LEU+ to HALEU transitions in advanced reactor fuel cycles

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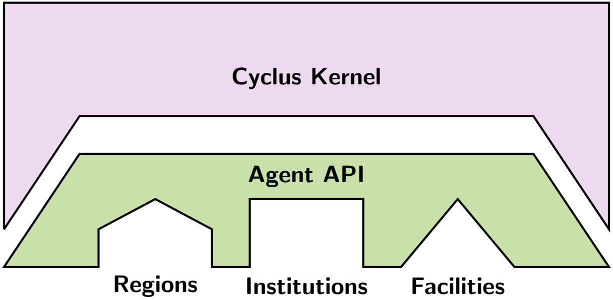
Outline

We use CYCLUS to model fuel cycles.

CYCLUS is an open-source agent-based fuel cycle code allowing for detailed facility and transaction modeling [1].



The CYCLUS ecosystem has many *archetypes*, or generic facility models, (like the CYCAMORE Reactor) that can be used to model different fuel cycle facilities.

What are our options if we cannot get HALEU fuel?

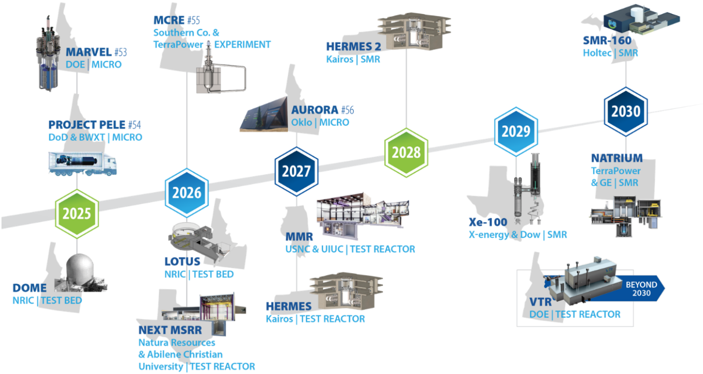


Figure 1: Advanced reactor demonstration and deployment projects [2].

Could we use low-enriched uranium plus (LEU+) while HALEU supply chains develop?

We simulate a 3-reactor-model transition for 2030-2100

Table 1: Advanced reactor design specifications.

Design Criterion	**MMR** [3]	**Xe-100** [4]	**AP1000**
Reactor Type	HTGR	HTGR	PWR
Power Output [MWe]	15	100	1000
Fuel Type	TRISO	TRISO	UO_2
Enrichment [% ^{235}U]	9.95, 19.75	9.95, 15.5	5
Cycle Length	20 [yrs]	Online Refuel	18 [mo]
Final Burnup [GWd/MTU]	82	168	65
Reactor Lifetime [yrs]	20	60	60

Outline

Greedy reactor deployment algorithm

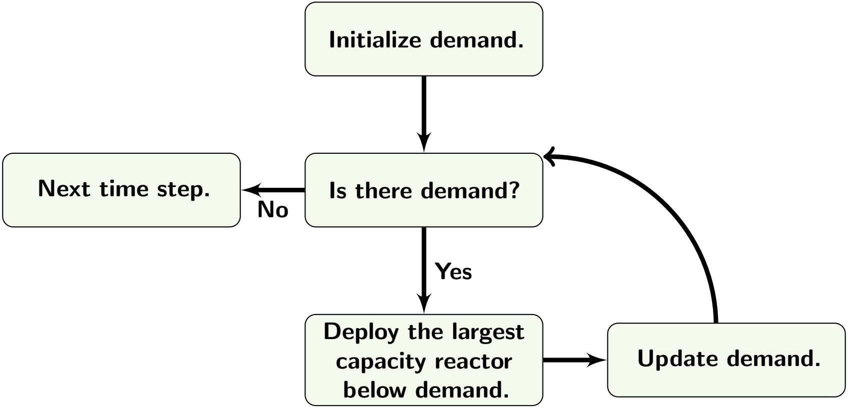


Figure 2: The greedy deployment diagram demonstrates a preference for the larger power capacity reactors, and shows how the scheme could under-deploy if the remaining capacity is less than the size of the smallest reactor.

Random reactor deployment algorithm

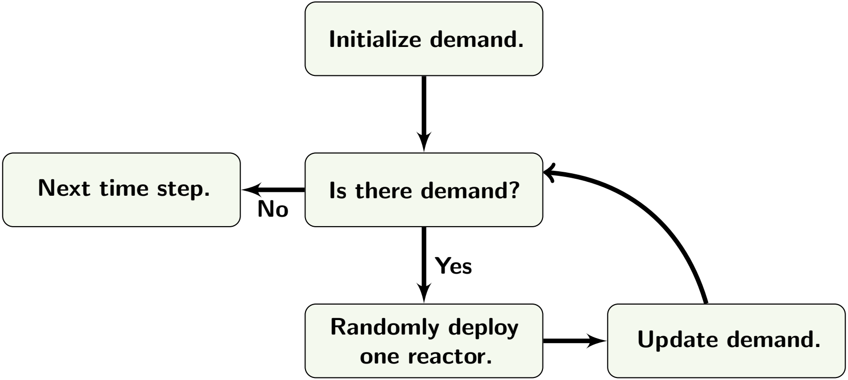


Figure 3: Random reactor deployment diagram. This algorithm randomly deploys reactors until the demand is met. If a reactor is deployed that exceeds the demand, it will simply be removed and the algorithm will try again.

Random + greedy reactor deployment algorithm

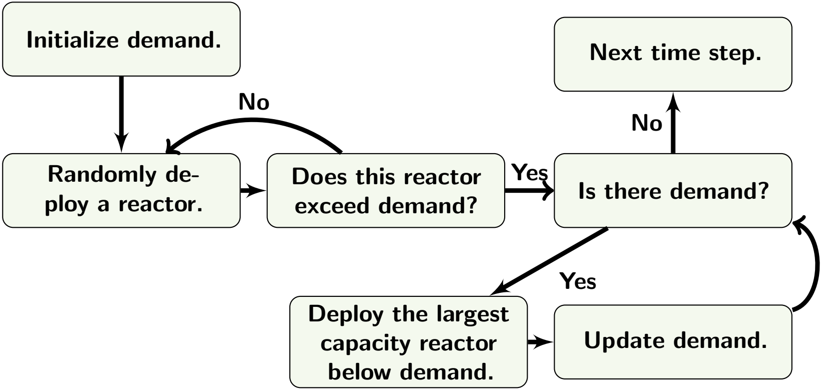


Figure 4: Random + Greedy deployment diagram. This algorithm first attempts to randomly deploy a reactor, and if that reactor exceeds demand, it will remove the last reactor and then use the greedy approach to fill in the remaining demand.

Outline

Our demand for energy is going up

We will compare each deployment algorithm with a demand growth scenario that:

- doubles nuclear capacity by 2050,

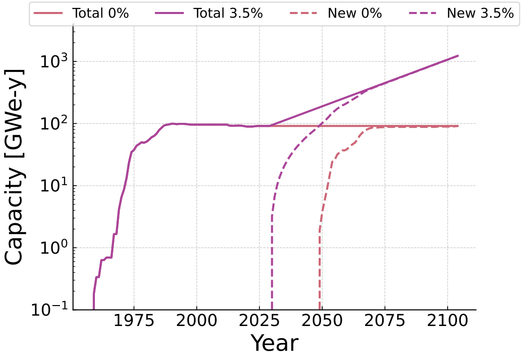


Figure 5: Nuclear electricity capacity to present day with projection of doubling nuclear by 2050 from DOE Liftoff Report [5].

Our demand for energy is going up

We will compare each deployment algorithm with a demand growth scenario that:

- doubles nuclear capacity by 2050,
- starts deploying the advanced reactors in 2030,

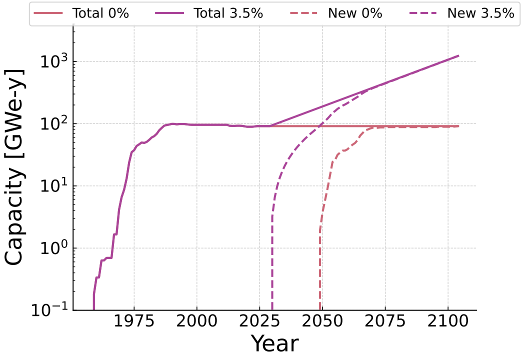


Figure 5: Nuclear electricity capacity to present day with projection of doubling nuclear by 2050 from DOE Liftoff Report [5].

Our demand for energy is going up

We will compare each deployment algorithm with a demand growth scenario that:

- doubles nuclear capacity by 2050,
- starts deploying the advanced reactors in 2030,
- and uses LEU+ from 2030-2040.

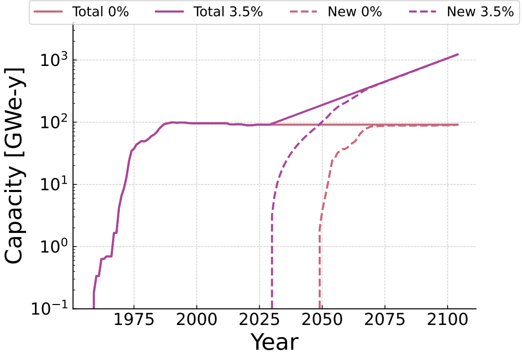
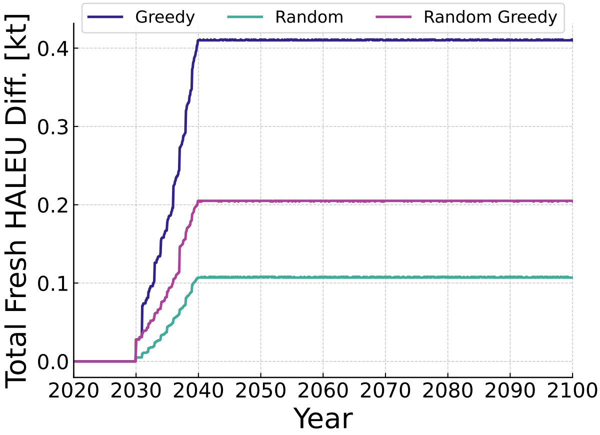
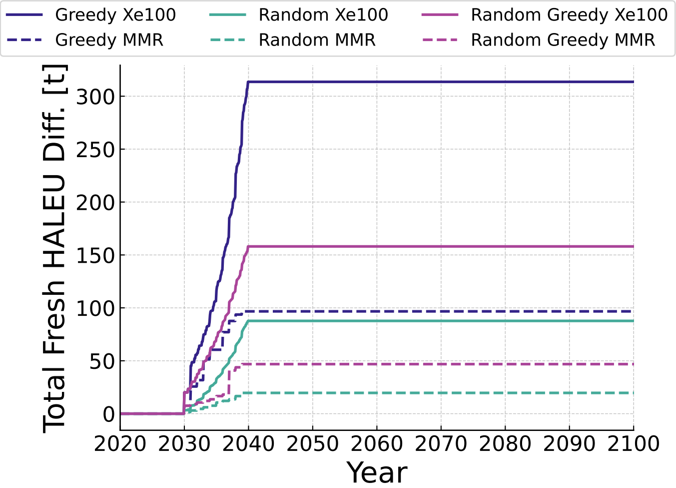


Figure 5: Nuclear electricity capacity to present day with projection of doubling nuclear by 2050 from DOE Liftoff Report [5].

The difference is on the order of hundreds of tons



Across reactor



Compare to a scenario without LEUP

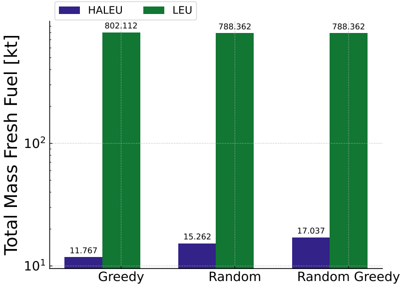


Figure 6: No-LEUP scenario.

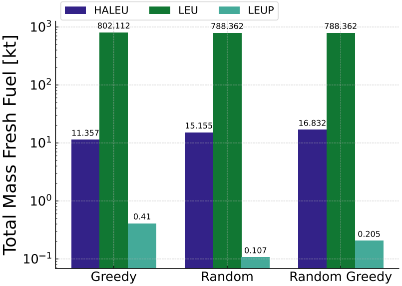


Figure 7: LEUP to HALEU scenario.

Outline

This is an upperbound on the amount of HALEU we could defer.

In our simple case, we transition from LEU+ to HALEU after 10 years of operation with no learning curve.

- For the Xe100 reactors, we need almost 315 less tons of HALEU.
- For the MMR reactors, we need almost 97 less tons of HALEU.

Next we need to characterize what the cost of this transition would be.

Future work

We are interested in:

- adapting neutronics models of the MMR and Xe-100 to be fueled with LEU+,
- investigating the impact of learning curves instead of a ready deployment on the results over time,
- and comparing these results with a triple-by-2050 scenario (also proposed in the Liftoff Report [5].)

Acknowledgement

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References I

[1] K. D. Huff, M. J. Gidden, R. W. Carlsen, R. R. Flanagan, M. B. McGarry, A. C. Opotowsky, E. A. Schneider, A. M. Scopatz, and P. P. H. Wilson, "Fundamental concepts in the Cyclus nuclear fuel cycle simulation framework," *Advances in Engineering Software*, vol. 94, pp. 46–59, Apr. 2016, arXiv: 1509.03604. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0965997816300229

[2] Simon M Pimblott, "Nuclear Science & Technology. Research and Development to Enable Advanced Reactor Demonstrations and Deployment," Idaho National Laboratory (INL), Idaho Falls, ID (United States), Mar. 2024, iNL/MIS-24-77148-Revision-0. [Online]. Available: https://inldigitallibrary.inl.gov/sites/sti/sti/Sort_94340.pdf

[3] Ultra Safe Nuclear Corporation, "USNC Micro Modular Reactor (MMR™ Block 1) Technical Information," *USNC*, p. 36, 2021. [Online]. Available: https://www.usnc.com/assets/media-kit/[022989][01]%20MMR%20Technical%20Information%20Document.pdf?v=a7e3f7d8d5

[4] NuScale, "Chapter One Introduction and General Description of the Plant," Oct. 2018. [Online]. Available: https://www.nrc.gov/reactors/new-reactors/design-cert/nuscale.html

References II

[5] Julie Kozeracki, Chris Vlahoplus, Ken Erwin, Alan Propp, Sonali Razdan, Rasheed Auguste, Tim Stuhldreher, Christina Walrond, Melissa Bates, Erica Bickford, Andrew Foss, Derek Gaston, Cheryl Herman, Rory Stanley, Billy Valderrama, Katheryn Scott, Tomotaroh Granzier-Nakajima, Paul Donohoo-Vallett, Tom Fanning, Brent Dixon, Abdalla Abou Jaoude, and Chris Lohse, "Pathways to Commercial Liftoff: Advanced Nuclear," *DOE Liftoff Report*, Sep. 2024. [Online]. Available: https://liftoff.energy.gov/wp-content/uploads/2024/09/LIFTOFF_DOE_AdvNuclear-vX6.pdf

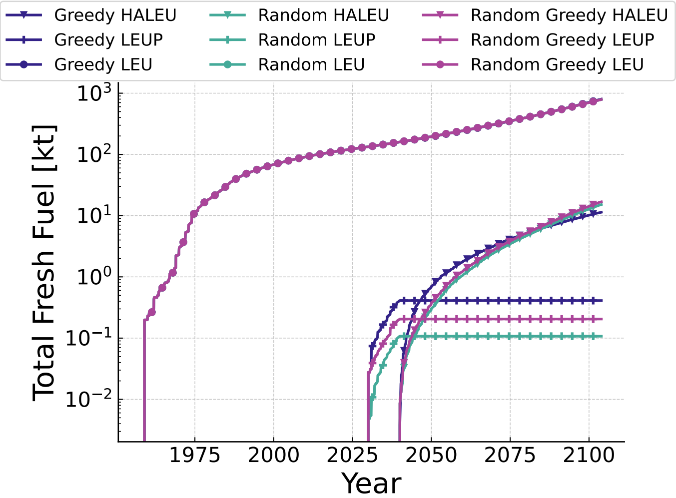
We define the enrichment levels as...

Table 2: Enrichment levels and their ranges.

Enrichment Level	**Range [% ^{235}U]**
Natural	< 0.711
LEU	0.711-5
LEU+	5-10
HALEU	10-20
HEU	≥ 20

These are a mash-up of economic and regulatory definitions.

Staggering enrichment could give the supply chain time to form



The differences between LEU demand are small in kt