Sensitivity analysis of fuel cycle transitions using Cyclus-Dakota

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ILLINOIS

Outline

The US wants to develop a supply chain of HALEU

- Multiple new reactor designs require High Assay Low Enriched Uranium (HALEU) fuel, which allows for:
  - Longer cycle lengths
  - Higher burnups

Table 1: Categories of uranium enrichment by weight fraction of uranium-235.

Category	Weight fraction (%)
Depleted	$<$0.711
Natural	0.711
LEU	$<$20
HALEU	$>$5, $<$20
HEU	$\geq$20

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- Multiple new reactor designs require HALEU fuel, which allows for:
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    - Higher burnups
- The US does not have a domestic commercial supply of HALEU
- Efforts have been made to quantify potential HALEU needs for the transition from LWRs to advanced reactors [3, 5]

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- Sensitivity analysis has previously been applied to fuel cycle transition analysis [4, 6, 12] to investigate the effect of the transition start time, fuel burnup, and the fleet share of advanced reactors

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- Sensitivity analysis investigates how model parameters affect the results of a simulation
- Sensitivity analysis has previously been applied to fuel cycle transition analysis [4, 6, 12] to investigate the effect of the transition start time, fuel burnup, and the fleet share of advanced reactors
- This work applies sensitivity analysis to a transition from LWRs to advanced reactors, with an emphasis on HALEU requirements
  - Understand how model parameters affect HALEU and other resource demand
  - Quantify the effect of each parameter on resource demand
  - There is no publicly available literature that applies sensitivity analysis to the transition to HALEU-fueled reactors

Outline

Transition assumptions

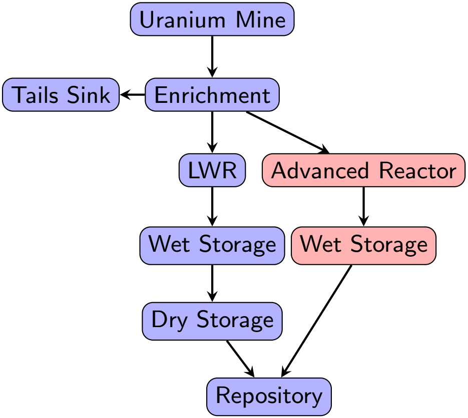
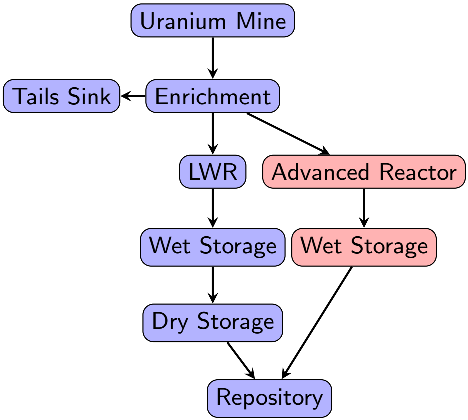


Figure 1: Fuel cycle facilities and material flow between facilities. Facilities in red are deployed after 2025 for the transition.

Model transitions using CYCLUS [7]

- Model reactor deployment from 1965-2090
- Transitions begin in 2025

Transition assumptions



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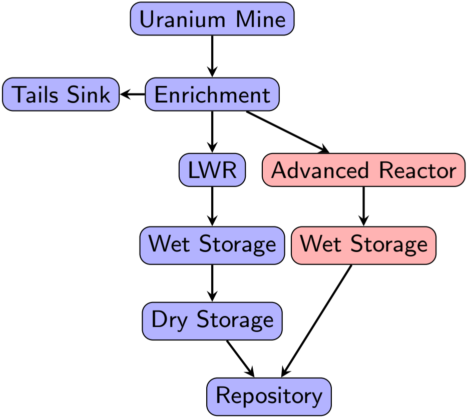

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- LWRs are assumed to operate until their current licenses expire
- Energy demand is constant 87.20 GWe-yr

Advanced Reactors

Table 2: Advanced reactor design specifications

Design Criteria	USNC MMR [2]	X-energy Xe-100 [8]	NuScale VOYGR [9, 10, 11]
Power (MWe)	5	80	77
Power (MWth)	15	200	250
Capacity Factor	100%	95%	95%
Enrichment (% ^{235}U)	19.75	15.5	4.09
Core residence time (yr)	20	3	4.5
Reactor Lifetime (yr)	20	60	60
Burnup ($\frac{MWd}{kgU}$)	82	168	45

$$\text{mass (kg)} = \frac{\text{Power (MWth)*cycle length (d)*number of cycles}}{\text{Burnup (MWd/kg)}} \quad (1)$$

Model inputs and outputs of interest

Model inputs (parameters)

- Transition start time, January 2025-January 2040
- LWR lifetime: percent of LWR fleet operating for 80 years, 0-50%
- Build share of each advanced reactor, 0-50%

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Model outputs (metrics, material requirements)

- Total fuel mass
- HALEU mass
- Total SWU
- SWU to produce HALEU
- Feed to produce HALEU
- SNF mass

Advanced reactor deployment scheme

Manually calculate the deployment scheme for advanced reactors

- Preferentially deploy reactors with larger power output first
- Deploy reactor with largest power output until an oversupply of power would be produced, deploy the next reactor until an oversupply of power, then deploy the last reactor until demand is met
- Deployment schedule is given to CYCLUS

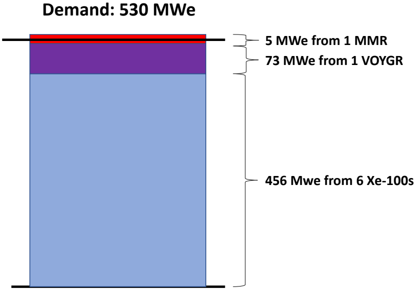

Figure 2: Example of how advanced reactors are deployed to meet a demand of 530 MWe.

Adjust deployment when varying the build share

- Deploy the specified reactor first to meet the build share
- Deploy the other reactors using the previous scheme (largest to smallest power output) to meet the remaining demand
- Deployment schedule is given to CYCLUS

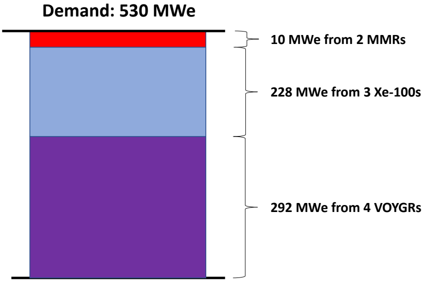

Figure 3: Deployment of advanced reactors to meet a demand of 530 MWe and a 50% VOYGR build share.

Outline

Varying input: Transition start time

- All of the metrics generally decrease with later transition starts
- Some metrics increase between start times because of changes in the number of each advanced reactor deployed
- All metrics reach a minimum with a January 2040 deployment time, but causes a gap of 36.7 GWe-yr between energy production and demand

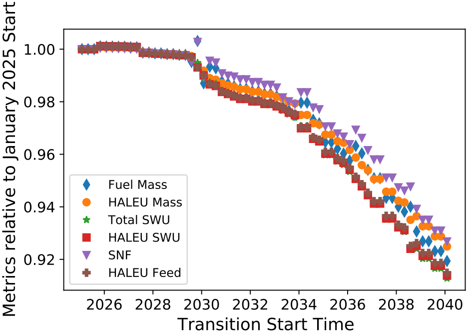

Figure 4: Relative change in metrics as a function of transition start time.

Varying input: LWR lifetime

- All of the metrics decrease by similar fractions
- Energy demand is fully met for all scenarios

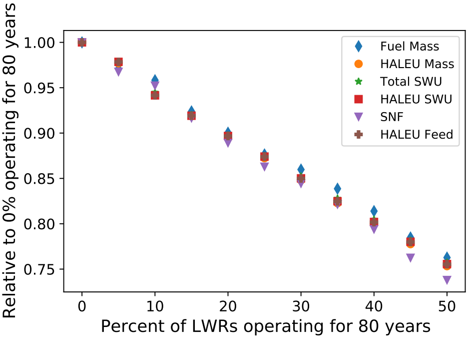

Figure 5: Relative change in metrics as a function of the percent of LWR fleet operating to 80 years.

Varying input: Xe-100 build share

- The HALEU-related metrics increase with increasing build share
- Total SNF and total fuel mass decrease with increasing build share
- Total SWU capacity is relatively constant, at most a relative change of 1.06

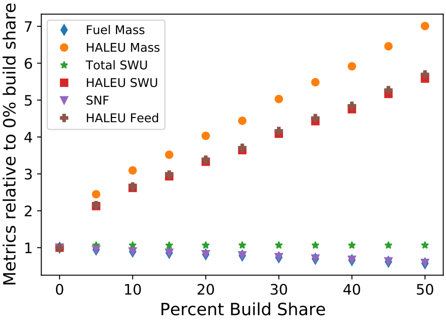

Figure 6: Relative change in metrics as a function of Xe-100 build share.

Varying input: MMR build share

- All of the metrics increase as build share increases
- HALEU mass has the smallest increase in relative change
- Total SWU capacity has the largest relative increase
- These results are primarily because of the deployment scheme

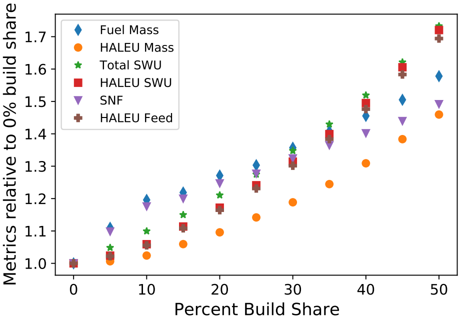

Figure 7: Relative change in metrics as a function MMR build share.

Varying MMR build share – Number of reactors deployed

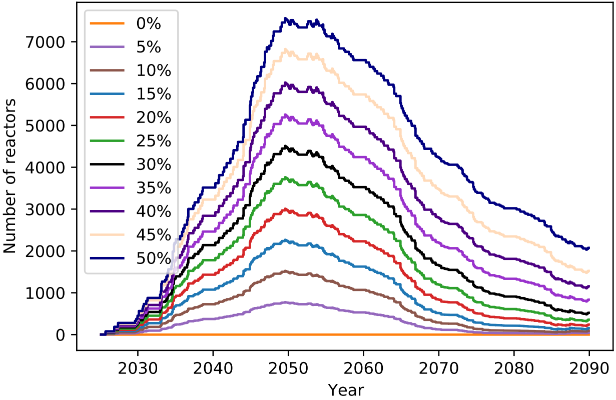

Figure 8: Number of MMRs deployed as a function of time when the MMR build share is varied.

Varying input: VOYGR build share

- Fuel mass and SNF mass increase while HALEU metrics decrease
- Total SWU capacity is relatively constant
- Opposite trends as increasing Xe-100 build share
- As the build share increases, the number of Xe-100s decreases and the number of MMRs is fairly constant

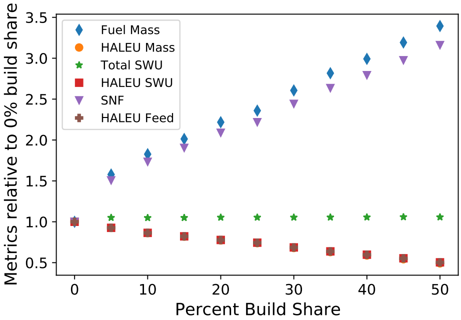

Figure 9: Relative change in metrics as a function of VOYGR build share.

Outline

Conclusions

- Delaying the transition or extending more LWR licenses generally decreases all material requirements for advanced reactors
- Increasing the Xe-100 build share increases HALEU-related metrics because of higher enrichment, but decreases total fuel and SNF mass because of high burnup
- Increasing VOYGR build share decreases the HALEU-related metrics because of LEU, but increases total fuel and SNF mass due to lower burnup. The HALEU SWU requirement decreases, but the total SWU capacity is constant
- Increasing MMR build share increases all front-end and back-end metrics, partly because MMRs have a shorter lifetime and are mostly replaced with VOYGRs because of the deployment scheme
- All of these scenarios will require a cumulative HALEU mass between 2,710 - 37,500 MT between 2025-2090

Future Work

- Edit the deployment scheme to have a 1:1 replacement of advanced reactors as they retire
- Expand to global sensitivity analysis, consider the interaction of model inputs
- Use sensitivity analysis to develop optimized transition scenarios, minimizing certain material requirements

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References I

[1] Power Reactor Information System (PRIS): Reference and On-line Access Manual.
Technical report, INTERNATIONAL ATOMIC ENERGY AGENCY, Vienna, 1989.

[2] USNC Micro Modular Reacotr (MMR Block 1) Technical Information.
https://usnc.com/assets/media-kit/[022989][01]%20MMR%20Technical%20Information%20Document.pdf?v=30823a846f, 2021.

[3] Amanda M. Bachmann, Roberto Fairhurst-Agosta, Zoë Richter, Nathan Ryan, and Madicken Munk.
Enrichment dynamics for advanced reactor HALEU support.
EPJ Nuclear Sciences & Technologies, 7:22, 2021.
Publisher: EDP Sciences.

[4] Gwendolyn J. Chee.
Sensitivity Analysis of Nuclear Fuel Cycle Transitions.
Master's thesis, University of Illinois at Urbana-Champaign, Urbana, IL, 2019.

[5] Brent Dixon, Son Kim, Bo Feng, Taek Kim, Scott Richards, and Jin Bae.
Estimated HALEU Requirements for Advanced Reactors to Support a Net-Zero Emissions Economy by 2050.
Technical Report INL/EXT-21-64913-Rev000, 1838156, January 2022.

References II

[6] B. Feng, S. Richards, J. Bae, E. Davidson, A. Worrall, and R. Hays.
Sensitivity and Uncertainty Quantification of Transition Scenario Simulations.
Technical Report ANL/NSE-20/38, Argonne National Lab. (ANL), Argonne, IL (United States), September 2020.

[7] Kathryn D. Huff, Matthew J. Gidden, Robert W. Carlsen, Robert R. Flanagan, Meghan B. McGarry, Arrielle C. Opotowsky, Erich A. Schneider, Anthony M. Scopatz, and Paul P. H. Wilson.
Fundamental concepts in the Cyclus nuclear fuel cycle simulation framework.
Advances in Engineering Software, 94:46–59, April 2016.
arXiv: 1509.03604.

[8] Eben J. Mulder.
Overview of X-Energy's 200 MWth Xe-100 Reactor, January 2021.

[9] NuScale.
Chapter Four Reactor.
https://www.nrc.gov/reactors/new-reactors/design-cert/nuscale.html, July 2020.
Rev. 5.

References III

[10] Jose Reyes.
NuScale Response to NASEM Questionnaire.
https://www.nationalacademies.org/event/07-14-2020/docs/DDB3F347BF200800E9B24B83380F2347BC20918B48C0, July 2021.

[11] Jose N. Reyes.
Correction of Factual Error in PNAS Paper titled "Nuclear waste from small modular reactors".
https://newsroom.nuscalepower.com/news/, May 2022.

[12] S. Richards and B. Feng.
Application of sensitivity analysis in DYMOND/Dakota to fuel cycle transition scenarios.
EPJ Nuclear Sciences & Technologies, 7:26, 2021.
Publisher: EDP Sciences.

Questions?

Energy share for transition start time

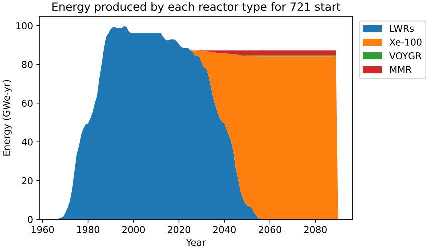

Figure 10: Share of energy produced by each reactor type when the transition starts in January 2025 (time step 721).

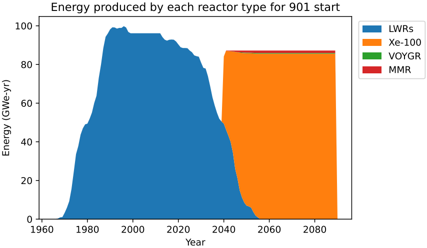

Figure 11: Share of energy produced by each reactor type when the transition starts in January 2040 (time step 901).

Energy share for LWR Lifetime extensions

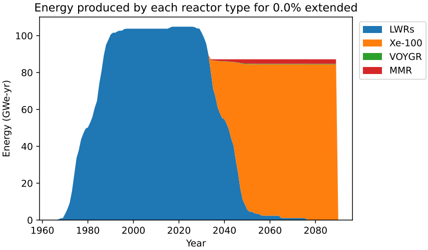

Figure 12: Share of energy produced by each reactor type when 0% of the LWRs operate to 80 years.

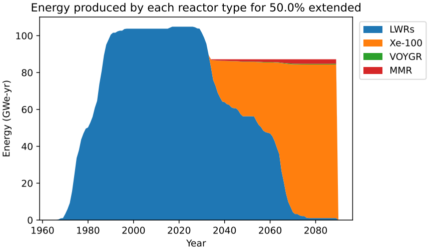

Figure 13: Share of energy produced by each reactor type when 50% of the LWRs operate to 80 years.

Energy share for Xe-100 build share

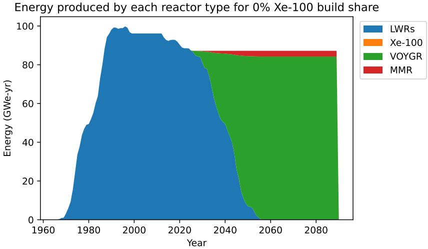

Figure 14: Share of energy produced by each reactor type when the Xe-100 has a build share of 0%.

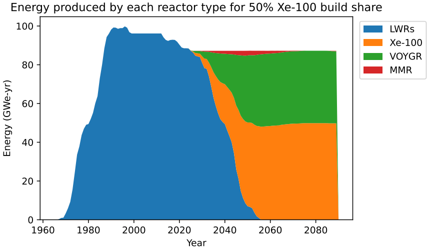

Figure 15: Share of energy produced by each reactor type when the Xe-100 has a build share of 50%

Energy share for MMR build share

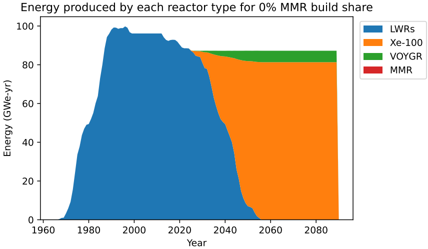

Figure 16: Share of energy produced by each reactor type when the MMR has a build share of 0%.

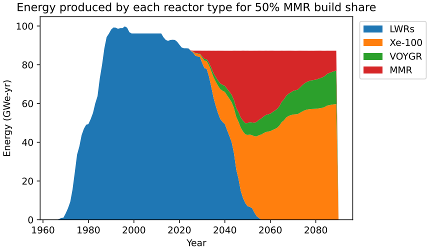

Figure 17: Share of energy produced by each reactor type when the MMR has a build share of 50%.

Energy share for VOYGR build share

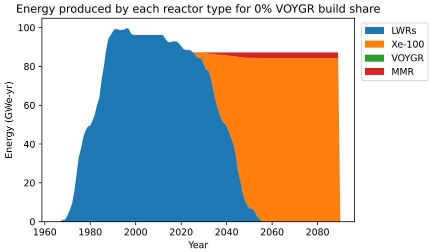

Figure 18: Share of energy produced by each reactor type when the VOYGR has a build share of 0%.

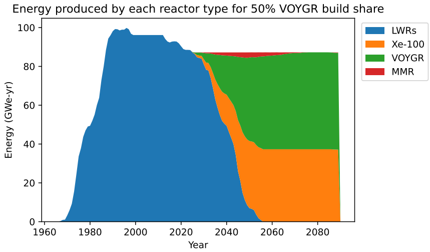

Figure 19: Share of energy produced by each reactor type when the VOYGR has a build share of 50%.