach

The spreadsheet model was initialized with information on existing reactors, reactors under construction, and planned retirements. New construction was then added, adjusted to reflect the availability of advanced reactors following demonstrations of designs supported by the Advanced Reactor Demonstration Program (ARDP) in 2028.

Nuclear capacity additions were estimated such that the overall electricity generation capacity projected by the GCAM analysis was matched in 2050. Existing nuclear capacity was based on legacy reactors operating to 80 years, except for recent and announced near-term retirements[c]. The GCAM analysis did not differentiate among different types of advanced nuclear reactors, so new reactor constructions assumed four reactor types split roughly equally to support their simultaneous and parallel deployments. This approach spreads the deployment load while also reducing the risk of failing to achieve needed overall construction rates; if one reactor type struggles or proves non-viable, deployment rates for the other three reactor types could be increased. The four reactor types were (1) GW-scale advanced light water reactors (ALWRs), represented by the AP-1000s currently under construction, (2) Small Modular Reactors (SMRs) based on LWR technology, represented by the NuScale concept currently moving through NRC licensing, (3) advanced sodium-cooled fast reactors (SFRs), represented by the Natrium concept, and (4) advanced high temperature gas-cooled reactors (HTGRs), represented by the Xe-100 concept.

[c] The analyses included in this study were performed in mid-2021. At that time, expected retirements included Indian Point 2 and Duane Arnold in 2020, Indian Point 3, Byron 1 & 2, and Dresden 2 & 3 in 2021, Palisades in 2022, and Diablo Canyon 1 & 2 in 2024-2025, for a total of 9.7 GW of lost legacy capacity.

The deployment schedule for new reactors assumed initial new orders of ALWRs could occur this year and will take 10 years to construct while the first of each of the three new reactor concepts would be completed based on current schedules. The model allowed for time to learn from the initial reactor builds while implementing an exponential growth rate for 10 years before leveling off to linear growth after the deployment rate was sufficient to achieve the target capacity in 2050.

New reactors were assumed to be constructed per the following approach:

- Advanced LWRs (LEU fuel):
  - Completion of Vogtle 3 & 4 in 2022-2023 and the initial LWR SMR (NuScale 12-pack) by 2030
  - Additional ALWRs completed starting in 2031 and SMRs in 2033, building by 2037 to 2 ALWRs (~2.2 GW) and 4 SMRs (~2.9 GW) completed per year
  - Total of 88 GW of new advanced LWRs by 2050
- Advanced non-LWRs (HALEU fuel):
  - Demonstration units of SFR (Natrium) and HTGR (Xe-100) completed in 2028
  - Additional SFR and HTGR units completed starting in 2031, building by 2040 to 8 SFRs (~2.8 GW) and 8 HTGR 4-packs (~2.6 GW) completed per year
  - Total of 74 GW of new non-LWRs by 2050

3.2 Results of Nuclear Deployment Projection

This approach resulted in the deployment schedule shown in Figure 3 and Table 1, which achieves the projected capacity of approximately 250 GW by 2050. Nuclear capacity initially declines slightly due to several pending retirements of legacy reactors and only two new reactors currently under construction. This trend reverses later in the decade as initial deployments of the three new reactor concepts are completed, accelerating after 2030 and reaching a sustained rate before 2040. While the projection ends in 2050, the deployment rates could be maintained after 2050 to provide continued growth and replacement capacity as legacy reactors retire.

The ramp up and sustained rates are both less than the ramp up in nuclear constructions in the late 1960s and early 1970s, when deployments rose from 0 to over 12 GW/yr between 1968-1974. It must be recognized that this ramp up occurred when the markets were regulated. Under the current market environment, either subsidies or a carbon tax or both would likely be needed to make this scenario plausible.

The non-LWRs and new ALWRs[d] will be fully flexible and able to load follow as needed to complement variable renewable generation. The sustained construction rates should provide stability in the supply chain and significant cost reduction over time based on learning and innovation.

[d] A few of the existing LWRs have also started providing some load following, while most provide base load generation.

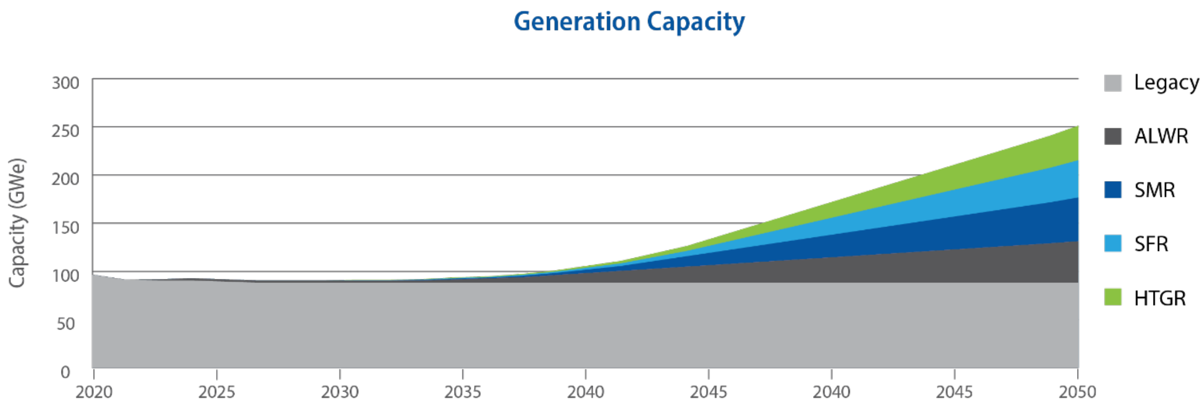

Figure 3. Projection of U.S. nuclear capacity for net-zero emissions by 2050.

Table 1. Reactor deployment schedule and total nuclear capacity from 2020 to 2050.

	Change in Reactor Units (number)					Change in Reactor Capacity (GWe)						Total Capacity
Year	Legacy	ALWR	SMR	SFR	HTGR	Legacy	ALWR	SMR	SFR	HTGR	Total	GWe, EOY
2020	-2					-1.56					-1.6	96.6
2021	-5					-5.13					-5.1	91.4
2022	-1	1				-0.77	1.1				0.3	91.8
2023		1					1.1				1.1	92.9
2024	-1					-1.12					-1.1	91.7
2025	-1					-1.12					-1.1	90.6
2026											0.0	90.6
2027											0.0	90.6
2028				1	1				0.35	0.32	0.7	91.3
2029											0.0	91.3
2030			1					0.72			0.7	92.0
2031		1		1	1		1.1		0.35	0.32	1.8	93.8
2032		1					1.1				1.1	94.9
2033		1	1	1	1		1.1	0.72	0.35	0.32	2.5	97.3
2034		2	1	1	1		2.2	0.72	0.35	0.32	3.6	100.9
2035		2	2	2	2		2.2	1.44	0.69	0.64	5.0	105.9
2036		2	2	2	2		2.2	1.44	0.69	0.64	5.0	110.9
2037		2	4	4	4		2.2	2.88	1.38	1.28	7.7	118.6
2038		2	4	4	4		2.2	2.88	1.38	1.28	7.7	126.4
2039		2	4	8	8		2.2	2.88	2.76	2.56	10.4	136.8
2040		2	4	8	8		2.2	2.88	2.76	2.56	10.4	147.2
2041		2	4	8	8		2.2	2.88	2.76	2.56	10.4	157.6
2042		2	4	8	8		2.2	2.88	2.76	2.56	10.4	168.0
2043		2	4	8	8		2.2	2.88	2.76	2.56	10.4	178.4
2044		2	4	8	8		2.2	2.88	2.76	2.56	10.4	188.8
2045		2	4	8	8		2.2	2.88	2.76	2.56	10.4	199.2
2046		2	4	8	8		2.2	2.88	2.76	2.56	10.4	209.6
2047		2	4	8	8		2.2	2.88	2.76	2.56	10.4	220.0
2048		2	4	8	8		2.2	2.88	2.76	2.56	10.4	230.4
2049		2	4	8	8		2.2	2.88	2.76	2.56	10.4	240.8
2050		2	4	8	8		2.2	2.88	2.76	2.56	10.4	251.2

4. HALEU NEEDS PROJECTION

The reactor deployment schedule in Table 1 was used to determine annual HALEU needs to support the reactor fleet. This schedule would require a combination of enrichment needs for the LWR and non-LWR plants, both for initial cores and reloads. Natural and enriched uranium needs were determined based on core size, fuel enrichment level, and average fuel residency time (based on burnup and capacity factor) for each type of reactor. Only the HALEU needs are reported here.

HALEU needs are reported based on a standardized enrichment of 19.75%. The totals reflect the impact of down-blending from 19.75% to the target enrichments for each type of non-LWR, which average around 16%.

The HALEU needs for the first cores begin in 2027 for the demonstration units. Reloads were normalized to annual rates based on the installed capacity. The results are shown in Figure 4. Annual amounts grow quickly from near 0 in 2030 to 520 MT/yr in 2050[e], ~1/3rd of which is for first cores.

Total cumulative HALEU needed by 2050 for this scenario is ~5,350 MT @ 19.75% ^{235}U.

Two additional scenarios were considered where the type of non-LWR reactor was varied, from all Xe-100 to all Natrium, providing a range of 3,450-7,175 MT HALEU. The differences are primarily due to a larger initial core mass per GWe in the fast spectrum Natrium reactor.

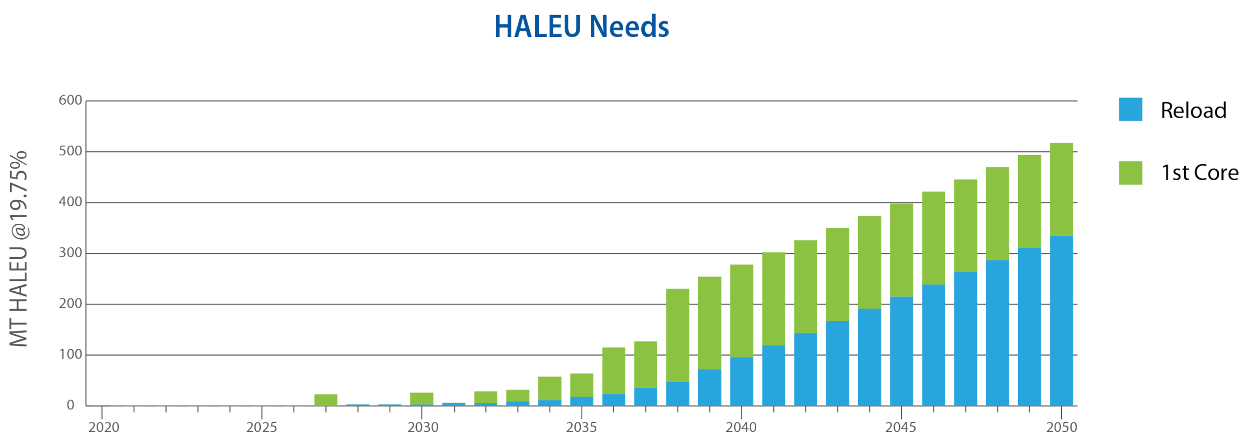

Figure 4. Projection of HALEU needs for advanced non-LWRs to 2050.

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[e] NEI has surveyed advanced reactor developers and fuel designers that plan to utilize HALEU to identify their annual needs to 2035. The reactors include a range of sizes from a few MWe to 100s MWe, starting the first deployment in 2021. The NEI's projected annual HALEU need in 2035 is about 500 MT, while the projected HALEU need in 2035 based on the decarbonization scenario is about 80 MT. The difference is due to different assumed deployment rates and deployment years of the advanced reactors, and the inclusion of HALEU needs for advanced fuel designs for the existing fleet of light-water reactors in the NEI tally.

5. ADDITIONAL CONSIDERATIONS

These scenarios do not consider the potential for the ALWRs/SMRs to use enrichments slightly over 5% to enable the use of some of the accident tolerant fuel concepts and the move to longer cycle lengths and higher discharge burnups. This would considerably increase HALEU needs, though for a much lower enrichment level. Projected cumulative LEU needs for 2021-2050 are ~78,000 MT, including reloads for existing reactors and first cores and reloads for new reactors. Comparison to the HALEU standard enrichment level of 19.75% was not estimated for this material as enrichment to that level followed by down-blending would be highly inefficient.

In the GCAM analysis, the carbon tax induces greater electrification of end-use sectors (buildings, industry, and transportation). For the transportation sector, electric vehicles (EV) were available as an option for light-duty passenger road transport. However, the analysis did not assume complete electrification of all road transport modalities or the complete phase-out of internal combustion engine vehicles by 2050.

Use of nuclear thermal energy for industrial process heat and hydrogen production was not investigated, even though initial demonstrations are being developed now. Applications of nuclear energy for dedicated industrial heat and hydrogen production could increase the nuclear capacity beyond the levels projected in this analysis. Broader applications of nuclear energy, beyond traditional power generation, could further ease the transition to a net-zero emissions economy.

The approach to satisfy the projected total U.S. nuclear energy demand was to simultaneously deploy four different reactor types[f], with the consideration that if one of the four was not able to meet projections, the deployment of the others could be increased to still meet the total demand. Total HALEU demand would change based on which reactor type dropped out of the mix. HALEU demand would also change if recycle was considered for the fast reactor as it has significant fissile material in the discharged fuel that could be recovered. Similarly, the GCAM net-zero scenario assumes simultaneous large-scale deployment of several other clean technologies. If any of these technologies is more or less successful than assumed, then the projected need for nuclear capacity and the related HALEU needs could also change.

6. SUMMARY FINDINGS

The primary purpose of this report is to provide a documented estimate of HALEU needs for commercial reactors that may be used in Department of Energy discussions with stakeholders as part of preparations to establish the HALEU Availability Program authorized by the Energy Act of 2020. This report employed a two-step process to estimate HALEU needed for commercial advanced reactors.

First, a scenario analysis was conducted using the Global Change Analysis Model (GCAM) to generate a projection of U.S. electricity generation capacity consistent with achieving economy-wide net-zero emissions by 2050. The model allows a tax to be imposed on all carbon emissions sources to progressively limit total annual CO_2 emissions for achieving the net-zero emission goal. A carbon tax of ~\$100/tCO_2 in 2025 and growing to ~\$350/tCO_2 by 2050 was required for a straight-line emissions reduction to net-zero by 2050. This resulted in significant changes in the electricity generation mix, including the addition of carbon capture and sequestration (CCS) to all fossil fuel-based generation, growth in renewable energy including biofuels with CCS, and growth of nuclear energy to ~250 GW installed capacity by 2050. The GCAM analysis did not differentiate among different types of nuclear reactors.

Second, a spreadsheet model was developed that achieved the GCAM projection for nuclear capacity in 2050 using an assumed mix of conventional and advanced nuclear reactors; some of these reactor types

[f] Microreactors were not included as most planned applications are off grid for critical facility resilience or for industrial heat rather than for bulk electricity generation and their HALEU needs would be comparatively small.

require HALEU and others do not. It was assumed that new construction would employ roughly equal capacity shares of four different reactor types:

- A GW-scale Light Water Reactor (LWR) represented by an AP-1000 design
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Total cumulative HALEU needed by 2050 for this scenario is ~5,350 MT @ 19.75% ^{235}U with a range of 3,450-7,175 MT depending on the advanced reactor mix. This estimation reflects the impact of down-blending from 19.75% to the target enrichments for each type of non-LWR, which average around 16%. The HALEU is first needed in small amounts for reactor demonstrations starting in 2027, then increases as more reactors are deployed, reaching ~520 MT/yr in 2050, split ~ 2/3rd for reloads and 1/3rd for start-up cores for new reactors.

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The HALEU needs may also vary significantly upward or downward if one of the four reactor types does not achieve assumed growth or other electricity generation technologies such as CCS mature differently than assumed.