Report on Fuel Cycle Facility Requirements for Deployment of Demonstration Reactors and Potential Evolutionary Fuel Cycle Scenarios

Nuclear Fuel Cycle and Supply Chain

Prepared for

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Systems Analysis and Integration

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Executive Summary

A series of fuel cycle scenarios studies were performed to inform on fuel cycle capacities and facilities needed for large-scale deployment of the Advanced Reactor Demonstration Program (ARDP) reactors and potential future evolutionary fuel cycle scenarios. The reactor deployment and evolutionary fuel cycle scenarios from the present to 2100 were developed based on the following assumptions:

- achievement of a net-zero emissions economy in the United States by 2050, which requires a nuclear energy generation capacity of ~250 GWe by 2050,
- the U.S. economic growth of 1% per year from 2051 to 2100, which results in ~340 GWe of nuclear energy capacity in 2100, and
- commercial-scale recycling and high burnup fuel technologies are available after 2050. Thus, evolutionary fuel cycles with those advanced nuclear technologies start after 2050.

A single once-through fuel cycle scenario was assumed from the present to 2050 to achieve a net-zero emissions economy in the United States, and the following four evolutionary fuel cycle scenarios from 2051 to 2100 were considered,

- Once through fuel cycle with ARDP reactors (Natrium and Xe-100),
- Once-through fuel cycle with Breed-and-Burn (B&B) fast reactors,
- Recycling fuel cycle of used metallic fuel in fast reactors, and
- Recycle fuel cycle of both used uranium oxide and metallic fuels in fast reactors.

The projected front-end and back-end fuel cycle capacity demands are compared with the current domestic and global (if needed) fuel cycle capacities. The resulting domestic comparisons in 2050 and 2100 are summarized in Figure E. 1. Note that the orange color indicates the demand variation depending on the fuel cycle scenarios.

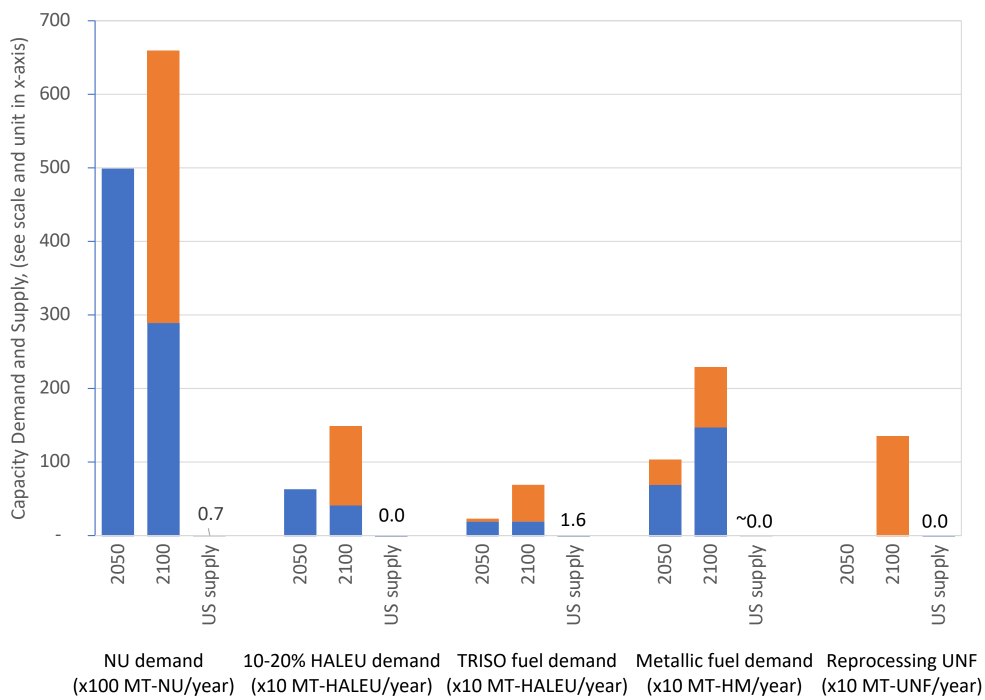

Figure E. 1 Comparison of fuel cycle capacity demand and supply

The United States requires a significant expansion of the existing nuclear fuel cycle capacities or the construction of new facilities. Figure E. 1 shows that the existing domestic nuclear fuel cycle capabilities are much smaller than what would be needed to support the projected nuclear energy generation capacity based on the deep decarbonization goal and the assumed the U.S. economic growth rate. For several fuel cycle elements (HALEU enrichment, advanced fuel fabrication, waste repository, used nuclear fuel reprocessing, etc.), there is no commercial-scale capability or facility in the United States even though the projected demands are high.

The higher burnup of ARDP reactors reduces the once-through back-end fuel cycle elements (in particular, spent nuclear fuel mass), but as a trade-off, the front-end fuel cycle elements (natural uranium (NU) demand, Separative Work Units (SWU), depleted uranium (DU) generation, etc.) are increased because higher enriched HALEU fuels are used. The evolutionary fuel cycle scenarios inform that the required front-end fuel cycle elements could be reduced by recycling used nuclear fuels or adopting a breed-and-burnup once-through fuel cycle with ultra-high burnup fuel.

Except for natural uranium, other fuel cycle elements could be met the projected demands by expanding existing fuel cycle facilities or deploying new facilities through further investments and financial incentives. However, the NU demand should be supplied through domestic uranium resource or import. Domestic uranium resources are much smaller than the projected demand even though there are activities [DOE 2020a] to revitalize and strengthen the domestic uranium mining industry. The domestic uranium shortage could make the uranium supply chain unreliable if specific countries control the uranium trade for their geopolitical interests. Thus, the potential shortage of NU could be a fundamental supply chain issue in the fuel cycle scenarios considered in this work, and efforts are needed to secure the supply of nuclear fuels, such as diversifying countries where uranium is imported, expanding domestic production, enriching depleted uranium, developing affordable uranium extraction technology from seawater, recycling used nuclear fuels, etc.

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Acronyms

ALWR	Advanced Light Water Reactor
ARDP	Advanced Reactor Demonstration Project
B&B	Breed-and-Burn
BS	Basis scenario
BWR	Boiling Water Reactor
CCS	Carbon capture and sequestration
DOE-NE	U.S. Department of Energy's Office of Nuclear Energy
DPC	Dual-purpose canister
DU	Depleted Uranium
EG	Evaluation group
EIA	Energy Information Administration
EPA	Environmental Protection Agency
EPRI	Electric Power Research Institute
ES	Evolutionary Scenario
FY	Fiscal Year
GCAM	Global Change Analysis Model
GWe	Gigawatt-electric
HALEU	High-Assay Low Enriched Uranium
HLW	High-level Waste
IAEA	International Atomic Energy Agency
iHM	initial Heavy Metal
IPM	Integrated Planning Model
IR	Inferred resource
kWe	kilowatt-electric
LEU	Low Enriched Uranium
LWR	Light Water Reactor
MRL	Manufacturing Readiness Level
MT	Metric ton
MWe	Megawatt-electric
NASEM	National Academies of Science, Engineering, and Medicine
NEMS	National Energy Modeling System
NRC	Nuclear Regulatory Commission
NREL	National Renewable Energy Laboratory
NURE	National Uranium Resource Evaluation
NU	Natural Uranium
NWTRB	Nuclear Waste Technical Review Board
PBC	Purpose-built canister
PWR	Pressurized Water Reactor
RAR	Reasonably assured resource
ReEDS	Regional Energy Deployment System
REGEN	Regional Economy, Greenhouse Gas, and Energy
SA&I	Systems Analysis and Integration
SMR	Small Modular Reactor
SNF	Spent Nuclear Fuel
SWU	Separative Work Units

TRL	Technology Readiness Level
TSRA	Technology and System Readiness Assessment
UFD	Used Fuel Disposition
UNF	Used Nuclear Fuel
WNA	World Nuclear Association

SYSTEMS ANALYSIS AND INTEGRATION CAMPAIGN

REPORT ON FUEL CYCLE FACILITY REQUIREMENTS FOR DEPLOYMENT OF DEMONSTRATION REACTORS AND POTENTIAL EVOLUTIONARY FUEL CYCLE SCENARIOS

1. Introduction

The U.S. Department of Energy launched the Advanced Reactor Demonstration Program (ARDP) [DOE 2020 (b)] in 2020 to speed the demonstration of advanced reactors through cost-shared partnerships with the U.S. nuclear industry. Two reactor vendors, TerraPower LLC and X-energy, were awarded funding by DOE to demonstrate construction and deployment of their Natrium and Xe-100 concepts respectively. The initiation of these large public-private cost-shared projects was the primary motivation of a series of fuel cycle studies by the Systems Analysis & Integration (SA&I) campaign to explore the benefits and challenges of potential large-scale commercial deployment of these reactors from a fuel cycle perspective.

The fuel cycle scenario study was initiated in FY 2021. As an extension of the last year's fuel cycle scenario study, additional fuel cycle scenario studies were conducted in FY 2022. The purpose of these additional studies was primarily to identify fuel cycle facilities needed for large-scale deployment of the two ARDP reactors and potential future evolutionary fuel cycle scenarios. The future fuel cycle scenarios were developed considering the emerging deep decarbonization goal (i.e., a net-zero emissions economy in the United States by 2050), the availability of advanced nuclear technologies, and the potential growth of the U.S. economy. In this work, it was assumed that the advanced nuclear technologies required for reprocessing used nuclear fuel and for ultra-high burnup for breed-and-burn (B&B) mode operation are commercially available after 2050. Thus, it was assumed that the United States fuel cycle would stay at once-through till 2050, and the evolution of the fuel cycle using advanced nuclear technologies would start in 2051.

The fuel cycle scenario studies were performed up to the year 2100. The projection of electricity demand and nuclear capacity was generated by using the Global Change Analysis Model (GCAM) [Calvin et al., 2019] model for a net-zero emissions economy by 2050 and supporting an ongoing 1% annual domestic economy growth rate thereafter until 2100. The front-end and back-end fuel cycle parameters were evaluated for the fuel cycle scenarios using the fuel cycle simulation codes DYMOND [Thierry et al., 2019] and CYCLUS [Huff et al., 2016]. A series of sensitivity analyses were conducted to capture the impact of potential uncertainties in the reactor deployment schedule and reactor performance parameters, such as enrichment, burnup, ratio of reactor types, etc. The resulting fuel cycle demands are compared with the current domestic and global capacities to identify the fuel cycle facilities needed for the large-scale deployment of the two ARDP reactors.

In this work, four evolutionary nuclear fuel cycle scenarios – two once-through fuel cycles and two recycling fuel cycles – with ARDP reactors and advanced nuclear technologies were simulated. The U.S. nuclear fuel cycle will be constantly evolving depending on the market situation and available nuclear technologies. The four fuel cycle scenarios considered in this work do not cover the wide range of future nuclear fuel cycles evolutions, but this study provides methodology for analysis of fuel cycle evolutions and fuel cycle data that are needed for development of a technology roadmap of the fuel cycle capabilities needed for deploying the ARDP reactors.

In Section 2, the fuel cycle scenarios are explained, including the assumptions, reactor design parameters of example reactors used for fuel cycle analysis, and the rationales for selecting specific fuel cycle scenarios. The front-end and back-end fuel cycle performances are discussed in Section 3. In particular, the fuel cycle capacity demands are compared with the current domestically and globally available fuel cycle capacities to identify the future needs. Initial information for a technology roadmap for deploying the potential fuel cycles for the ARDP reactors is provided in Section 4, and the conclusion of this study is summarized in Section 5. Finally, several supporting information, analysis and data used in the fuel cycle scenario studies are provided in the Appendices.

2. Nuclear Fuel Cycle Scenarios

This section describes the rationale for selecting the fuel cycle scenarios, assumptions, nuclear capacity projections, and the analysis results. In addition, a series of sensitivity analyses were conducted because of uncertain reactor performance parameters, including delay of the advanced reactor deployment, variation of discharge burnup, different economic growth rates, the variation of reactor mix, etc.

This work studied the fuel cycle scenarios through the year 2100. Considering the fuel cycle goals and the availability of advanced nuclear technologies, the timeline was divided into two periods: near-term from the present day to 2050 and long-term from 2051 to 2100. The primary purpose of the near-term fuel cycle scenario is to support the achievement of a net-zero emissions economy in the United States to mitigate anthropogenic climate change. The long-term nuclear fuel cycle scenario aims to maintain deep decarbonization and support ongoing economic growth. To capture progress in advanced nuclear technologies for achieving high burnup fuel for breed-and-burn (B&B) mode operation in a fast reactor and the recycling of used nuclear fuel, etc., various evolutionary nuclear fuel cycle options are only considered in the long-term fuel cycle scenario.

2.1 Assumptions

Table 2.1 shows the assumptions and reactor design parameters used for the scenario studies. The term 'legacy reactors' denote the operating Light Water Reactors (LWR). The Small Modular Reactor (SMR) indicates an LWR-based reactor such as NuScale, and the non-LWR small reactors (Natrium and Xe-100) are treated separately. In January 2021, the President established goals for a carbon pollution-free power sector by 2035 and a net-zero emissions economy by 2050 [Whitehouse 2021], and it was recognized that the lifetime extensions of the legacy LWRs resulted in a few hundred billion dollars of mitigation cost savings for the United States under the deep decarbonization scenario [Kim et al. 2021]. Thus, based on the deep decarbonization policy and the reactor lifetime extension study, it was assumed that the lifetime of the legacy LWRs is extended to 80 years except for reactors that have been announced to be retired soon.

Table 2.1 Assumptions and parameters used for scenario analysis

	Assumption or design parameters				
Simulation period	Now – 2100				
Start of fuel cycle evolution	2051				
Nuclear capacity demand	- GCAM projected electricity demand to achieve the net-zero emissions economy in the United States by 2050 - 1% growth from 2051 to 2100				
	Example reactor concepts				
Reactor	Legacy LWRs	ALWR (AP1000)	SMR (NuScale)	Natrium - like SFR	Xe-100 – like HTGR
Power, MWe	~1000	~1200	50 – 77	336	80
Capacity factor, %	90	90	90	90	90
Thermal efficiency	~33	~33	~30	40	42
Lifetime, year	80	80	80	80	80
Fresh fuel enrichment, %	< 5.0	< 5.0	< 5.0	16.9	15.5
Burnup, GWd/t	~50	50 -60	34 – 45	133.0	168.5
First deployment, year	Existing	Constructing	2030	2028	2028

Various reactor types are available and under development by industry, national laboratories, and universities. Two AP1000 reactors are under construction at Vogtle, and NuScale is under license. Two ARDP reactors are assumed to be deployed commercially following their demonstrations by 2027-2028. Thus, in this work it is expected that four reactor types would be deployed depending on the evolutional fuel cycle scenario, which include (1) GW-scale advanced light water reactors (ALWRs), represented by the AP-1000s currently under construction, (2) LWR-based SMRs, 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.

The core physics parameters (such as burnup, fuel composition at charge and discharge, etc.) are needed for the fuel cycle scenario studies, but this information is protected as proprietary for the two ARDP reactors. Instead, required core physics parameters were calculated by the SA&I campaign, and the two ARDP type reactors in this study are named "*Natrium-like SFR*" and "*Xe-100-like HTGR*" in the table. The calculated core physics data are sufficiently close to the ARDP reactors, but it should be noted that there could be small disagreements with the values reported in the open literature. The first deployment of an SMR was assumed to be in 2030. The demonstration of the two ARDP reactors would be in 2028 as required by the ARDP project, with deployments assumed to follow.

2.2 Projection of Nuclear Capacity

The projection of electricity demand is dependent on various factors, such as the energy policy, available energy sources, energy market situation, etc. In this work, the projection of the electricity demand was made by dividing the timeline into near-term from the present to 2050 and long-term from 2051 to 2100.

> ***Key observations on nuclear energy capacity***
>
> - *Nuclear energy plays an important role to achieving a net-zero economy along with other low emission energy sources. In 2050, the nuclear share is projected to be about 24% of the total power demand with a nuclear generation capacity of ~250 GW, which is consistent to projections by other studies.*
> - *By assuming the 1% annual economic growth rate after 2050, the nuclear generation capacity in 2100 is ~340 GWe.*

In this work, the Global Change Analysis Model (GCAM) code [http://jgcri.github.io/gcam-doc, Calvin et al., 2019] was employed for the electricity demand projection. And the results are compared with the predicted by the Electric Power Research Institute (EPRI) and World Nuclear Association (WNA).

EPRI simulated the electric sector capacity expansion models using multiple tools utilized for informing on planning, technology assessment, and policy analysis [Bistline et al. 2022]. The multiple tools include the Integrated Planning Model (IPM) from the U.S. Environmental Protection Agency (EPA), National Energy Modeling System (NEMS) from the U.S. Energy Information Administration (EIA), Regional Energy Deployment System (ReEDS) model from the National Renewable Energy Laboratory (NREL), and Regional Economy, Greenhouse Gas, and Energy (REGEN) model from EPRI. The study projected that total installed nuclear capacity will be in the range of 2 – 329 GWe in 2050, depending on the cost of nuclear energy and CO_2 policies. With a low nuclear capital cost (i.e., $2,000/kWe starting 2030) and a zero CO_2 policy, the total nuclear capacity projections increase to 285 – 329 GW by 2050.

WNA projected the global nuclear capacity in 2040 for several scenarios[WNA 2020]. For the nuclear capacity expansion scenario developed to achieve the 2015 Paris Agreement of keeping the increases in the global average temperature well below 2 °C above the pre-industrial level, the projected global nuclear capacity in 2040 is a factor of two larger than the current global nuclear capacity.

In the GCAM model, the electricity demand projection was predicted by dividing the period into two parts: i.e., from now to 2050 and from 2051 to 2100. First, a net-zero emissions economy by 2050 was imposed in a technology-neutral manner. The net-zero emissions in all end-use sectors (power, building, industry, and transpiration) 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-emission energy technologies throughout the economy, which results 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, and growth of nuclear energy. It was assumed that the energy mix to achieve the net-zero emissions economy in the United States in 2050 would continue till 2100. Thus, both growth rates of the total electricity demand and the nation's economy are identical from 2051, which is assumed to be 1.0% yearly in this study.

The resulting projection of electricity generation from various energy sources is plotted in Figure 2.1. It is noted that the total installed capacity of renewable energy source (wind, solar) is about factor of 5 – 6 higher than the electricity generation shown in Figure 2.1 because of their low-capacity factor. Conversely, the installed nuclear capacity is closed to the electricity generation because of its high-capacity factor. The coal and gas generations indicate the generation with carbon capture sequestration (CCS). For electrification of all end-use sectors, total electricity generation in 2050 will grow to about double the entire electricity generation in 2020. In 2050, the nuclear share is about 24% of the total power generation, with a nuclear generation capacity of ~250 GW, which is a factor of ~2.5 larger than the current nuclear capacity. This projection is consistent with the projections by EPRI. Assuming the 1% annual economic growth rate after 2050, the nuclear generation capacity in 2100 will grow to about 340 GWe.

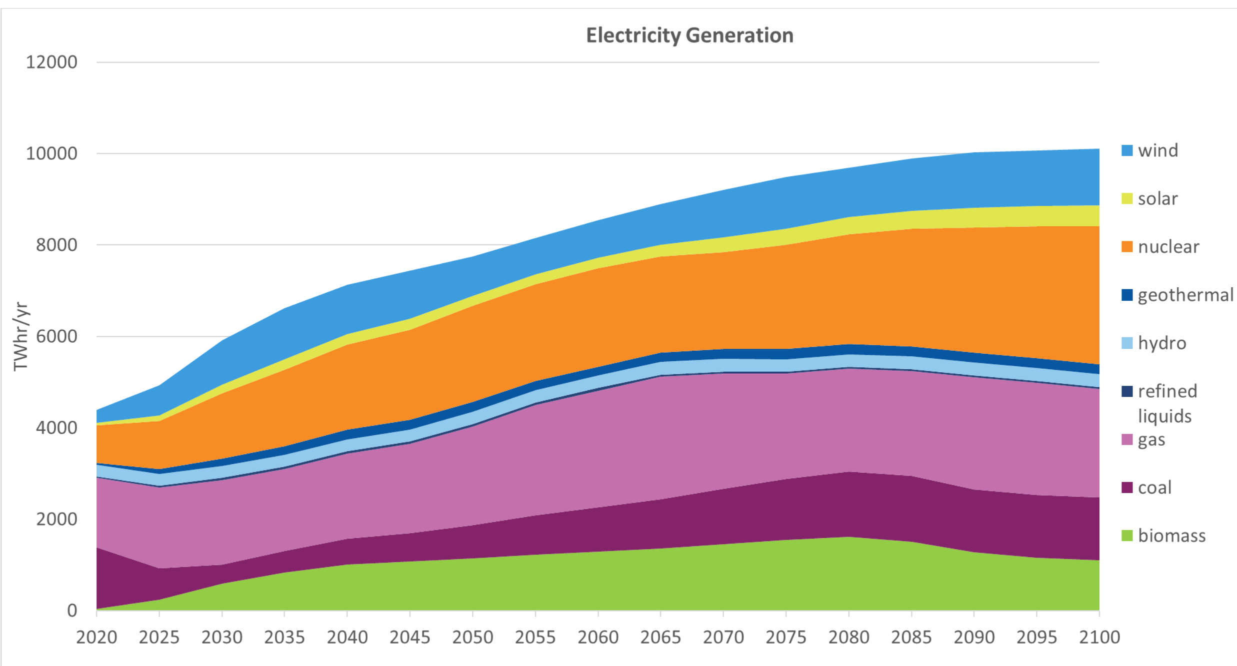

Figure 2.1 Projection of electricity generation

2.3 Scenario Descriptions

Figure 2.2 shows an overview of the fuel cycle evolution scenarios. The major events are shown at the top of the figure. The ARDP reactors are expected to be demonstrated and deployed starting in the late 2020s.

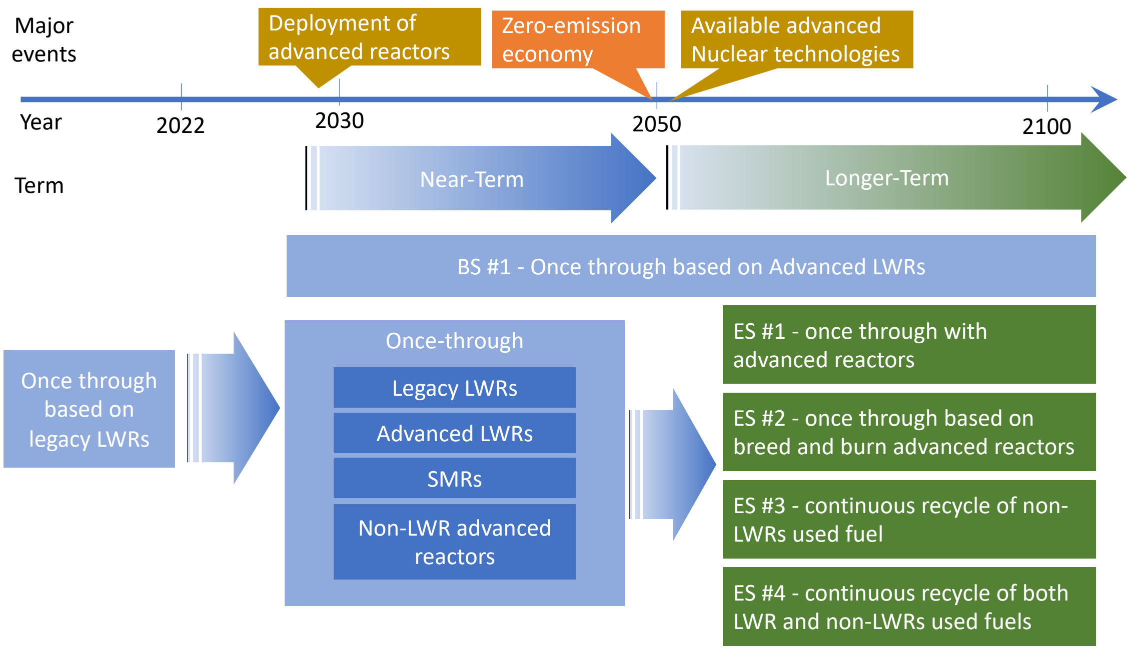

Figure 2.2 Overview of evolution of fuel cycle scenarios

A key goal to be achieved in the energy sector is a net-zero emissions economy in the United States by 2050. The vendors of the two ADRP reactors have released information that the ARDP reactors are under development aiming at a once-through fuel cycle [Neider 2021, Mulder 2020]. Thus, all reactor types to be deployed in the near term would be once-through.

Various advanced nuclear technologies, such as a very high burnup fuel for B&B mode operation in a fast reactor, separation technologies for recycling used nuclear fuels (UNF), etc., are currently under development by the nuclear industry [Neider 2021] and DOE-NE. The R&D roadmaps for the advanced nuclear technology development [Croson et al. 2017, Kim et al. 2018] indicate that the technologies will be available commercially after 2050. Thus, using advanced nuclear technologies, the long-term fuel cycles could evolve to other fuel cycles such as a continuous recycling fuel cycle, a B&B once-through fuel cycle, etc.

2.3.1 Near-term Fuel Cycle Scenario

A single fuel cycle scenario was considered in the near-term period, which is a once-through using a combination of legacy LWRs, ALWRs, SMRs, and ARDP reactors. The legacy LWRs are still operating in the near-term period based on the lifetime extension of 80 years. The energy demand projection during this period is provided in Section 2.2, and four reactor types (ALWR, SMR, Natrium, and Xe-100) will be deployed to fill the difference between the electricity demand and the supply from the legacy LWRs.

The deployment schedule of the four reactor types in the near-term period was assumed to be roughly the same (i.e., about 25% share between four reactor types), but the first deployment schedule of the four reactor types were determined considering the current construction schedule of ALWRs, and the licensing schedule of SMRs, and the demonstration schedule of the ARDP reactors. A total of 164 GWe of nuclear energy capacity is added by 2050 to achieve the net-zero emissions economy. Of this, 88 GWe is a mixture of SMRs and ALWRs utilizing a once-through LEU fuel cycle. The remaining 76 GWe is provided by ARDP-type reactors utilizing a once-through HALEU fuel cycle. It is noted that "HALEU" denotes a uranium enrichment higher than 5.0% but lower than 20%. However, in the present work, *HALEU refers to only 10%–20% enriched uranium* because most advanced reactor concepts utilize that enrichment range. Detailed information on the reactor deployment schedules is provided in [Dixon et al., 2021a].

2.3.2 Long-term Evolutionary Fuel Cycle Scenarios

In the long-term period (2051 – 2100), the nuclear fuel cycle scenarios were developed based on two assumptions. First, there is no additional construction of LWR-based reactors (LWR, ALWR, SMR). Thus, the legacy LWRs and ALWR/SMR deployed before 2050 operate until the end of their lifetime and then retire. Second, advanced nuclear technologies required to achieve high burnup fuel for fast reactors, separation technologies for recycling used nuclear fuels, etc. are fully developed before 2050 and are commercially viable throughout the simulation period. Thus, the nuclear fuel cycle could evolve into evolutionary nuclear fuel cycle options in the long-term period. In this work, the four evolutionary fuel cycle scenarios are considered and compared against a basis-of-comparison scenario.

Evolutionary Scenario #1 (ES #1): Once-through with non-LWR advanced reactors

- Nuclear fleet evolves to a once-through fuel cycle using non-LWR advanced reactors, which are assumed to be ARDP reactors.
- Non-LWR advanced reactors with 10-20% HALEU fuel are continuously deployed to support 1% growth of the economy and retirement of legacy LWRs (see the nuclear energy generation mix in Figure 2.3).
- All discharged fuels are stored in interim storage and sent to a repository.

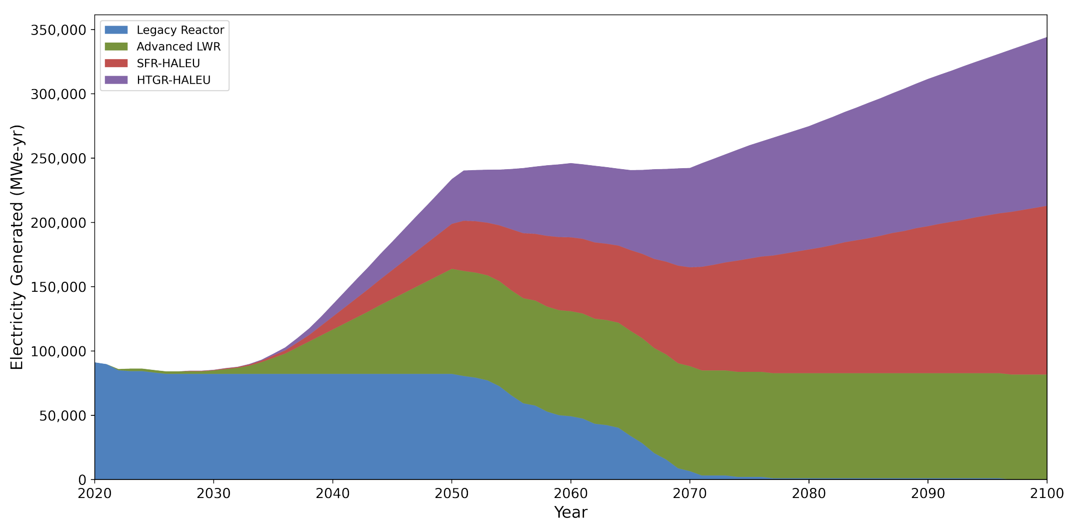

Figure 2.3 Capacity sharing by reactor types in ES #1

Evolutionary Scenario #2 (ES #2): Once-through with B&B non-LWR advanced reactors

- Nuclear fleet evolves to a B&B mode once-through fuel cycle using fast reactors.
- From 2051, B&B mode advanced reactors are newly deployed to support 1% growth the of economy and retirement of legacy LWRs (see the nuclear energy generation mix in Figure 2.4).
- B&B mode fast reactors start with 10-20% HALEU, while the following cycles use natural uranium.
- All discharged fuels are stored in interim storage and sent to a repository.

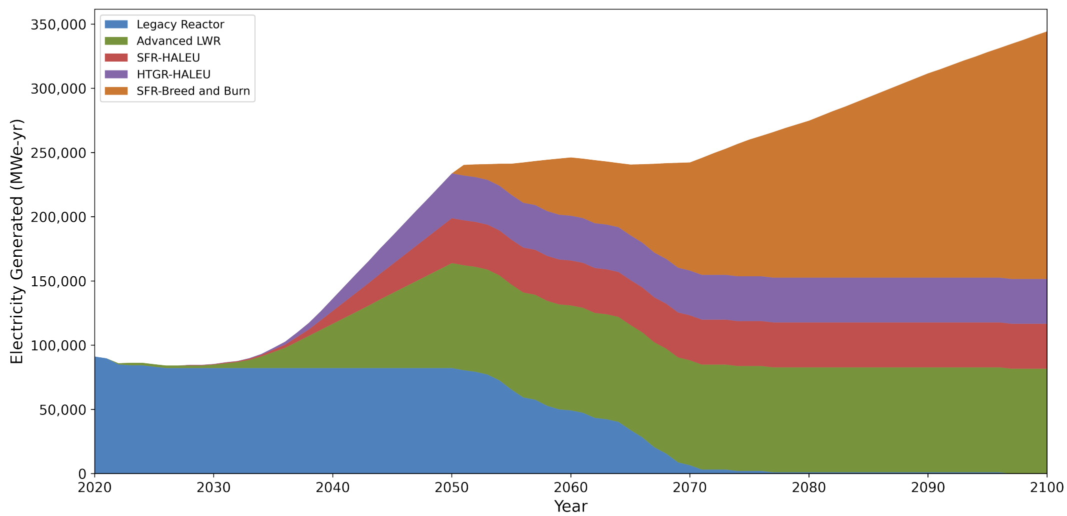

Figure 2.4 Capacity sharing by reactor types in ES #2

Evolutionary Scenario #3 (ES #3): Recycle of used fuel discharged from fast reactors

- Nuclear fleet evolves to a continuous recycle fuel cycle using fast reactors.
- Additional fast reactors with metallic fuel are deployed to support 1% growth of the economy and retirement of legacy LWRs (see the nuclear energy generation mix in Figure 2.5).
- Fast reactors start with 10-20% HALEU, while the following cycles use the recovered actinides from fast reactor used nuclear fuel, which is metallic fuel.
- The non-recovered materials (mostly, fission products) are stored in interim storage and sent to a repository.
- Discharged fuels from LWR/ALWR/SMR/HTGR reactors are stored in interim storage and sent to a repository.

Evolutionary Scenario #4 (ES #4): Recycle of used fuel discharged from all reactors

- The nuclear fleet evolves to a continuous recycle fuel cycle using fast reactors.
- Additional fast reactors with metallic fuel are deployed to support 1% growth of the economy and retirement of legacy LWRs (see the nuclear energy generation mix in Figure 2.5).
- Both uranium oxide and metallic fuel discharged fuels from LWRs and fast reactors are reprocessed, and the recovered actinides are recycled in fast reactors. The reprocessing of HTGR UNF is not considered in this scenario. The non-recovered materials (mostly, fission products) are stored in interim storage and sent to a repository.

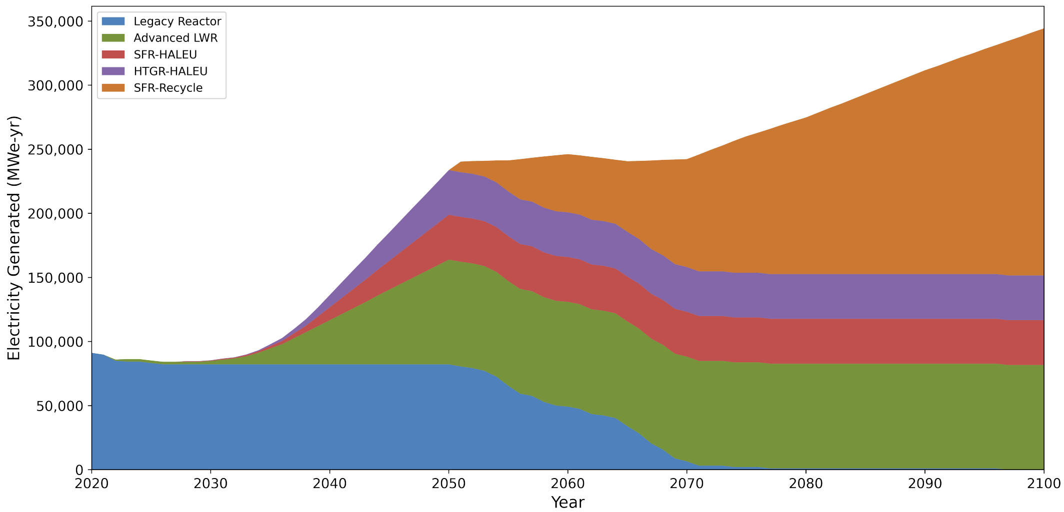

Figure 2.5 Capacity sharing by reactor types in ES #3 and ES #4

Both ES #1 and ES #2 are once-through fuel cycle scenarios. However, ES #2 does not need an external feed of enriched uranium except for the newly deployed start-up reactors because the reactor operates in a B&B mode. It is expected that ES #2 requires much less natural uranium (NU) and enrichment separative work units (SWU) compared to ES #1 even though both are once-through fuel cycles.

Both ES #3 and ES #4 are continuous recycles in fast reactors with metallic fuel. The difference between the two recycling scenarios is the extent of recycling of used nuclear fuels. ES #3 recycles only the used metallic fuel discharged from fast reactors, while ES #4 recycles used nuclear fuels discharged from ALWR, SMR, and fast reactors. The recycle of HTGR used fuel was not considered in this work. These two recycling scenarios were selected to assess the impacts of required reprocessing technologies and fissile material availability. In this study, a fast reactor with metallic fuel was used as an example fuel and reactor concept for the recycling option. Electrochemical pyroprocessing is assumed to be the primary technology for reprocessing the discharged metallic fuel. However, aqueous reprocessing is assumed to recycle the used nuclear fuel of advanced LWRs. Thus, ES #3 is assumed to require a single electrochemical pyroprocessing technology, while ES #4 is assumed to require both electrochemical pyroprocessing and aqueous technologies. The fast reactors are assumed to have break-even cores, providing only enough fissile material recovered during recycle to support continued operation of the existing reactor. Thus, in ES #3 an enriched uranium feed is needed to start the new reactors needed to support the 1% growth. However, ES #4 may not need external enriched uranium because the recovered fissile from all reactors may be sufficient to fill the start-up core of a new reactor.

Finally, the following basis-of-comparison was considered for comparing fuel cycle parameters between the four evolutionary fuel cycle scenarios.

Basis-of-comparison Scenario #1 (BS #1): Once-through with LWRs only

- Nuclear fleet stays with a once-through fuel cycle using ALWRs.

- Any new addition from the present to 2100 is only provided by ALWRs with <5% LEU, and there is no addition of non-LWR advanced reactors (see the nuclear energy generation mix in Figure 2.6).
- All discharged fuels are stored in interim storage and sent to a repository.

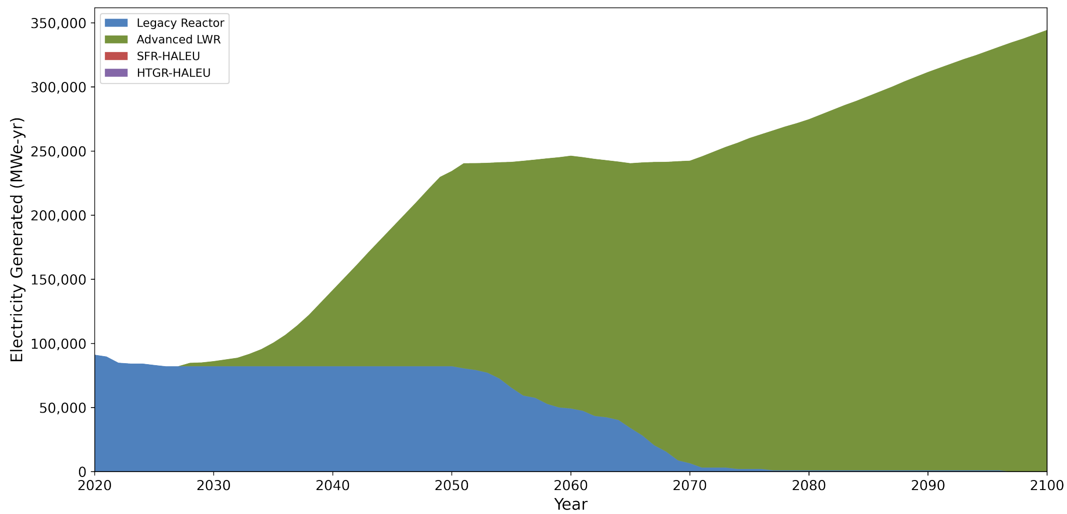

Figure 2.6 Capacity sharing by reactor types on the basis-of-comparison scenario (BS) #1

2.4 Sensitivity and Uncertainty Analysis

The detailed information on the design parameters and deployment schedules of the ARDP reactors are provided in Section 2.1. However, the design parameters could evolve, and the deployment schedule could change due to the potential uncertainties in technology development and supply chain issues. For instance, TerraPower proposed a higher burnup fuel development plan using the irradiation data from the demonstration reactors, and a gradual increase in the metallic fuel burnup is expected.

To capture the impact of technological development progress and potential variation of the deployment schedule, a series of sensitivity and uncertainty quantification studies were conducted using the CYCLUS code [Huff et al. 2016]. The detailed modeling and simulation used for sensitivity and uncertainty quantification studies are provided in Appendix C., and the impacts are briefly summarized in this section. Evolutionary scenario #1 (Once-through fuel cycle with ARDP reactors) was selected for sensitivity and uncertainty quantification analysis.

First, the NU demand and SWU were evaluated in terms of fuel enrichment and discharge burnup, and the results are visualized in Figure 2.7 and Figure 2.8, respectively. The equations used for the calculations of NU demand and SWU are provided in Appendix B. The NU and SWU demands of the example reactor concepts are also pointed out in the figures. In the figures, the NU or SWU demand is the same when the color is the same, and the demands decrease from red to green. The figures inform on how to reduce the NU demand or SWU – increase discharge burnup and thermal efficiency (move up) or decrease charge enrichment (move left). Natrium requires more NU and SWU than the ALWR (AP1000) because it is fueled by HALEU, but the Xe-100 requires less than Natrium because of its fuel's slightly lower enrichment and slightly higher burnup and thermal efficiency.

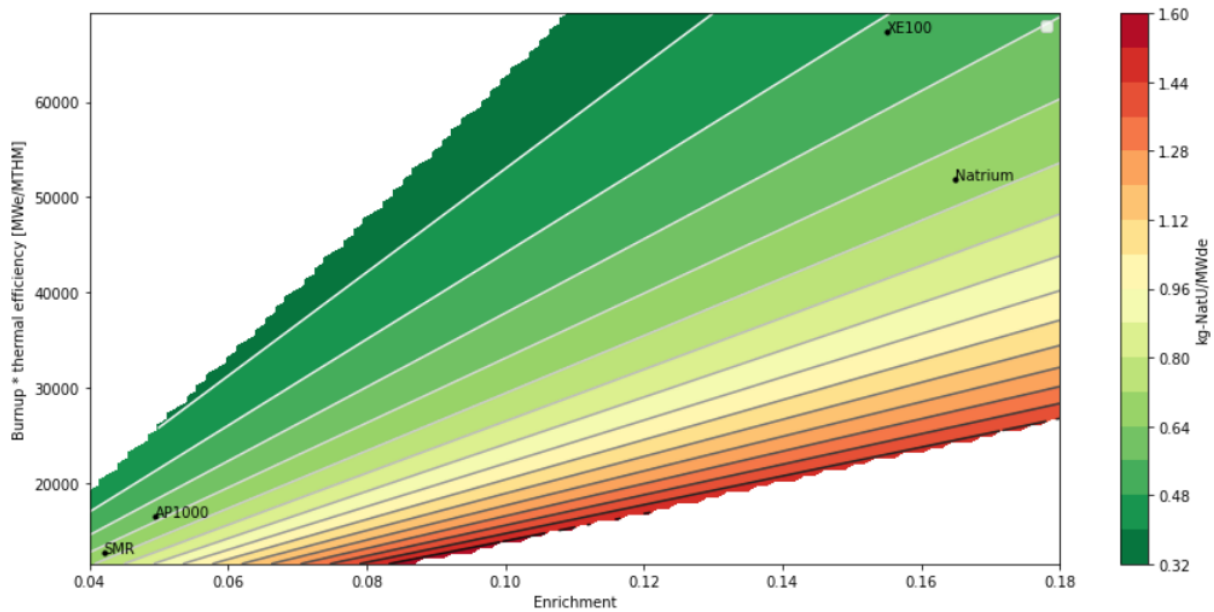

Figure 2.7 Visualization of NU demand per generated electricity in terms of burnup, thermal efficiency, and fuel enrichment

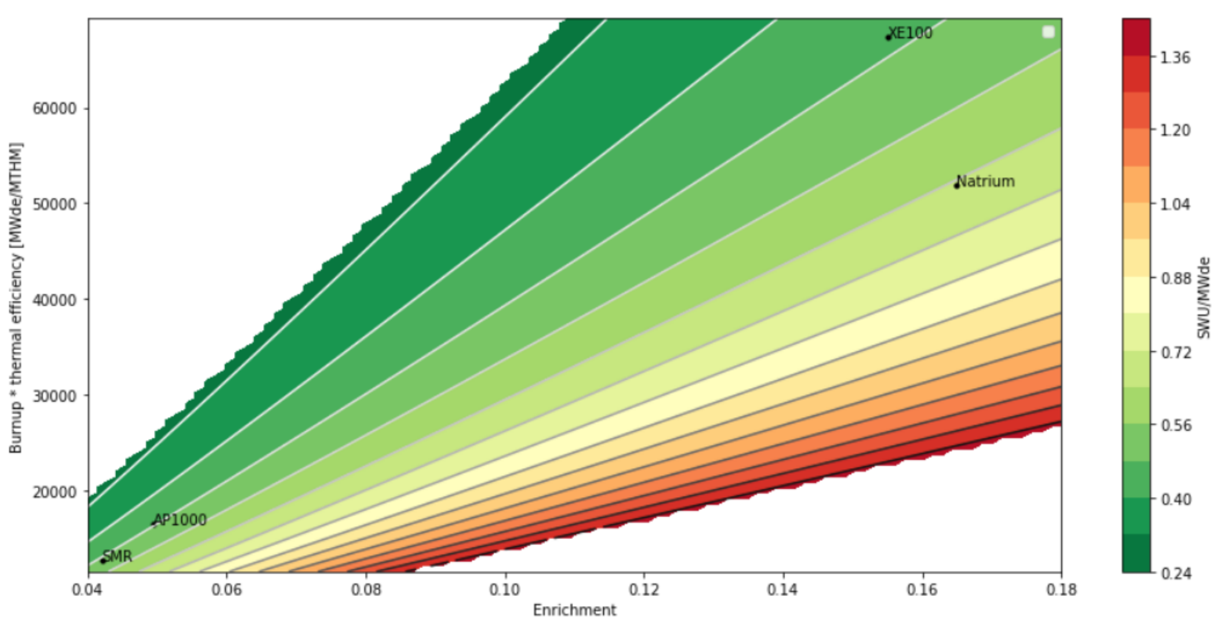

Figure 2.8 Visualization of SWU demand per generated electricity in terms of burnup, thermal efficiency, and fuel enrichment

Second, the sensitivity and uncertainty quantification studies were conducted for the following perturbations.

- **Reactor deployment fractions**: equal capacity mixture of four example reactor types (i.e., 25% of each reactor) was assumed in the base scenario, but the capacity mixture rates between four example reactors are randomly varied.
- **Delay of ARDP deployment year**: the first deployment of ARDP reactors was assumed in 2028 in the base scenario, but it was randomly varied in the deployment year from 2027 to 2040.
- **Nuclear capacity demand**: the total nuclear capacity followed the GCAM projection in the base scenario, but it was randomly varied in the range of -5% to +5%.
- **Uncertainties in ARDP reactor burnup and evolution of burnup**: a single burnup was used in the base scenario, but a randomly sampled burnup from an assumed burnup distribution was used. In addition, the increase in burnup (a few percent increases per decade) was assumed.

Two front-end fuel cycle parameters, NU demand and SWU, were evaluated. It is noted that the total generation of electricity was conserved in the sensitivity and uncertainty analysis. Thus, ALWRs and SMRs are additionally deployed to supplement for any lack of generation capacity due to ARDP reactor deployment delay; as a result, the delay of ARDP reactor deployment does not significantly affect the NU demand and SWU. In addition, the gradual increase in metallic fuel does not significantly affect the NU demand and SWU. However, the NU demand and SWU were affected significantly by the variation of the reactor deployment fraction and nuclear capacity demand. The NU demand and SWU have a linear correlation to the nuclear capacity demand: i.e., both front fuel cycle parameters increase as much as the nuclear capacity increases. As shown in Figure 2.7 and Figure 2.8, the larger deployment of reactor types requiring low NU demand and SWU per unit electricity generation reduces the NU demand and SWU. The overall variation of the NU and SWU demand is 10 – 15% depending on the type of reactor deployed in 2050. The range of uncertainties of NU and SWU demand has been studied and the results are shown in Appendix C.

3. Projections of Fuel Cycle Parameters and Facilities Needs

In this section, projections of front-end and back-end nuclear fuel cycle elements of the four evolutionary fuel cycle scenarios are provided. The required fuel cycle capabilities or facilities to support these projections are also discussed.

3.1 Front-end Fuel Cycle Facilities

3.1.1 Natural Uranium

The annual and cumulative natural uranium (NU) demand projections from 2020 to 2100 are provided In Figure 3.1 and Figure 3.2, respectively. For comparison purposes, the basis-of-comparison fuel cycle scenario (BS #1, once-through with ALWRs) is included in both figures. As explained in Section 2.3, a single fuel cycle scenario was assumed in the near-term fuel cycle scenario (2020 ~ 2050), and the four evolutionary scenarios started in 2051. Thus, the NU demands of the four evolutionary scenarios are identical through 2050 and vary thereafter. It is noted that the current annual NU demand (or consumption) in the United States to support ~100 GWe of nuclear power capacity is ~18,000 metric tons (MT).

Key observations on natural uranium demand

- *To achieve net-zero emissions economy, annual NU demand increases to ~50,000 metric tons (MT) in 2050, which is ~ 2.8 times larger than the current NU demand.*
- *By 2100, the annual NU demand increases to ~66,000 MT for once-through but decreases to ~29,000 MT for recycle or once-through based on breed-and-burn mode operation.*
- *Cumulative global NU demand is ~3 million and ~12.5 million MT by 2050 and 2100, while worldwide recoverable uranium resource is ~17 million MT.*
- *Considering low domestic mining capacity and the current geopolitical situation, the uranium supply chain could become unstable, and various efforts are needed to secure nuclear fuel supply, which could include diversifying countries where uranium is imported, expansion of domestic uranium mining capability, enriching depleted uranium, developing affordable uranium extraction technologies from seawater, recycling used nuclear fuels, etc.*

The projection informs that the annual NU demand increases to ~50,000 MT in 2050 to support a nuclear capacity of 250 GWe to support achieving a net-zero emissions economy. The cumulative NU demand by 2050 is ~0.97 million MT. For the basis-of-comparison scenario (BS #1), the annual and cumulative NU demands are smaller than those of ES #1 but larger than other evolutionary fuel cycle scenarios. The HALEU fuel of the ADRP reactors increases the NU demand in ES #1.

The projection of NU demand varies by scenario after 2051. Except for ES #1, the annual demand of other evolutionary fuel cycle scenarios peaks in ~2050 then decreases because of the significant reduction of the enriched uranium needs. For ES #1, the annual NU demand is roughly constant from 2050 to 2070 with the new deployment of ARDP reactors offset by the retirement of legacy LWRs. This effect can also be seen in the total fleet capacities during this time frame in figures in Section 2.2. After this, however, the annual NU demand increases up to 66,000 MT, and the cumulative NU demand reaches ~3.8 million MT in 2100. For recycle scenarios (ES #3 and ES #4) and once-through with B&B mode reactors (ES #2), NU (or DU) is needed as make-up feed and for HALEU for the start-up cores, resulting in annual NU demand in 2100 of ~29,000 MT and the total cumulative NU demand of ~2.6 million MT.

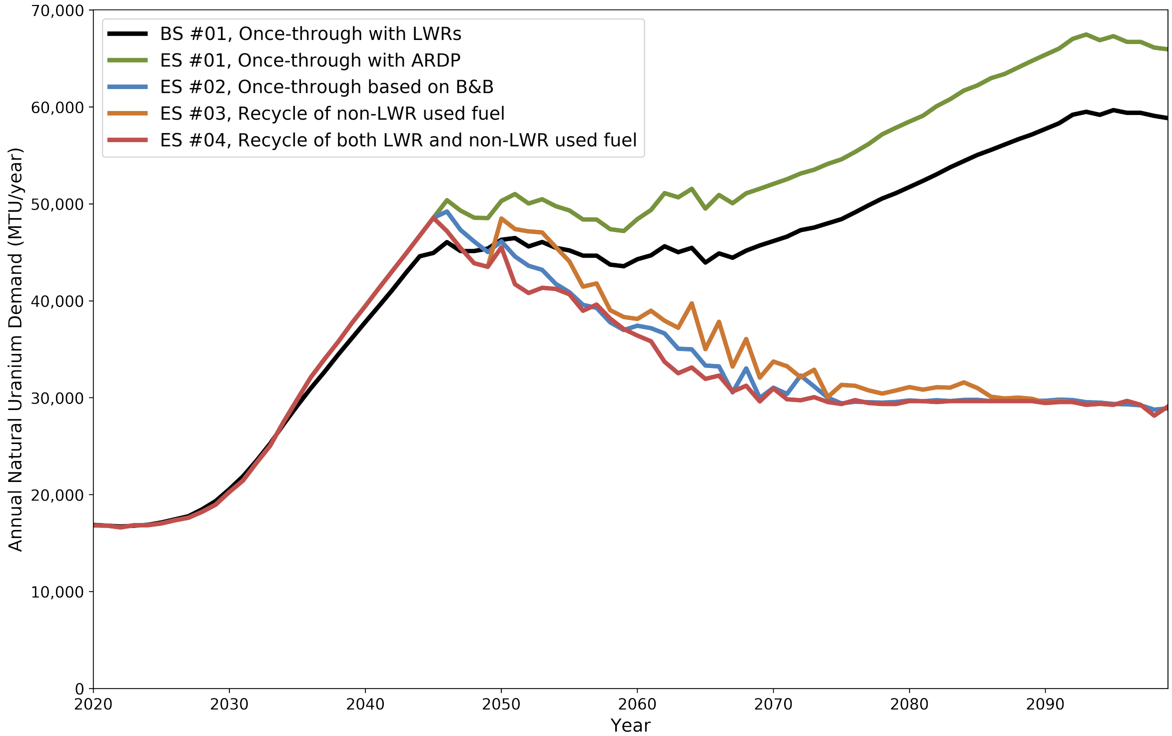

Figure 3.1 Projection of annual natural uranium demand

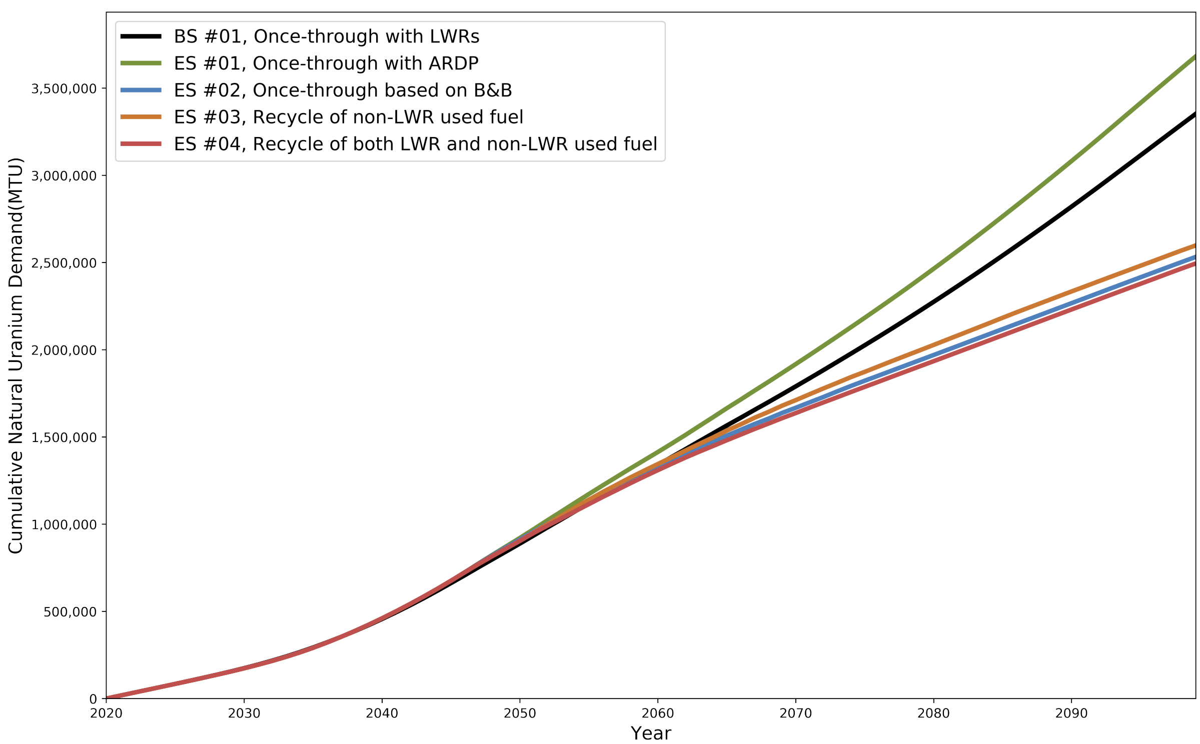

Figure 3.2 Projection of cumulative natural uranium demand since 2020

The global NU demand was projected, and the cumulative NU demand by 2050 and 2100 are plotted in Figure 3.3. The NU demands are divided into two groups: the United States and the sum of non-U.S. countries. For the U.S. NU demand, two fuel cycle scenarios (ES #1 and ES #4) are compared. Through 2050, the U.S. NU demand of ES #1 and ES #4 are identical. The global NU demand by 2050 was obtained from the IAEA's nuclear capacity expansion data to 2050 [IAEA 2020]. For consistent comparison with the U.S. fuel cycle scenarios, it was also assumed that the global nuclear capacity increases by 1% per year from 2051 to 2100, and there is no reprocessing in the non-U.S. countries. The detailed information on the global NU demand is provided in Appendix A. The global uranium demand of non-U.S. countries is ~2.0 million MT by 2050 and ~8.7 million MT by 2100. Overall, the total cumulative NU demand by the United States and other countries is ~3 million MT in 2050 and 11.2 – 12.5 million MT in 2100.

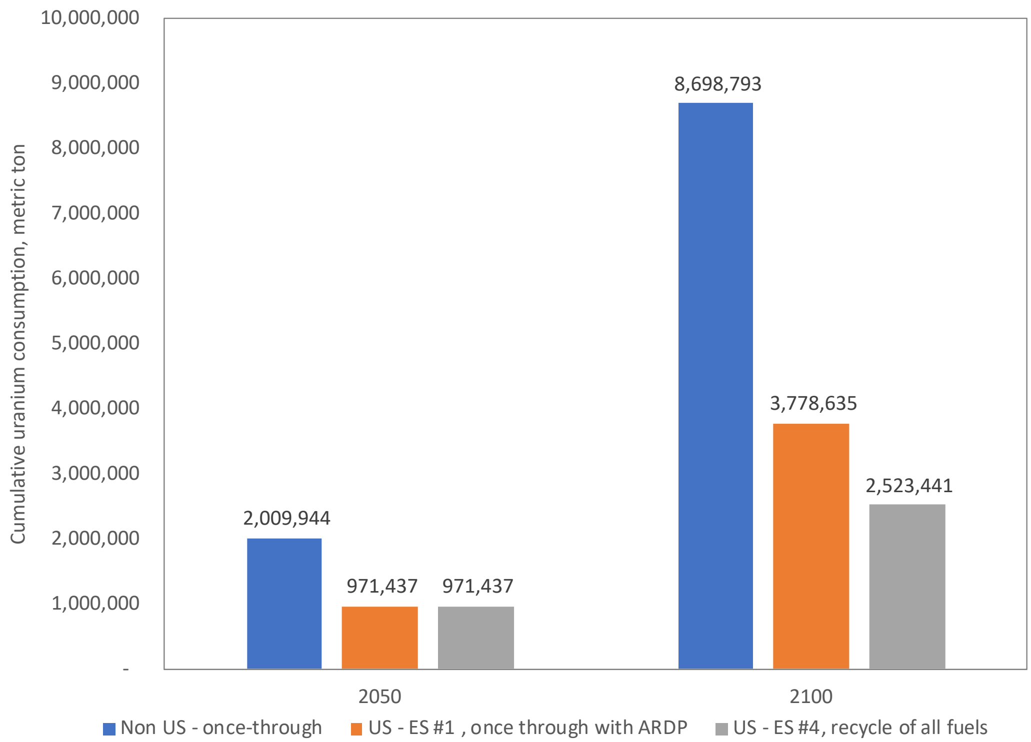

Figure 3.3 Projection of global uranium demand by 2050 and 2100

The following two questions are addressed in this work regarding the projection of the domestic and global NU demands:

- Question #1- Is the recoverable uranium resource sufficient to support the global NU demands?
- Question #2 - Is the domestic infrastructure or supply chain sufficient to support the domestic NU demand?

For the first question, the recoverable uranium resource should be larger than the global NU demand. New uranium deposits can be found, and a few billion MT of uranium exists in sea water. However, to use uranium in nuclear plants, the recovery cost of the uranium resource should be reasonably low. Otherwise, the uranium resource is not attractive because it increases the overall fuel cycle cost of nuclear plants. Based on the NEA and IAEA definition, the ***recoverable uranium resource*** consists of ***reasonably assured resource*** (RAR, known or discovered resource) and ***inferred resource*** (IR, inferred to occur based on geological evidence) that can be recovered and sold the yellow-cake (U_3O_8) less than \$100/lb-U_3O_8. It is noted that the abundant uranium found in sea water is not considered a recoverable uranium resource because its recovery cost is currently too expensive.

Figure 3.4 shows the global recoverable uranium resources. Abundant amounts of recoverable uranium resources are found in Australia, Kazakhstan, Canada, Russia, South Africa, Namibia, and Brazil. Furthermore, the majority of low-cost (< \$30/lb-U_3O_8) uranium resources exist in Kazakhstan and Canada. The total recoverable uranium is about 17.3 million MT [OECD 2020], which is larger than the cumulative global NU demand by 2100. Table 3.1 shows the recoverable uranium amount per uranium price [NEA 2020]. By assuming that cheaper uranium resource is mined first, any recoverable uranium resource less than \$30/lb-U_3O_8 would be exhausted by 2050. Thus, the uranium retail price would be expensive in the latter half of this century. The average retail price or uranium purchased by owners and operators of U.S. civilian nuclear power plants was \$33.91/lb-U_3O_8 in 2021 [EIA 2021].

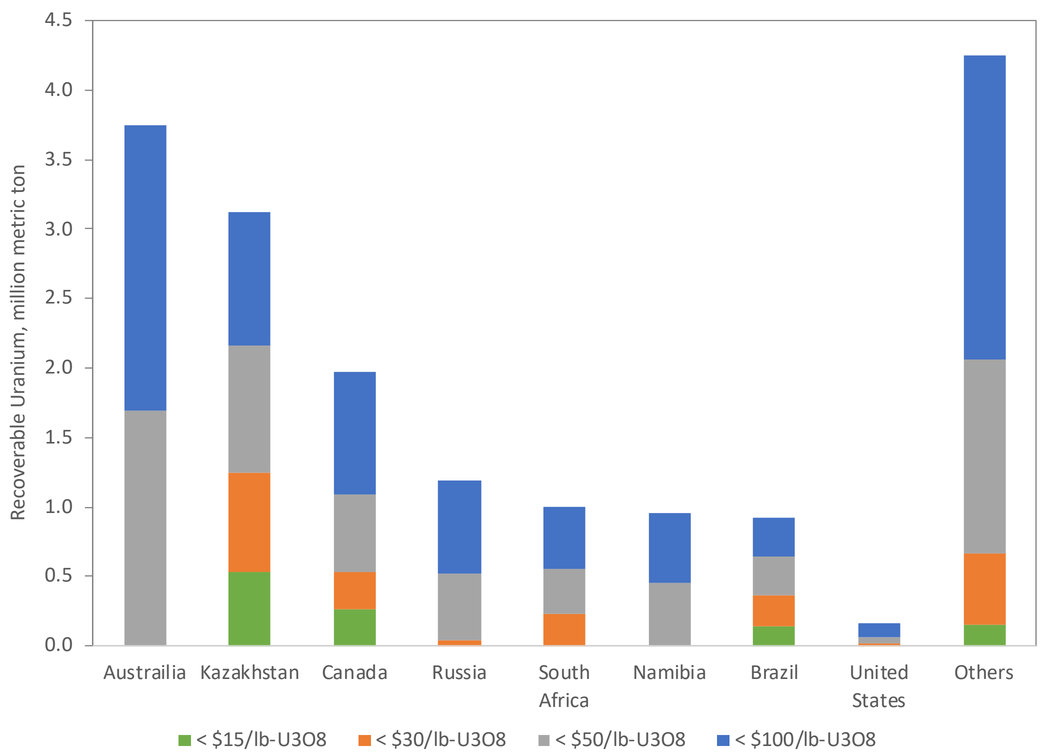

Figure 3.4 Recoverable Uranium

Table 3.1 Total recoverable uranium amount

Uranium Price, \$/lb-U_3O_8	Million metric ton
< 15	1.1
15 – 30	2.0
30 – 50	6.1
50 – 100	8.1
Total	17.3

To answer the second question, the recoverable uranium resource and the uranium production (mining) in the United States have been reviewed. Figure 3.4 indicates that the United States has limited uranium resources. The total recoverable uranium resource in the United States is about 164,000 MT[a] which is less than 1% of the global recoverable uranium resource. Figure 3.5 shows the domestic uranium production and consumption rates since 1996. The yellow solid line indicates the fraction of domestic uranium production to the uranium consumption. Historically, the domestic uranium production peaked at ~17,000 MT (or ~ 43.7 million pounds of yellowcake, U_3O_8) in 1980, but the production decreased continuously since then, and the domestic productions was 557 MT (or 1.45 million pounds of U_3O_8) in 2018 and 67 MT (or 0.17 million pounds of U_3O_8) in 2019.

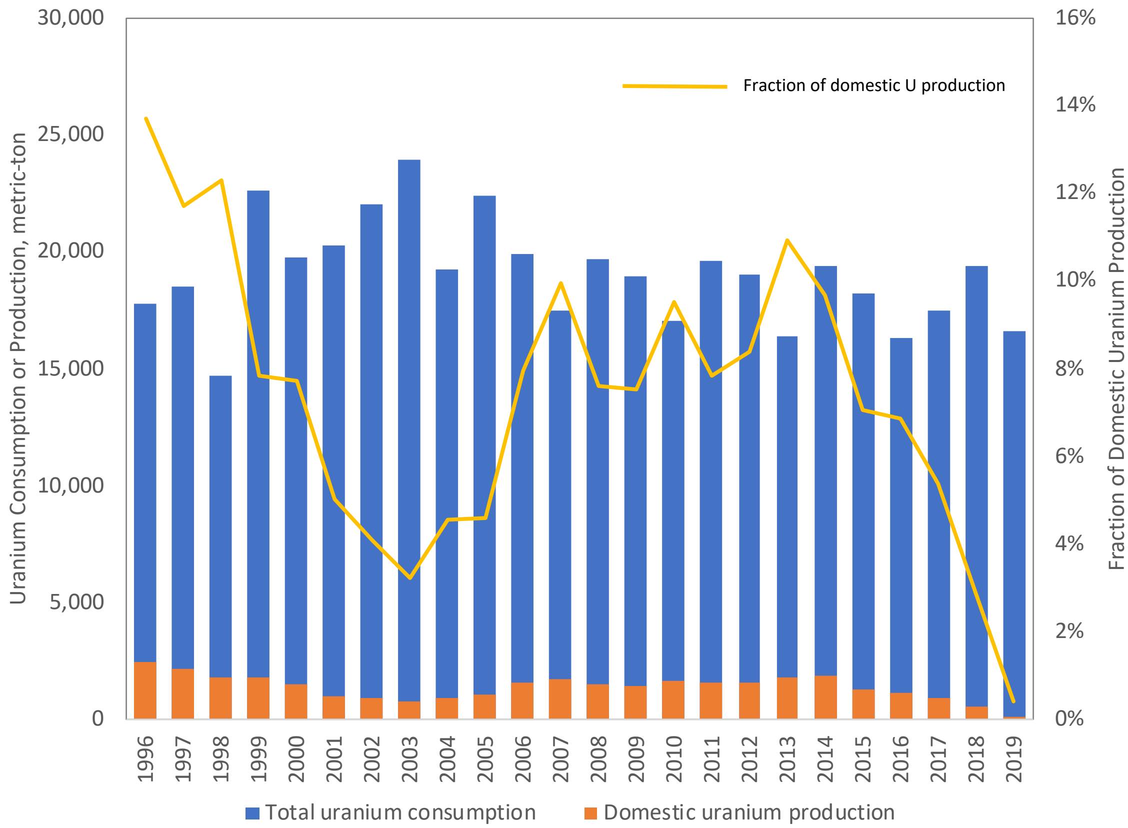

Figure 3.5 Uranium consumption and production in the United States

Domestic uranium production provided for more than 90% of U.S. uranium consumption in 1980, but it decreased to less than 1% of U.S. uranium consumption recently. The decrease in the domestic

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[a] Uranium resource estimates are prepared by industry and reported to the US Energy Information Administration (US EIA) through the survey of EIA-815A. The uranium reserves estimated in 2010 [EIA 2010] were based on data collected by the U.S. EIA and data developed by the National Uranium Resource Evaluation (NURE) program. The 2010 estimation is a factor of three (472 ,000 MT) larger than the uranium estimates provided in "Uranium 2020" [OECD 2020]. The US EIA data covered approximately 200 uranium properties, with reserve estimates collected from 1984 through 2002. The NURE data covered approximately 800 uranium properties with reserve estimates, developed from 1974 through 1983. Because the NURE data has not been comprehensively updated for many years, it is therefore no longer considered a current data source. Thus, this work adopted the value in the book of "2020 Uranium."

production is mainly due to a global oversupply of uranium and consequently low uranium prices [NEA 2020]. The low prices have dramatically impacted the domestic mining industry, and as a result the domestic uranium production was historically low (< 1%) in 2019. Even though there are activities (see Nuclear Fuel Working Group Strategy recommendation on April 23, 2020 [DOE 2020(a)]) to revitalize and strengthen the uranium mining industry, domestic uranium resources and production are much smaller than the NU demand.

Due to the low domestic recoverable uranium resources and historically low uranium mining capability, significant amount of natural (or enriched) uranium are currently imported from foreign countries.

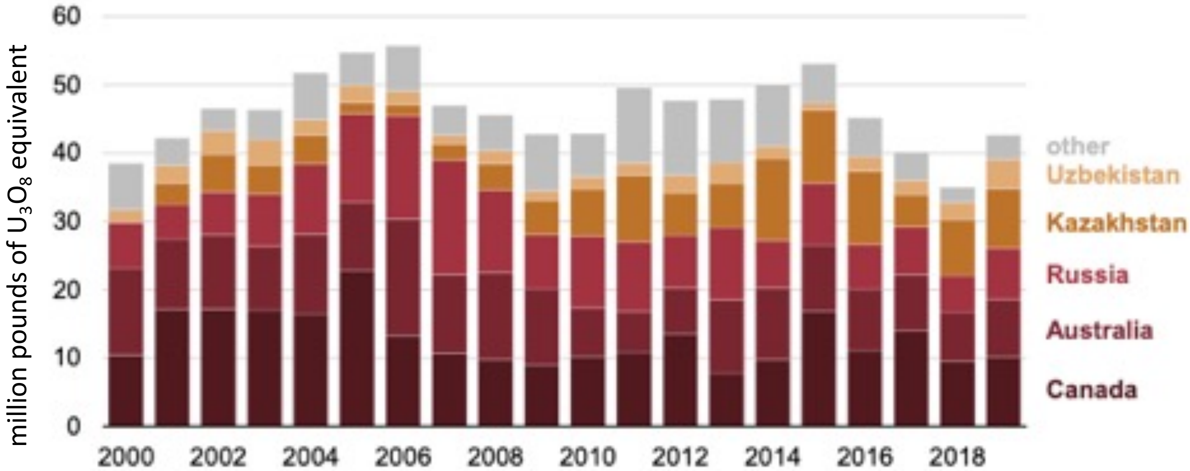

Figure 3.6shows the origin of uranium purchased for the U.S. civil nuclear plants [EIA 2021]. Most uranium is imported from Canada, Australia, Russia, Kazakhstan, and Uzbekistan. The current geopolitical situation shows that the uranium supply chain would be at risk when uranium trade is controlled by specific countries for their geopolitical interest. Thus, various efforts are needed to secure the supply of raw materials for nuclear fuel, which include diversifying countries where uranium is imported, enrichment of deplete uranium, recovering the fissile material from used nuclear fuels, uranium extraction from seawater, etc. Otherwise, the capacity expansion of nuclear energy required to achieve the net-zero emissions economy and the support required for the future economy growth would be at risk.

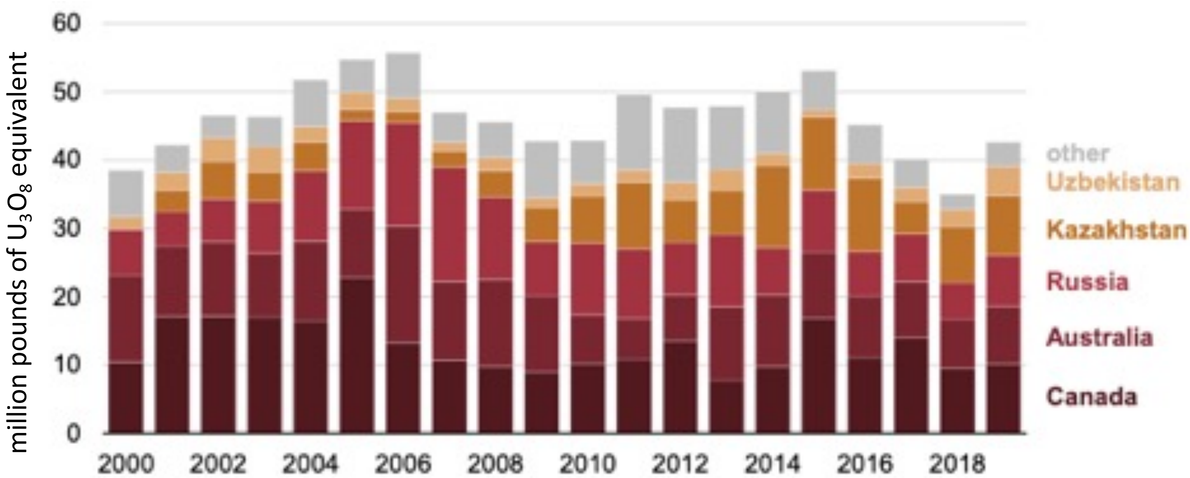

Figure 3.6 Origin of imported uranium for commercial nuclear plants

3.1.2 Conversion

Jessup et al. (2018) informs that all commercial conversion companies that are currently providing services are located outside of the United States. The only domestic uranium conversion plant, Metropolis Work (MTW) plant of Honeywell, has suspended operations since October 2017 due to the significant challenge faced by the nuclear industry from the Fukushima accident and the situation with worldwide oversupply of UF_6. However, in March 2020, the plant received the NRC's approval to run for 40 more years, and it is in the process of restarting, and will come online in 2023 [WNN 2021, Patel 2021].

The Metropolis plant was built in 1958 and the nameplate capacity is 15,000 MT of uranium per year. While this capacity is similar to the current demand of 18,000 MT, the annual NU demand (consumption) in 2050 is ~50,000 MT, and thus, the conversion capacity from the sole conversion plant in the United States is insufficient. Note that NU in UF_6 form involves significant volumes, so having conversion occur near enrichment can be beneficial. Domestic conversion capacity is only useful to the extent that it is matched with domestic enrichment capacity.

3.1.3 Enrichment

3.1.3.1 Projection of Enriched Uranium and SWU

Projections of the annual <5% LEU and 10-20% HALEU demands of evolutionary scenarios are provided in Figure 3.7 and Figure 3.8, respectively. For <5% LEU, the annual demand of the basis-of-comparison fuel cycle scenario (BS #1) is about 1,800 MT in 2020 and increases to ~5,100 and ~6,600 MT in 2050 and 2100. The four evolutionary fuel cycle scenarios have the same demand line (red line shows the overlapped four lines in the figure) because of a single fuel cycle scenario through 2050, and no construction of ALWRs from 2050 onwards. The annual <5% LEU demand increases to ~3,150 MT by ~2050 and decreases to ~1,580 MT as the legacy LWRs retire.

Key observations on uranium enrichment and SWU

- *Annual demand of <5% LEU and 10-20% HALEU in 2050 are 3,150 and ~620 MT, respectively, and further increase in HALEU demand by 2100 is expected.*
- *Annual enrichment demands in 2100 varies from 23.6 to 59.7 million-SWU depending on fuel cycle scenarios, which are much higher than the current domestic enrichment capacity of ~5.0 million-SWU/year.*
- *A significant SWU shortage is expected globally because of nuclear energy capacity expansion to achieve a deep decarbonization goal such as the Paris Agreement in 2015.*

The basis-of-comparison scenario (BS #1) does not need HALEU, while evolutionary scenarios do. For ES #1, the annual HALEU demand increases to ~620 MT in 2050 and ~1,500 MT in 2100. However, for other evolutionary scenarios, the annual HALEU demand peaks to ~670 MT in ~2050 and stabilizes at ~400 MT in 2100.

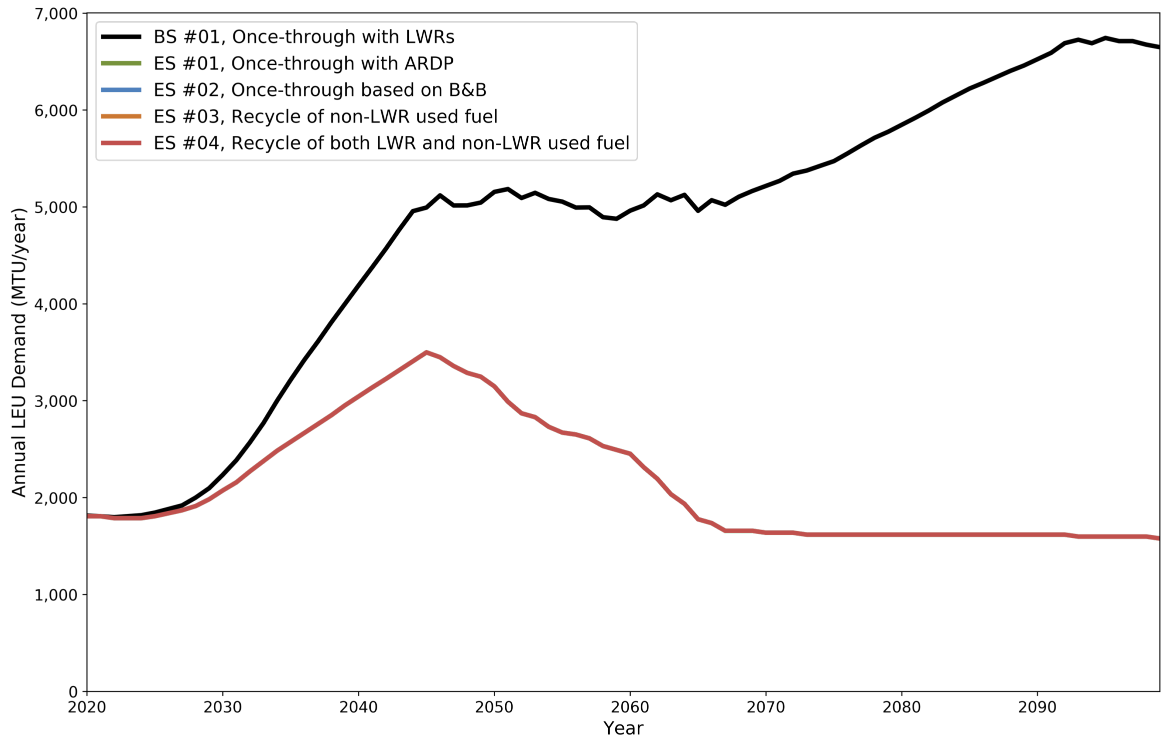

Figure 3.7 Projection for <5% LEU demand

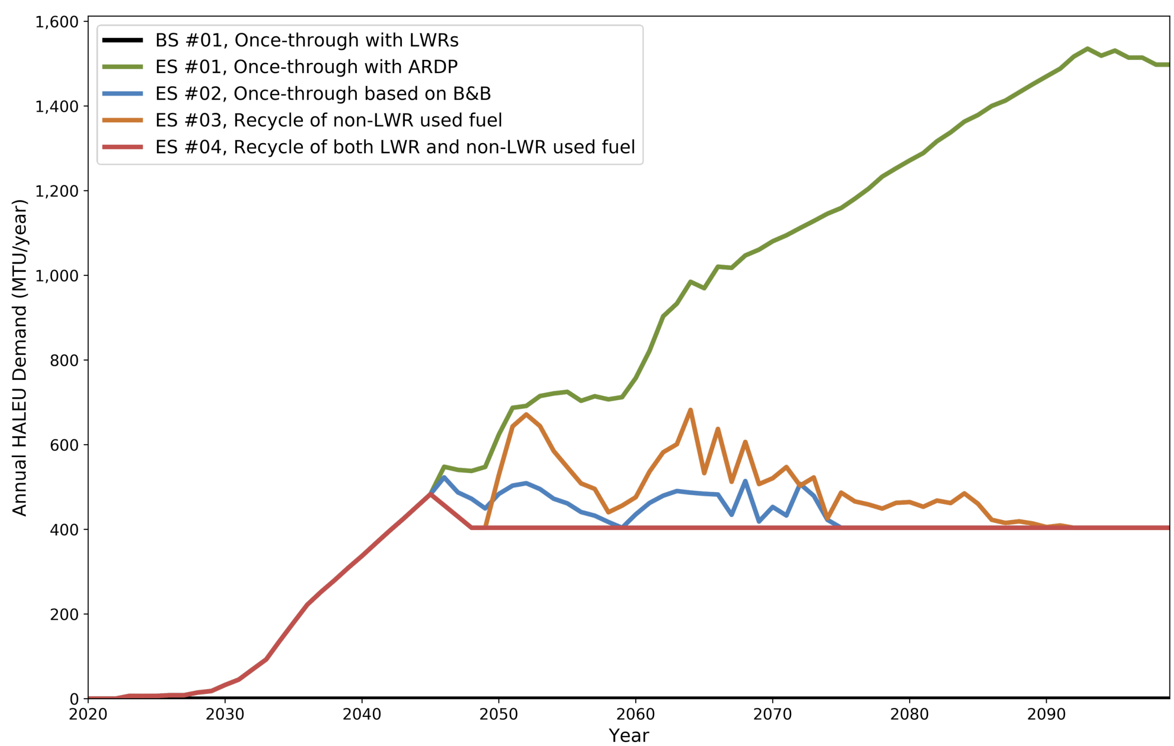

Figure 3.8 Projection for HALEU demands

Figure 3.9 shows the projection of the enrichment effort measured by the separative work units (SWU). It is noted that the current annual SWU requirement in the United States is ~12 million SWU. Of the three once-through scenarios (BS #1, ES #1, and ES #2), the basis-of-comparison (BS #1) requires <5% LEU only, but ES #1 and ES #2 require both <5% LEU and 10-20% HALEU. ES #1 requires more SWU compared to the basis-of-comparison because of the HALEU fuels. ES #2 also requires more SWU till 2050 because ARDP reactors require HALEU. However, the SWU demand of ES #2 decreases after the start of the B&B operation. For the two recycling scenarios (ES #3 and ES #4), the SWU demand decreases since the recycling starts in 2051. In 2100, ES #1 requires ~59.7 million SWU/year, but the other evolutionary scenarios (ES #2, ES #3, and ES #4) require ~23.6 million SWU/year.

Figure 3.10 shows the recent enrichment services purchased to support civil nuclear plants of the United States [EIA 2021]. The domestic enrichment capacity is ~5.0 million SWU/year, which is about 30% of the total SWU requirement in 2018. Comparing the projection of the annual SWU demand in Figure 3.9, the domestic uranium enrichment capacity is smaller. Even in the scenarios where the U.S. fuel cycle evolves to recycle (ES #3 or ES #4) or once-through using the B&B reactors, the domestic uranium enrichment capability is smaller than the demand.

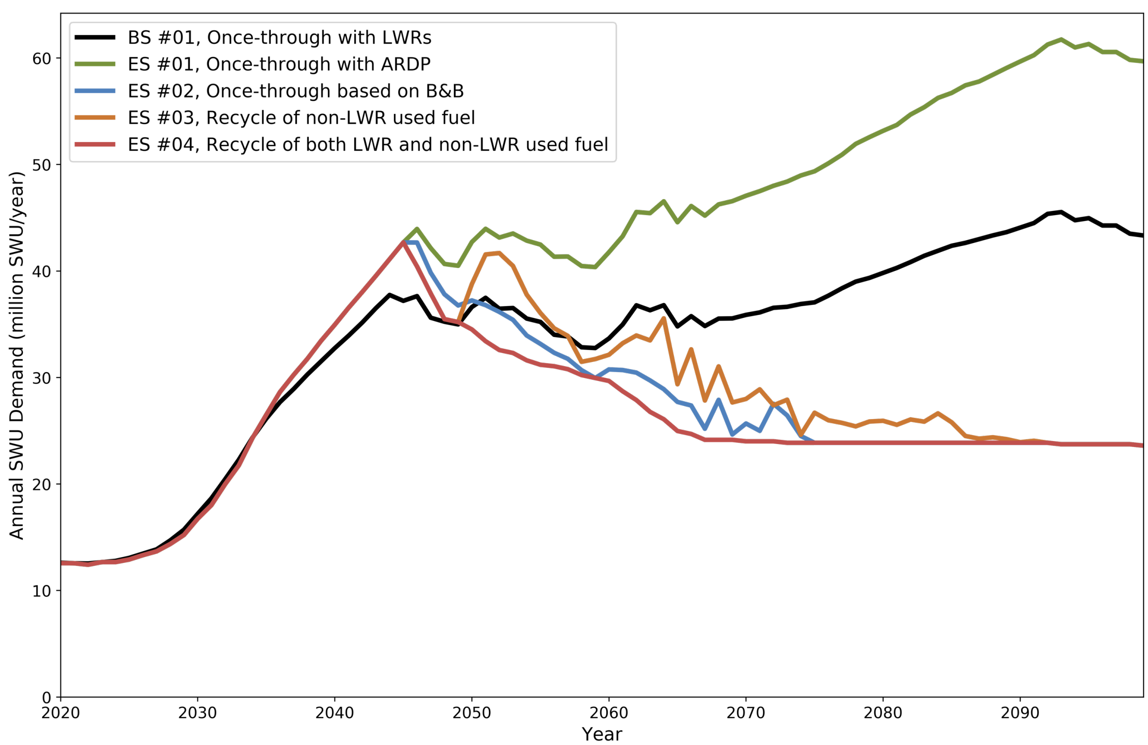

Figure 3.9 Projection of total annual separative work unit

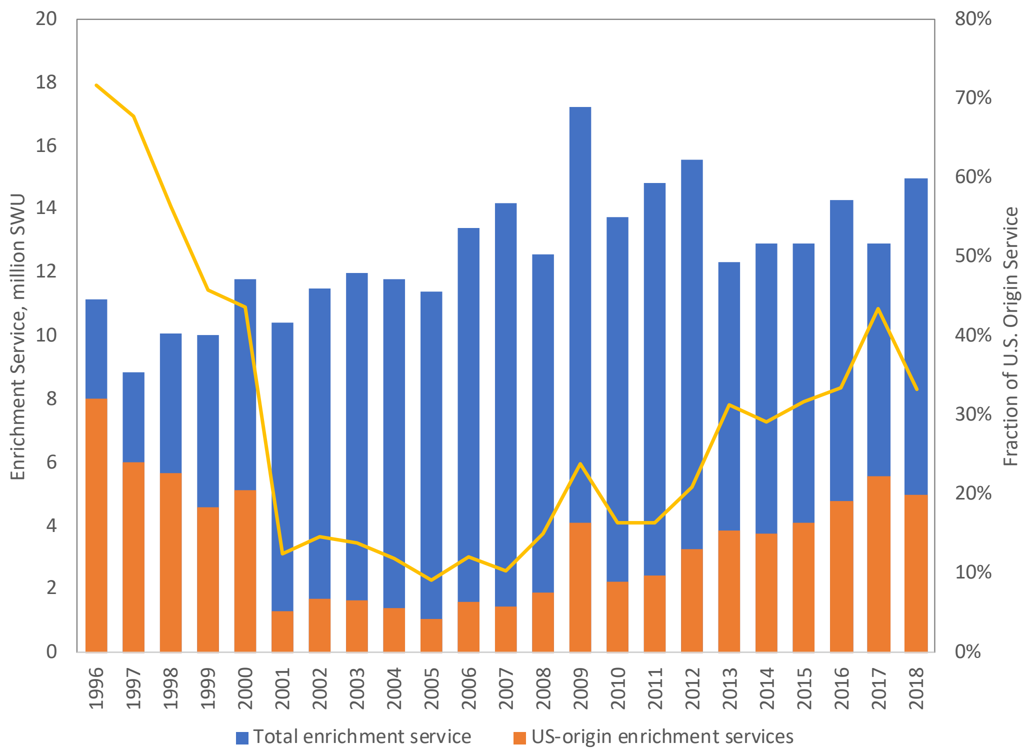

Figure 3.10 Enrichment service in the United States

The global enrichment capacity is provided in Figure 3.11 [WNA 2020]. The World Nuclear Association (WNA) projected the global enrichment capacity by 2040, including the enriched uranium demand based on lower, reference (medium), and upper reactor deployment scenarios. It is noted that the upper scenario was developed to keep the increases in the global average temperature well below 2°C above pre-industrial level (the Paris Agreement), which is close to the deep decarbonization goal considered in this study.

The global SWU capacity is more than 59.7 million SWU/year in 2019, which is higher than the current SWU demand of ~57 million SWU/year. The global SWU capacity is expected to grow up to ~80 million SWU/year by 2040, but the global SWU demand based on the upper reactor deployment scenario will exceed the supply around 2025. Overall, a significant shortage of SWU is expected soon when nuclear capacity expands globally to achieve deep decarbonization goals. It is also important to note that although the same technology is used to enrich uranium to 5% or to 20%, there might be regulatory differences (cf. Section 3.1.3.2) which may lead to only a fraction of the installed SWUs to be made available to produce HALEU. Currently, only China and Russia have HALEU enrichment capabilities. The only U.S. source for uranium enriched to greater than 5% is uranium produced from down-blending government owned high enriched uranium (HEU). Down-blending has been conducted at the Nuclear Fuel Services (NFS) facility in Erwin, TN, and at the Department of Energy’s Y-12 facility in Oak Ridge, TN [NEI, 2018].

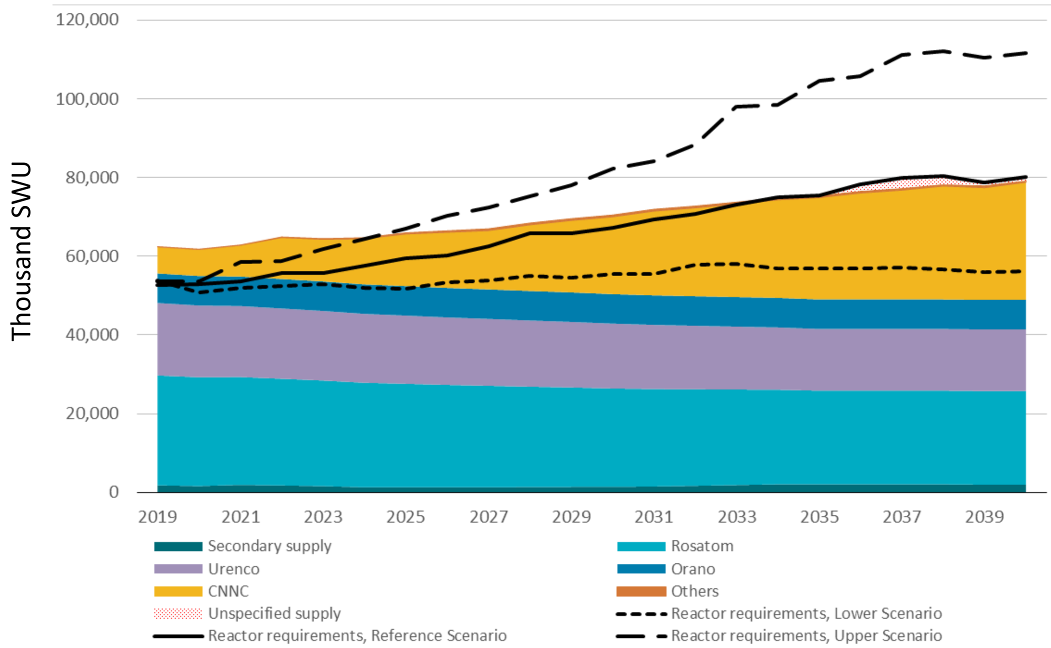

Figure 3.11 Global enrichment demand and installed capacity

3.1.3.2 Cascade Enrichment using Category-II and Category-III Facilities

Key observations on cascade enrichment scheme

- *Category-II enrichment facilities, with more stringent security requirements, are needed for 10-20% HALEU.*
- *A cascade enrichment scheme (i.e., enrich uranium up to 5% first in a Cat-III facility, and conduct additional enrichment up to HALEU in a Cat-II facility) can reduce the Category-II facility capacity needs and overall enrichment cost.*

Based on the classification of nuclear fuel facilities by the U.S. Nuclear Regulatory Commission (NRC), a 10-20% enrichment facility is classified as a ***Category-II*** or moderate strategic significance facility, while a fuel facility with up to 10% enrichment is classified as a ***Category-III*** or low strategic significance facility [U.S. NRC 2020]. An enrichment facility in Category-II requires more stringent security requirements than the current commercial enrichment facilities in Category-III. It would therefore be expected to have a higher cost for enrichment. Thus, to reduce the cost, the future enrichment infrastructure required for HALEU production is anticipated to minimize the enrichment in a Category II facility.

One of the ways to reduce the enrichment cost for HALEU production is to utilize a two-stage cascade enrichment scheme as depicted in Figure 3.12. In a single-stage enrichment scheme, all enrichment from NU to HALEU is performed in a Category-II facility, while the two-stage cascade enrichment scheme is to enrich the uranium up to 5% in a Category-III facility and additionally enrich up to 10 -20% in a Category-II facility. The total SWU is identical in either single- or two-stage enrichment schemes. However, the two-stage scheme can split the SWU between the Category-III and Category-II facilities to ~90% and ~10%, respectively

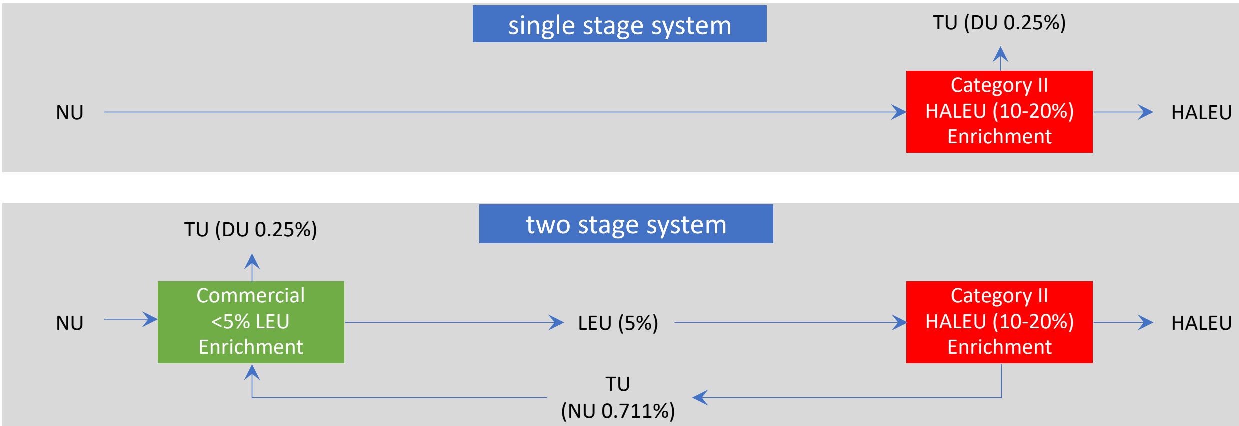

Figure 3.12 Overview of potential future HALEU enrichment infrastructures

The two-stage enrichment scheme was applied to ES #1, and the SWU allocations to the Category-III and Category-II facilities are plotted in Figure 3.13. The legacy LWRs and ALWRs require <5% LEU fuel until they retire. The left box in the two-stage system shows the Category-III facility needed to support the production of <5% LEU fuels, and the red color shows the Category-II facility that produces 10-20% HALEU. For the HALEU production , the two-stage scheme divides the SWU between Category-II and Category-III facilities. Overall, the required SWU of ES #1 (once-through with ARDP reactors) in 2050 and 2100 are 42.7 and 59.7 million SWU/year, respectively. However, the required SWU in the Category-II facility could be reduced to 6–- 11% of the total SWU based on the two-stage cascade enrichment scheme.

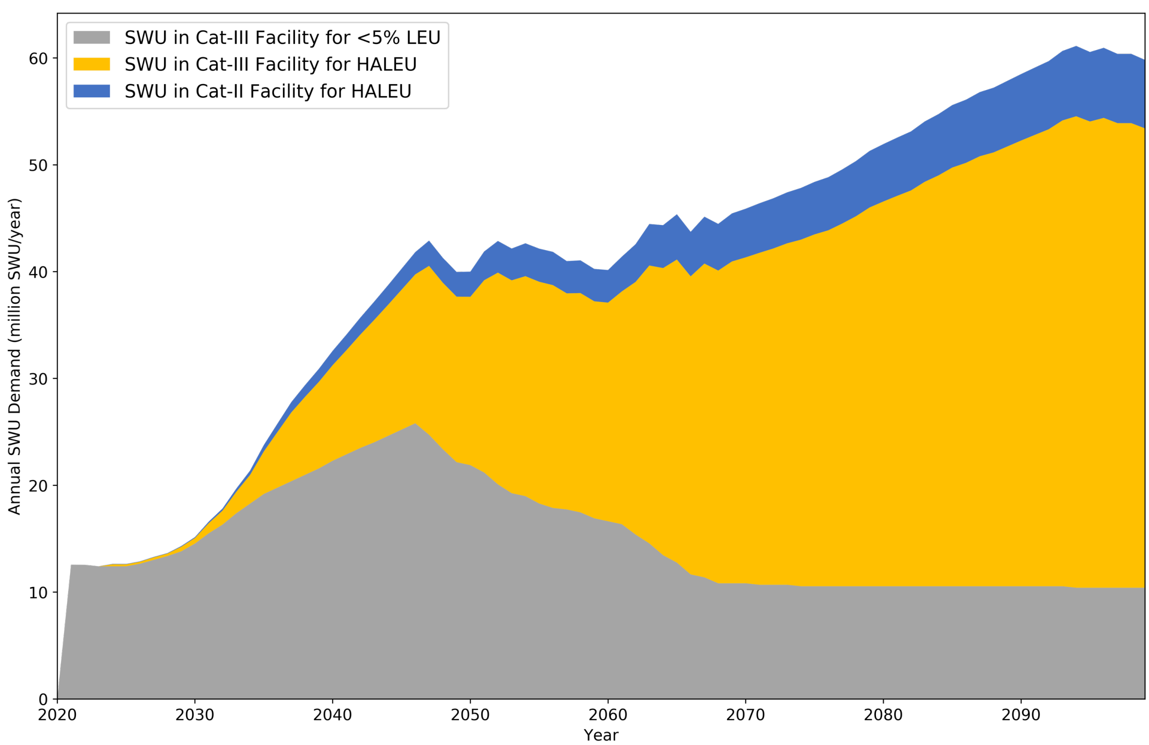

Figure 3.13 SWU allocations to Cat-II and Cat-III facilities for ES #1 -Once through with ARDP reactors

3.1.4 Depleted Uranium and Deconversion

> ***Key observations on depleted uranium generation***
>
> - *DU production trend is similar to NU demand: i.e., HALEU fuel of ES #1 increases DU generation, but recycle or B&B mode once-through mitigates DU generation.*
> - *By 2100, ES #1 generates ~3.5 million tons of DU, while other evolutionary fuel cycle scenarios produce ~2.4 million tons of DU.*

The cumulative depleted uranium (DU) mass and enriched uranium demand from 2020 to 2100 is compared in Figure 3.14. The cumulative DU mass before 2020 is not counted in the figure. The summation of DU mass and enriched uranium demand in the figure denotes the cumulative NU demand. With the assumed tails assay of 0.25%, about 90% of NU is discharged as depleted uranium from enrichment facilities. Thus, the trends of the DU generation are similar to the NU demands.

Currently DOE has about 521,000 MT of DU (or 771,000 MT of UF_6). The basis-of-comparison scenario (BS #1) generates ~3.0 million MT of DU from 2020 to 2100. ES #1 creates more DU (~3.5 million MT) during the same period because HALEU fuel is used, but the other evolutionary scenarios (ES #2, #3, and #4) generate about 2.4 million MT of DU. Annual DU generation peaks in 2050 and decreases gradually. The annual DU generation rates are 27,000 – 63,000 MT in 2050 and 42,000 – 46,000 MT in 2100.

DU could be a significant source of enriched uranium. However, the re-enrichment of DU has been limited since it is only economic in enrichment plants with spare capacity and low operating costs. Russia, Netherlands, and Sweden have re-enriched DU and used the products. For instance, re-enriched uranium (1 – 3.7%) by Russia was an important source of uranium for European reactors between 2005 and 2009. Uranium 2020 [NEA 2020] informs that about 5,700 MT of re-enriched uranium was produced from DU by 2015 in the United States.

The depleted uranium hexafluoride (DUF_6) discharged from the enrichment facility is in a solid state at ambient temperatures and could be stored long term. However, the conversion to more stable forms such as U_3O_8, UF_4 or UO_2 is preferable for reuse, storage, or disposal. Currently, about 771,000 MT of DUF_6 generated from the DOE gaseous diffusion plants are stored at the Portsmouth and Paducah sites. Those inventories are expected to be converted in approximately 18 – 30 years through the DOE's DUF6 conversion project. Based on the World Nuclear Association [WNA 2022], the total deconversion capacity in both places is 31,000 MT per year, and an additional deconversion plant with the capacity of 6,500 MT per year will be available soon.

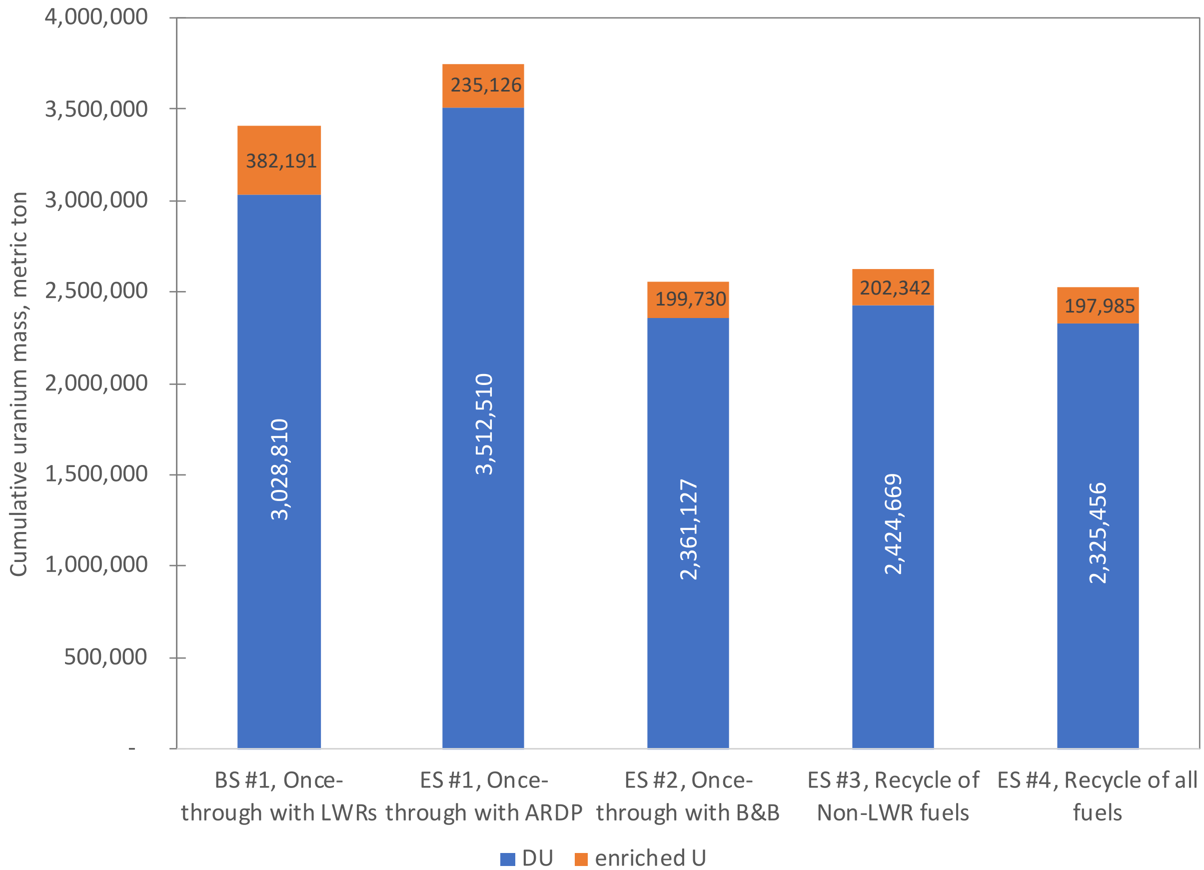

Figure 3.14 Projection of cumulative depleted uranium since 2020

3.1.5 Fuel Fabrication

> ***Key observations on fuel fabrication***
>
> - *Domestic capacity of uranium oxide fuel fabrication is sufficient to support evolutionary fuel cycle scenarios, but there is no commercial-scale facility for advanced reactor fuels (TRISO and metal) .*
> - *Annual demand of oxide fuel: 1,980 – 3,770 MT.*
> - *Annual demand of TRISO : 190 – 700 MT.*
> - *Annual demand of metallic fuel with HALEU: 270 – 990 MT.*
> - *Annual demand of metallic fuel with recovered actinides: 380 – 1,350 MT/year.*

Fuel form and amount to be fabricated are dependent on the reactor types and fuel cycle scenarios. In this work, legacy LWRs, ALWRs, SMRs and two ARDP reactors (Natrium representing SFR and Xe-100 representing HTGRs) are the reactor types considered to be deployed by 2050. The fuel forms of those reactor types are uranium oxide (UO_2) fuel, bond-sodium free metallic fuel, and pebble/TRISO fuel. The reactor types and fuel forms of recycling scenarios after 2050 are tentatively assumed to be a fast reactor and bond-sodium free metallic fuel. Thus, the following fuels are needed to support the evolutionary fuel cycle scenarios considered in this work,

- Uranium oxide (UO_2) fuel with <5% LEU to support legacy and future ALWRs and SMRs,
- Pebble/TRISO fuel with HALEU to support HTGRs (Xe-1000),

- Sodium-free metallic fuel with HALEU to support once-through SFRs (Natrium) and start-up core of recycling fast reactors,
- Sodium-free metallic fuel with recovered actinides to support recycling fast reactors.

Figure 3.15 shows the projection of the annual oxide fuel demand in terms of the enriched uranium mass. If the non-heavy metal composition (oxygen) is counted, the total oxide fuel demand is ~12% larger than values shown in the figure. For the basis of comparison (BS #1), the annual demand of uranium oxide fuel is about 1,800 MT to support the operating LWR fleet, and it will increase 5,150 MT and 6,650 MT in 2050 and 2100. Because HALEU is not needed in the basis of comparison, all oxide fuel requires <5% LEU. For evolutionary scenarios (ES #1–- ES #4), the annual oxide fuel demand increases up to 3,770 MT by 2050 due to the capacity expansion of ALWRs and SMRs, then decreases 1,980 – 3,080 MT in 2100 due to the retirement of legacy LWRs. Among the annual oxide fuel demand in 2100, about 400 – 1,500 MT is the oxide fuel with HALEU.

Figure 3.16 shows the projection of the annual pebble/TRISO fuel demand in terms of HALEU mass. If the non-heavy metal composition (graphite matrix) is counted, the total pebble/TRISO fuel mass is a factor ~27 [b] larger than the values shown in the figure. For ES #1, HTGR capacity increases continuously, which requires TRISO fuel of 240 MT-HALEU/year in 2050 and 700 MT-HALEU/year in 2100. For the other evolutionary scenarios (ES #2 – ES #4), the TRISO fuel demand is 190 MT-HALEU/ by 2100.

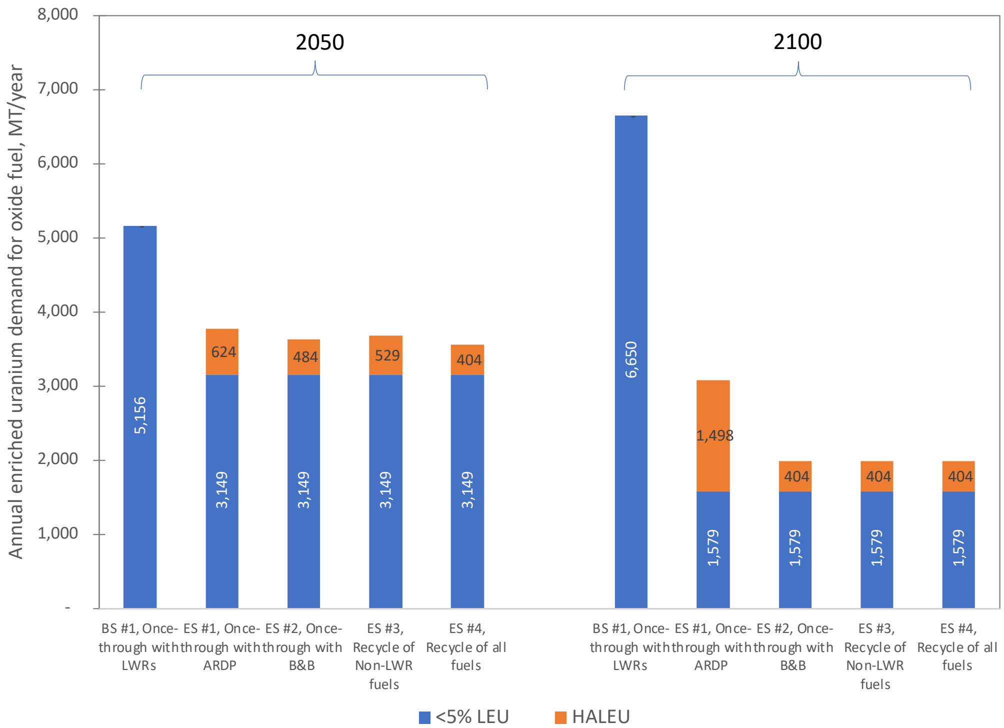

Figure 3.15 Projection of annual oxide fuel demand

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[b] The graphite mass of Xe-100 pebble was calculated using the A3-3 graphite density (1.68 g/cc), pebble diameter of 6.0 cm, and Uranium mass per pebble of 7g.

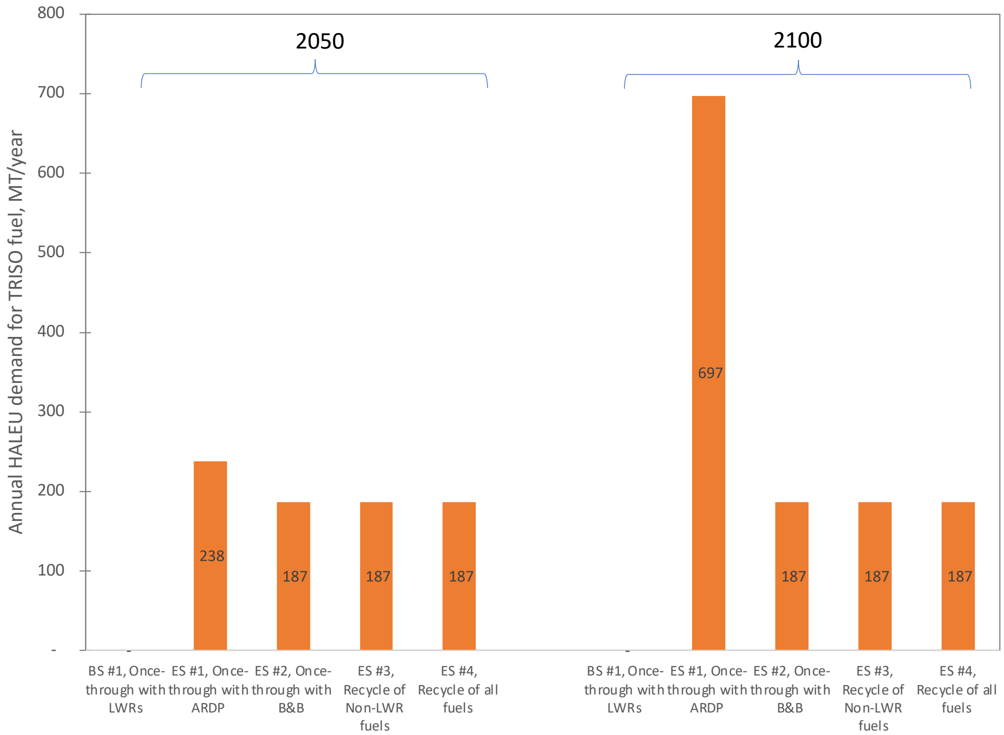

Figure 3.16 Projection of annual pebble/TRISO fuel demand

Figure 3.17 shows the annual demand of metallic fuel. Currently, binary or ternary alloy with 10% Zr matrix is considered as the metallic fuel, but a metallic fuel without matrix material is also considered as the future metallic fuel. Thus, the metallic fuel demand was calculated using the heavy metal (HALEU and recovered actinides) were calculated. If the metallic fuel contains non-heavy metal matrix, the total metallic fuel demand will be increased as much as the fraction of non-heavy metal in the fuel.

The metallic fuel with HALEU is needed to support once-through fast reactors (ES #1 and ES #2) or the start-up core of newly deployed fast reactors of recycling scenarios (ES #3 and ES #4). The metallic fuel with the recovered actinides is needed to support subsequent cycles following the startup of fast reactors of recycling scenarios (ES #3 and ES #4). The metallic fuel demand with HALEU is 380 – 890 MT-HALEU/year in 2050 and 270 – 990 MT-HALEU/year in 2100. The metallic fuel with recovered actinides (RA) is 270 – 380 MT-RA/year in 2050 and 730 – 1,200 MT-RC/year in 2100.

The domestic uranium oxide fuel fabrication capacity by three companies (Framatome Inc, Global Nuclear Fuel, and Westinghouse) is about 4,000 MT [WNA 2020], which is sufficient to support the evolutionary fuel cycle scenarios. However, there are currently no commercial fuel fabrication facilities for the metallic and TRISO fuels.

TerraPower LLC. and its partners (Centrus Energy) plan to establish a new Category II metal fuel fabrication facility that is scaled to meet the needs of the Natrium demonstration program. The facility will include the capability to manufacture the Natrium technology's advanced metal fuel forms that will be included as lead test assemblies in the demonstration plant (TerraPower 2020).

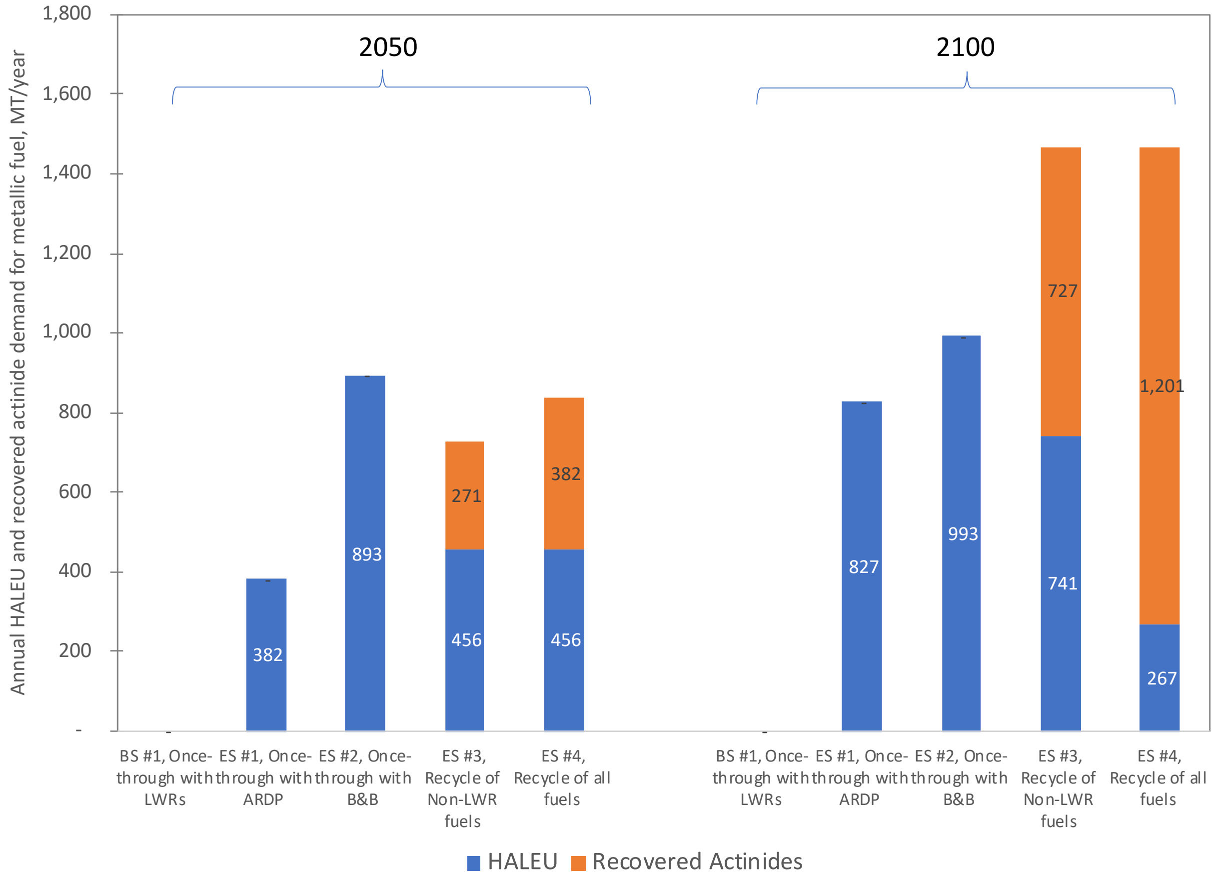

Figure 3.17 Projection of annual metallic fuel demand

TRISO-X LLC, a wholly owned subsidiary of X-energy LLC, has selected the Horizon Center Industrial Park in Oak Ridge, Tennessee as the site for its commercial TRISO fuel fabrication facility, the nation's first HALEU based fuel fabrication facility. It is scheduled for commissioning and start-up as early as 2025. The TRISO-X Fuel Fabrication Facility (TF3) is being commissioned through funding, in part, from the U.S. Department of Energy's (DOE) Advanced Reactor Demonstration Program (ARDP). The commercial facility's cross-cutting design will enable manufacturing of fuel for any number of advanced or small nuclear reactors based on TRISO fuel. The facility will initially produce 8 MT per year (MTU/year) of fuel that can support about twelve Xe-100 reactors. The TRISO-X team aims to expand the facility's capacity to 16 MTU/year by the early 2030s.

3.2 Back-end Fuel Cycle Facilities

Figure 3.18 shows the material flow in the back-end of the fuel cycle. In this work, discharged fuel is categorized into two waste streams: spent nuclear fuel (SNF) and high-level waste (HLW). SNF refers to the discharged fuel to be stored in interim storage and sent to a repository for direct disposal without further treatment. Discharged fuels from the once-through scenarios, which included the basis-of-comparison (BS #1), ES #1, and ES #2, are treated as SNF.

In recycling scenarios, which are ES #3 and ES #4, discharged fuel is stored in an interim storage and some of this fuel is reprocessed for recovering heavy metal isotopes, while some fuel is disposed without further treatment. For distinguishing purpose, the fuel to be reprocessed is called Used Nuclear

Fuel (UNF) in this report. The non-recovered materials and byproducts from the reprocessing process are treated as HLW and sent to a repository.

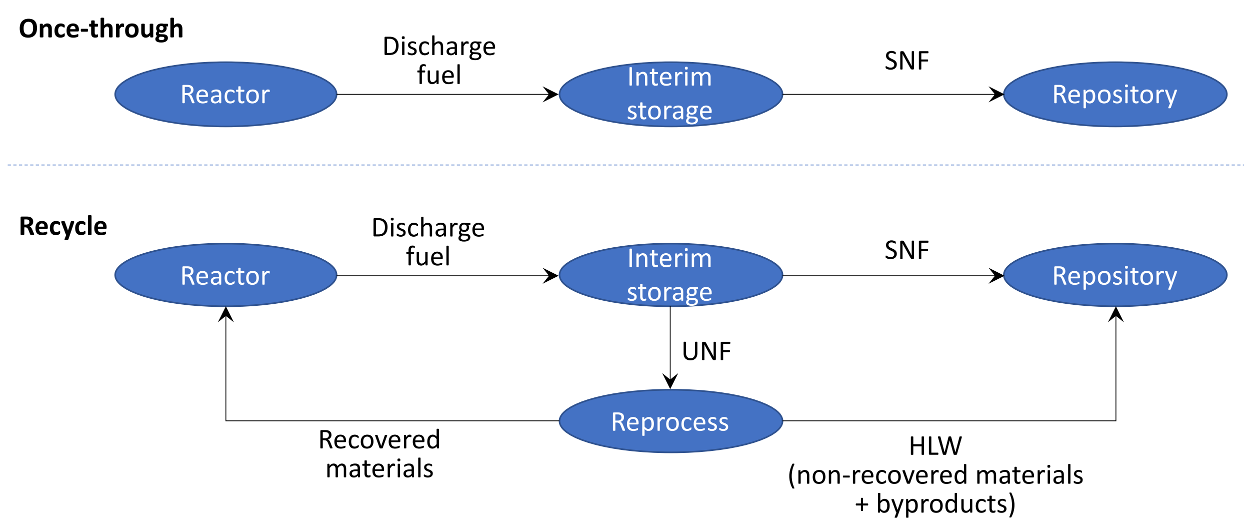

Figure 3.18 Material flow diagram

3.2.1 Interim Storage

> ***Key observations on interim storage***
>
> *Because of the higher burnup, the cumulative discharged fuel mass (or interim storage) from the once-through ARDP reactors is comparable to the current once-through LWRs fleet even though the nuclear capacity increases by a factor 2.5 by 2050.*

Discharged fuel assemblies are stored in interim storage before shipment to a disposal site or reprocessing facilities. There are two interim storage concepts: reactor on-site pool and dry cask storage. Most fuel assemblies discharged from legacy LWRs are stored in the on-site pool, and the dry cask storage is used when the on-site pool is nearly occupied up to the design limit. Based on the information from the U.S. NRC, there are 68 interim dry cask storage facilities at reactor sites and 27 facilities away from reactors as of February 2022. The dry cask storage capacity grows to accommodate fuels discharged from operating LWRs. In 2021 the Nuclear Regulatory Commission issued a license to Interim Storage Partners LLC to construct and operate a consolidated interim storage facility for spent nuclear fuel in Andrews, Texas [NRC News 2021]. The license authorizes the company to receive, possess, transfer, and store up to 5,000 MT of spent nuclear fuel.

A dry cask typically has a cylindrical shape containing an inner cylindrical canister. The canister is designed to hold multiple discharged fuel assemblies enclosed within a metal or concrete outer shell to provide radiation shielding. There are several canister concepts, including Purpose-built canister (PBC) and Dual-purpose canister (DPC). PBC was specially designed for a particular repository concept, while DPC was designed to meet the waste transportation and storage requirements of 10 CFR Part 71 and 72.

The majority of SNF in existing dry storage is in DPCs and nearly all new dry storage transfers are in DPCs as well [UFD 2014].

The DPC design can store 32 PWR assemblies or 68 BWR assemblies. The existing discharged fuel mass from legacy LWRs as of 2020 is about 80,000 MT. By assuming the annual SNF generation rate of 2,000 MT from the operating legacy LWRs, the Used Fuel Disposition (UFD) campaign estimates that by the year 2050, the total accumulated SNF is 146,000 MT [c] [UFD 2014].

In this work, it was assumed that DPC would be used as the canister for dry cask interim storage. Figure 3.19 shows the projection of the cumulated discharged fuel amounts from the evolutionary fuel cycle scenarios after 2020. The existing discharged fuel mass of ~80,000 MT as of 2020 should be added to the values in the figure for projection of total cumulative discharge fuel amount in the future. The total number of DPCs for storing discharged fuel assemblies from the evolutionary scenarios are calculated and the results are summarized in Table 3.2.

Compared to the UFD estimates by 2050 (no deep decarbonization and once-through with LWRs), the evolutionary fuel cycle scenarios generate a comparable discharged fuel mass because of a factor of 2 – 3 higher burnup even though the nuclear capacity will expand to ~250 GWe to achieve the zero-emissions economy from the current capacity of ~100 GWe. For the evolutionary fuel cycle scenarios, about 11,500 DPCs are needed by 2050 and 19,000 – 23,000 DPCs are need by 2100. Compared to the basis-of-comparison (BS #1), the evolutionary fuel cycle scenarios generate less discharged fuel. A National Academies of Science, Engineering, and Medicine (NASEM) study informs that new reactors have sufficient space to accommodate the used nuclear fuels for the duration of the reactor lifetime [NASEM 2006]. Thus, the necessity of dry casks with DPC could be delayed until the on-site pools are fully occupied.

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[c] 4,000 MT of SNF was added to the UFD campaign estimation of 142,000 MT by 2048.

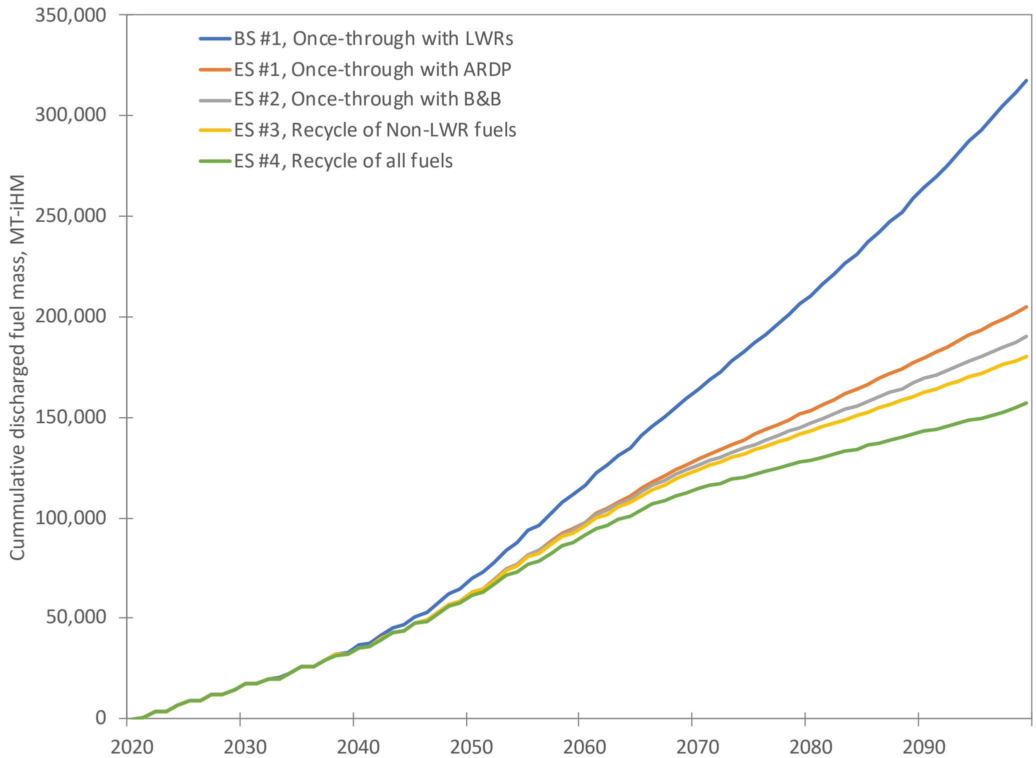

Figure 3.19 Projection of cumulated discharge fuel mass since 2020

Table 3.2 Projection of discharge fuel amount and number of dual-purposed canisters

Scenario	SNF, MT a)		Number DPCs needed	
	2050	2100	2050	2100
UFD estimation	146,000	N/A	11,734	N/A
BS #1, Once-through with LWRs	149,881	397,471	12,046	31,946
ES #1, Once-through with ARDP	143,020	284,808	11,495	22,891
ES #2, Once-through with B&B	143,020	269,937	11,495	21,696
ES #3, Recycle of fast reactor fuels	142,659	260,307	11,466	20,922
ES #4, Recycle of all fuels	141,621	237,428	11,383	19,083

a) Existing discharged fuel mass of ~80,000 MT as of 2020 was added to the SNF mass.

3.2.2 Reprocessing of Used Nuclear Fuel

Key observations on used nuclear fuel reprocessing

- *A commercial reprocessing facility is required a few years earlier than the starting year of the evolutionary recycling fuel cycles in 2051.*
- *The required annual reprocessing capacity increases gradually and peaks to 820 MT/year and 1,350 MT/year in ES #3 and ES #4, respectively.*

Projections of the annual reprocessing amounts of two recycling fuel cycles scenarios (ES #3 and ES #4) are compared in Figure 3.20 and Figure 3.21, respectively. In the figures, the total mass of both reprocessing and non-reprocessing masses indicates the discharge fuel mass. The reprocessing is required to start a few years earlier than 2050 to fill the core using recovered materials starting 2051. Additionally, UNF is not considered available for reprocessing until at least 5 years of cooling and the reprocessing process is considered to take 1 year. It is also assumed that there is sufficient reprocessing capacity available to process all available UNF that is needed to meet demand. In ES #3, the discharge metallic fuels from advanced reactors are reprocessed, while discharged fuels from ALWRs/SMRs are processed in ES#4 as needed. Thus, the annual reprocessing amount is higher in ES #4. The required reprocessing capacity increases after 2050 and the maximum required reprocessing capacity by 2100 is 820 MT-UNF/year and 1,350 MT-UNF/year in ES #3 and ES #4, respectively.

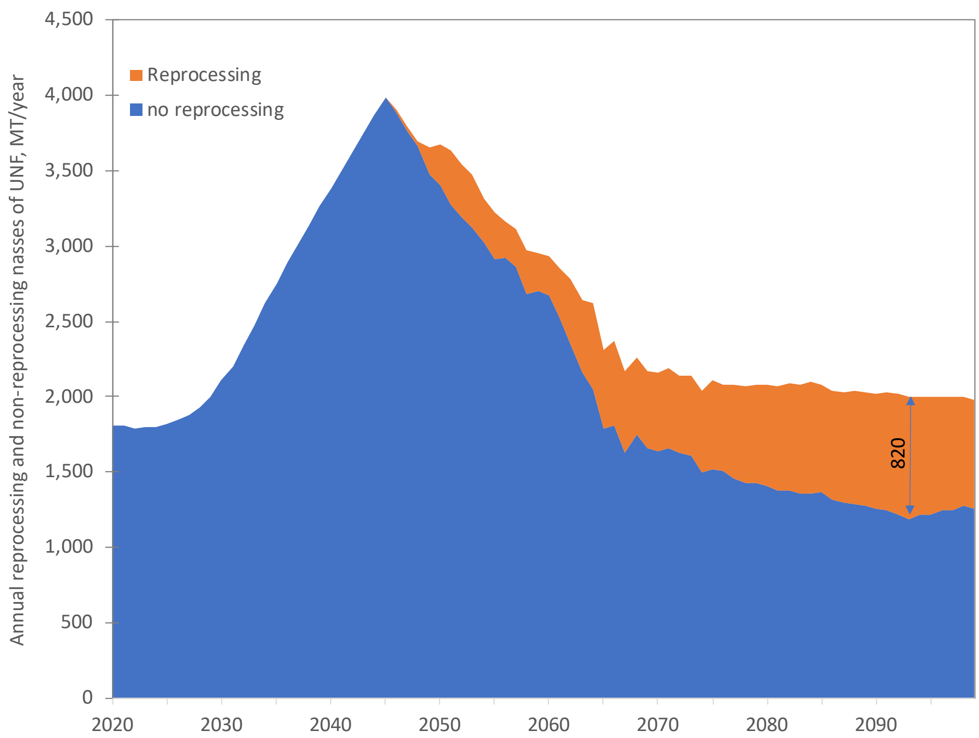

Figure 3.20 Annual reprocessing amount of discharged fuel in ES #3

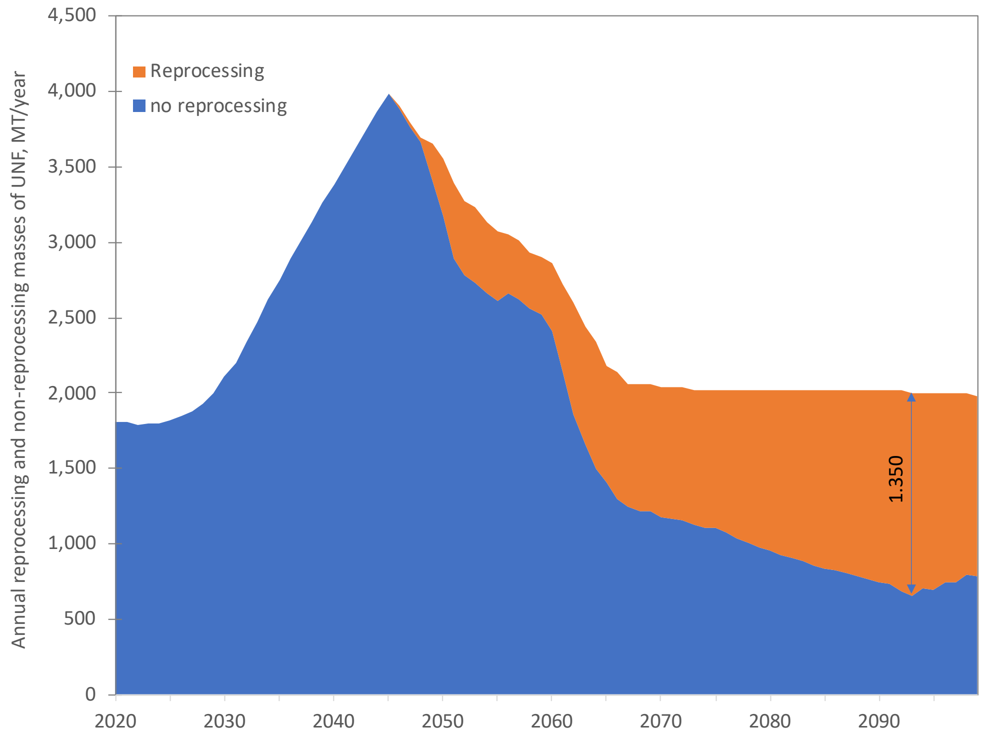

Figure 3.21 Annual reprocessing amount of discharged fuel in ES #4

3.2.3 Radioactive Waste Mass and Volume

3.2.3.1 Radioactive Waste Mass

Key observations on radioactive waste mass and volume

- *Both SNF and HLW are considered radioactive waste streams.*
- *Cumulative waste mass from evolutionary fuel cycle scenarios by 2100 would be 94,000 - 193,000 MT, compared to 293,000 MT from the basis-of-comparison.*
- *Evolutionary fuel cycle scenarios do not reduce the waste volume even though waste mass is reduced due to the relatively high SNF volume from HTGRs (Xe-100).*

Projections of waste mass to be disposed are compared in Figure 3.22. The once-through fuel cycle scenarios have one waste stream, which is SNF. However, in the recycling fuel cycle scenarios, there are two waste streams: SNF and HLW (see Figure 3.18). For evaluation purposes, it was assumed that the electrochemical process was used for reprocessing metallic fuel, and the mass conversion factor from the discharged fuel mass to HLW mass is provided in Appendix D, which was calculated using EBR-II and FFTF metallic fuel treatment data [UFD 2014].

In Figure 3.22, the disposal mass of recycle fuel cycle scenarios include HLW and SNF. The cumulative waste mass (heavy metal and fission product) to be disposed of is about 293,000 MT by 2100 for the basis-of-comparison (BS #1), while it is about 169,000–- 193,000 MT by 2100 for ES #1, #2, and #3. For the full recycling scenario, cumulative waste mass by 2100 is less than 94,000 MT.

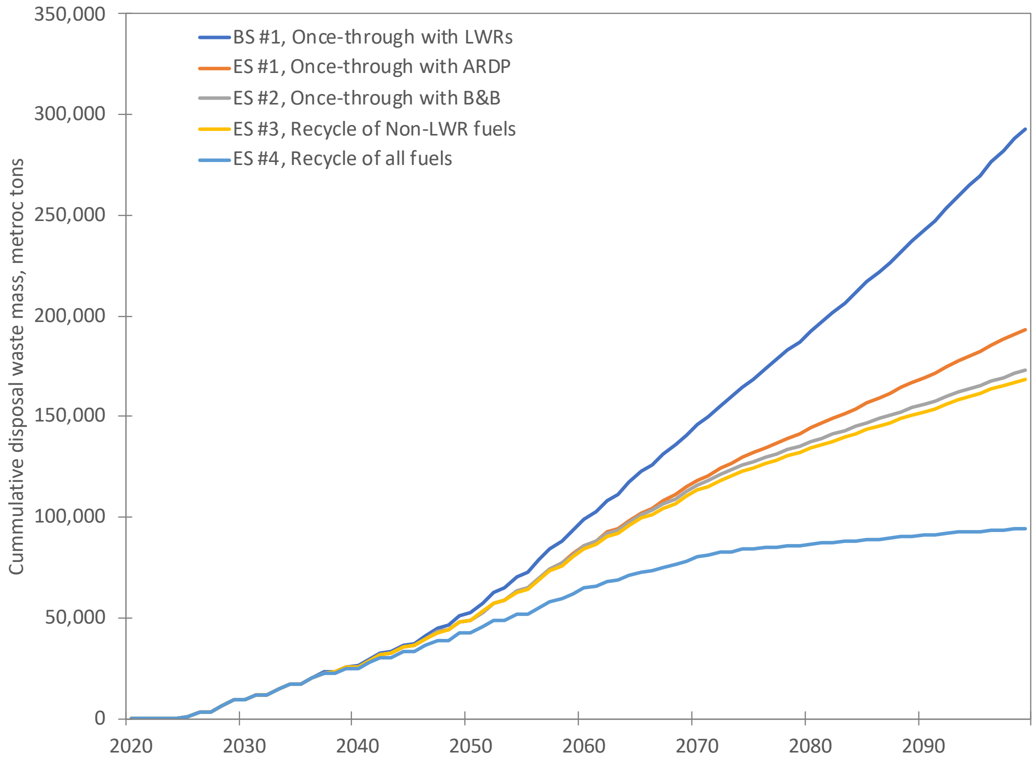

Figure 3.22 Projection of SNF+HLW to be disposed

3.2.3.2 Radioactive Waste Disposal Volume

In this work, waste disposal volume was defined by the total volume of canisters that are needed to accommodate all SNF assemblies or HLW generated from reactors and reprocessing facilities. This volume is consistent with the disposal volume estimate made by the U. S. Nuclear Waste Technical Review Board (NWTRB) in the development of recommendations for the nation's nuclear waste management program [NWTRB 2021]. For this analysis, the Dual-purpose canister (DPC) for storing SNF assemblies and the HLW canister used in EBR-II and FFTF metallic fuel treatment were selected [UFD 2014].

The total canister volume was calculated using the SNF or HLW waste mass-to-volume conversion factors. Note that the discharged fuel masses of the four evolutionary fuel cycle scenarios were provided in the previous section. The detailed information of canisters and conversion factors are provided in Appendix D, and the resulting conversion factors are provided in Table 3.3, including the disposal waste volume per unit electricity generation (m^3/GWe-year).

In general, the SNF or HLW discharged from non-LWR advanced reactors have higher waste mass-to-volume conversion factors compared to LWR SNF because of larger non-fuel regions of an SFR assembly (such as gas plenum, axial reflectors, coolant inlet nozzle, fuel handling, etc.), and also due to the low power density of the HTGRs. The byproducts from the reprocessing of the fast reactor used nuclear fuels also increase the waste mass-to-volume conversion factor. However, when normalizing the waste disposal volume to a unit electricity generated, fast reactors produce less waste volume and HTGRs produces a factor of 12 more waste volume compared to the LWRs.

Table 3.3 SNF or HLW mass to volume conversion factors

Waste stream	SNF			HLW
Source of waste stream	SNF from LWR or ALWR	SNF from SFR	SNF from HTGR/pebble	Electrochemical process
conversion factor, m^3/t-discharge fuel	1.14	2.67	56.39	2.15
Disposal waste volume per electricity generation, m^3/GWe-year	25.0 (1.0) [a)]	18.8 (0.8)	288.8 (11.6)	13.1 (0.5)

a) Values in parenthesis are the relative values to the disposal volume of LWR SNFs.

The cumulative waste disposal volumes from the fuel cycle scenarios are compared in Figure 3.23. For the basis-of-comparison, the required space for disposal of all SNFs is ~328,000 m^3 in 2100. The evolutionary fuel cycle scenarios require more disposal space even though the disposal SNF and HLW masses are smaller than that of the basis-of-comparison (see the SNF and HLW masses in Figure 3.22). For instance, the required space of ES #1 increases to ~1,263,000 m^3 in 2100 because of the large contribution of HTGR disposal volume, but it only increases to ~599,000 m^3 in ES #4. The disposal volumes of ES #1 are broken down by the generation sources in Figure 3.24. In ES #1, as with all of the evolutionary scenarios, the dominant source of the waste disposal volume is the TRISO fuels discharged from HTGRs.

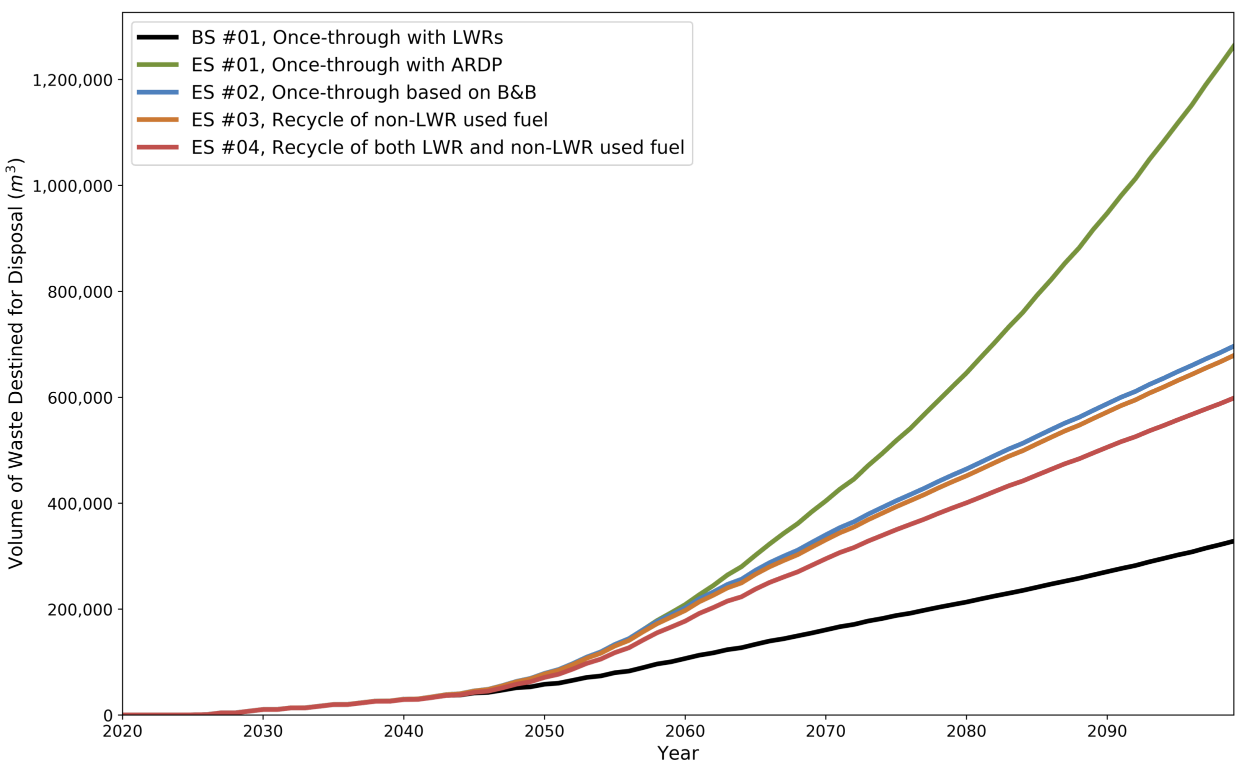

Figure 3.23 Cumulative radioactive waste disposal volume

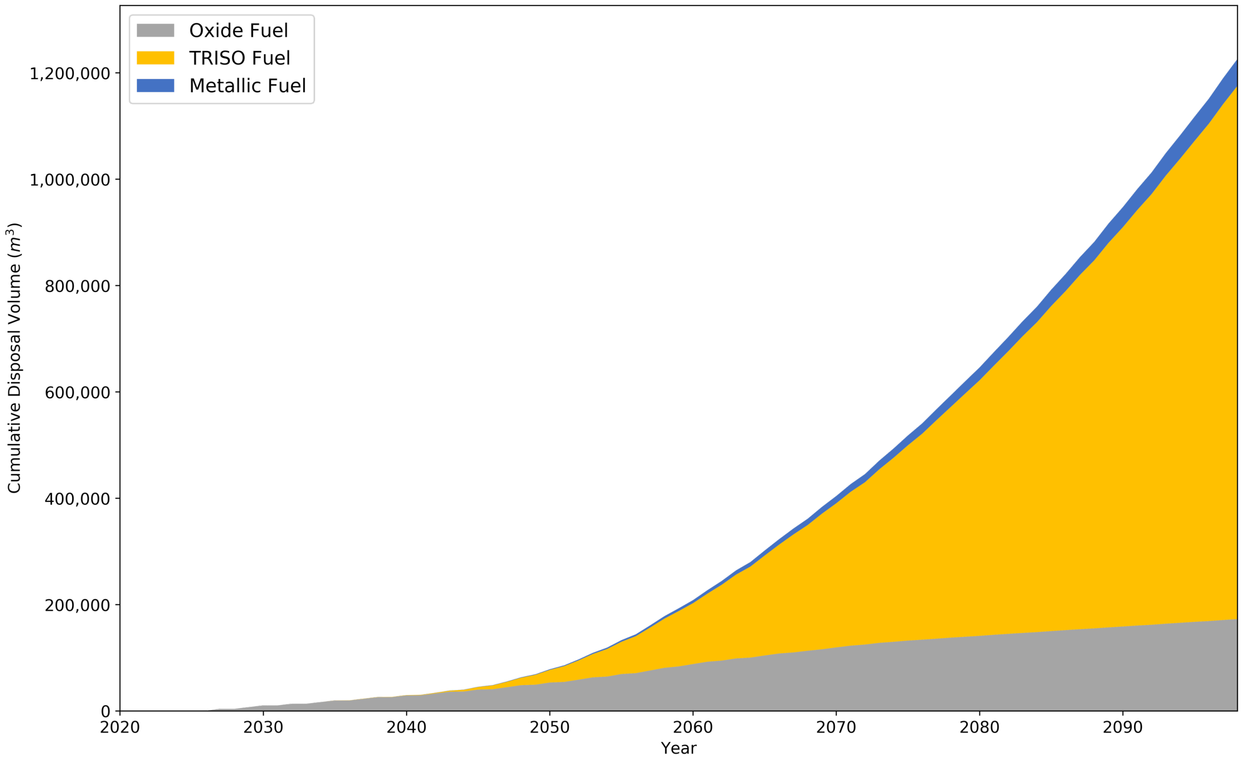

Figure 3.24 Waste disposal volumes per sources in ES #1

3.3 Other supply chain items

The anticipated commercial-scale deployment of advanced reactors face supply chain challenges. In addition to the traditional (LWR) supply chain items, advanced reactors will often require additional materials, not only HALEU, as discussed in the previous study, but also nuclear-grade graphite, high purity molten salts, sodium, and others. The new supply chain challenges the nuclear industry is facing are compounded by decades of neglect of the traditional nuclear supply chain, due to very limited construction of new nuclear reactors, and general U.S. economy-wide issues. In 2021, Executive Order 14017, "America's Supply Chains," directed the Secretary of Energy to submit a report on supply chains for the energy sector industrial base. The resulting report was published in February of 2022 [DOE 2022]. This section echoes some of the most salient findings of [DOE 2022], as well as from previous studies [INL 2010, DOE 2021, NEA 2020].

Traditional Nuclear Supply Chain Items – Equipment

LWRs have large components such as vessels, pressurizers or steam generators, that cannot currently be forged/fabricated in the U.S. This is unlikely to be an obstacle to the deployment of advanced reactors, which are typically SMRs and have smaller components. The U.S. maintains an industrial capability to produce such smaller components, however suppliers need to obtain certifications to produce nuclear-grade components.

Nuclear-grade graphite

Several advanced reactor concepts utilize graphite, either as in-core structural materials or in fuel (TRISO). Since the 1950s there is no domestic production of natural near-isotropic graphite which is needed for nuclear applications [Burchell 2007], and it is imported primarily from China. According to the U.S. Geological Survey [USGS, 2022], there are 10 U.S. sites containing significant graphite resources; a study is under way to assess the feasibility of the Graphite Creek deposit in Alaska for domestic production of graphite.

While the United Kingdom has continuously produced nuclear-grade graphite over the past 40 years, the last graphite reactor built in the U.S. was the HTGR at Fort St. Vrain, Colorado, in the late 1970s. To enable the development of advanced reactors with graphite, standardized specifications for nuclear grade graphite were developed (ASTM D7219-19 for graphite subjected to high neutron irradiation, and ASTM D7301-21 for graphite subjected to low neutron irradiation dose), and a "Graphite Technology Development Plan" has been established [INL 2010]. However, currently there are limited U.S. suppliers of nuclear-grade graphite.

Nuclear-grade sodium

Liquid sodium is the primary coolant material of a fast reactor. Sodium is the fifth most abundant metal, making up about 2.3% of the earth's crust. For utilizing sodium as the primary coolant, impurity control is important because the impurities of potassium (K) and Calcium (Ca) are activated during normal operation. For instance, Ar-39 and Ar-41 are produced in a sodium-cooled fast reactor based on the reactions of K-39 (n,p)Ar-39, K-41 (n,p) Ar-41, and Ar-40 (n,γ)Ar-41.

Table 3.4 shows the sodium quality that is currently sold by a French commercial sodium supplier [MSSA 2022]. The impurity level of reactor grade sodium is less than 300 ppm of potassium and 10 ppm of Calcium. There are multiple domestic sodium suppliers, but the detailed quality of the sodium is proprietary information. Considering the abundance and available domestic suppliers, sodium would not be a problem to supply for advanced fast reactors, except for concerns regarding impurity control. With higher demand, a supplier could provide the high-quality sodium for a low price. During the early stages of advanced reactor deployment, some investment would be needed to produce high-quality sodium, or the reactor would need to be designed with adequate shielding and a sodium purification control system to protect workers.

Table 3.4 Quality of commercial sodium

	S GRADE	S+ GRADE	SOPURE GRADE	R GRADE	ER GRADE
Na	99,80%	99,80%	99,90%	99,90%	99,98%
Ca	< 550 ppm	< 400 ppm	< 200 ppm	< 10 ppm	< 10 ppm
K	< 300 ppm	< 300 ppm	< 300 ppm	< 300 ppm	< 10 ppm
Cl+Br	< 20 ppm	< 20 ppm	< 20 ppm	< 20 ppm	< 20 ppm

Molten Salts

Molten salt reactors utilize high purity lithium (Li) or chlorine (Cl)-based salts. The U.S. produces less than 2% of the world's supply of lithium, most of which comes from South America and Australia. Moreover, the lithium supply for nuclear applications is in competition with the increasing requirements of the battery industry. Enrichment, as well as fuel salt synthesis, is required for both Li and Cl, and they are not available domestically at commercial-scale levels. As an example, enrichment of Li-7 is currently only performed in China and Russia, which demonstrates the vulnerability of this supply chain [GAO 201].

Others

Numerous minerals are used in various alloys used in current and advanced reactor concepts. Examples of materials with a potential disruption in supply chains are nickel (50% imported), chromium (70% imported), or hafnium, indium, and niobium (no domestic sources).

4. Status of Roadmap for Deploying Fuel Cycles Supporting ARDP Reactor Concepts

Last year, SA&I conducted a preliminary assessment of the readiness of fuel cycle technologies, facilities and equipment needed for deployment of fleets of the Natrium and Xe-100 ARDP demonstration reactors. The main findings of the study are summarized here:

- “There are few technology needs outside of the proprietary areas being covered by the vendors, but there are some facility and equipment issues that will impact deployment if not addressed.”
- “While the vendors are maturing proprietary designs for both the reactors and fuels and proprietary processes for fabricating the fuels, those designs and processes rely heavily on previous research and development by others, including NE. Continued research in these areas can help other vendors develop their own designs and processes and further evolve the technology foundation for advanced nuclear energy systems.”

The report recommended more detailed exploration of the status of fuel cycle facilities/equipment and government research in the areas of fuels and reactors related to the ARDP concepts. The next step is the development of pathways for maturing the technologies and establishing the facilities/equipment needed. This roadmap will include identification of commercial infrastructure and general areas of vendor proprietary research which is beyond the scope of government programs, while also identifying where government research and facilities may be needed.

This section updates the status of facility and equipment issues and plans for more detailed assessment of fuels development in FY-23.

4.1 HALEU System Readiness

The previous analysis found there were no critical technology elements identified for the processes to extract, refine, convert, and enrich uranium to HALEU, but two items were noted to have the potential to improve efficiency and economics of the HALEU supply system. In addition, facility insufficiencies were identified as mentioned previously in this report. These areas are described along with their status here.

4.1.1 Domestic Conversion Capacity

As mentioned in Section 3.1.2, there is currently no domestic capability operating for conversion of “yellowcake” uranium oxide powder from uranium mining (U_3O_8) into the uranium hexafluoride chemical form needed for enrichment (UF_6). Converdyn’s Metropolis Works conversion facility has been the sole conversion facility in the US for many years. The plant first entered service in 1958 and operated continuously until November 2017 when it was placed into standby status due to a global oversupply of uranium and reduced market demand. Earlier in 2017, the plant capacity was reduced from 15,000 tU/yr to 7,000 tU/yr. The facility has supplied over 500,000 tU of UF_6 to US and global customers over this period.

Plans are underway to restart the Metropolis facility. The facility recently receiving an operating license extension to 2060 and on February 9, a restart was announced with staff hiring throughout 2022 and resumption of operations expected in 2023. Converdyn has also indicated the original name plate capacity of 15,000 tU/yr could be reinstated if supported by demand.

4.1.2 Security Requirements for Hazard Category II Facilities

As mentioned in Section 3.1.3.2, facilities and transportation involving LEU enriched above 10% will require higher security than current supply chain facilities supporting LWR fuels.

Security requirements for fuel cycle facilities in the United States stem from Title 10, Section 73 of the Code of Federal Regulations (10CFR73)[d]. These regulations set out a graded approach to physical protection based upon the "strategic significance" of the material at hand (related to its ability to be utilized in a nuclear weapon). Category III, or low strategic significance, materials include up to 15 grams of U-235 at greater than 20% enrichment, 10kg of U-235 at 10-20% enrichment, or any amount of uranium at less than 10% enrichment. Category II, or moderate strategic significance, permits any quantity of uranium at up to 20% enrichment, but retains a limit of 1kg of U-235 in greater than 20% enrichment (in combination with limits on U-233 and plutonium which are not relevant in this context). Category II requirements are relevant to the commercial quantities of HALEU required for the proposed advanced reactor demonstration projects.

Category II physical security requirements are found in 10 CFR 73.67, which addresses both Category II and Category III materials. An "Informational Sheet" on NRC staff's current regulatory approach indicates the staff's approach is tailored and "considers the need for supplemental security measures" that "would generally be site-specific". This makes it difficult to develop physical security capital and operating cost estimates without a specific, detailed facility plan, resulting in a source of uncertainty in economic assessments. The Centrus Energy HALEU enrichment demonstration facility was licensed by NRC in June, 2021[e], but specifics of security costs have not been revealed. If they did become available, the size of the facility (16 centrifuges) would not provide a direct comparisons to a commercial scale facility. In the future, experience with licensed commercial-scale facilities could provide a basis for more accurate cost estimates of proposed facilities. However, planning for initial facilities will need to include provisions to address the existing uncertainty.

4.1.3 Transportation Packages for HALEU Uranium Hexafluoride

The design and sizing of transportation cylinders for uranium hexafluoride must balance the competing requirements of larger sizes that permit more economical shipments of commercial quantities of fuel and smaller sizes that permit higher enrichment within a given criticality safety margin. The large, commercially relevant cylinders have been designed to accommodate a maximum enrichment around 5%, consistent with current commercial light water reactor fuel needs. Moving above 5% enrichment, cylinders are focused more on transportation of small quantities of highly enriched uranium; compared to the 48A cylinder that can accept 9,555kg of 4.5% enriched UF6, the 8A cylinder size can accept 116kg of 12.5% enriched UF6, and the 5A/5B cylinders can accept 25kg of 100% enriched UF6[f]. Two efforts are currently underway by industry to address this gap.

Orano NCS GmbH has designed a variant of their DN30 cylinder for use with UF6 of up to 10% (DN30-10) or 20% (ND30-20) enrichment which utilizes a fixed grid of stainless steel tubes filled with boron to control for criticality. The DN30-10 can hold 1600kg of UF6, and the DN30-20 can hold 1250kg. This

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[d] https://www.nrc.gov/reading-rm/doc-collections/cfr/part073/index.html

[e] https://www.energy.gov/ne/articles/centrus-becomes-first-us-licensed-haleu-production-facility

[f] https://web.evs.anl.gov/uranium/guide/prodhand/sld035.cfm

design was submitted to the NRC for acceptance on Oct. 19, 2021 under docket number 71-9388 with the expectation that a certificate of compliance could be issued by August 2022[g].

In addition to UF6, the fuel cycle for the advanced reactor demonstrations will also require transportation of solid forms of HALEU. As with UF6, few commercial-scale options exist that are licensed for the increased enrichment. An initial screening activity [Eidelpes et al. 2019] compared two commercial cask designs and examined their suitability for use with HALEU according to the relevant regulations for criticality control, shielding, and thermal requirements. From this activity, it was recommended that the NAC International OPTIMUS-L package be given further analysis and consideration as a potential solution for transport of HALEU materials.

4.2 Fuel and Fuel Fabrication Readiness

The fuels development and fuel fabrication facilities for both demonstration reactors are active, ongoing activities. However, they are also proprietary, limiting the availability of information that could be used in developing a roadmap. Instead, the focus is on open source research information on the underlying technologies, with efforts planned in FY-23 to develop more detailed information on both fuel types.

4.2.1 Sodium-Free Annular Metallic Fuel Fabrication

While casting has traditionally been used in the fabrication of metallic fast reactor fuels, advanced techniques utilizing extrusion are being investigated to reduce costs while achieving required material properties. Some of this work is ongoing at Idaho National Laboratory; it is planned for fiscal year 2023 to engage in Technology Readiness Level (TRL) determination with those performing this work to both create a formal estimate of the readiness level of the technology and to refine and adapt the systems readiness assessment methodology through the application to this new specialty field. This application will focus general issues of extrusion technology for fuel applications as possible to avoid concerns with sensitive or proprietary information. As the extruded fuel is not expected to be utilized in the near term, this will exercise mid-TRL levels of the Technology and System Readiness Assessment (TSRA) process. If applicable and if sufficient information is available, Manufacturing Readiness Levels (MRL) may also be determined to assist in identification of next steps for higher-TRL technologies. Initial outreach activities have been undertaken to identify and establish availability of relevant subject matter experts.

4.2.2 TRISO Fuel Fabrication

Oak Ridge National Laboratory (ORNL) is involved with the development of TRISO fuel fabrication technology in support of the Xe-100 ARDP project. Following similar techniques as previous TRL assessments, the approach is to collaborate with experts at ORNL to refine and apply the TSRA process to TRISO fuel production. Initial identification of and outreach to involved researchers is currently underway. As TRISO fuel has a relatively long history of production, this will exercise primarily the high-TRL levels of the TSRA process and may include MRL determinations as well.

[g] https://www.nrc.gov/docs/ML2129/ML21291A064.pdf

5. Summary and Conclusions

5.1 Summary

Fuel cycle scenario studies were conducted to inform on the fuel cycle capacities and facilities needed for large-scale deployment of the Advanced Reactor Demonstration Program (ARDP) reactors (Natrium and Xe-100) and potential evolutionary fuel cycle scenarios. The reactor deployment and evolutionary fuel cycle scenarios from the present to 2100 were developed based on the following assumptions:

- achievement of a net-zero emissions economy in the United States by 2050, which requires a nuclear energy capacity of ~250 GWe by 2050,
- economic growth of 1% per year from 2051 to 2100, which results in ~340 GWe of nuclear energy capacity in 2100, and
- commercial-scale recycling and high burnup fuel technologies are available after 2050. Thus, the evolutionary fuel cycles with reprocessing technologies or ultra-high burnup fuel can start in 2051.

A single once-through fuel cycle scenario with advanced light water reactor (ALWR), small modular reactor (SMR), and ARDP reactors was assumed from the present to 2050 to achieve a net-zero emissions economy in the United States. Then, the following four evolutionary scenarios (ES) from 2051 to 2100 were considered,

- ES #1: Once-through by deploying ARDP reactors only,
- ES #2: Once-through with Breed and Burnup (B&B) fast reactors,
- ES #3: Recycle of used metallic fuels in fast reactors, and
- ES #4: Recycle of both used uranium oxide and metallic fuels in fast reactors.

In addition, the lifetime extension of legacy LWRs to 80 years and no deployment of LWR-based reactors beyond 2050 were assumed.

The front-end and back-end fuel cycle parameters were projected, and the results in 2050 and 2100 were compared with the domestic capacities in Table 5.1. The fuel cycle parameters are highlighted in orange when the domestic fuel cycle capacities are much smaller than the projected demands,

Natural uranium

The natural uranium (NU) demand increases to ~50,000 MT/year by 2050, while the current NU demand is ~18,000 MT/year. The demand increases further to ~66,000 MT/year by 2100 for the once-through scenario with ARDP reactors (ES #1), but it decreases to 28,900–- 29,100 MT/year in the B&B once-through scenario (ES #2) or recycling scenarios (ES #3 and #4). The projected cumulative NU demand from 2020 to 2100 is 2.5 – 3.8 million MT. The domestic production capability and recoverable uranium resource are much smaller than the projected NU demand. The current domestic uranium production is historically low (~67 MT in 2019) due to a global oversupply of uranium and low uranium prices, and the recoverable uranium, which includes the known uranium resource, discovered uranium resource, and inferred uranium resource based on geological evidence, in the United States is ~0.16 million MT. Most uranium is currently imported from Canada, Australia, Russia, Kazakhstan, and Uzbekistan.

Table 5.1 Comparison of fuel cycle demands and available domestic capacities

Fuel cycle elements	Demand in 2050	Demand in 2100				Current domestic capacity
	once-through with ALWR, SMR, ARDP reactors	ES #1	ES #2	ES #3	ES #4	
Annual NU demand, MT/year	~ 50,000	66,000	28,900	29,100	29,100	2018: 557MT, 2019: 67 MT
Cumulative NU demand from 2020, million MT	~ 0.97	3.8	2.6	2.6	2.5	Recoverable uranium [a]: 0.16
Annual <5% LEU demand, MT/year	~ 3,150	1,580	1,580	1,580	1,580	~ 632 MT of 5% LEU
Annual HALEU demand, MT/year	~ 620	1,500	~400	~400	~400	Zero commercial capacity
Annual SWU demand, million-SWU/year	~ 42.7	59.7	23.6	23.6	23.6	~5.0 million SWU
Annual conversion demand, MT/year	~ 50,000	66,000	28,900	29,100	29,100	Zero commercial capacity [b]
Annual deconversion (=DU generation), MT/year	~ 46,500	62,900	26,900	27,100	27,100	37,500 MT-DUF_6/year
Annual oxide fuel demand, MT-U/year	~ 3,770	3,080	1,980	1,980	1,980	4,200 MT-UO_2/year
Annual TRISO fuel demand, MT-U/year	~ 240	700	190	190	190	8 – 16 MT in 2030
Annual metallic fuel demand - MT-HALEU/year - MT-recovered actinides/year	 ~ 700 ~ 380 [c]	 830 -	 990 -	 740 730	 270 1,200	Zero commercial capacity
Peak annual reprocessing demand (year), MT-UNF/year	~ 380 (2050) [c]	-	-	820 (2093)	1,350 (2093)	Zero commercial capacity
Cumulative disposal SNF mass, MT-iHM [d]	~ 143,000	285,000	270,000	260,000	237,000	95 interim storage facilities (2022), but no geological disposal site

a) Recoverable uranium resource consists of ***reasonably assured resource*** (known or discovered resource) and ***inferred resource*** (inferred to occur based on geological evidence) that can be recovered and sold the yellow-cake (U_3O_8) less than $100/lb-$U_3O_8$.
b) Metropolis Work plant will be online in 2023 with 15,000 MT-U capacity.
c) Reprocessing capacity is needed a few years earlier than the start of ES #3 or ES #4 in 2051.
d) The existing 80,000 MT of SNF-IHM is added to the SNF mass.

Enrichment

Demands of <5% LEU and 10-20% HALEU in 2050 are ~3,150 MT/year and ~620 MT/year, respectively, and those increase further by 2100 for once-through (ES #1) but gradually decrease in the recycle (ES #3 and #4) and B&B mode once-through (ES #2). The Separative Work Units (SWU) demand in 2100 is in the range of 23 – 60 million-SWU/year depending on fuel cycle scenarios, but the current domestic enrichment capacity is only ~5.0 million SWU (which can produce about 632 MT of <5% LEU). The United States does not have a Category-II commercial-scale facility that is needed for 10-20% HALEU enrichment. This study shows that a cascade enrichment scheme (i.e., enriching uranium up to 5% first in Category-III facility, followed by additional enrichment up to 10-20% in Category-II facility) can reduce the required Category-II facility capacity and overall enrichment cost.

Fuel fabrications

The domestic uranium oxide fuel fabrication capacity is sufficient to support legacy and advanced LWRs. The demand of TRISO fuel is ~240 MT/year in 2050 and 190 -700 MT/year in 2100. The total demand of metallic fuels with HALEU and recovered actinides is ~1,0380 MT/year in 2050 and 830 – 1,470 MT/year in 2100. There is no commercial-scale fuel fabrication facility for TRISO and metallic fuels. Currently, TRISO and metallic fuel fabrication capacities are under built by industry and national laboratories to support ARDP reactors.

Reprocessing used nuclear fuels

Among the four evolutionary fuel cycle scenarios, two scenarios (ES #3 and #4) are recycling fuel cycle scenarios. A reprocessing facility of used nuclear fuel (UNF) is required a few years earlier than the start of the two recycling fuel cycles in 2051. The reprocessing capacity increases gradually and peaks 820 MT/year and 1,350 MT/year near 2100 for ES #3 and ES #4, respectively. Currently, there is no commercial-scale reprocessing facility in the United States.

Radioactive waste mass

The cumulative spent nuclear fuel (SNF) mass discharged from the four evolutionary fuel cycle scenarios is ~143,000 MT of initial heavy metal (iHM) in 2050, which includes the existing SNF mass of 80,000 MT-iHM as of 2020. It is noted that the cumulative SNF mass of the current LWR fleet (~100 GWe) will be ~146,000 MT-iHM by 2050. Thus, the four evolutionary fuel cycle scenarios generate slightly smaller SNF mass by 2050 than the current LWR fleet even though the nuclear capacity will be 2.5 times higher by 2050 because the discharge burnup of ARDP reactors increases by a factor of three. The projected cumulative SNF mass in 2100 is 237,000 – 285,000 MT-iHM.

5.2 Conclusions

The United States requires a significant expansion of the existing nuclear fuel cycle capacities or the construction of new facilities. The existing domestic nuclear fuel cycle capabilities are much smaller than what would be needed to support the projected nuclear energy generation capacity based on the deep decarbonization goal and the assumed the U.S. economic growth rate. For several fuel cycle elements (HALEU enrichment, advanced fuel fabrication, waste repository, used nuclear fuel reprocessing, etc.), there is no commercial-scale capability or facility in the United States even though the projected demands are high.

The higher burnup of ARDP reactors mitigates the once-through back-end fuel cycle elements (in particular, spent nuclear fuel mass), but as a trade-off, the front-end fuel cycle elements (natural uranium (NU) demand, Separative Work Units (SWU), depleted uranium (DU) generation, etc.) are increased because higher enriched HALEU fuels are used. The evolutionary fuel cycle scenarios inform that the required front-end fuel cycle elements could be reduced by recycling used nuclear fuels or adopting a breed-and-burnup once-through fuel cycle with ultra-high burnup fuel.

Except for natural uranium, other fuel cycle elements could be met the projected demands by expanding existing fuel cycle facilities or deploying new facilities through further investments and financial incentives. However, the NU demand should be supplied through domestic uranium resource or import. Domestic uranium resources are much smaller than the projected demand even though there are activities [DOE 2020a] to revitalize and strengthen the domestic uranium mining industry. The domestic uranium shortage could make the uranium supply chain unreliable if specific countries control the uranium trade for their geopolitical interests. Thus, the potential shortage of NU could be a fundamental supply chain issue in the fuel cycle scenarios considered in this work, and efforts are needed to secure the supply of nuclear fuels, such as diversifying countries where uranium is imported, expanding domestic production, enriching depleted uranium, developing affordable uranium extraction technology from seawater, recycling used nuclear fuels, etc.

References

APS 2007, "Consolidated Interim Storage of Commercial Spent Nuclear Fuel: A Technical and Programmatic Assessment," American Physics Society, Feb. 2007.

Bistline, J., et al. (2022) "Nuclear Energy in Long-Term System Models – A Multi-Model Perspective," EPRI, April 2022.

Calvin, K., et al., "GCAM v5.1: representing the linkages between energy, water, land, climate, and economic systems, Articles, Vo. 12, 677-698 (2019).

Croson D., H. D. Gougar, "High-Temperature Gas-cooled Reactor Research and Development Roadmap – Draft for Public Comment," INL/EXT-18-41803, Rev. 3, September 2017.

Dixon (2021a), B., S. Kim, B. Feng, T. Kim, S. Richards, and J. Bae, "Estimated HALEU Requirements for Advanced Reactors to Support a Net-Zero Emissions Economy by 2050," INL/EXT-21-64913 (2021).

DOE (2000), 65 FR 56565 -Department of Energy; Record of Decision for the Treatment and Management of Sodium- Bonded Spent Nuclear Fuel.

DOE (2020 (a)), "Restoring America's Competitive Nuclear Energy Advantage: A strategy to assure U.S. national security," Department of Energy (2020)

DOE (2020 (b)), "Energy Department's Advanced Reactor Demonstration Program Awards $20 million for Advanced Reactor Concepts," https://www.energy.gov/ne/articles/energy-departments-advanced-reactor-demonstration-program-awards-20-million-advanced.

DOE (2021), "Critical Minerals and Materials: U.S. Department of Energy's Strategy to Support Domestic Critical Mineral and Material Supply Chains (FY2021-FY2031)," January 2021 (https://www.energy.gov/downloads/critical-minerals-and-materials)

DOE (2022), "Supply Chain Deep Dive Assessment," U.S. Department of Energy Response to Executive Order 14017, "America's Supply Chains", February 2022 (https://www.osti.gov/biblio/1871592)

EIA (2010), "U.S. Uranium Reserves Estimates," U.S. Energy Information Administration, July 2010.

EIA (2021), "2020 Uranium Marketing Annual Report," U.S. Energy Information Administration, May 2021.

Eidelpes, E., J. Jarrell, H. Adkins, B. Hom, J. Scaglione, R. Hall, B. Brickner, "UO_2 HALEU Transportation Package Evaluation and Recommendations", INL/EXT-19-56333, November, 2019.

GAO (2013), "Managing Critical Isotopes – Stewardship of Lithium-7 is Needed to Ensure a Stable Supply," Report to the Ranking Member, Subcommittee on Oversight, Committee on Science, Space, and Technology, House of Representative, U.S. Government Accountability Office, September 2013.

Huff, K. D., et al., "Fundamental concepts in the Cyclus nuclear fuel cycle simulation framework," Advances in Engineering Software, Volume 94, April 2016.

IAEA (2020), "Energy, Electricity and Nuclear Power Estimates for the Period up to 2050," Reference data series No. 1, International Atomic Energy Agency (2020).

INL (2010), Next Generation Nuclear Plant Project No. 23747, "Graphite Technology Development Plan", October 2010

Jessup W., et al., "United States Nuclear Manufacturing Infrastructure Assessment," 1660-001-RPT-001, revision 1, MPR Associates, Inc. (2018).

Kim, S. H., T. Taiwo, and B. Dixon, "The Carbon Value of Nuclear Power Plant Lifetime Extension in the United States," Nuclear Technology, https://doi.org/10.1080/00295450.2021.1951554, 2021.

Kim, T. K, C. Grandy, K. Natesan, R. N. Hill, "Research and Development Roadmaps for Liquid Metal Cooled Fast Reactors – Draft for Public Comment," ANL/ART-88, Rev. 2, September 28, 2018.

Mulder E. J., W. A. Boyes (2020), "Neutronics Characteristics of a 165 MWth XE-100 Reactor," Nuclear Engineering and Design 357 (2020).

NASEM (2006), "Safety and Security of Commercial Spent Nuclear Fuel Storage: Public Report (2006)," The National Academies of Science Engineering Medicine, 2006.

MSSA (2022), "Sodium Metal," https://www.metauxspeciaux.com/wp-content/uploads/2017/08/MSSA-SODIUM-METAL-EUROPE.pdf.

NEA (2020), "Uranium 2020: Resource, Production and Demand," A Joint Report by the Nuclear Energy Agency and the International Atomic Energy Agency, 2020.

NEI (2018), "Addressing the Challenges with Establishing the Infrastructure for the front-end of the Fuel Cycle for Advanced Reactors", 2018

Neider, T., P. Hejzler (2021), "Natrium," Presentation to National Academy of Sciences, February 22, 2021.

NRC 2020, "Safeguard Categories of SNM," United States Nuclear Regulatory Commission, Updated on March 11, 2020.

NRC 2021, "Storage of Spent Nuclear Fuel," United States Nuclear Regulatory Commission, Updated on May 03, 2021.

NWTRB (2021), "Six Overarching Recommendations for How to Move the Nation's Nuclear Waste Management Program Forward," The U.S. Nuclear Waste Technical Review Board, April 2021.

OECD (2020), "Uranium 2020: Resources, Production and Demand," NEA No. 7551, A Joint Report by the Nuclear Energy Agency and the International Atomic Energy Agency (2020).

Patel S., "Honeywell to Reopen Sole U.S. Uranium Conversion Plant," Power, https://www.powermag.com/honeywell-to-reopen-sole-u-s-uranium-conversion-plant/, Feb. 9, 2021.

TerraPower (2020), "TerraPower announces plan to invest in domestic advanced nuclear fuel production to ensure U.S.-based fuel supply for advanced reactors," September 1, 2020, https://www.terrapower.com/terrapower-announces-plan-to-invest-in-domestic-advanced-nuclear-fuel-production/

Thierry, H., C. Senac, and B. Feng, "DYMOND 6 User Manual," Argonne National Laboratory (2019).

UFD (2014), "Evaluation of Options for Permanent Geologic Disposal of Spent Nuclear Fuel and High-Leve Radioactive Waste – In Support of a Comprehensive National Nuclear Fuel Cycle Strategy," FCRD-UFD-2013-000371, Revision 1, Used Fuel Disposition Campaign, April 15, 2014.

USGS (2022), "Graphite deposits in the United States", retrieved from https://www.usgs.gov/data/graphite-deposits-united-states on 06/10/2022

Whitehouse 2021, "Tackling the Climate Crisis at Home and Abroad," Executive Order 14008, February 1, 2021.

WNA (2020), "The Nuclear Fuel Report: Expanded Summary – Global Scenarios for Demand and Supply Availability 2019 - 2040," World Nuclear Association (2020).

WNA (2022), "Conversion and Deconversion," World Nuclear Association, Updated January 2022.

WNN (2021), “US conversion plant gears up for next 40 years,” World Nuclear News, April 14, 2021.

Appendix A. Projection of global natural uranium demand

The International Atomic Energy Agency (IAEA) projected the nuclear energy capacity till 2050 [IAEA 2020]. Figure A. 1 shows the region-wise projection of the nuclear energy capacity to 2050. IAEA collected the deployment of nuclear plants from each member country. For the United States, IAEA accounted for under construction (Vogtle) and planned retirements but did not account for potential new construction to achieve a net-zero emissions economy. Thus, the last columns denote the projection in America to reach the net-zero emissions economy goal by 2050.

The IAEA projection informs that the current worldwide nuclear capacity is 392 GWe and will grow to 714 GWe in 2050. Nuclear capacity is growing significantly in Asia. When considering the high growth in the United States to achieve the net-zero emissions economy goal, the total projection is 868 GWe in 2050.

Based on the IAEA's projection of the nuclear capacity, the global uranium demand was estimated, and the resulting forecast is plotted in Figure A. 2. The U.S. uranium demand in 2050 is 15,000 – 52,000 MT per year. The variation in the U.S. uranium demand depends on the decarbonization policy. Except for the United States, the global uranium demand is 92,000 MT per year, which is roughly double the uranium demand of the United States.

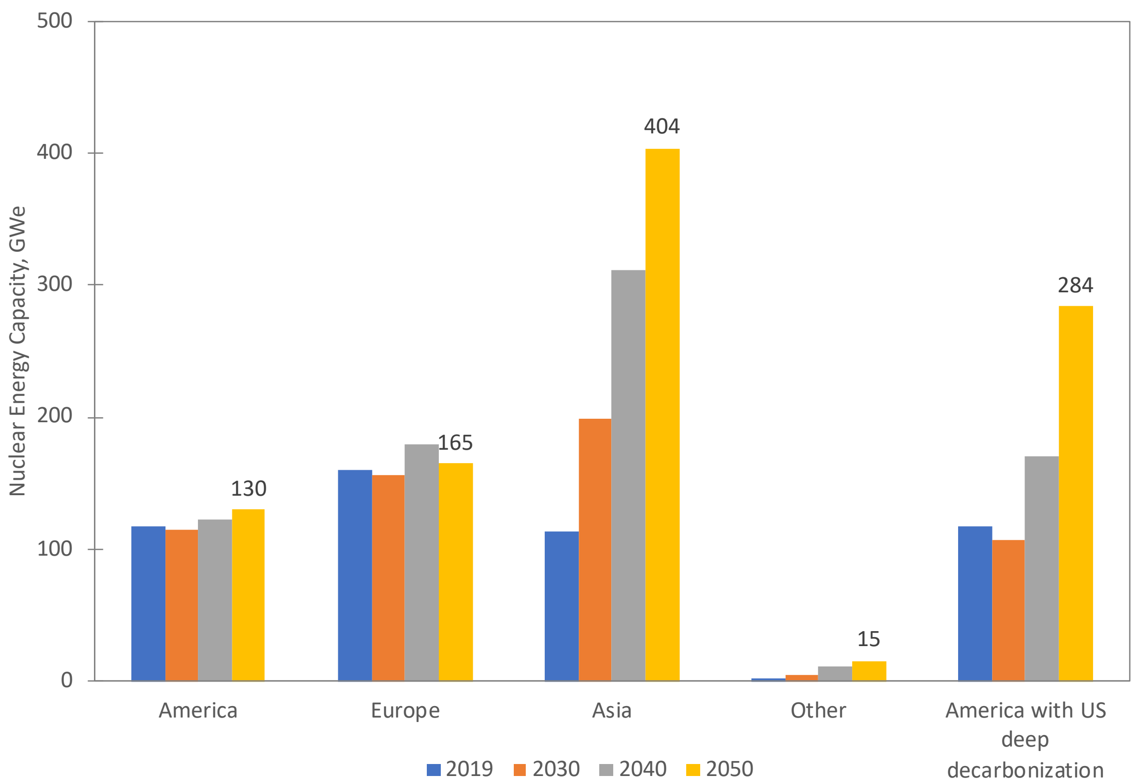

Figure A. 1 IAEA projection of nuclear energy capacity with US decarbonization added
(The last column is the projection in America to reach the net-zero emissions economy goal by 2050)

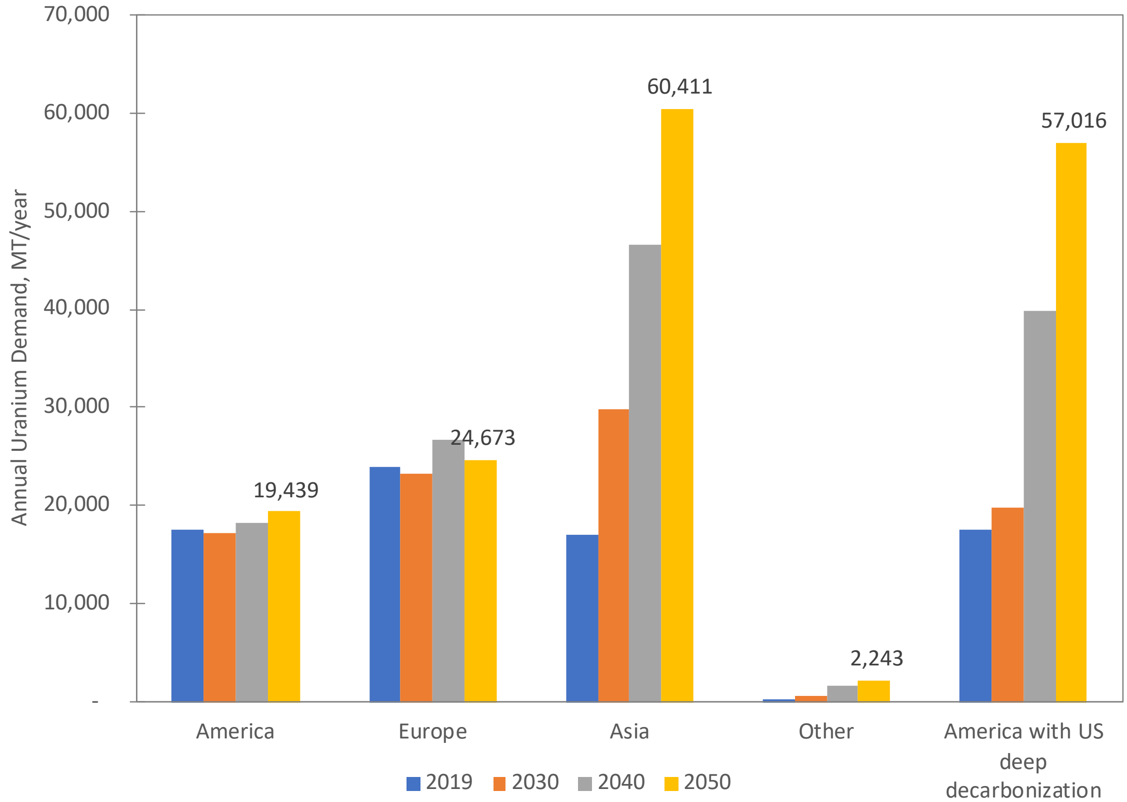

Figure A. 2 Projection of annual uranium demand based on augmented IAEA projection of nuclear energy capacity

(The last column is the projection in America to reach the net-zero emissions economy goal by 2050)

Appendix B. Derivation of DU and SWU Quantities

The natural uranium (NU) demand and enrichment (SWU) demand required to generate a unit of electric energy (MWd-e) can be calculated using the following equation

$$SWU\ (\frac{SWU}{MWe \times D}) = \frac{1}{B}(\frac{MTHM}{MWt \times D}) \times \frac{1}{\eta}(\frac{MWt}{MWe}) \times SWU(\epsilon_f, \epsilon_w, \epsilon_p) \times 1{,}000,$$

$$NU\ (\frac{kg-NU}{MWe \times D}) = \frac{1}{B}(\frac{MTHM}{MWt \times D}) \times \frac{1}{\eta}(\frac{MWt}{MWe}) \times F(\epsilon_f, \epsilon_w, \epsilon_p),$$

where B and η are the discharge burnup and thermal efficiency, and SWU and F are the separative work unit and the NU mass ratio to the enriched uranium (EU) mass in terms of U-235 contents of natural uranium (ϵ_f=0.0071), tail uranium (ϵ_w=0.0025), and enrichment of EU (ϵ_p). The equations indicate that the NU and SWU demands are inversely proportional to the discharge burnup and thermal efficiency, but proportional to the fuel enrichment.

The resulting NU and SWU demands are visualized in Section 2.4 (see Figure 2.7, Figure 2.8, respectively). A higher burnup fuel requires a smaller amount of enriched uranium fuel, but at the same time, the higher burnup fuel requires higher enrichment that increases NU and SWU demands. The NU and SWU demands of the example reactor concepts are also present on the figures. In the figures, the NU or SWU demand is the same when the color is the same, and the demands decrease from red to green.

The figures show that Xe-100 requires less NU or SWU demands compared to other reactor concepts due to the higher discharge burnup. On the other hand, Natrium requires slightly higher NU and SWU demands compared to the ALWR because the fuel enrichment is high. The figures inform how to reduce the NU or SWU demands – increase discharge burnup and/or thermal efficiency (move up) or decrease charge enrichment (move left). The widths of the bands also show the sensitivity of the resource utilization coefficient, which might help guide R&D directions (i.e., whether to focus on increasing burnup or decreasing enrichment, if we must optimize for one parameter).

Appendix C. Sensitivity and Uncertainty Analysis of ES #1

C.1 Introduction

A set of uncertainty quantification and sensitivity studies have been conducted to explore the impact of reactor design and fuel cycle parameters with a range of uncertainty used in the fuel cycle simulation, such as projected power demand, the fraction of reactors deployed to meet power demand, and the year of ARDP deployment. For the uncertainty quantification and sensitivity studies, the once-through fuel cycle scenario with ARDP reactors (ES #1) was selected in this work.

The computational flowchart is shown in Figure C. 1. The agent-based fuel cycle simulator Cyclus [Huff et al. 2016] is used for this analysis. The Cyclus input file, containing the deployment scenario, reactor specifications, and fuel compositions, is automatically generated by combining the data and user input using Python scripts. Data that the Cyclus input generation module uses are: (1) the legacy reactor deployment and decommission times from the legacy reactor database from IAEA PRIS, (2) the reactor specific data (Table 2.1), and (3) the GCAM capacity demand for calculating the deployment scenario (see Section 2.2). Along with this data, the user adds reactor deployment fraction, ARDP deployment start year, and nuclear demand perturbation. By default, 25% of each reactor type is deployed to meet capacity demand, ARDPs are started in year 2028, and there is no nuclear demand perturbation. These user parameters are explained in more detail later in this section. The data and user inputs are read by the Cyclus input generation module. The generated input is run, and the output is postprocessed to obtain metrics such as HALEU demand each year, SWU demand each year, and natural uranium demand each year.

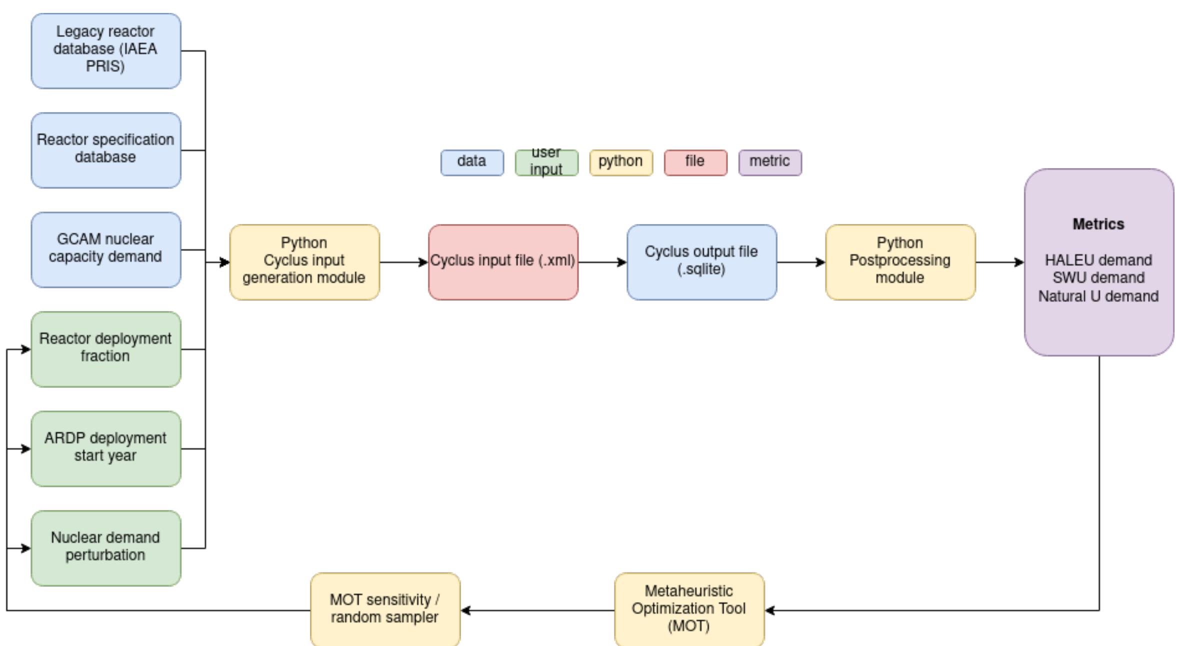

Figure C. 1 Computational flowchart for sensitivity and uncertainty qualification analysis

Since the entire process can be automated using Python scripts, we can use the Metaheuristic Optimization Tool (MOT) to automate the sampling of different user inputs to observe their impact on the output metrics. For example, MOT can generate, run, and postprocess hundreds of cases that are sampled from a range of uniformed-distributed reactor deployment fractions to statistically observe the range of metrics with perturbations in reactor deployment fraction.

C.2 Base Scenario

Four reactor types are involved in the ES #1 fuel cycle scenario from the current legacy LWRs: advanced light water reactors (AP1000), LWR-based small modular reactors (NuScale), and two ARDP reactors (Natrium and XE-100). The information on reactor types, design parameters, and fuel cycle scenario are provided in Section 2.

The reactor deployment fraction is specified by the user for each of the four reactor types to meet the nuclear demand. The baseline scenario assumed an even deployment of the four reactor types (e.g., roughly 25% of four reactor types). Before the end of the ARDP demonstration period (default 2028+5 years), additional ARDP reactors are not deployed, and any nuclear capacity deployed is split between the two LWRs (AP1000s and NuScale). The nuclear energy capacity expansion projected by the GCAM model, and the capacity expansion of the baseline scenarios is shown in Figure C. 2. The installed nuclear power capacity increases to 250 GWe to achieve net zero emissions economy by 2050 and continues increasing to 350 GWe in 2100 to support an economic growth rate of 1% per year.

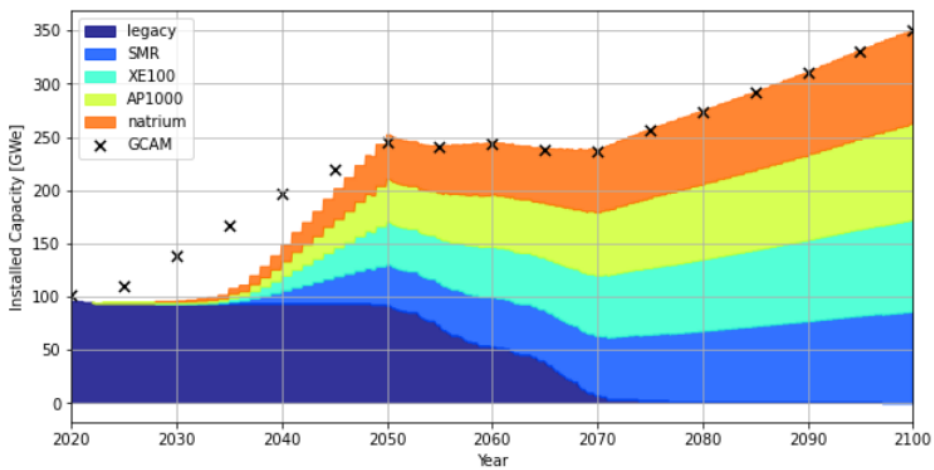

Figure C. 2 Baseline nuclear capacity expansion scenario used for uncertainty and sensitivity study

Three metrics are of focus in this work: HALEU demand, natural uranium demand, and SWU demand. The natural uranium and SWU demand are calculated from the fuel mass and fuel enrichment. The assay of natural uranium and tailing are assumed to be 0.711wt% and 0.25 wt% U-235, respectively.

The base case assumes that the four reactors are deployed equally (in capacity) to meet nuclear capacity demand. Figure C. 3 shows the capacity of each reactor deployed each year (left) and the cumulative reactor installed capacities (right). The bars in the left figure show the deployment of each reactor types at a given year, and the right figure shows the cumulative sum of those deployed capacity. The two AP1000s deployed near the start of the scenario are the Vogtle plants. Since reactors are deployed in integer values and have different unit capacities, there is a slight difference in the capacity deployed. The other front-end fuel cycle parameters such as NU demand, SWU, and charge fuel demands have been calculated. The resulting front-end fuel cycle parameters to 2100 are similar to the results shown in Section 3.1 with some variations due to the different assumptions and nuclear fuel cycle simulator codes (DYMOND vs. Cyclus). DYMOND can only model five unique reactor designs, so the SMR and ALWR are modeled as the same reactor, but linearly scaled. Cyclus does not have this limitation, so SMRs are modeled as the specifications listed in the reactor design application.

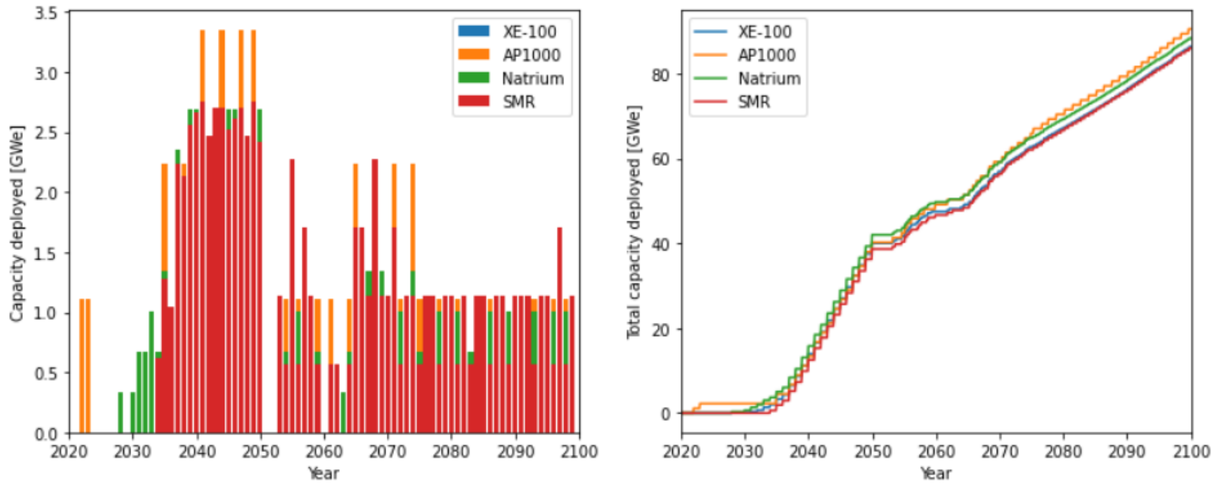

Figure C. 3 Reactor capacity expansion of baseline scenario

C.3 Sensitivity Study on Perturbation of Nuclear Capacity Demand

The nuclear power demand directly impacts the number of nuclear reactors deployed in a nuclear fuel cycle simulation. From the baseline scenario, the post-2050 values were perturbed to calculate the impact of increasing or decreasing the nuclear demand. The demand values prior to 2050 were not perturbed. Figure C. 4 shows the nuclear capacity demand curve with the perturbations.

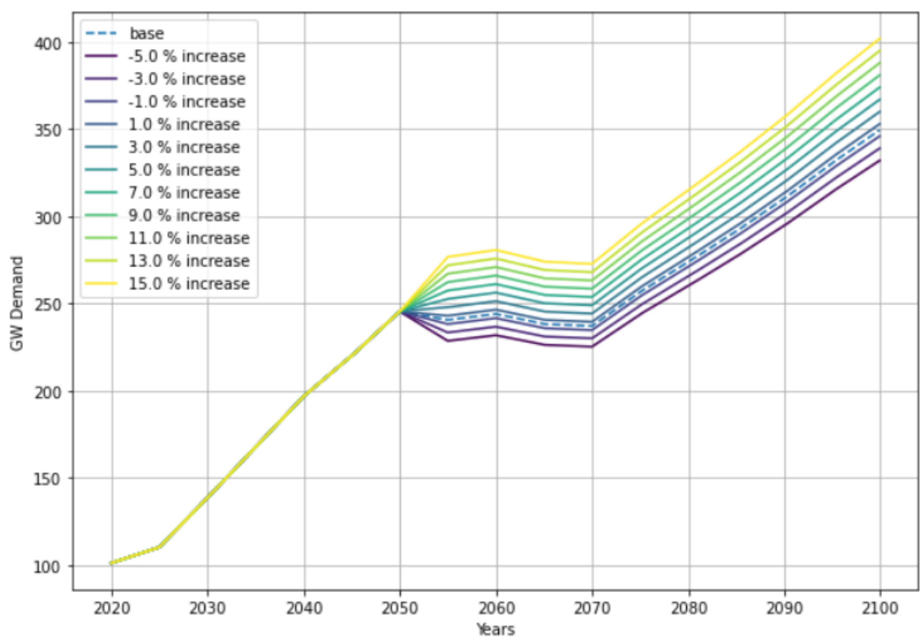

Figure C. 4 Perturbation of nuclear capacity demand from 2050

The assumed nuclear capacity demand was perturbed from –5% to +15% after 2050 to observe the impact of changes in nuclear capacity to the front-end fuel cycle resource and facility demands. A total of 30 cases were run with linearly-spaced perturbation values from –5 to +15%. Figure C. 5 shows the change in the SWU and annual NU demand change with capacity perturbation. Table C. 1 shows the statistics of the 30 cases in 2100 for the cumulative front-end fuel cycle demand from the simulations.

The sensitivity analysis indicates that the NU demand and SWU are linearly proportional to the nuclear capacity. The mean NU demand and SWU increased by 6% compared to the base scenarios when the nuclear capacity varies from -5 to +15%.

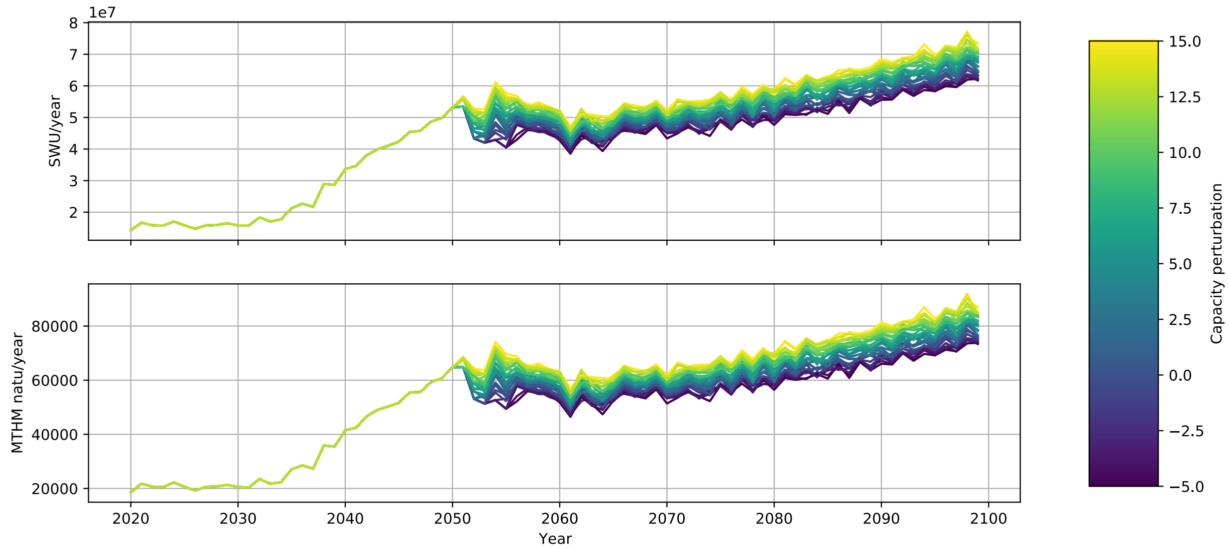

Figure C. 5 Variation of NU and SWU demand per change of nuclear capacity demand

Table C. 1 NU demand and SWU for nuclear capacity variation

	Year	Base scenario	Perturbation scenario	
			Mean	σ
NU demand, MT/year	2100	7.522E+04	7.981E+04	4.151E+03 (5.2%)
Enrichment, SWU/year	2100	6.349E+07	6.729E+07	3.544E+06 (5.2%)

C.4 Sensitivity Study on Perturbation of First ARDP Deployment Year

In the base scenario, the ARDP reactors (Xe-100 and Natrium) are assumed to be deployed in 2028 to begin their five years of the demonstration phase following which they transition into the commercialization phase. Potential delays of ARDP reactor deployment can impact various fuel cycle parameters. Figure C. 6 shows the impact of a 9-year delay in ARDP demonstration, where the LWRs (AP1000 and SMRs) are deployed to meet the nuclear capacity demand during the 2030s. The nuclear capacity fraction in 2050 therefore differs significantly between the two scenarios, where the installed capacity of ARDPs is almost halved.

The ARDP start year is sampled uniformly from 2027 to 2040 to observe the impact of delayed ARDP deployment to the front-end fuel cycle demands. A total of 14 cases are run to represent ARDP deployment years from 2027 and 2040. Figure C. 7 shows the change in the SWU and NU annual demand depending on the first ARDP deployment year, and

Table C. 2 shows the results in 2100. The resulting NU demand and SWU of the perturbed years of the first ARDP reactor deployment are comparable to the base scenario: i.e., a significant difference in the front-end fuel cycle demand is not seen for the perturbation of the first ARDP deployment year because ALWRs (AP1000) and SMRs are additionally deployed to compensate for the delay of ARDP reactor deployment.

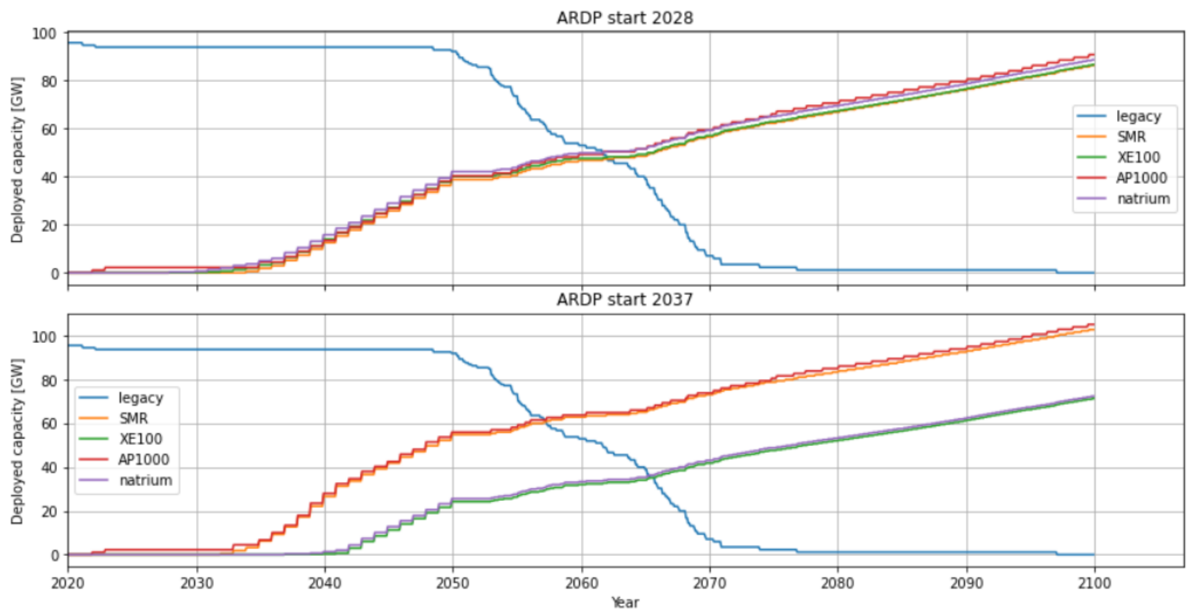

Figure C. 6 Perturbation of ARDP rector deployment year

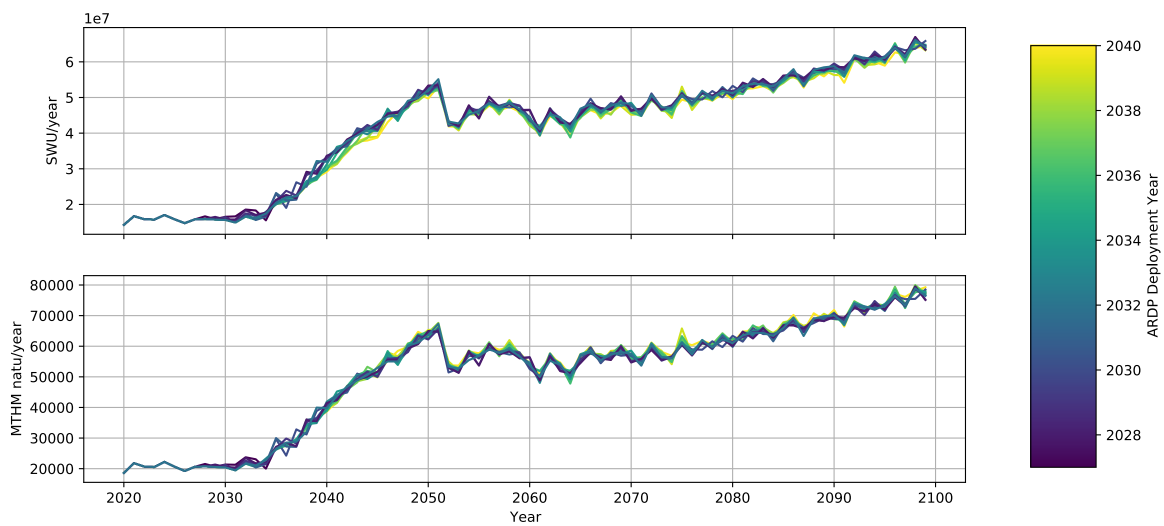

Figure C. 7 Variation of NU and SWU demands per first ARDP deployment year

Table C. 2 NU demand and SWU for perturbation of first ARDP deployment year

	Year	Base scenario	Perturbation scenario	
			Mean	σ
NU demand, MT/year	2050	6.475E+04	6.384E+04	9.644E+02 (1.5%)
	2100	7.522E+04	7.710E+04	1.113E+03 (1.4%)
Enrichment, SWU/year	2050	5.314E+07	5.170E+07	9.312E+05 (1.8%)
Enrichment, SWU/year	2100	6.349E+07	6.417E+07	6.888E+05 (1.0%)

C.5 Uncertainty Quantification on ARDP Burnup

In the base scenario, the ARDP reactors' specifications are fixed at the values given in Section 2. Currently, there are numerous publications and announcements on the expected discharge burnup of the ARDP reactors, and the value is different based on the evaluators and applied methods. In order to account for the uncertainty of the technological achievements of the ARDP reactors' burnup, a random Monte Carlo sampling technique was applied to identify the initial and future burnup values for the ARDP reactors. A Monte Carlo simulation is a model used to predict the probability of different outcomes by sampling for various input parameters from a probability distribution function.

For the Monte Carlo simulation, the burnup distributions of both ARDP reactors are needed, but those are not available because the ARDP reactor has not been deployed. In this work, the burnup values for the ARDP reactors are assumed to be a discrete distribution of four discrete values with probabilities attributed to each burnup value as shown in Figure C. 8. The distribution covers the base burnup value and discrete values higher and lower than the base value, but the distributions are randomly selected for this study.

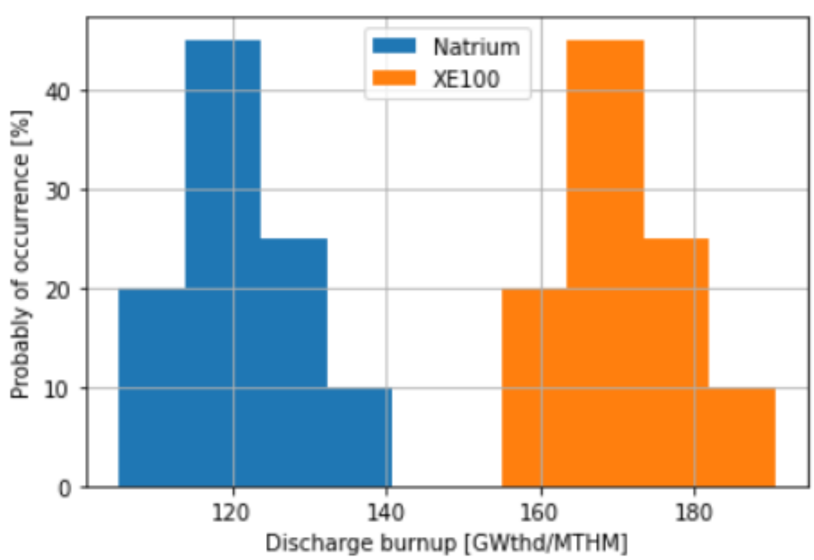

Figure C. 8 ARDP reactor burnup distribution used for random sampling

The ARDP reactor developers have announced the evolution to a higher burnup fuel cycle. Initially, the reactor starts operation with relatively lower burnup fuel due to the qualification issues of high burnup fuel, but as the reactor continues to operate, it is assumed that there will be a gradual change in loading fuel with higher and higher burnup. In order to capture the high burnup fuel development, this work adopted multiple scenarios of burnup increases as shown in Figure C. 9. The five lines in the figure show five simulations, where the initial burnup value is sampled from the discharge burnup probability distribution function, and then the discharge burnup is either increased or maintained every 10 years. At the end of each simulation all five simulations have unique burnup trajectories over time.

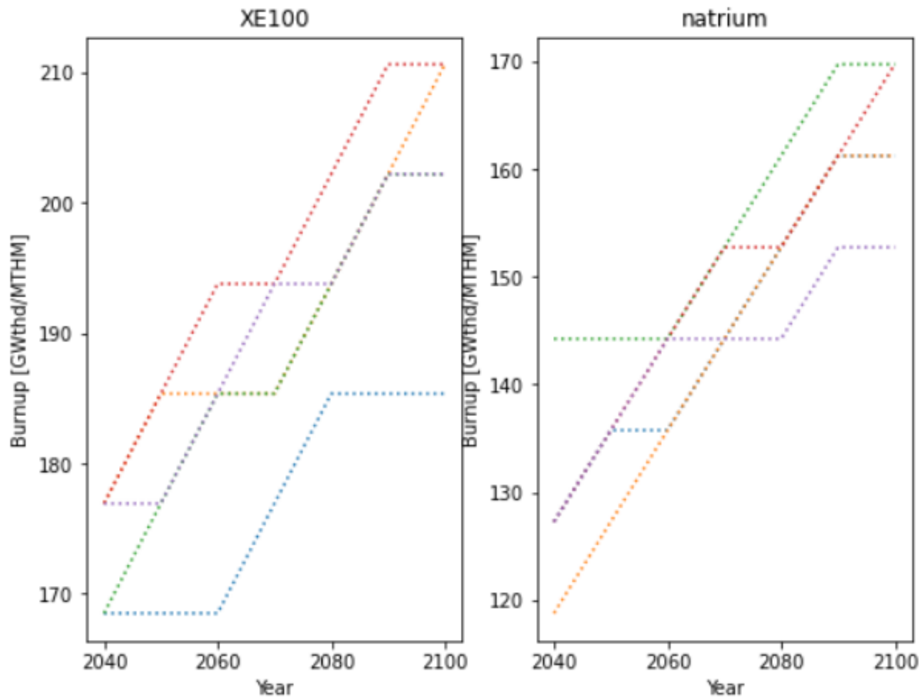

Figure C. 9 Hypothetical increase in discharge burnup

Figure C. 10 shows the NU demand and SWU depending on the evolution of ARDP reactor burnup, and Table C. 3 shows the uncertainties in 2050 and 2100. The NU demand and SWU variations from the ARDP reactor burnup uncertainties is small (less than 2%) because the ARDP reactors only take up 50% of the capacity deployed in the base scenario. Additionally, due to the small increments of increase in burnup, the ARDP reactor burnup uncertainty on the front-end resource demand is not significant.

C.6 Uncertainty Quantification of Reactor Deployment Fraction

The fraction of ALWR (AP1000), SMR, Natrium, and Xe-100s are randomly varied from 0 to 100% in deployed capacity, to observe the impact it has on the front-end fuel cycle demands. One thousand random samples are generated for this uncertainty quantification. Figure C. 11 shows an example deployment fraction for 32% Xe-100, 48% Natrium, 6% SMRs, and 14% AP1000.

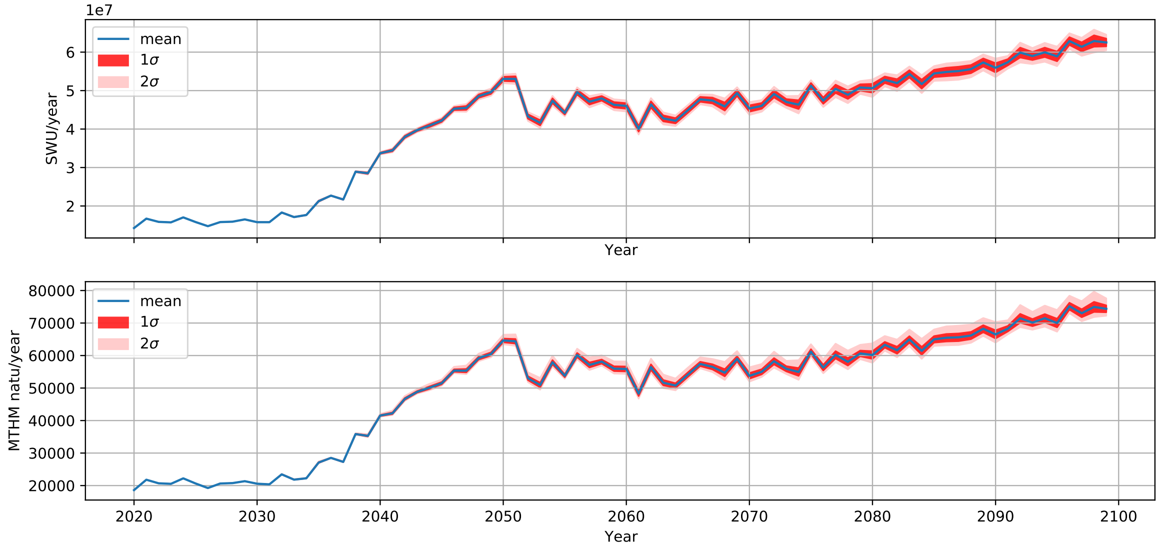

Figure C. 10 NU demand and SWU for ARDP burnup variation

Table C. 3 NU demand and SWU uncertainties for ARDP burnup

	Year	Base scenario	Uncertainty Analysis	
			Mean	σ
NU demand, MT/year	2050	6.475E+04	6.464E+04	5.958E+02 (0.9%)
	2100	7.522E+04	7.436E+04	1.076E+03 (1.4%)
Enrichment, SWU/year	2050	5.314E+07	5.303+07	5.663E+05 (1.0%)
	2100	6.349E+07	6.250E+07	1.022E+06 (1.6%)

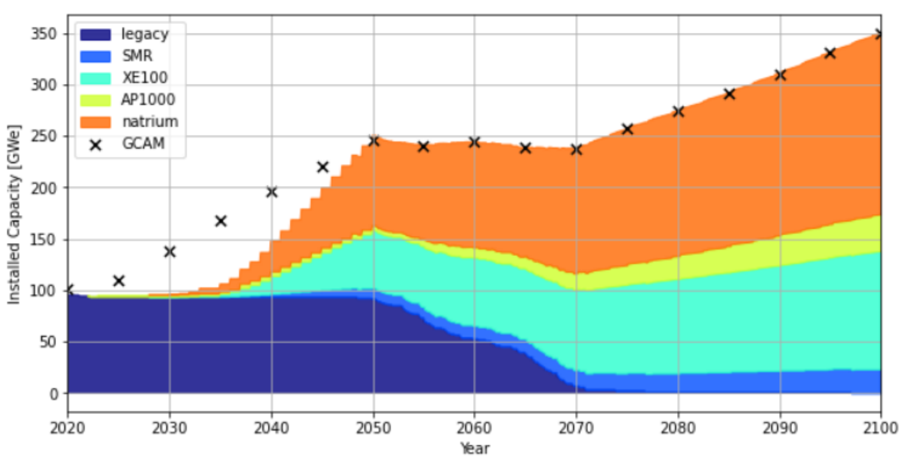

Figure C. 11 Perturbation of reactor deployment fraction

Figure C. 12 shows the NU demand and SWU depending on the variation of reactor fractions, and Table C. 4 shows the uncertainties in 2050 and 2100. Figure C. 13 shows the distribution of cumulative natural uranium and SWU demand with reactor fraction. In Figure C. 13, the columns denote each reactor type fractions deployed for each simulation, and rows denote the total front-end fuel cycle demand metric (sum across all reactor types). This pair-plot shows the trend and impact of each reactor type. Reactors requiring more NU and SWU per unit electricity generation (SMR and Natrium, see Figure 2.7 and Figure 2.8) show an upward trend where an increase in reactor fraction increases the resource demand. On the other hand, reactors requiring less NU and SWU per unit electricity generation (AP1000 and Xe-100) show a downward trend because as the reactor fraction increases the total resource demand decreases. As any one reactor fraction increases, the NU demand and SWU (y values) are narrower because the resource demand is dominated by one reactor type, and the impact of other reactor fractions lessen. For example, given an AP1000 fraction of 0.5, the remaining 0.5 can be filled with Xe-100s, which will lead to lower resource demand, or Natrium reactors, which will lead to higher resource demand. Overall, the front-end resource demands (NU and SWU) are significantly varied due to the uncertainty of the reactor deployment fractions (8-11%).

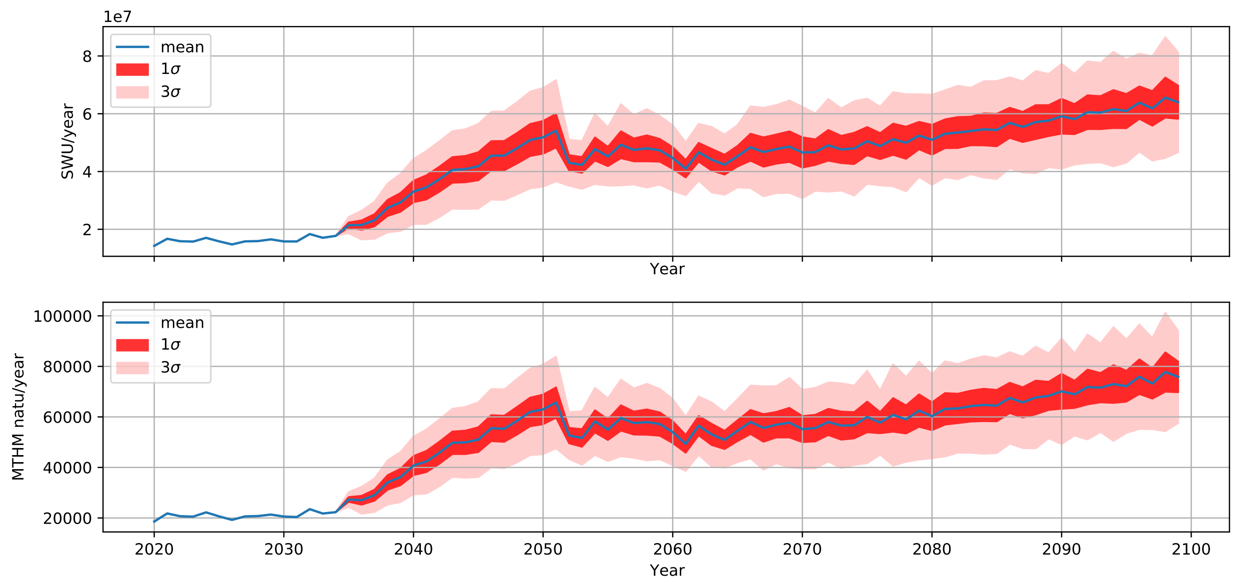

Figure C. 12 NU demand and SWU for reactor deployment fractions

Table C. 4 NU demand and SWU uncertainties for reactor deployment fractions

	Year	Base scenario	Uncertainty Analysis	
			Mean	σ
NU demand, MT/year	2050	6.475E+04	6.297E+04	5.925E+03 (9.4%)
	2100	7.522E+04	7.582E+04	6.099E+03 (8.0%)
Enrichment, SWU/year	2050	5.314E+07	5.184E+07	5.715E+06 (11.0%)
	2100	6.349E+07	6.397E+07	5.775E+06 (9.0%)

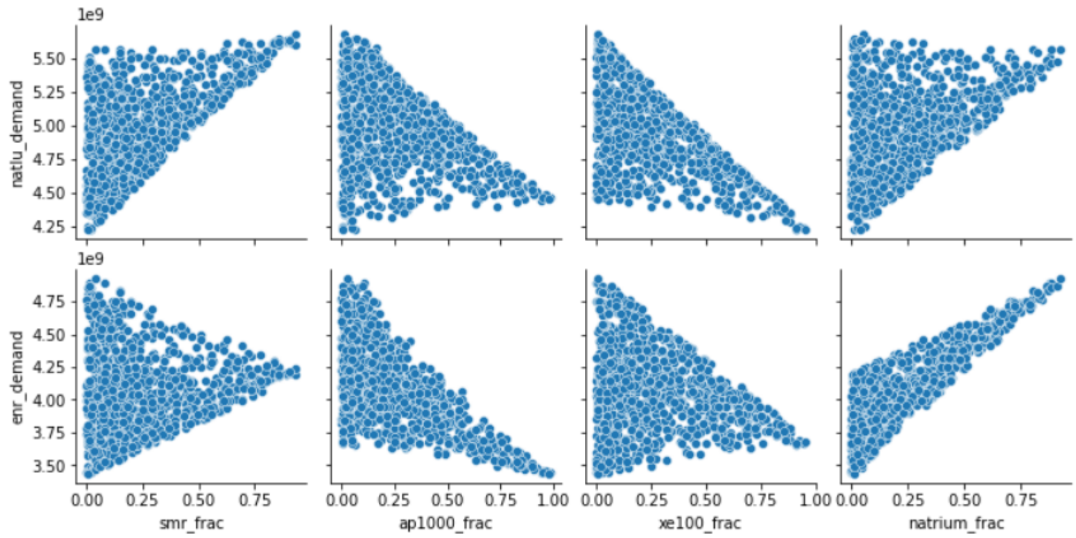

Figure C. 13 Distribution of cumulative NU demand and SWU with reactor fraction

C.7 Conclusions

The biggest challenge in estimating the future demand for natural uranium and enrichment capacities is the uncertainty in the future nuclear fleet. We modeled a base case scenario of the future U.S. nuclear fleet that assumes a dramatic increase in nuclear capacity with a mixed portfolio of advanced LWRs (AP1000, NuScale SMR) and ARDP reactors (Natrium, Xe-100). In the base case, the enrichment and natural uranium demand increases approximately 240% by 2050.

The uncertainty quantification and sensitivity analysis explore the impact of the uncertainty in future assumptions such as ARDP deployment year, future nuclear reactor fraction, nuclear capacity demand, and ARDP discharge burnup values. Sensitivity analyses show that the front-end fuel cycle demand is most sensitive to nuclear capacity demand (up to 12% difference in projections), and not sensitive to ARDP deployment year (less than 2% difference in projection).

This set of studies informs stakeholders that the focus should be set on reducing the uncertainties in parameters such as reactor types being deployed, enrichment and burnup to reduce the uncertainty in projected resource demand.

Appendix D. Waste Volume Conversion Factors

The spent nuclear fuel (SNF) and high-level waste (HLW) generated from advanced reactors or The spent nuclear fuel (SNF) and high-level waste (HLW) generated from advanced reactors or reprocessing facilities are considered as radioactive waste that requires geologic disposal. In this work, SNF refers to the discharged fuel assembly to be disposed of directly without further treatment, while HLW refers to the non-recovered actinides and byproducts from the reprocessing of used fuel.

The SNF or HLW mass-to-volume conversion factors were calculated using the methods used by the U. S. Nuclear Waste Technical Review Board (NWTRB) in the development of recommendations for how to pursue the nation's nuclear waste management program [NWTRB 2021]. NWTRB calculated the waste volume as the total volume of Dual-Purpose Canisters (DPCs) needed to accommodate SNF assemblies. There are multiple concepts of canisters, including the Purpose-built canister (PBC) and DPC. PBC was specifically designed for a particular repository concept, while DPC was designed to meet the waste transportation and storage requirements of 10 CFR Part 71 and 72. The majority of SNF in existing dry storage is in DPCs and nearly all new dry storage transportation has been conducted using DPCs.

Table D. 1 shows the design parameters of DPC used to evaluate options for permanent geologic disposal of SNF and HLW [NWTRB 2021, UFD 2014]. The DPC can accommodate 32 legacy PWR assemblies, which is equivalent to the volume of 6.24 m^3 (=32 x volume of 17x17 Westinghouse assembly (0.195 m^3)). Assuming that discharge fuel is stored in on-site reactor pools for five years before loading to the canister, a single DPC can hold the thermal energy of 41.6 kW (32 x decay heat of a single PWR assembly after 5-year cooling of 1.3 kW).

Table D. 1 Design parameters of DPC

Parameter	Value
Diameter, m	2.0
Hight, m	5.13
Volume, m^3/DPC	16.1
Number of PWR assemblies, #/DPC	32
Thermal energy, kW/DPC	41.6 [a)]
Space for SNF in DPC, m^3	6.24 [b)]

a) Decay heat of 32 PWR SNF assemblies with 50 GWd/t burnup after 5 years post-irradiation cooling.
b) Volume of 32 PWR assemblies.

The number of SNF assemblies accommodated in a single DPC is mainly limited by factors such as maximum temperature (or decay heat), available internal space to accommodate fuel assemblies (pebbles), re-criticality, and radioactivity at the surface of DPC. In this work, the number of SNF assemblies accommodated in a single DPC was determined by how many SNF assemblies (or pebbles) are loaded into a single DPC until either total SFR assembly (or pebble) volume or decay heat is equal to the volume of 32 PWR assemblies or their decay heat. The decay heat and radioactivity at the surface have been calculated, but those are the secondary factors.

The resulting SNF assemblies or number of pebbles per DPC and the disposal DPC volume after generation of unit electricity are provided in Table D. 2. The design parameters of SFR and HTGR were obtained from the analysis of example reactor concepts. A single DPC can accommodate 32 PWR assemblies, 58 SFR assemblies and 40,903 pebbles, which can hold spent nuclear fuel of 14.1 MT, 6.1 MT, and 0.3 MT of PWR, SFR, and HTGR spent nuclear fuels, respectively. The resulting mass-to-volume conversion factors are 1.14, 2.67, and 56.39 for the PWR, SFR and HTGR.

Table D. 2 SNF mass to volume conversion

	LWR or ALWR	SFR with sodium free fuel	HTGR with pebble a)
Fuel (HM+FP) mass, t/assembly or t/pebble	0.442	0.106	7.0E-6
Assembly or pebble volume, m^3	0.195	0.108	1.53E-4
Decay heat at 5 years, kW/assembly	1.30	0.41	N/A
SNF assemblies or pebbles per DPC, #/DPC	32	57	40,828
SNF mass per DPC, t/DPC	14.1	6.0	0.3
DPC volume, m^3/DPC	16.1		
SNF mass to volume conversion factor, m^3/t-SNF	1.14	2.67	56.39

a) Values for pebbles.

It is noted that DOE decided to treat sodium-bonded metallic fuel prior to disposal [DOE 2000]. Considering DOE's decision and the similarity of the fuel forms, the waste volume conversion factor of HLW was calculated by assuming that the recovery of metallic fuel is achieved using the electrochemical technology.

A commercial canister for the HLW recovered from the electrochemical process has not been developed. Thus, the HLW production rate and canister information were obtained from the government EBR-II and FFTF metallic fuel treatment [UFD 2014]. Table D. 3 shows the HLW waste generation from the EBR-II and FFTF metallic fuel treatment. Two types of HLW are created in the electrochemical process: salt (ceramic waste form) and metal (metallic waste form) waste. For treatment of a unit metric ton of used nuclear fuel, about 1.98 metric ton of salt waste and 0.23 metric ton of metal waste are generated. Table D. 4 shows the design parameters of the HLW canister. The salt and metal wastes are stored in a cylinder and disk forms. Then, both cylinder and metal disk are loaded to the HLW canister. Using the data in both tables, the UNF mass to disposal volume conversion factor can be calculated.

The disposal waste volumes per unit electricity generation are compared in Table D. 5. The HTGR generates the smallest SNF mass because of its highest burnup. However, due to the large mass-to-volume conversion factor, The HTGR generates the largest SNF volume. Compared to the PWRs, HTGRs generate a factor of ~12 times more SNF volume. For the SFRs with a sodium-free metallic fuel, the SNF volume is about 80% of PWRs. For the recycle fast reactor, disposal waste volume is about half of PWRs.

Table D. 3 Design parameters of HLW canister

Parameter		
EBR-II used fuel inventory, t-UNF	25.8	
	Salt waste form	Metal waste form
Total HLW generation, t	50.96	5.85
Normalized HLW generation, t-HLW/t-UNF	1.98	0.23

Table D. 4 Design parameters of HLW canister

Parameter		Salt waste form	Metal waste form
Sub-components	Form	Cylinder	Disk
	Diameter, m	0.5	0.381
	Length or thickness, m	1.0	0.127
	Mass, t-HLW/cylinder or disk	0.4	0.012
Canister	Diameter (internal/outer), m	0.58 / 0.61	
	Length (internal/outer), m	2.50 / 3.00	
	Volume (internal/outer), m^3	0.67 / 0.88	
	Capacity, - No. cylinder or disk /canister - ton-HLW/canister	 2 0.8	 8 0.10
	Volume-to-HLW mass, m^3/t-HLW	0.98	
UNF mass to volume conversion, m^3/t-UNF		2.15	

Table D. 5 Comparison of disposal waste volume per unit electricity generation

	Once-through			Recycle
	LWR or ALWR	SFR with sodium free fuel	HTGR	Fast reactor
Burnup, GWd/t	50.0	129.8	168.5	150.0
Thermal efficiency, %	33.3	40.0	42.3	40.0
SNF mass, t/GWe-year	21.9	7.0	5.1	-
HLW mass, t/GWe-year	-	-	-	13.4
Disposal volume, m^3/GWe-year	25.0	18.8	288.8	13.1
Relative value to PWR	1.0	0.8	11.6	0.5