Evaluating Changing Paradigms across the Nuclear Industry

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Meet the Presenter

Dr. Jessica Lovering is the co-founder of the Good Energy Collective, a new organization working on progressive nuclear policy.

She recently completed her PhD in Engineering and Public Policy at Carnegie Mellon University. Her dissertation focused on how commercial nuclear trade affects international security standards and how very small nuclear reactors could be deployed at the community level.

She is a Fellow with the Energy for Growth Hub, looking at how advanced nuclear can be deployed in sub-Saharan Africa.

She was formerly the Director of the Energy Program at the Breakthrough Institute, a pioneering research institute changing how people think about energy and the environment.

She is the American Nuclear Society winner of the November 2020 “Pitch your Ph.D. Research”.

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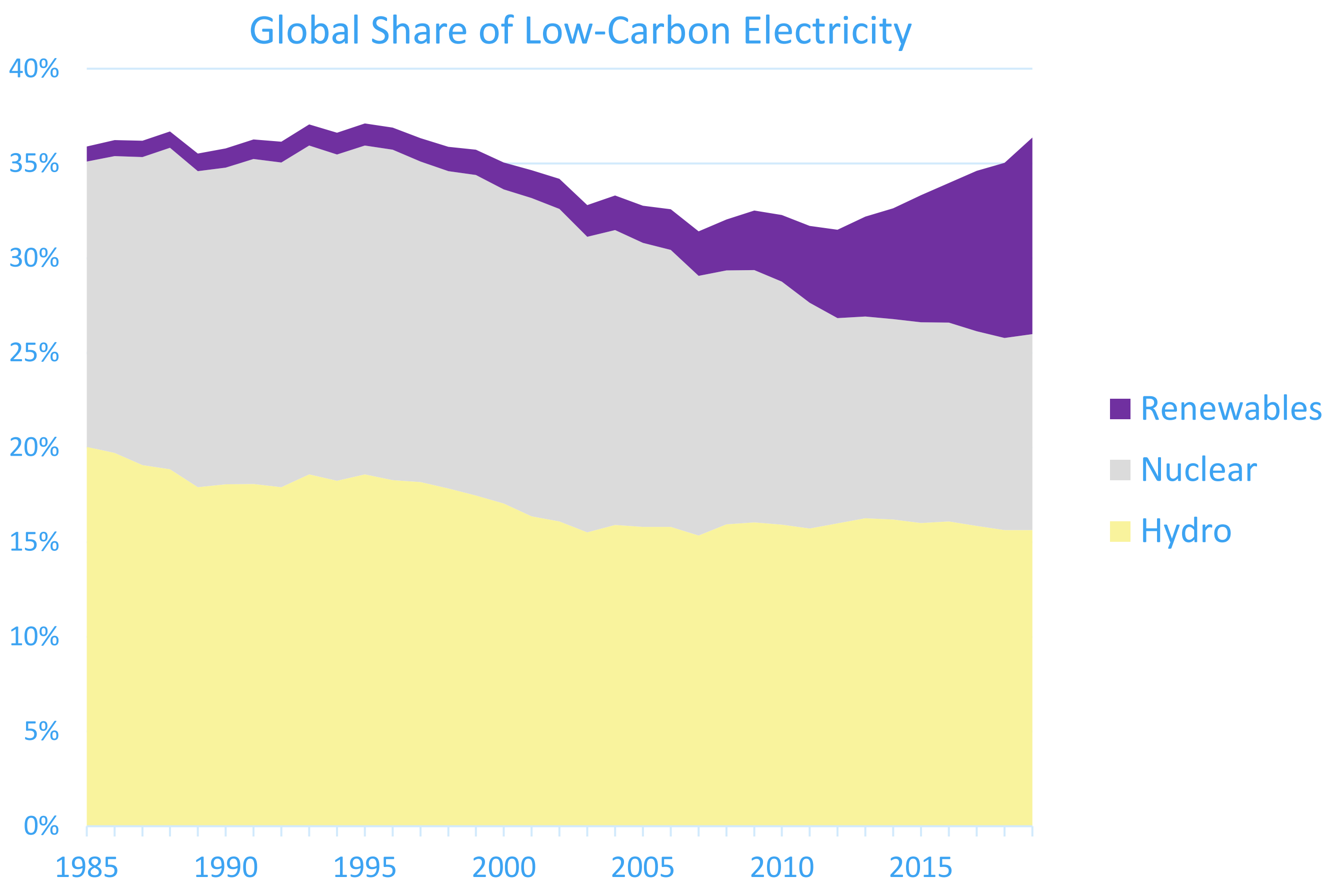
The World Needs More Low-Carbon Energy, A Lot More

- IPCC: world needs to reach net-zero emission in the energy system by 2050 (IPCC 2018)
- IEA: global nuclear capacity will double by 2050 to meet aggressive decarbonization targets (IEA 2015)
- Yet zero-carbon sources of electricity have been flat at ~35% for more than 30 years (BP 2020)



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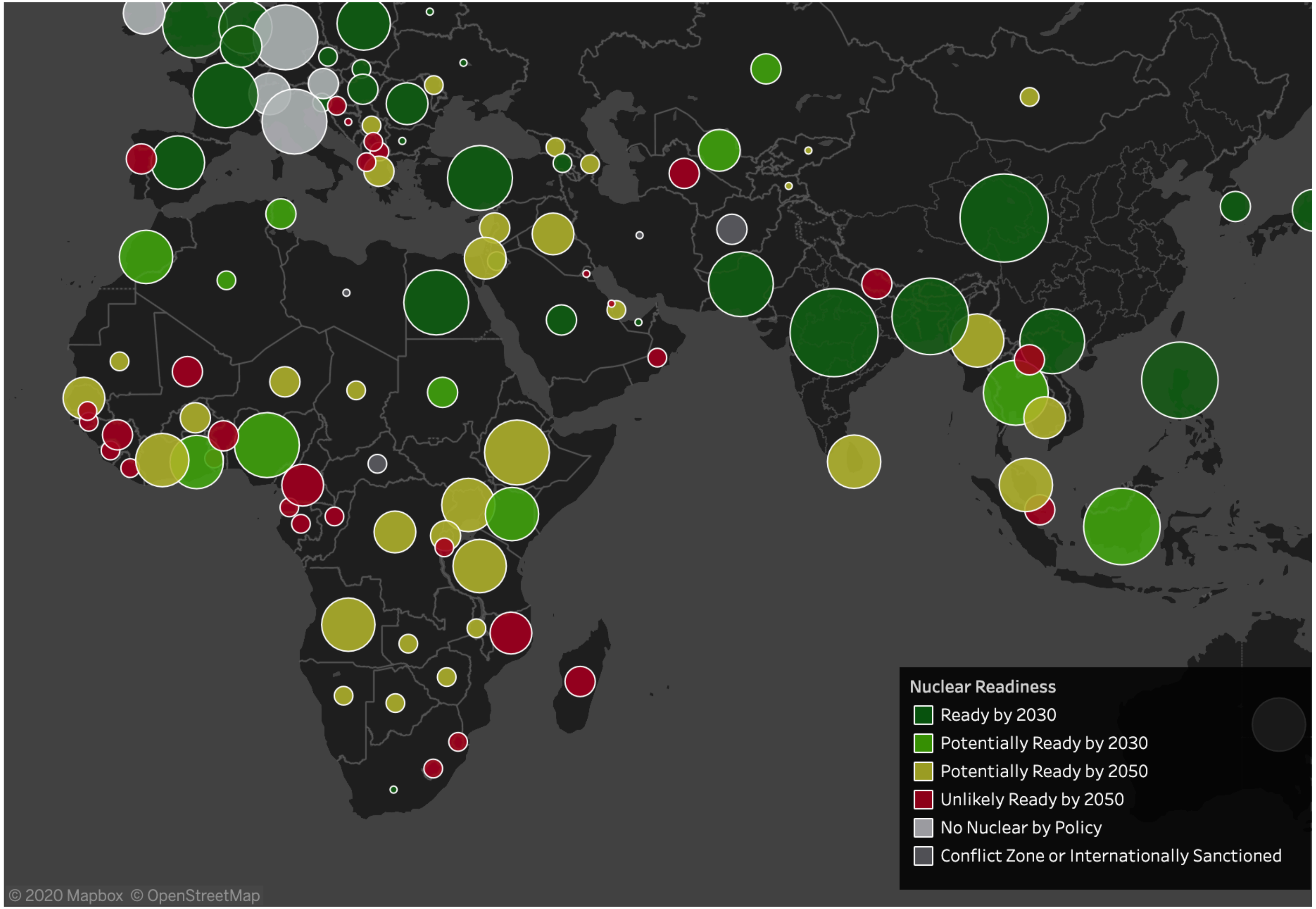
Large Potential Global Market for New Nuclear

Image credit: Kempfer et al. (2020). *Mapping the Global Market for Advanced Nuclear.* Third Way and Energy for Growth Hub



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Most of these countries have agreements with Russia or China already

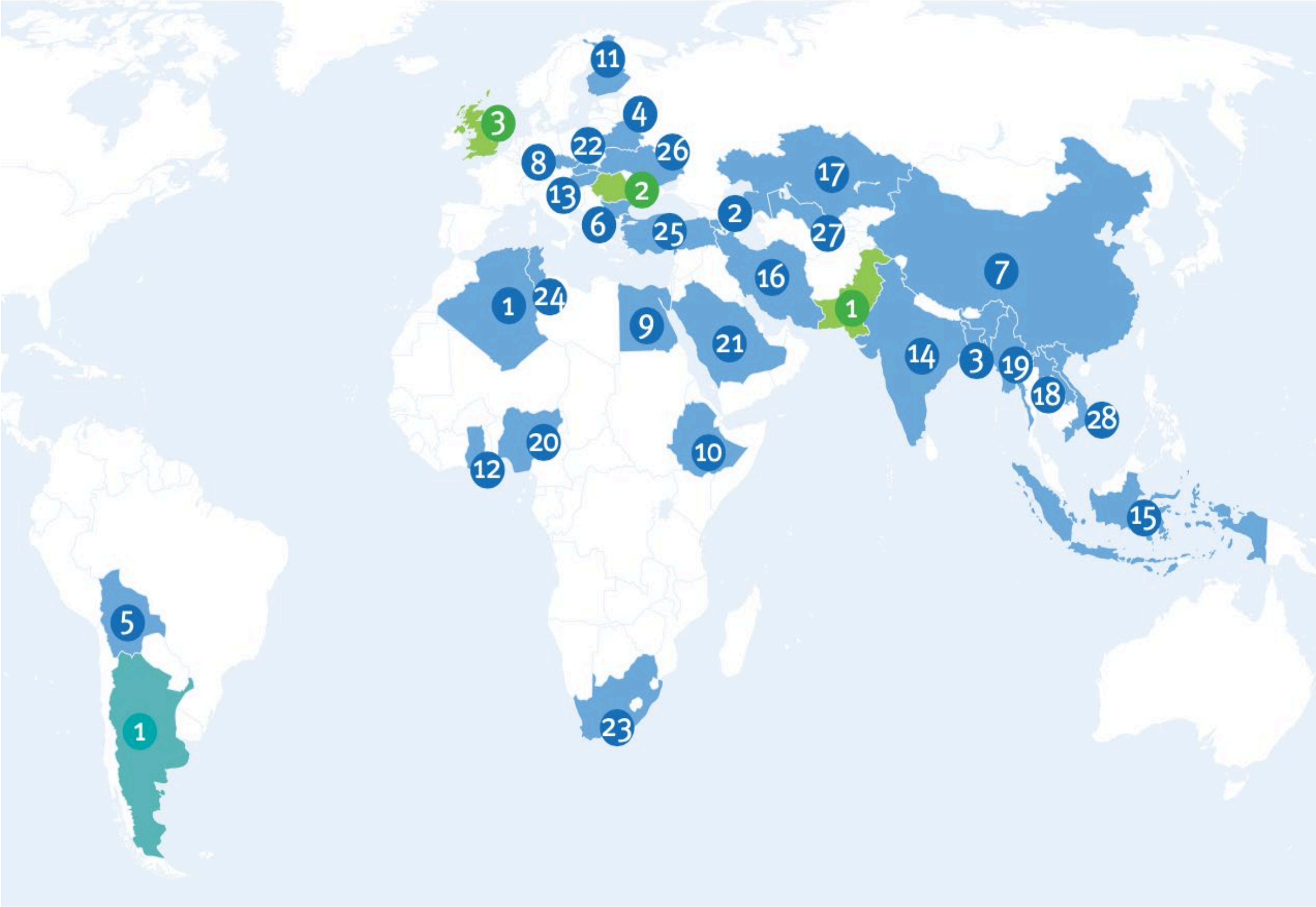

Image Credit: Global Nexus Initiative (2017). *Nuclear Power for the Next Generation: Addressing Energy, Climate, and Security Challenges.*

U.S. Nuclear Exports Have Declined Dramatically

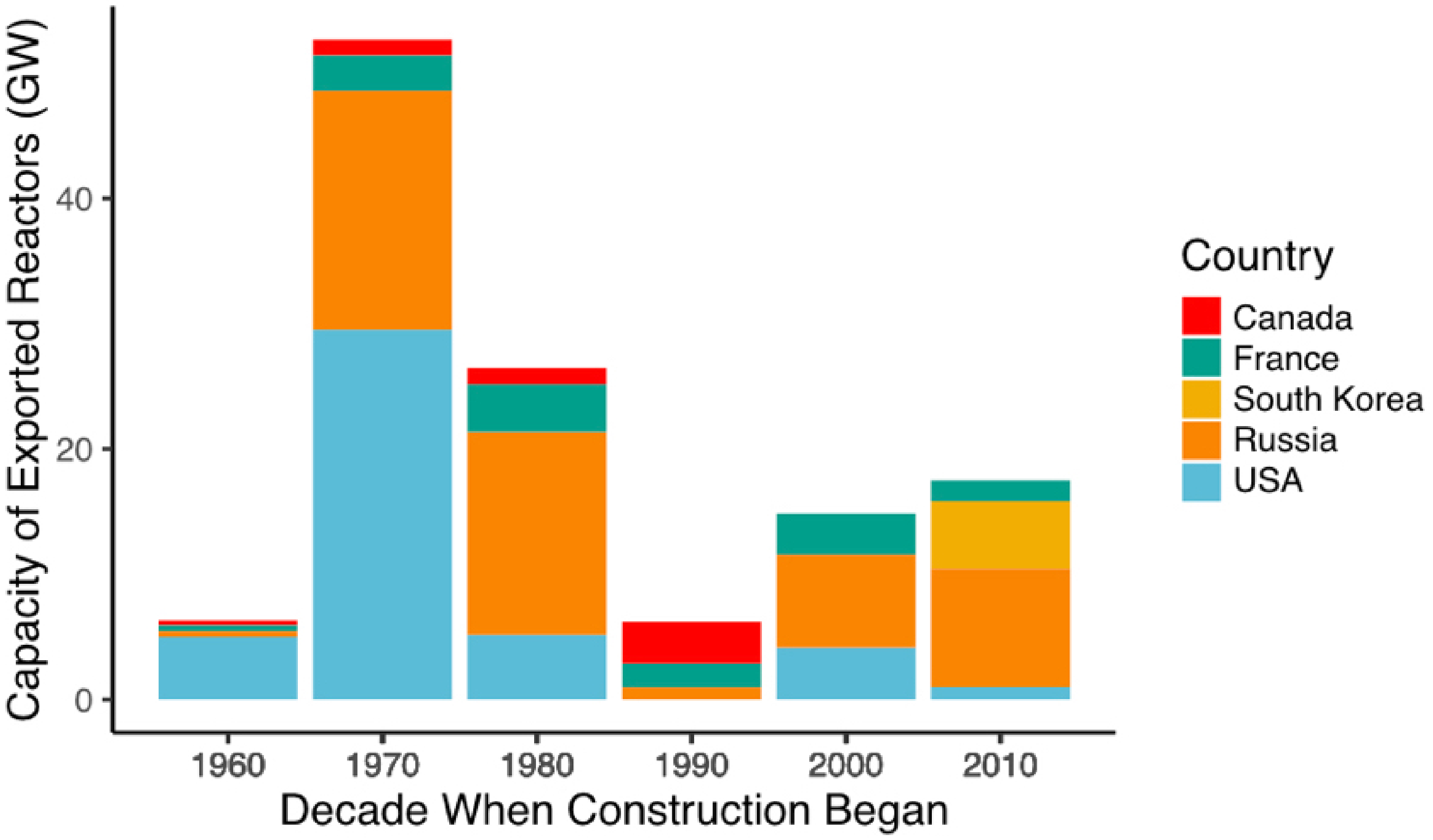

Image: Lovering et al. (2020). Data: IAEA PRIS

Expert Assessments of Strategies to Enhance Global Nuclear Security

Published as: Lovering, J. R., Abdulla, A. & Morgan, G. Expert assessments of strategies to enhance global nuclear security. *Energy Policy* 139 (2020).

Main research questions:

- What was the role of commercial nuclear exports in setting international safety, security, and non-proliferation standards?
- What strategies might strengthen US influence in global nuclear security regimes?
- How effective and feasible are these strategies?

Held Expert Participatory Workshop September, 2018

- Two-day workshop with 21 experts from nuclear energy and security fields.
- Pre-Readings and Introductory presentations to frame the conversation.
- Experts evaluated our foundational premises and six proposed strategies to increase U.S. influence
- Also brainstormed four additional strategies that were evaluated in a follow-up survey.

Main Results from Workshop

- Export Control not seen as main obstacle
- Expensive and radical policy programs not seen as feasible.
- Diplomatic strategies viewed as more effective but especially difficult with Trump Administration
- But big take-away: experts did not think the U.S. could compete with large LWRs (i.e. traditional nuclear).

Proponents and energy analysts think advanced nuclear technologies could be cheaper, faster, safer.

U.S. Has 60+ Advanced Nuclear Companies

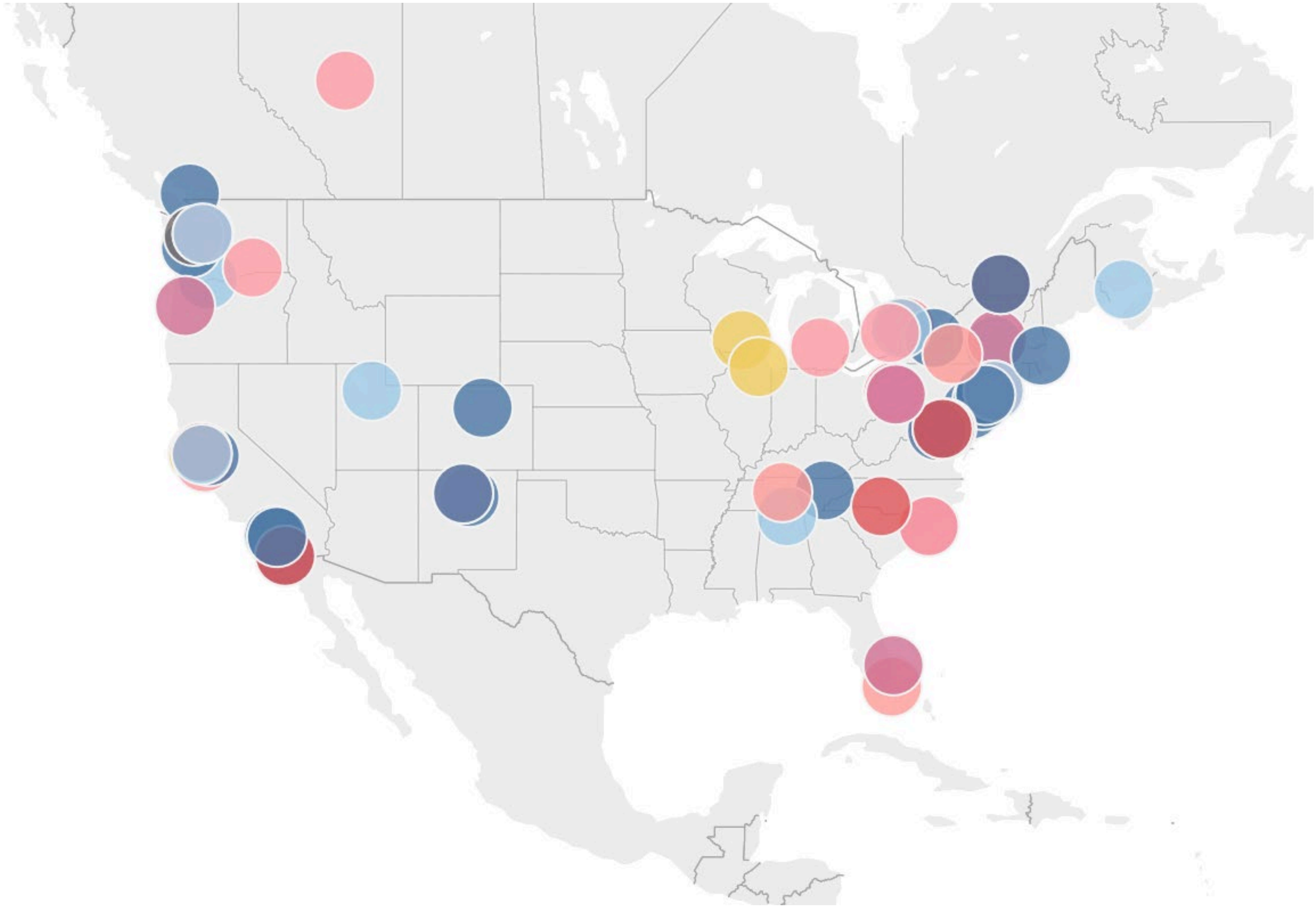

Image credit: Milko, Kempfer, and Allen. *Advanced Nuclear Map*. Third Way (2019)

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Experts disagreed as to whether new nuclear technologies would be commercialized soon enough to matter

Two concerns:

- Commercializing a single advanced reactor design in the U.S. could take decades and cost billions of dollars (Secretary of Energy Advisory Board 2016).
- The U.S. government has not been investing nearly enough to commercialize advanced reactor technologies (Abdulla et al. 2017).

Two emergent trends that motivated my research:

- Several advanced reactor vendors moving toward licensing in the U.S. and Canada, especially small and very small modular reactors.
- Move toward private funding and seeking niche markets to build a commercial demonstration on short timescales.

Microreactors could be marketable export products that also come with security and non-proliferation benefits

- Main nuclear vendors are focused on large LWR (although all do have SMR programs)
- Diversity of private U.S. companies working on microreactors, aiming to commercialize and demonstrate faster than SMRs and larger advanced nuclear technologies.
- AND they could have international security benefits:
    - Lifetime cores (i.e. no on-site refueling) will facilitate a Build-Own-Operate-Remove (BOOR) export model.
    - This could get commercial nuclear into countries much sooner than large LWRs, but more importantly…
    - The BOOR model avoids many of the security challenges of nuclear newcomer countries: developing domestic fuel handling and waste storage capabilities.

Microreactors Targeting Niche Markets with High Energy Costs

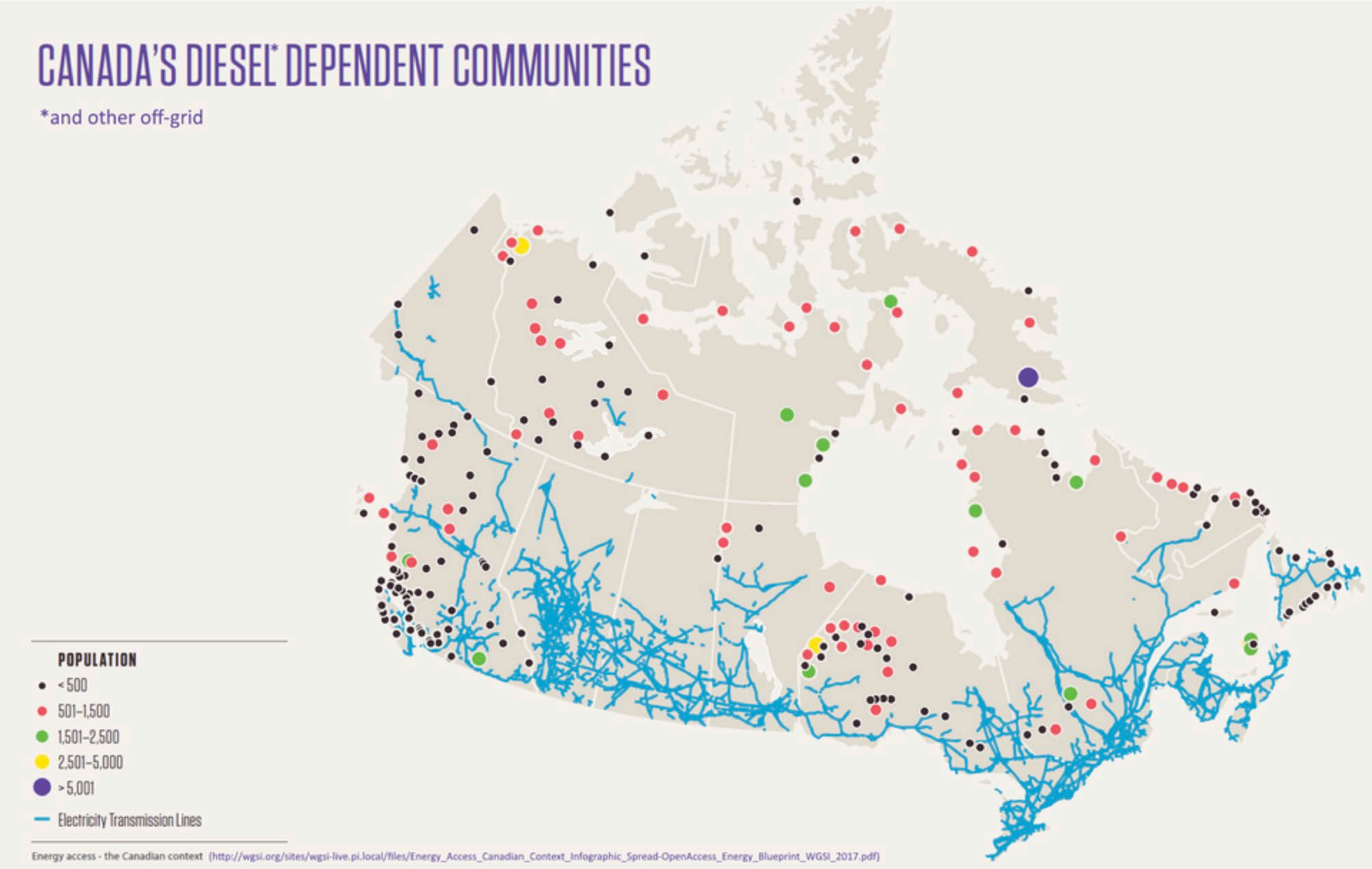


Image Credit: Brooks, M. & Moore, N. *OpenAccess Energy Blueprint*. Waterloo Global Science Initiative (2017).

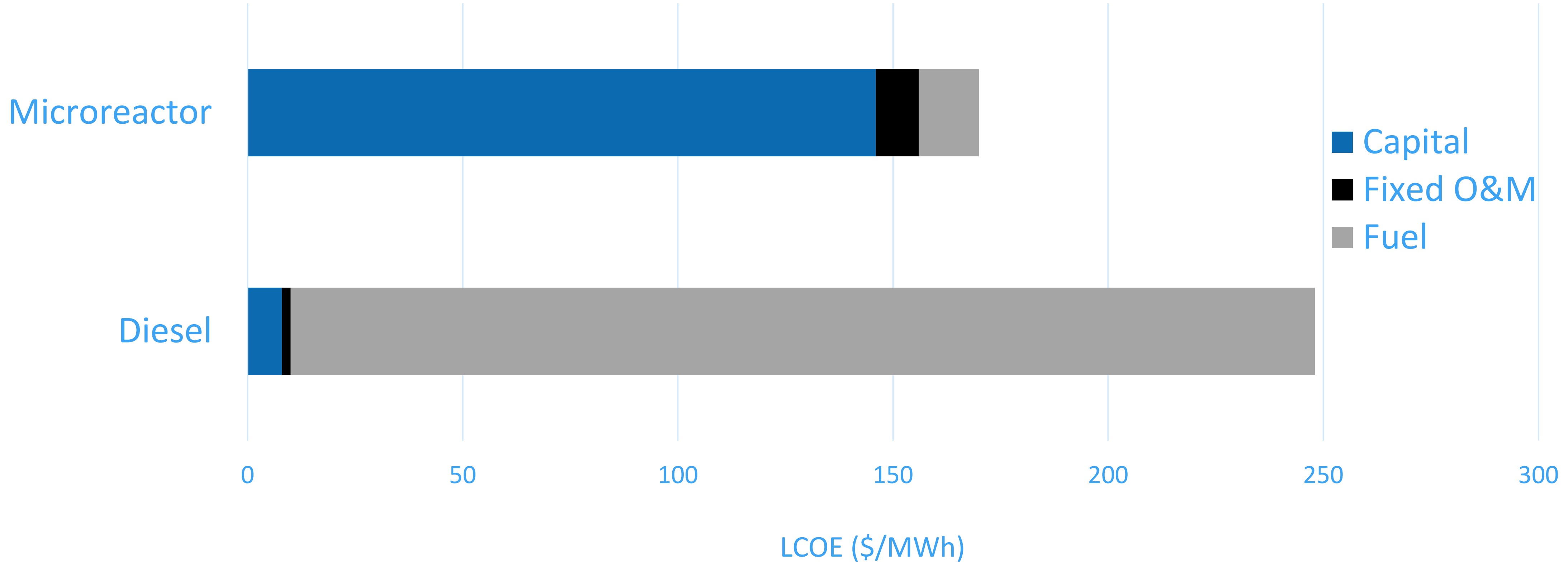
Case Studies of Microreactors for Microgrid Applications

Main Research Questions

– Under what conditions would a small nuclear reactor be the optimal choice for a microgrid installations?

- What would a microreactor need to cost to be cost-competitive with alternatives for microgrids: diesel, renewables, batteries?
- How important is load-following for microreactors operating alone on a microgrid and with renewables?
- How sensitive is this optimal choice to fuel prices and the parameters of the microreactor?

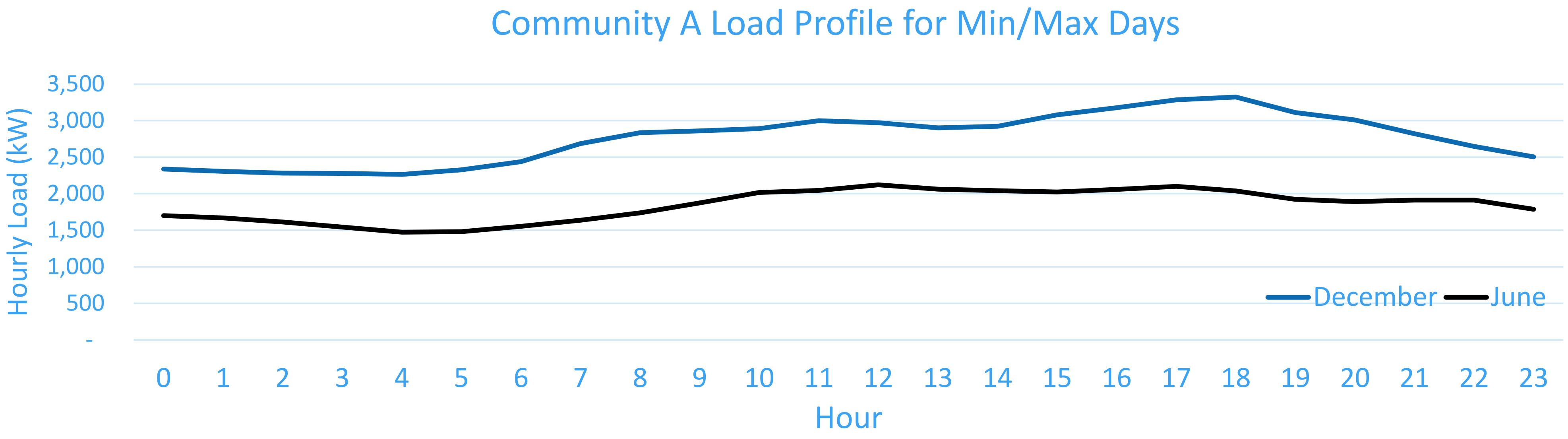
Microreactors Could be Cost-Competitive with Diesel; this study evaluates at what capital cost, load factor, and diesel price this is true.



Diesel cost from Lazard (2014) “Lazard’s Levelized Cost of Energy Analysis — Version 8.0”

Microgrid Optimization Using HOMER

- Finds least-cost grid mix to meet specified electrical (and thermal) load, based on generation options included.
- Includes catalogue of generic technologies (renewable, fossil, battery, etc.) as well as links to weather and renewable resource data by location.



Case Studies with Real Hourly Load Data

	Load	Average Load (MW)	Peak Load (MW)	Load factor	Peak Month	Day-to-Day Variance	Timestamp Variance
Comm. A	Elec.	2.41	3.66	0.66	Feb.	3.96%	2.70%
Comm. B	Elec.	1.18	1.77	0.67	Feb.	4.47%	3.65%
Fairbanks Hospital	Elec.	1.49	2.35	0.64	May	13.16%	8.58%
	Therm	1.47	4.47	0.33	Dec.	16.79%	9.19%
UW Madison	Elec.	208	329	0.63	Jul.	7.47%	3.86%
	Therm	107	229	0.47	Jan.	16.13%	6.72%

Modeled four microgrid systems, constraining the deployable technological mix in each to compare their cost and performance

Mix 0	Mix 1	Mix 2	Mix 3
100% Diesel Business-As-Usual	100% Micronuclear Generic 1MW Microreactor	Nuclear & Diesel	Nuclear & Batteries
All four done first without and then with renewables included.			

I developed a generic 1MW microreactor component to use in HOMER, with nuclear-specific parameters taken from NEI (2019) and IEA (2015).

Results: Optimal system depends on your constraints, but nuclear with batteries was the cheapest, low-carbon system.

	Lowest Cost	Lowest Cost, Zero-Carbon
Including Nuclear	3MW Nuclear + 3.3MWh Battery LCOE = $0.16/kWh	3MW Nuclear + 3.3MWh Battery LCOE = $0.16/kWh
Excluding Nuclear	4.1MW Diesel + 6MW Wind LCOE = $0.29/kWh	54MW PV + 21MW Wind + 325 MWh Battery LCOE = $1.0/kWh

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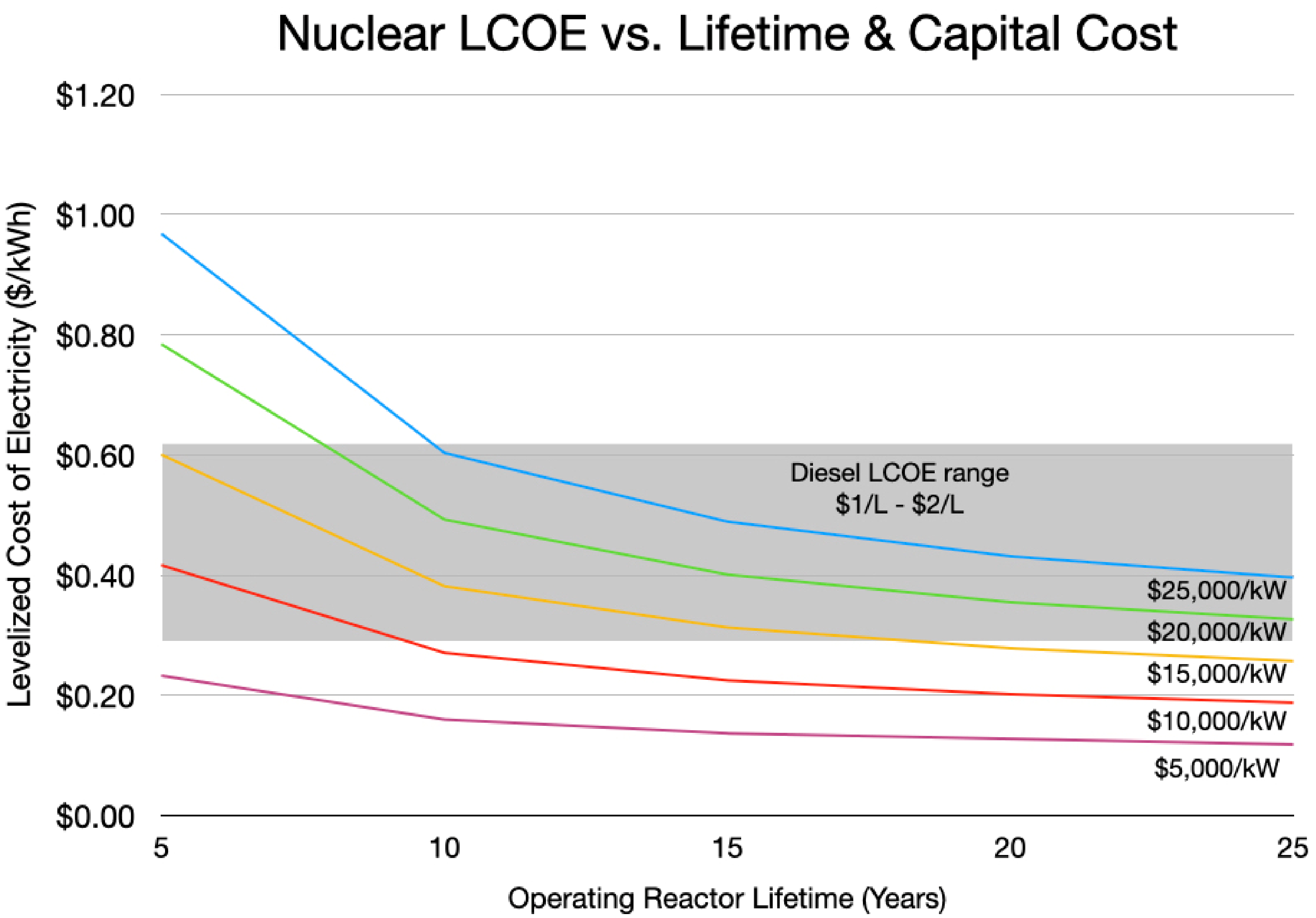
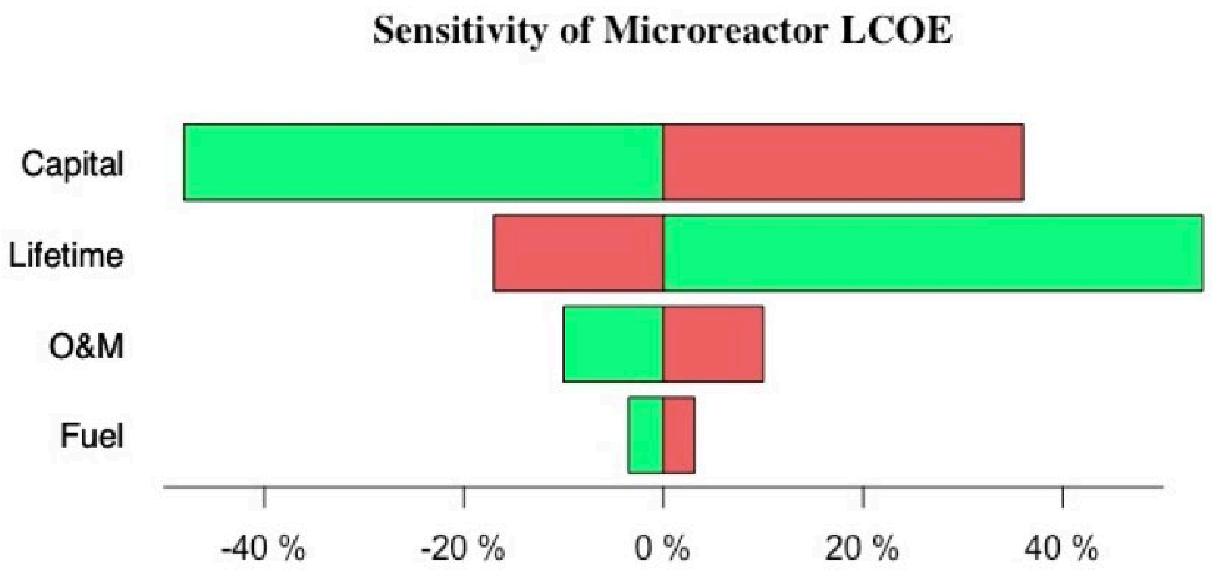
Microreactor LCOE Sensitive to Capital Cost & Lifetime



Conclusion: Microreactors can be cost-competitive with diesel if capital costs are moderate and diesel prices are high.

- Microreactors not competitive with grid electricity, needs carbon price of \$60-\$120/tonne
- Largest uncertainty comes from capital cost, and lifetime/refueling model



Sensitivity of levelized cost of electricity for a 100% nuclear system. For all parameters, the input was varied by ±50%. Baseline parameters were \$10,000/kW for capital cost, 10 years for lifetime, \$790,000/yr for $O\&M$, and \$550/kg for fuel.

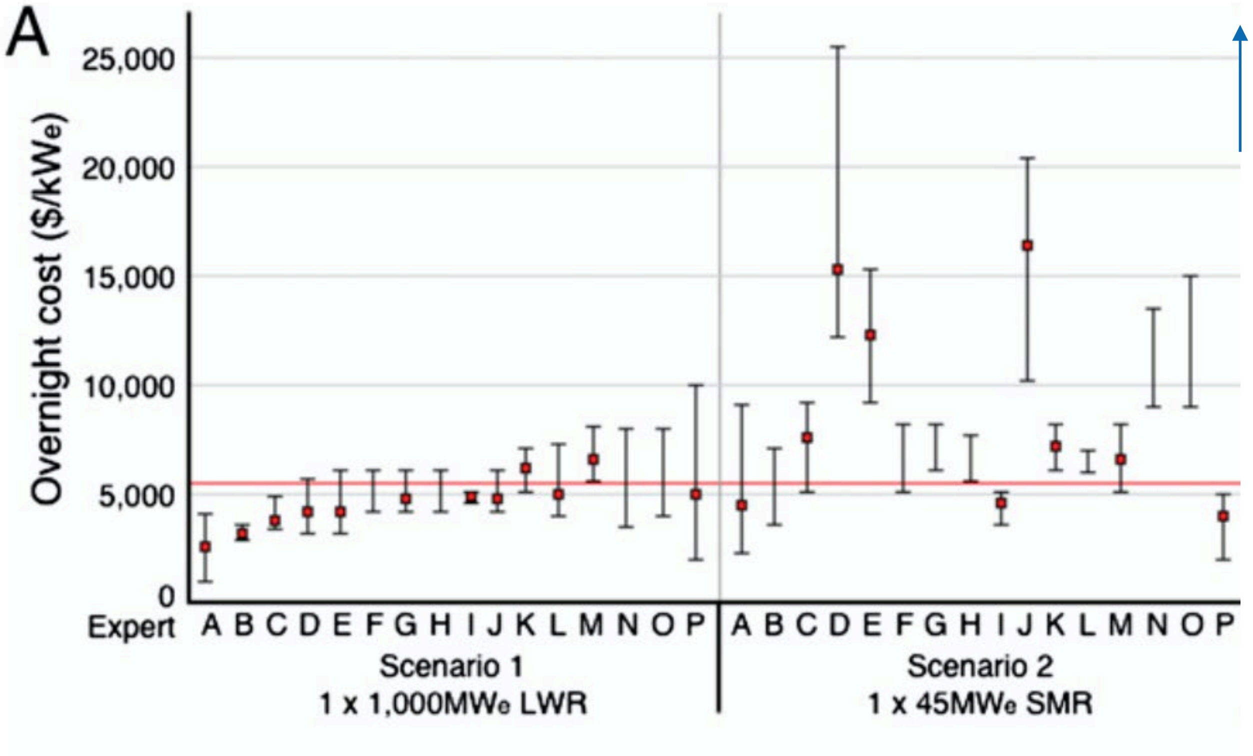
Trade-offs between economies of scale and economies of volume for very small modular nuclear reactor

- Do nuclear reactors experience economies of scale? How large is this effect?
- What learning rates are expected for factor fabricated SMRs?
- Can economies of volume from factory fabrication offset potential diseconomies of scale? Where is the break-even point?
- What is the potential range of capital cost for nth-of-a-kind microreactors?

Parts of this work have been included in the following publication:
Lovering, J.R. and J.R. McBride. "Chasing Cheap Nuclear: Economic Trade-Offs for Small Modular Reactors." *The Bridge.* National Academy of Engineering. Fall (2020).

No consensus on cost of future SMRs or microreactors

Expert elicitation of NOAK nuclear costs from Abdulla, Azevedo, and Morgan (2013)



Froese et al. (2020): $130,000/kW. 3MW
Moore (2016): $35,000/kW. 10MW

Oklo: $6,700/kW. 1.5 MW

NuScale: $4,400/kW. 12x 60MW

Traditional Scaling Relation & Learning Curve

$$Cost_{SMR} = Cost_{NPP} \times \left(\frac{SMR\,MW_e}{NPP\,MW_e} \right)^{n-1}$$

$$c(u) = c_0 u^b$$

$$LR = 1 - 2^b.$$

From the literature:
n = 0.25-1.0

From the literature:
LR = negative to 6%

Almost entirely based on U.S.
cost history from 1970s

Microreactors will be too expensive if traditional scaling relations apply

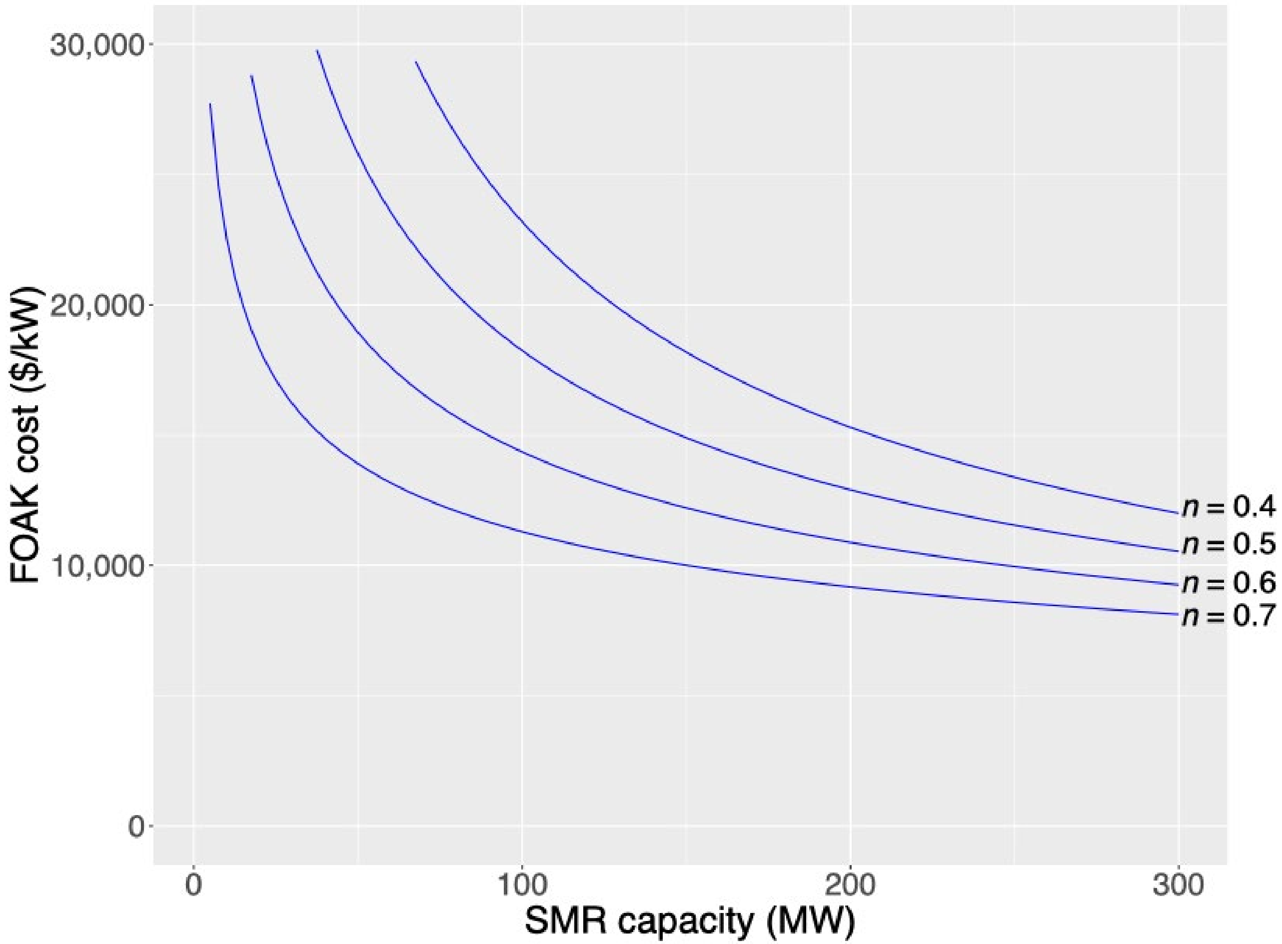


Illustration of the standard scaling relation for a base plant of OCC = $5, $500/kW$ and $Capacity$ = $1100MW$. The blue lines show the first-of-a-kind cost for an SMR as a function of size in MW for four different scaling factors. (For an example of how these factors are applied, see IAEA (2013))

However, Learning Rate may be more dependent on size than on technology

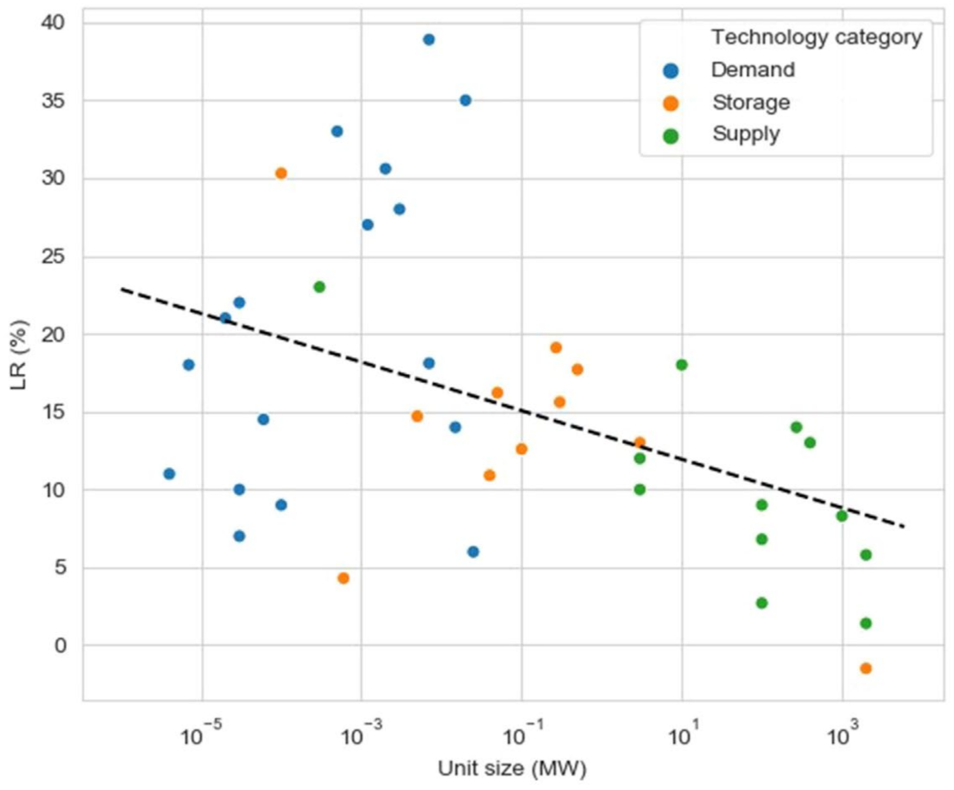
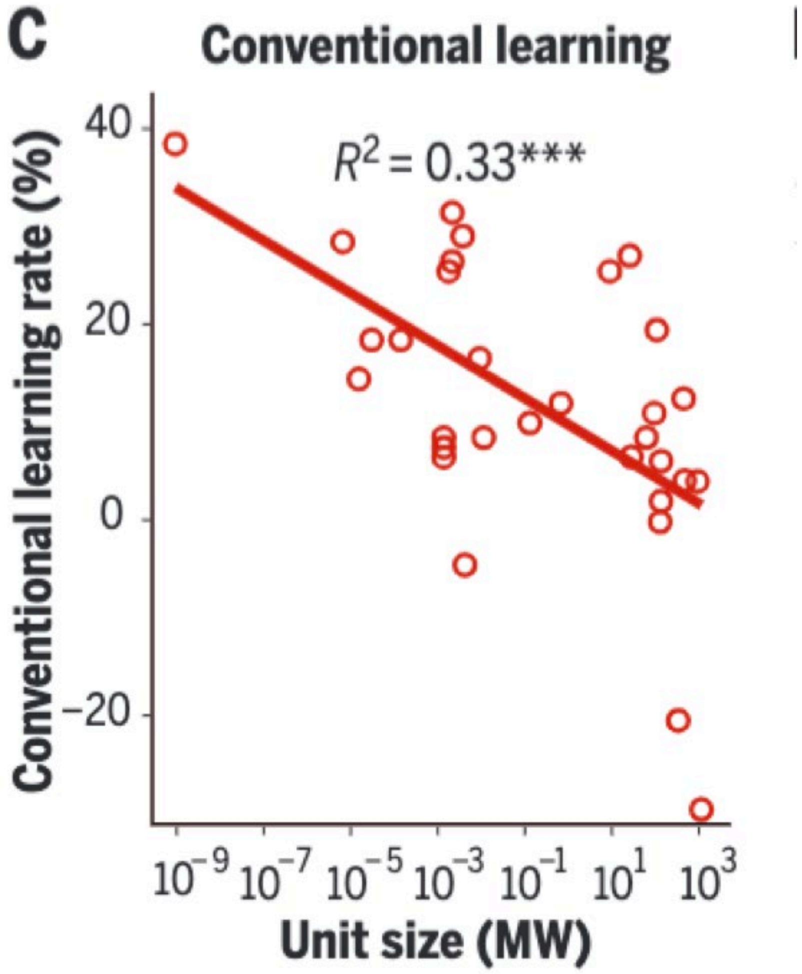


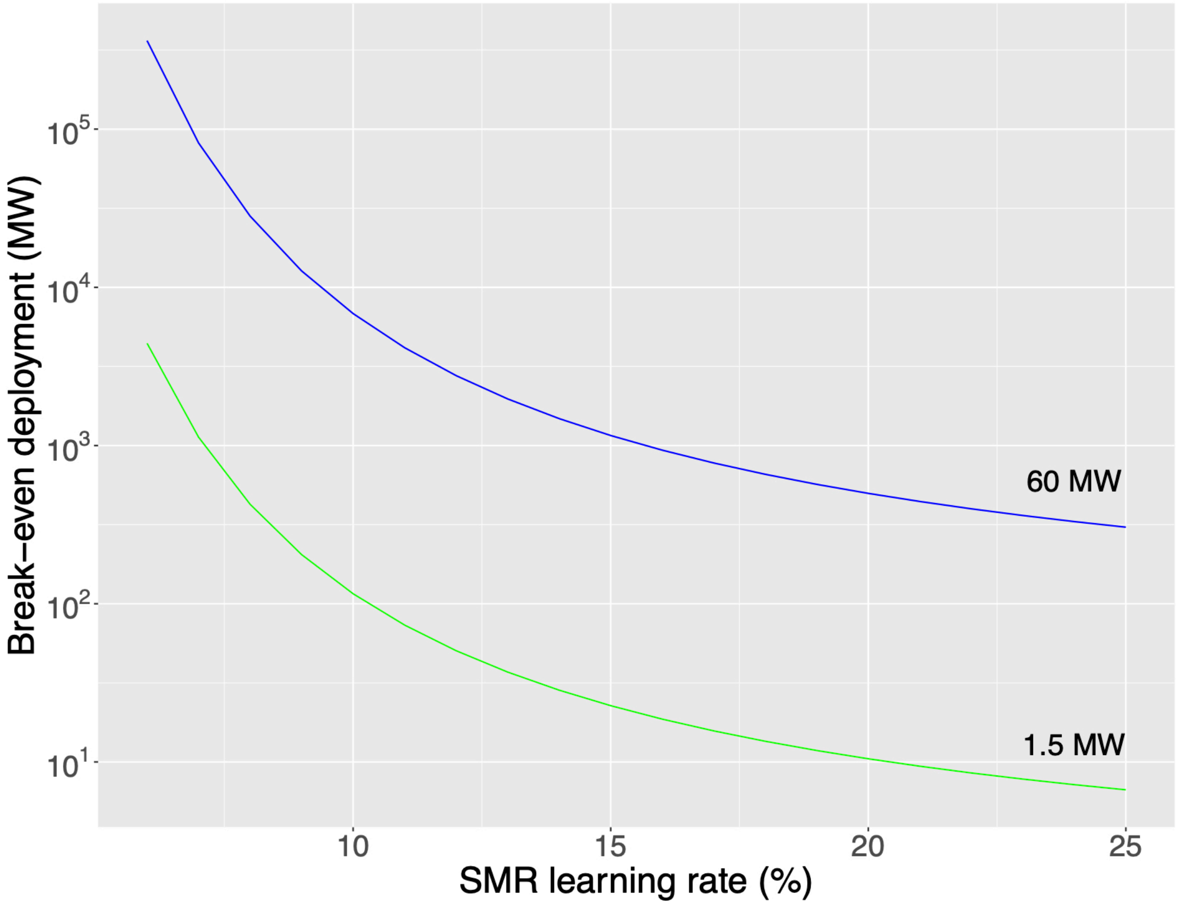
Figure 1. LRs for 41 Energy Technologies
The logarithmic fit shows a negative relation between unit size and observed LR. The logarithmic parameter (a = −0.68, R^2 = 0.22) translates into a 1.5% decrease in LR for each order of magnitude increase in unit size.



Sweerts, Bart, Remko J Detz, and Bob van der Zwaan (2020). “Evaluating the Role of Unit Size in Learning-by- Doing of Energy Technologies”. *Joule*, pp. 1–4.

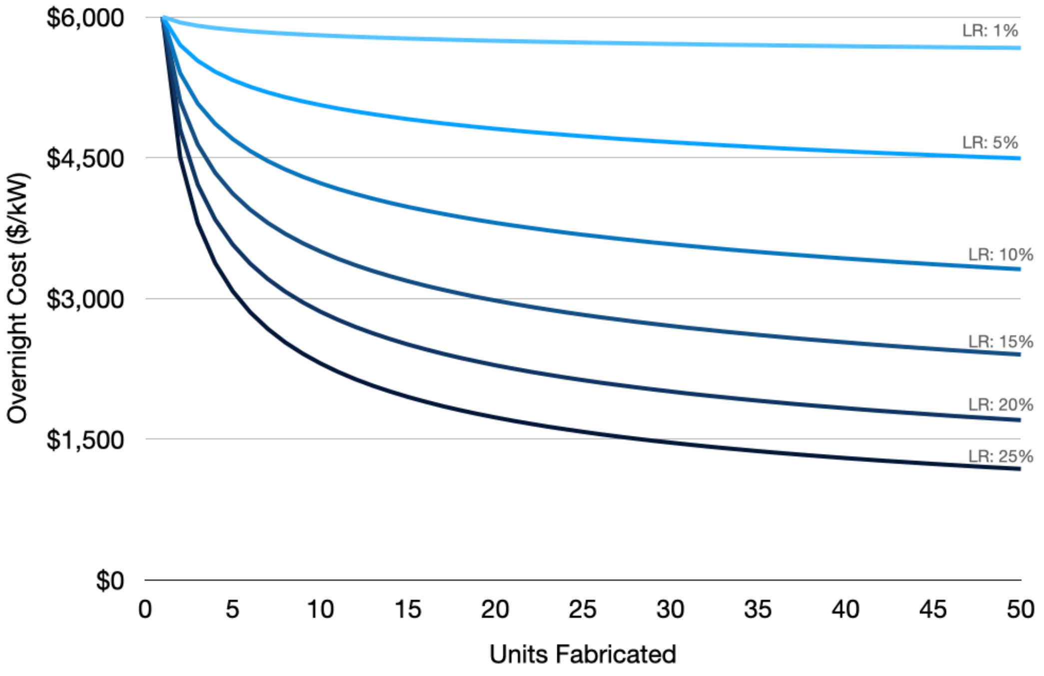
Wilson, C. et al. (2020). “Granular technologies to accelerate decarbonization”. *Science* 368.6486, pp. 36–39.

Unit size can also make a big difference in cost declines

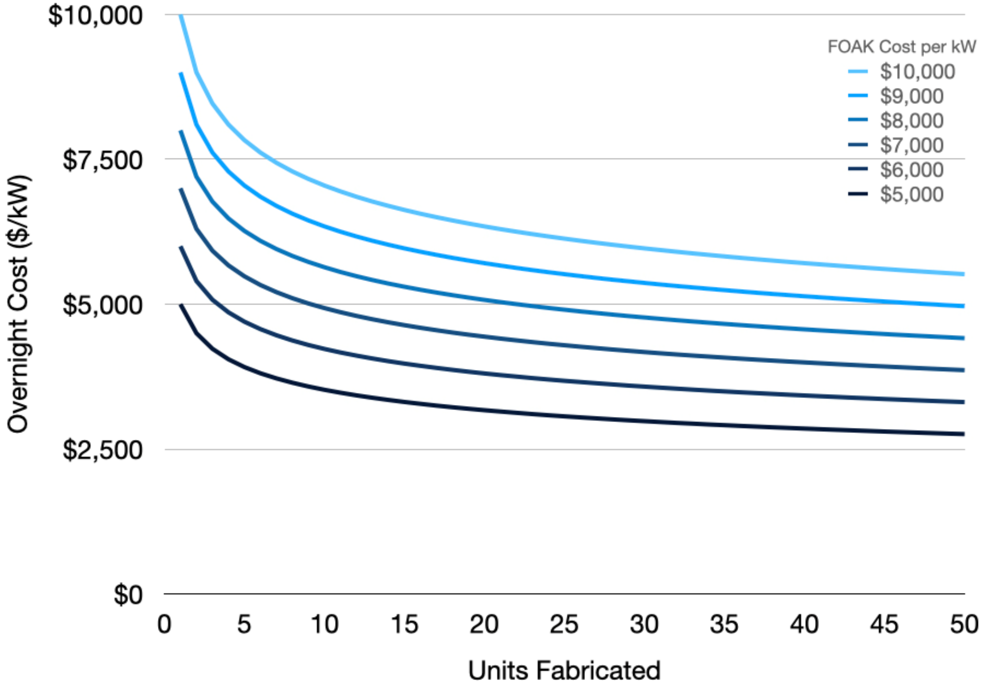


SMR deployment needed to reach cost-parity with an AP1000 reactor, assuming it starts at $5,500/kW, 1,100MW and a learning rate of 1%. The break-even deployment is shown as a function of learning rate for the 60MW reactor (in blue) and the 1.5MW reactor (in green), assuming both start at $11,000/kW.

Cost trajectory depends more on learning rate than FOAK cost.

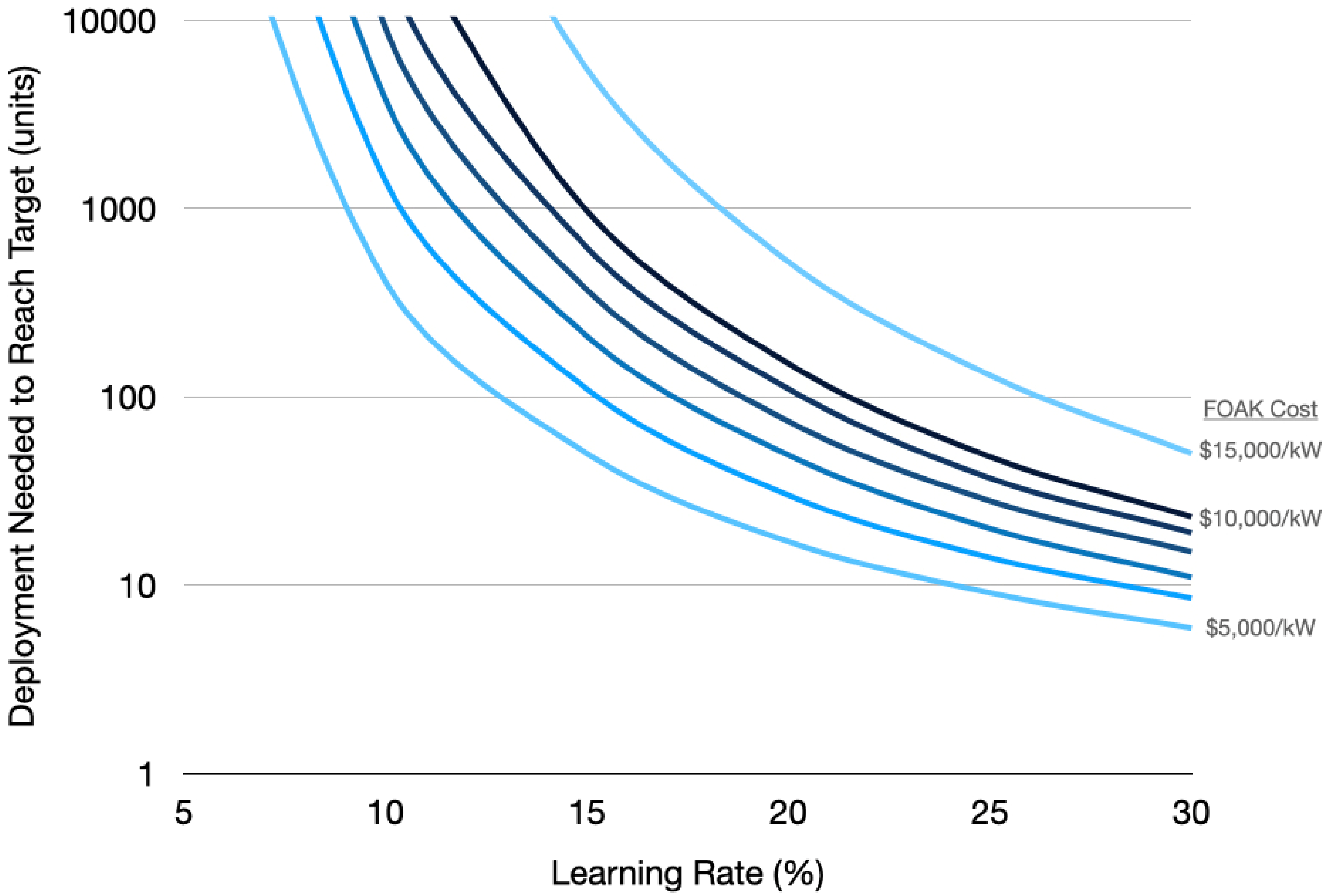


Learning curves for a generic SMR as a function of units fabricated and learning rate. The starting cost for every curve is $6,000/kW.



Learning curves for a generic SMR as a function of units fabricated and starting cost. The learning rate for every curve is 10%.

Putting this all together, how many units do you need to build to reach a $2,000/kW cost target?



Synthesis

- Experts who participated in our workshop agreed that U.S. commercial nuclear exports helped strengthen international nuclear security regimes.
- BUT they didn't see the U.S. being competitive with Russia and China going forward.
- Microreactors could offer security benefits and an attractive export product comparable with a BOOR model for nuclear newcomer countries, IF they can be made cost-competitive
- Microreactor concepts could be competitive with diesel for off-grid applications.
- However, to scale up and be cost-competitive with grid electricity, costs will need to decline significantly.
- Such cost declines are possible if economies of scale don't apply to novel designs, and if learning rates are above 20%

Policy Implications

- Breetz, Mildenberger, and Stokes (2018) argue that both components of experience curves — cost and deployed capacity — are affected by policy and politics.
- Therefore, need policies that facilitate deployment across the commercialization timeline:
    - Need demand-side policies that foster the first few dozen builds.
    - Need modernization of licensing that is appropriate for mass-produced reactors.
    - Need new export regimes for Build-Own-Operate-Remove with microreactors.

Upcoming Webinars

Date	Title	Presenter
26 August 2021	Graded Approach: Not just Why and When, but How	Mr. Vince (Alois) Chermak, INL, USA
23 September 2021	Experimental R&D in Russia to Justify Sodium Fast Reactors	Dr. Iuliia Kuzina, IPPE, Russia
28 October 2021	Metal Fuel for Prototype Generation-IV SFR : Design, Fabrication and Qualification	Dr. Chan Bock Lee, KAERI, Republic of Korea