Small and Micro Nuclear Reactors

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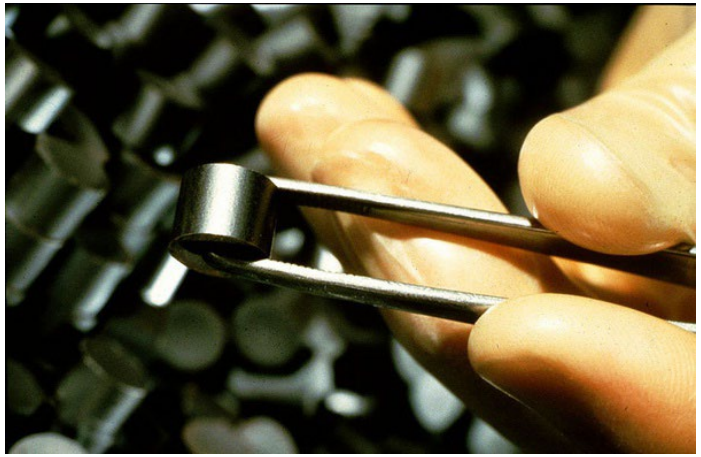
What I’m going to cover today

- ‘Big picture’ for nuclear power – focus on economics/costs
- A look at two types of nuclear power that might be of interest to rural communities
  - Small modular reactors
  - Microreactors
- A few examples of the research we do at UW-Madison into these technologies
- **I am very happy to answer any questions on nuclear power/ nuclear reactors!**

Current U.S. operating nuclear reactors are ~1 GW, and often more than one on same site

The fuel is made of uranium oxide pellets, which are placed in long, thin metal tubes



Images: Exelon, WNA

Nuclear power in Wisconsin

- La Crosse Boiling Water Reactor – small and built in the 1960s – retired in the 1980s
- Kewaunee Power Station – ceased operation in 2013 due to falling price of national gas.
- Point Beach Power Station – near Green Bay, still operational (~50 years old)

Nuclear power in Minnesota

- Prairie Island Nuclear Generating Plant
  - 2 units licensed to operate until mid 2030s
- Monticillo Nuclear Generating Plant
  - One Unit licensed to operate until 2030
- Currently a moratorium on new nuclear plants in Minnesota

South Dakota – no nuclear power plants
Iowa – one former power plant, closed in 2020

Current Status of Nuclear Power in US

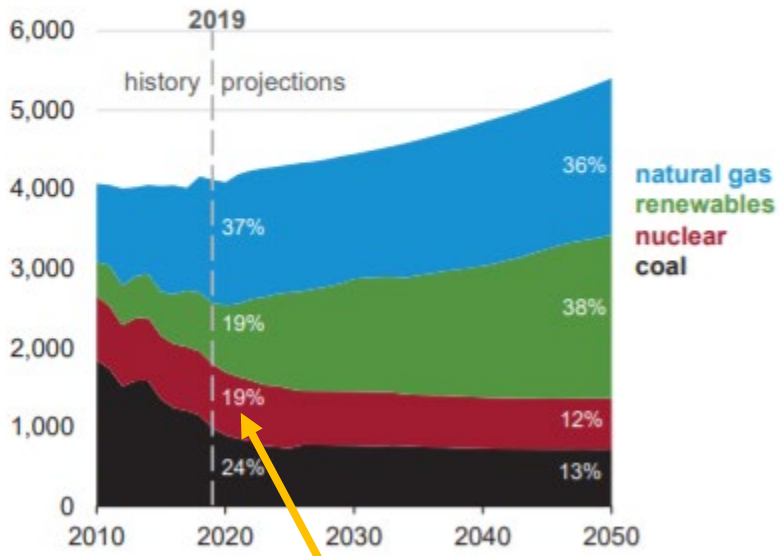
Operating Plants

- ~90 operating nuclear reactors in the US
  - 11 units (across 6 stations) in Illinois
- In recent years several nuclear plants have closed due to economic reasons – cheap gas + variability in prices
  - Nuclear plants have been (marginally) less economic than natural gas
- Dramatic reversal of fortunes in past 12 months
  - Bipartisan infrastructure bill – Federal subsidy to existing plants
  - Rise in gas prices
  - Focus on energy security
  - Planned closures reversed (e.g., Diablo Canyon, CA)
  - Uprates (getting more power out of existing plants) being considered

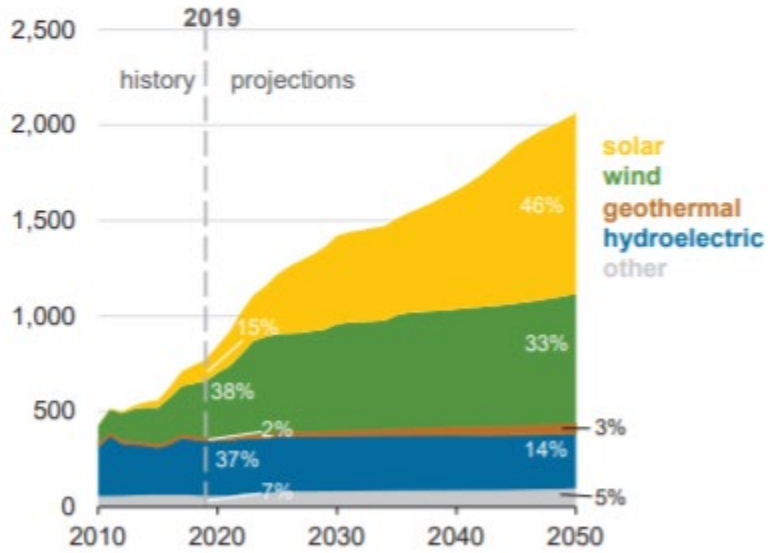
Outlook for nuclear energy in US (EIA)

Electricity generation from natural gas and renewables increases as a result of lower natural gas prices and declining costs of solar and wind renewable capacity, making these fuels increasingly competitive

Electricity generation from selected fuels (AEO2020 Reference case)
billion kilowatthours



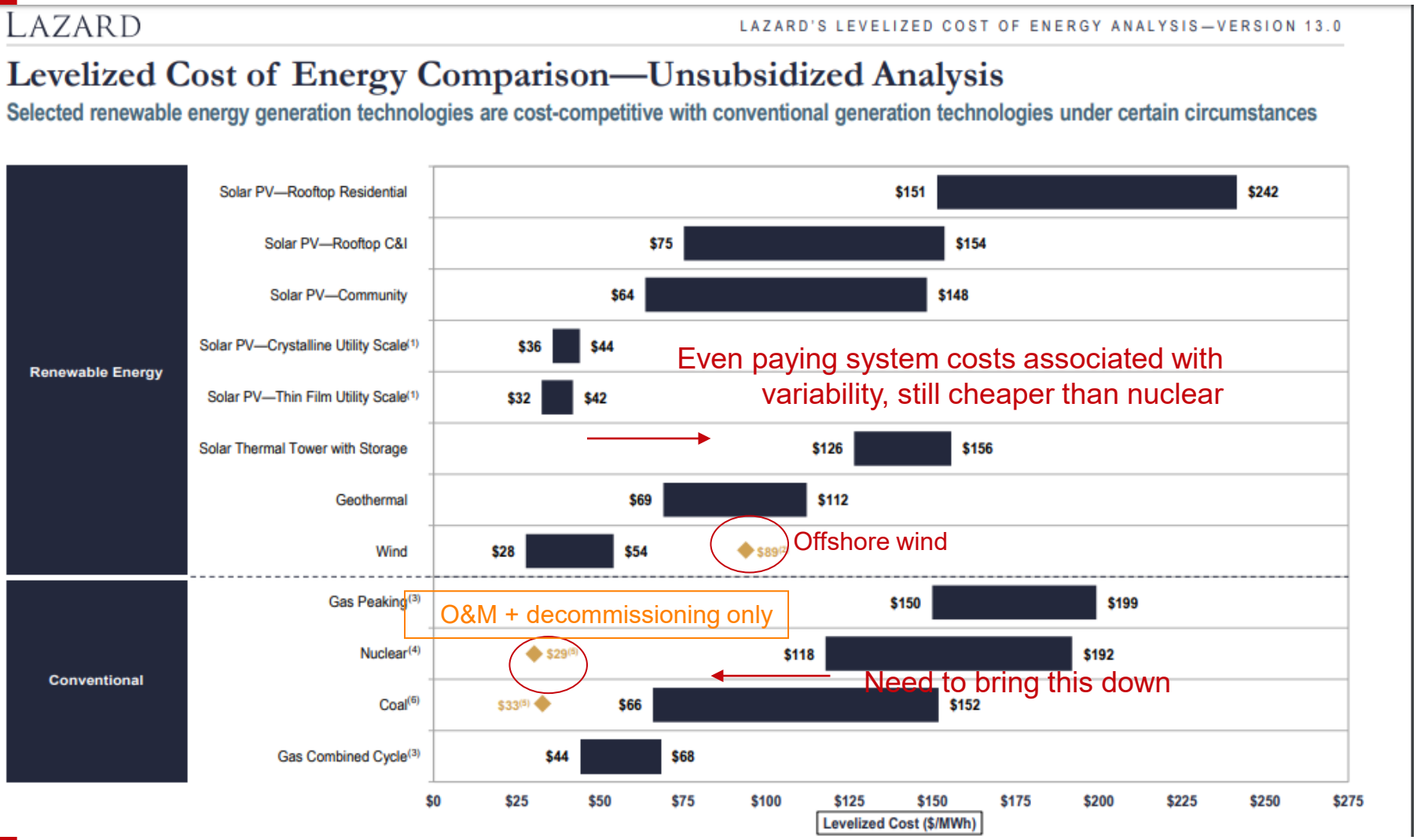
Renewable electricity generation, including end use (AEO2020 Reference case)
billion kilowatthours



Significant contributor today – predicted to gradually drop as existing plants shut down – no new nuclear in baseline scenarios

Cost of Electricity

System costs associated with variability of renewables (need for backup, forcing other generators off the system, storage) – not currently born by the renewable generators.



https://www.lazard.com/media/451086/lazards-levelized-cost-of-energy-version-130-vf.pdf

Do we need firm power?

- Variable electricity prices are problematic for nuclear power
  - Cost of reactor is high
  - Cost of Operations & Maintenance is significant
  - Cost of fuel is low
  - Therefore: want to operate all the time
- System costs of variable renewables rise as the penetration becomes very high
- Roughly – perhaps 70% as maximum variable renewable share in the system. After that curtailment, storage, backup costs become high.
  - This is contested (<50-100%)

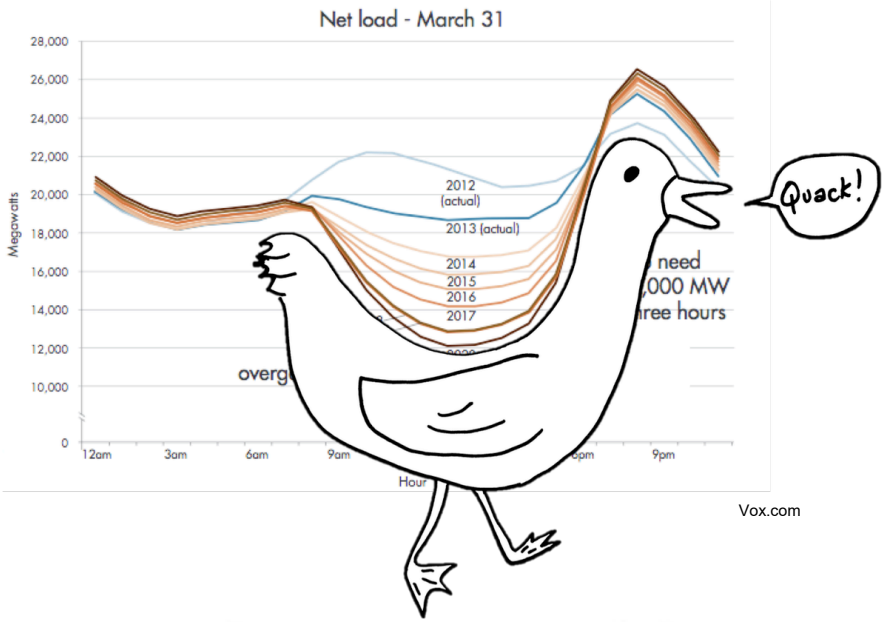
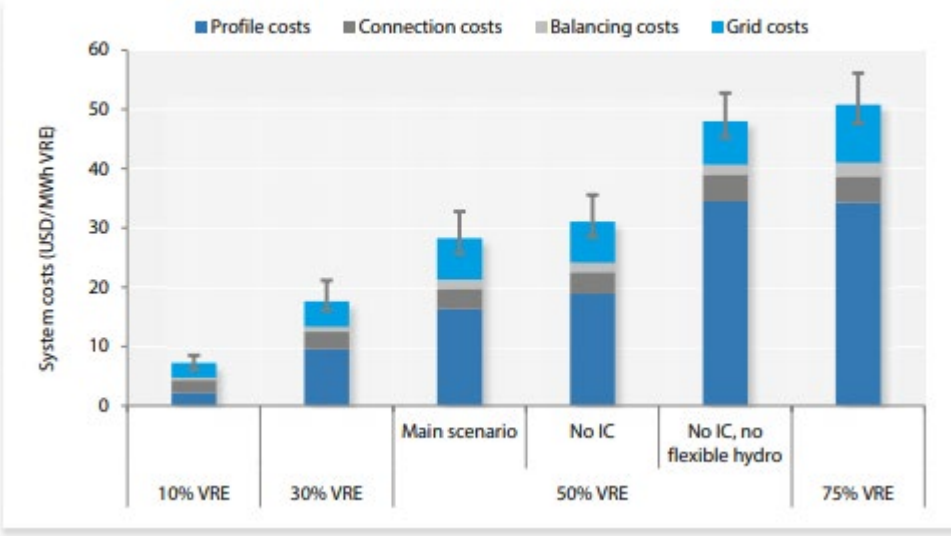


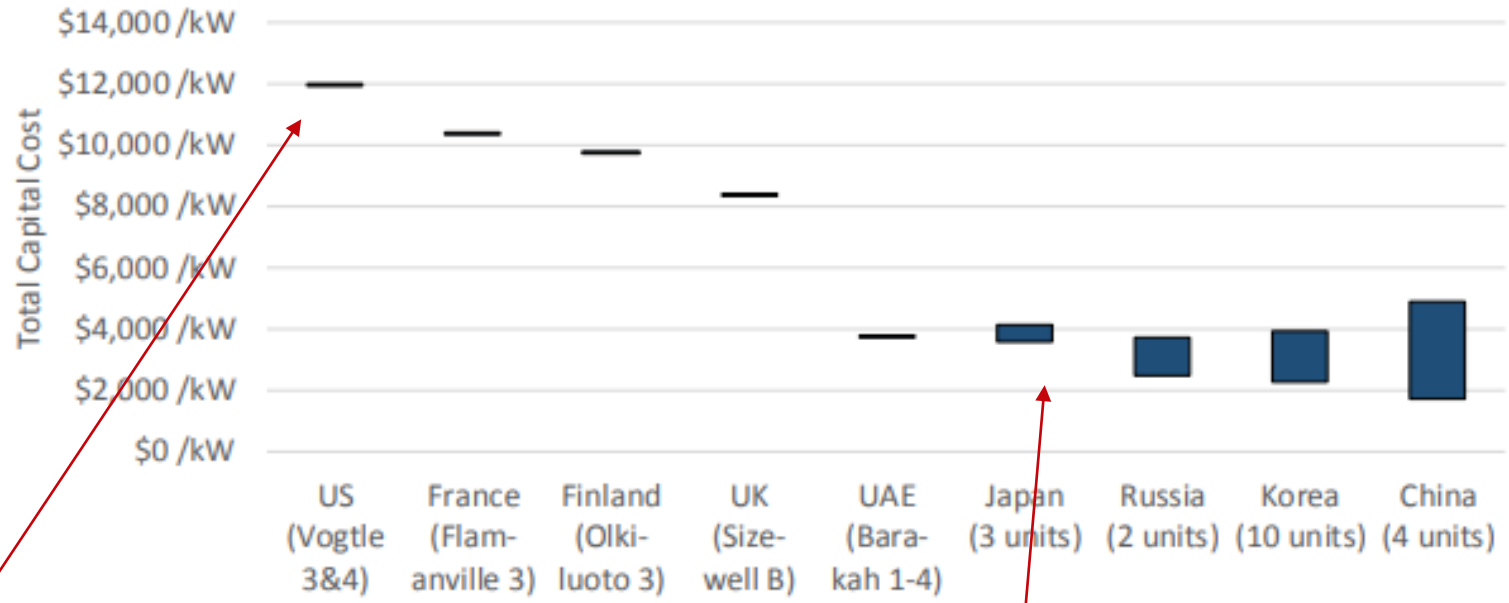
Figure ES6. **System costs per MWh of VRE**



https://www.forbes.com/sites/brianmurray1/2019/06/17/the-paradox-of-declining-renewable-costs-and-rising-electricity-prices/#2615082e61d5
https://www.oecd-nea.org/ndd/pubs/2019/7299-system-costs.pdf
doi: 10.13140/RG.2.2.34054.29766 doi: 10.1039/C7EE03029K doi: 10.1016/j.energy.2017.01.115

Nuclear target costs vs current costs

Figure 1. Total Capital Costs for Historical and Ongoing Nuclear Projects in Database



Recent construction of large reactors in the west is not cost competitive at current prices

Here is OK – achieved repeatedly in Asia

The ETI Nuclear Cost Drivers Project: Summary Report – Energy Technologies Institute, 2018

Nuclear New Build

New build nuclear power plant

- One new power plant constructed in Georgia, just being completed now (Vogtle) – two ~GWe scale power plants
- Very late and over budget. Many reasons for this:
  - Most of cost of nuclear power plant is **on site construction**
  - 'Megaproject' for which industry had lost knowledge of how to complete successfully
  - Construction started when only 20% of design completed
  - Project poorly managed
  - Delays in design approval and construction license and lots of rework required

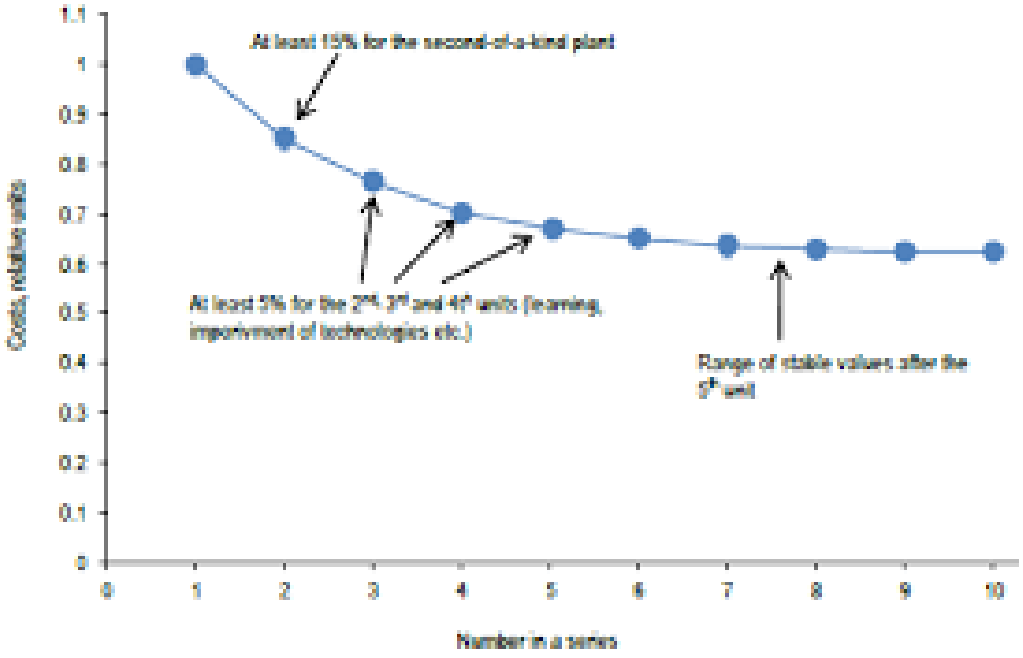
Small Modular Reactors (SMRs)

- Reduce size of nuclear reactor to ~50-400 MWe (instead of >1 GWe)
- Reduce cost so that individual project is easier to finance

- **Modularity**
  - Build everything at the factory, where productivity is high and things are cheap, efficient and well optimized
  - Minimize on-site construction, which is expensive and prone to delays
  - Particularly beneficial in countries with high labour costs for on-site construction
- **Standardization**
  - Have one design and stick to it
  - Build the same thing over and over and over again
  - Not just the design – the supply chain and the manufacturing process

Learning Rate

- Building things more quickly and cheaply once experience is gained
- Reduce costs by maybe 30-40% from First of a Kind (FOAK) to Nth of a Kind (NOAK)
- Regular build programme – same reactor
- Learning effects were crucial in reducing costs of wind and solar – but to reach the same point in nuclear requires successful construction of first unit and then repeat construction of same thing



https://inldigitallibrary.inl.gov/sites/sti/sti/6293982.pdf

When well implemented, we can mostly achieve these things with large reactors (some of the components may be too large to transport) – as demonstrated in Asia where large reactors are successfully built at competitive prices

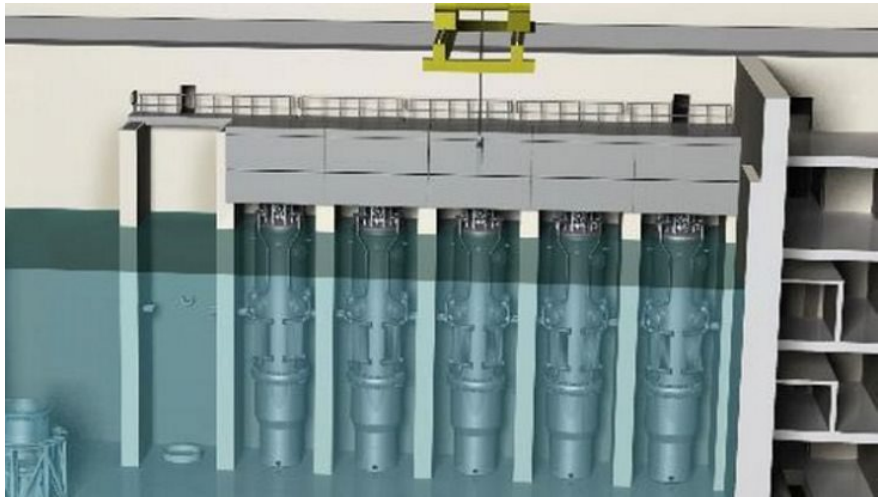
In the West, we do not have the level of state intervention required to implement a large reactor programme successfully. We need private financing. Large reactors are too big to finance privately.

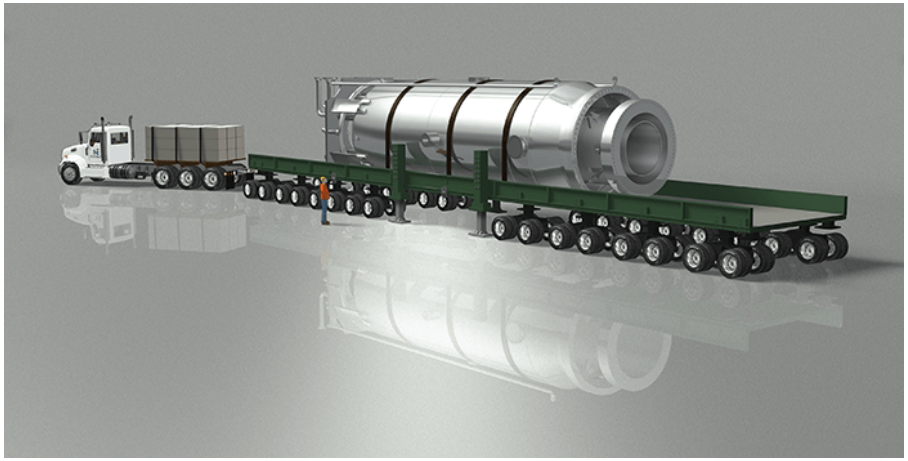
SMR ➔ small ➔ can finance ➔ can build lots ➔ competitive LCOE

A well implemented SMR programme and a well implemented large reactor programme have similar target costs (~$80-100/MWh)

NuScale

- **Small modular reactor developer headquartered in Oregon**
- Recent memorandum of understanding with Dairyland Power to evaluate potential of NuScale technology
- Up to 12 factory built modules shipped to site and operated from single control room
- Construct modules in factory and ship to site by road (this constraint contributes to sizing the module)
- Stated target is $3600/kWe, $65/MWh (probably USD2020) https://www.nuscalepower.com/newsletter/nucleus-spring-2020/featured-topic-cost-competitive
  - Since then, the plant power has been increased (not aware of figures on impact on cost)
- Cost is yet to be proven but modular design and volume factory manufacture addresses cost/performance points raised earlier





https://www.nuscalepower.com/technology/technology-overview
https://www.dairylandpower.com/nuscale-power-and-dairyland-announce-mou-evaluate-potential-technology

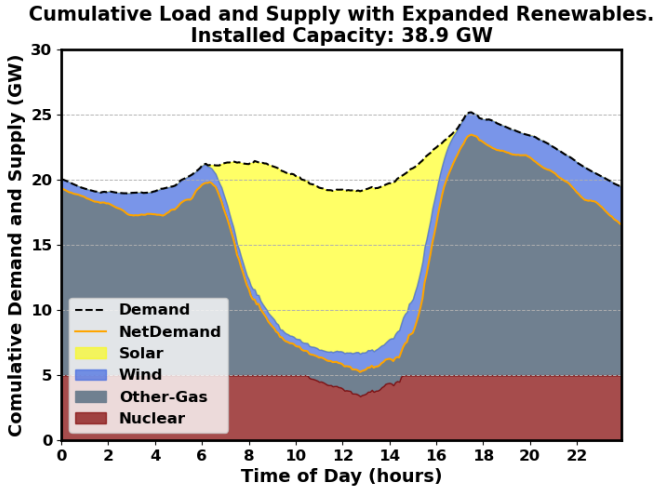
A word on siting and emergency planning zones…

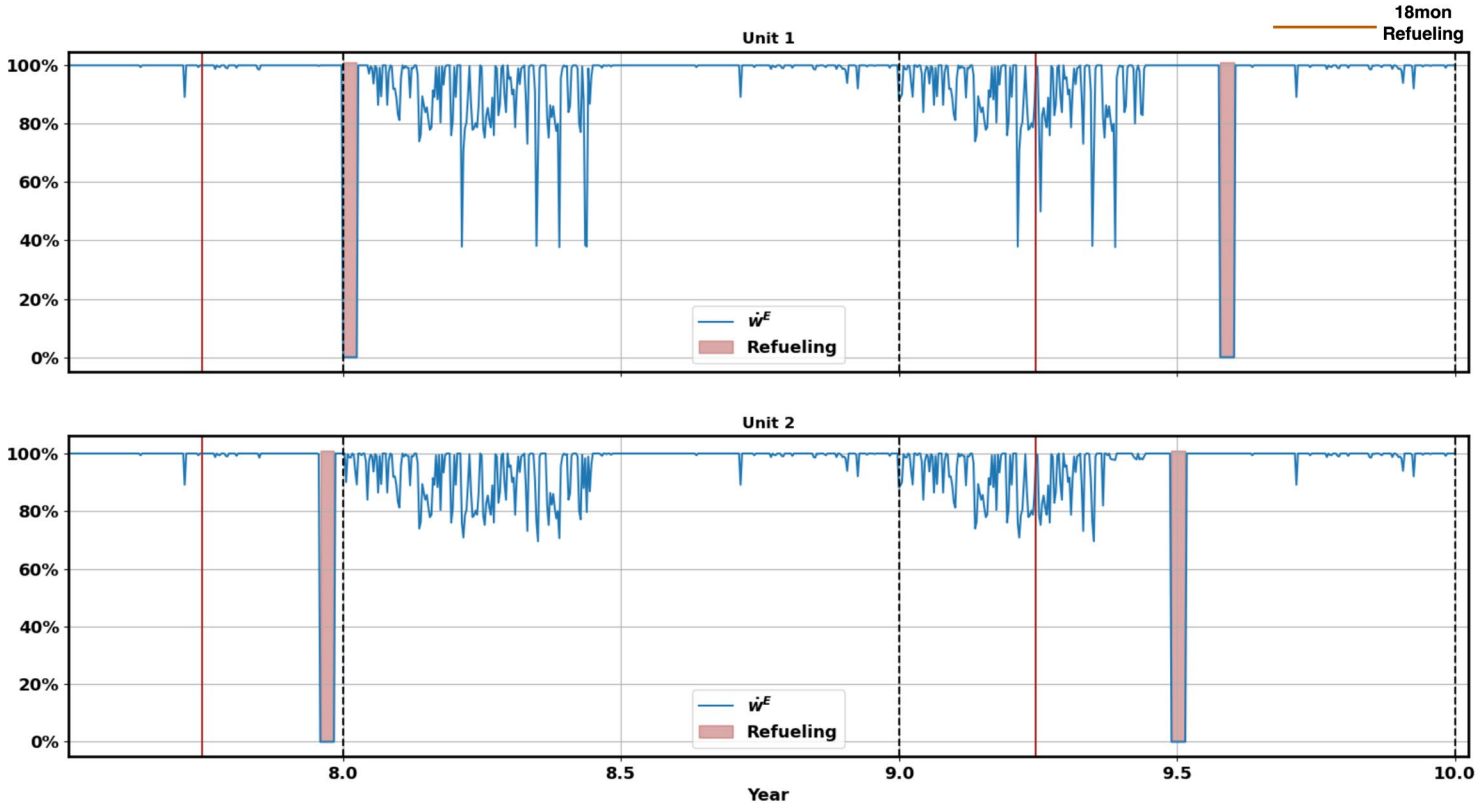
- Area around plant where emergency procedures are in effect
  - In principle, the area which might be evacuated in a bad accident
  - Never in the US
  - Fukushima (massive Tsunami + old reactor + clear failure to plan for the tsunami) and Chernobyl (poor Soviet design operated recklessly)
- Traditionally 10 miles for conventional power plant
- NuScale (and other new designs) target reduction of emergency planning zone to site boundary
  - Simple design with extra safety features
  - Smaller independent modules
- Bottom line: no significant risk of radiation exposure, no evacuations
  - There are a few subtleties depending on specifics of the actual site
- **Future nuclear construction should (and I hope will) only be based on consent of the community and empower community in decision making.**

https://fermi.ee/wp-content/uploads/2021/02/23-gb-tolkidele-marti-jeltsov-kelk-gb.pdf

Our Research - NuScale

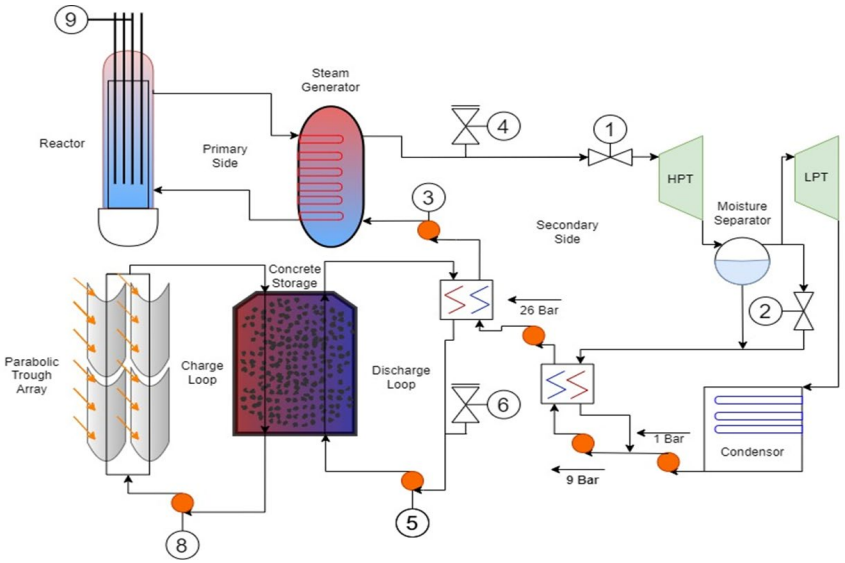
Optimize when to refuel multi-unit NuScale plant, when operating flexibility to meet fluctuations in electricity price and demand

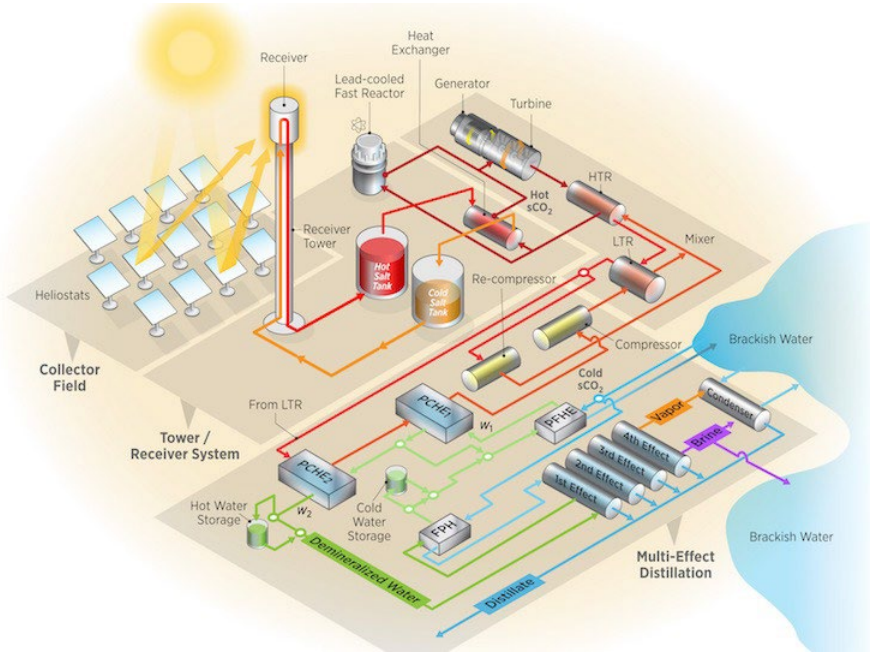




Our Research – linking Nuclear and Solar

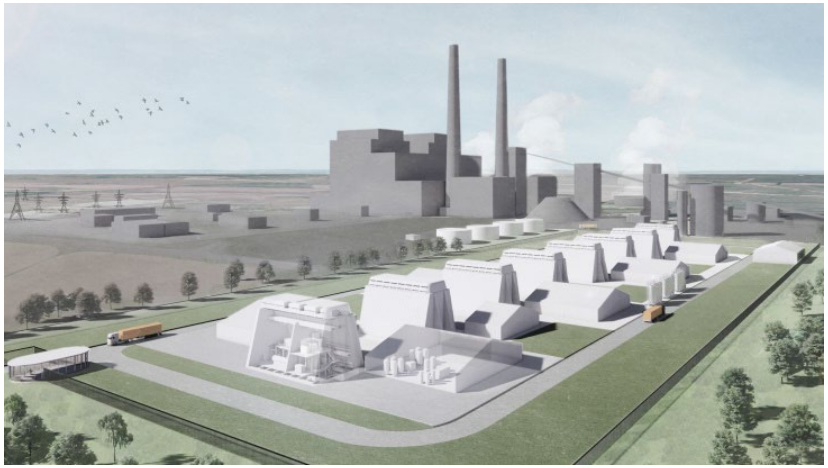
- Can we get improved/more flexible energy system that combines, solar power (variable), nuclear power (wants to operate at 100% all the time) and thermal energy storage – and optimize electricity production to meet demand?





Nuclear Coal Repowering

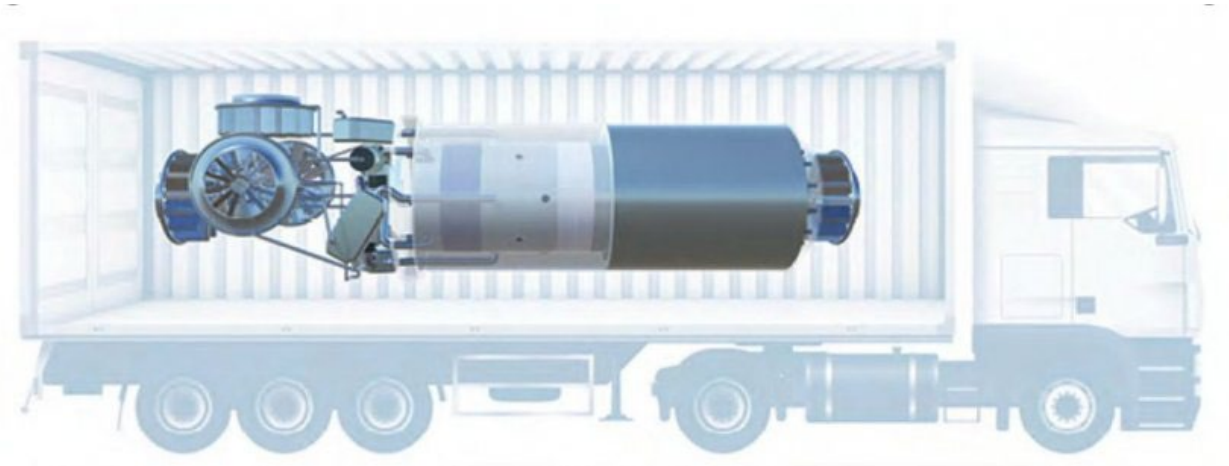
- Early closure of coal fired power stations is considered by many environmentally crucial but politically and economically difficult
- Plans to build demonstration reactor at Kemmerer, Wyoming on site of coal fired power station slated for closure
- Building at sites of coal fired power stations also offers a route to political support and community acceptance (preserve jobs)
- Some possibilities for site and equipment reuse
- We are collaborating with U.Wyoming and others to develop a standardized approach to advanced nuclear reactors – including coal repowering



https://www.world-nuclear-news.org/Articles/Digital-platform-launched-for-repowering-coal-plan

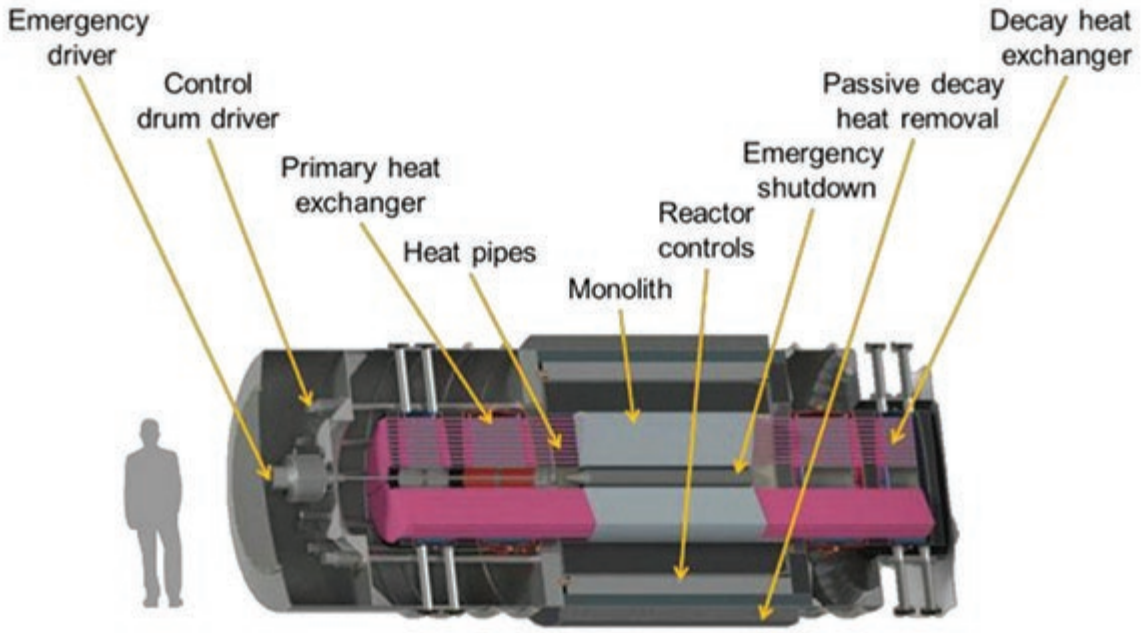
What is a Microreactor?

New designs of Microreactor produce a few MW and can be transported to site by truck



Images:X-energy, Powermag, energy.gov

What is a Microreactor?

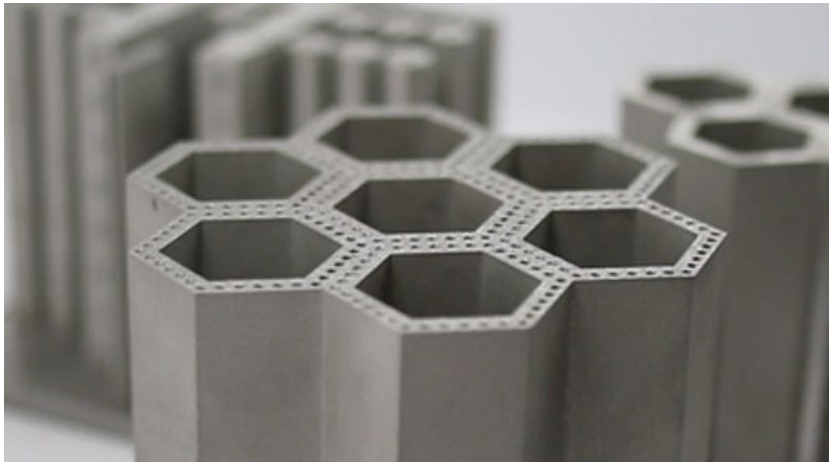


Many designs – but the above is typical. The nuclear fuel is encased in a solid block. Heat pipes are tubes that remove heat through capillary action (like a candle) – very few moving parts. The power density is much lower than a typical nuclear reactor, so removing the heat under all conditions is less difficult.

Images:Westinghouse

Microreactor Fuel

Most microreactor designs use a special type of nuclear fuel called TRISO (seen here, much zoomed in). These tiny particles of uranium ceramic fuel are coated in three different layers of graphite and more ceramic. They do not melt, and they have been shown to be robust to extremely high temperatures



This fuel can be packed into graphite or silicon carbide blocks, much like a nuclear rocky road

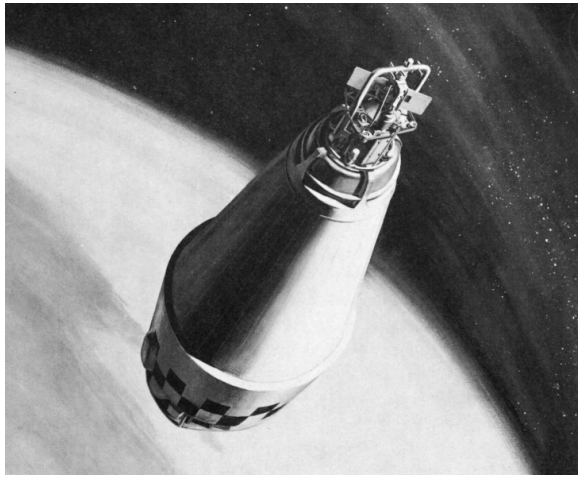
Images:bwxt

Why were microreactors developed?

Two very compelling use cases

Long life and high energy density make microreactors very well suited to long space missions with high payloads – e.g., mission to Mars.

U.S. operated a reactor in space in the 1960s



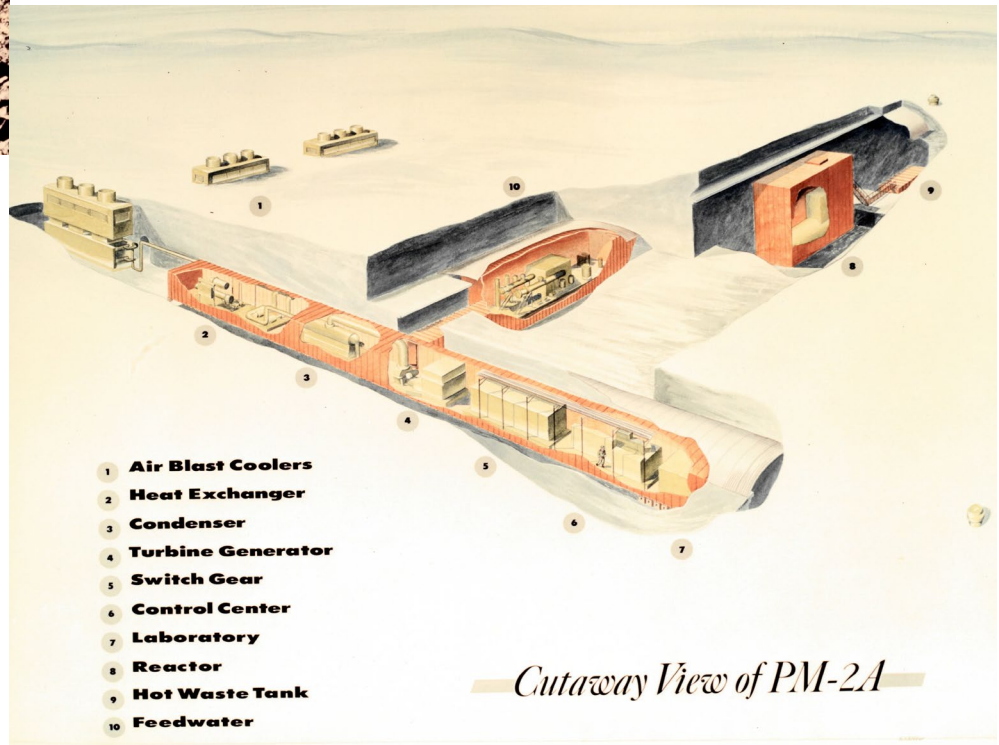
Resilient power source in remote communities (e.g., mining) in Northern Canada and Alaska

Crucial that power source does not fail and diesel (for generator) is **very** expensive

Images: Westinghouse, beyond NERVA

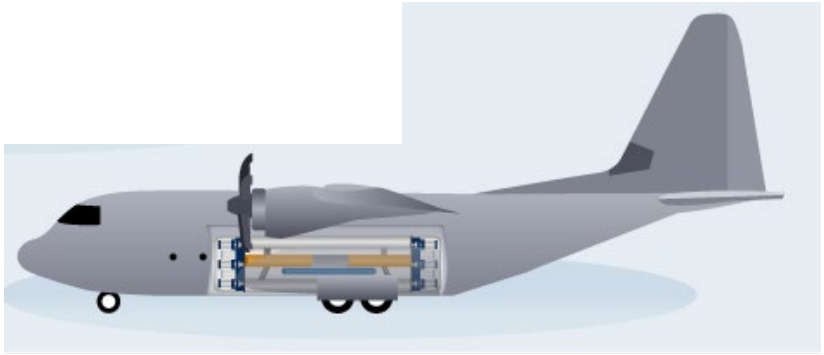
- Reactor powered McMurdo Station, Antarctica for several years

- Reactor operated under Greenland's snow/ice for several years



Widening Interest

Transportable reactor for military bases. Reduce shipments of fuel to sites – reduce casualties

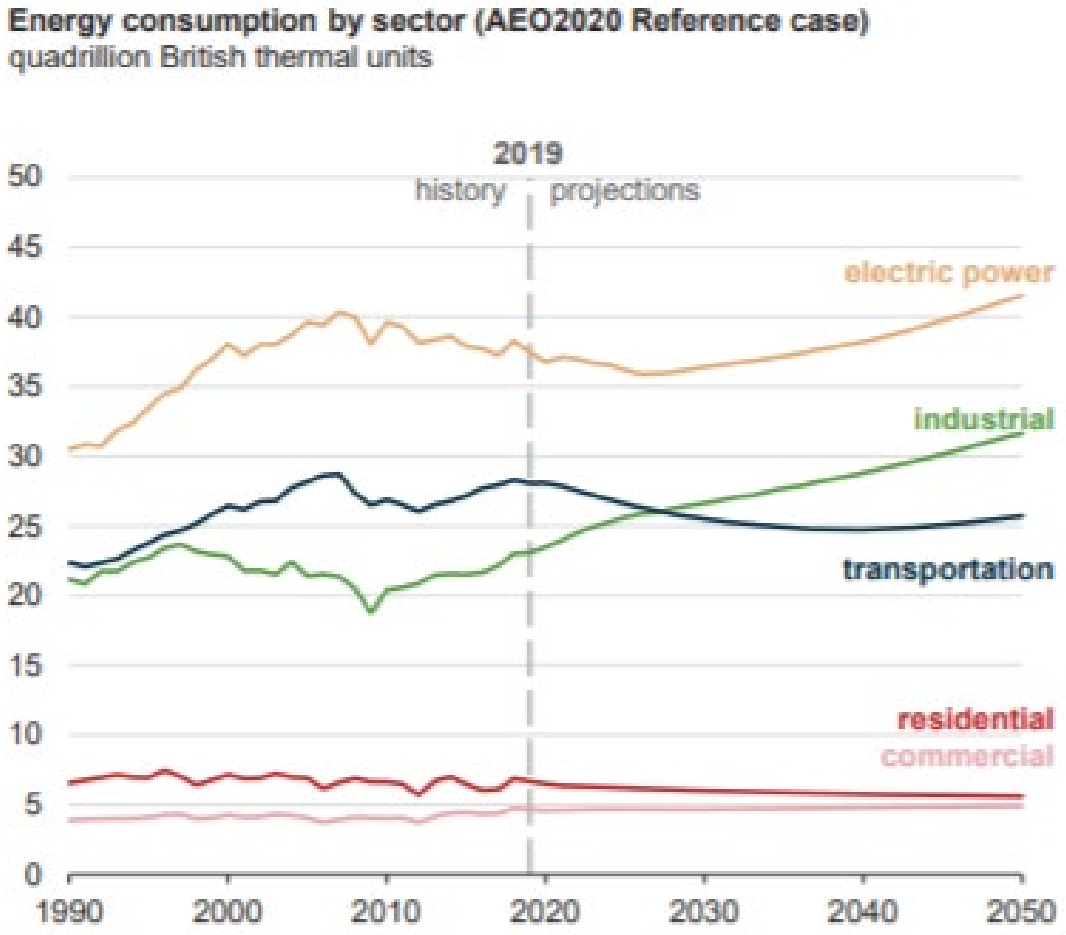


Combined heat and power in local energy systems

Low carbon **process heat**

Images: gao.gov, https://www.hydrogen.energy.gov/pdfs/review20/ne01_bragg-sitton_boardman_2020_o.pdf

Most of our energy consumption is not electricity…



…but many things will be electrified.

Generate Local?

Generate Local?

Affordable, Green ☑

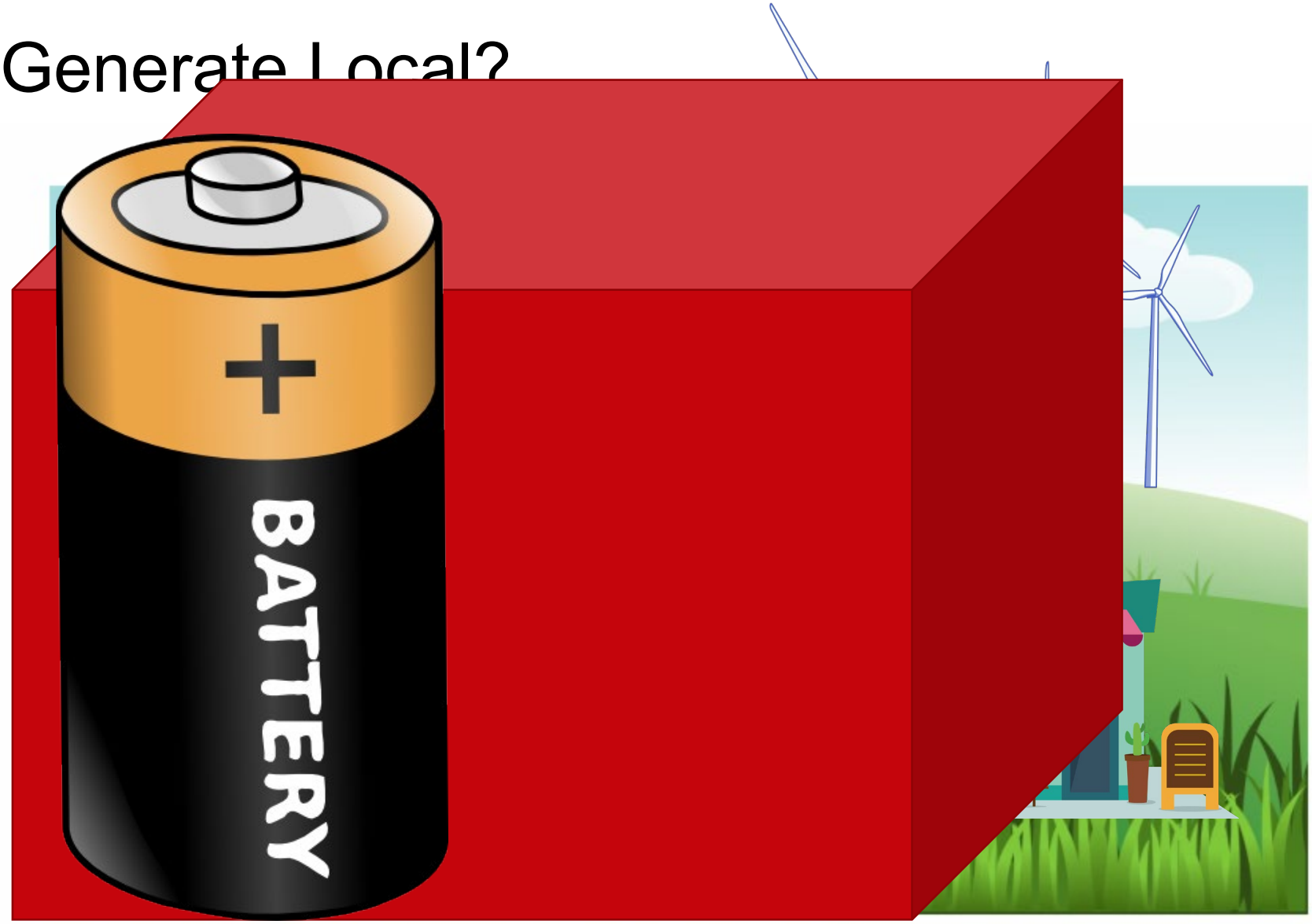
Variable

Generate Local?

Affordable, Green ☑

Still not enough…

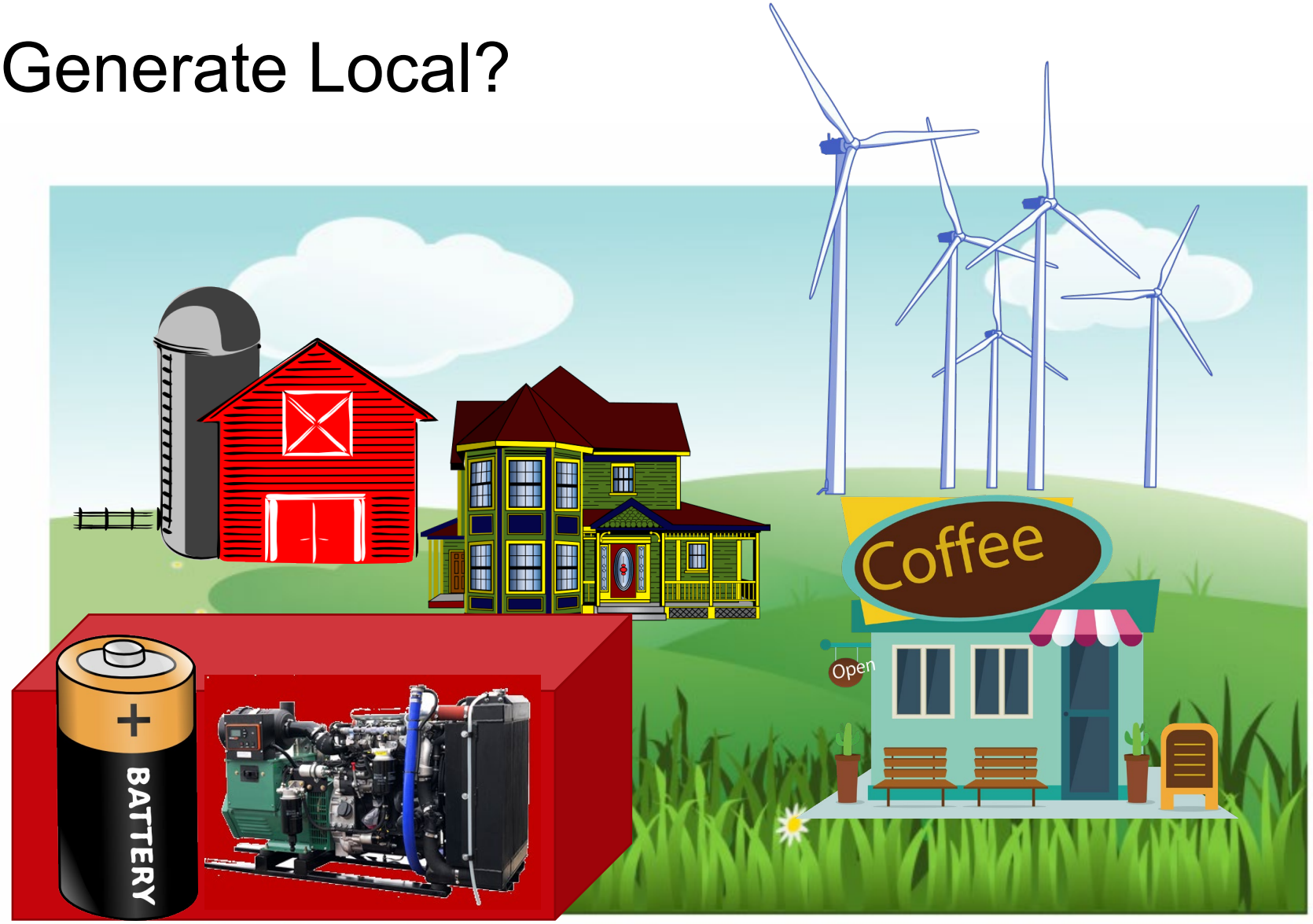
Generate Local?



Green ☑

Now expensive!

Generate Local?



Affordable

Quite green, still uses fossil fuels

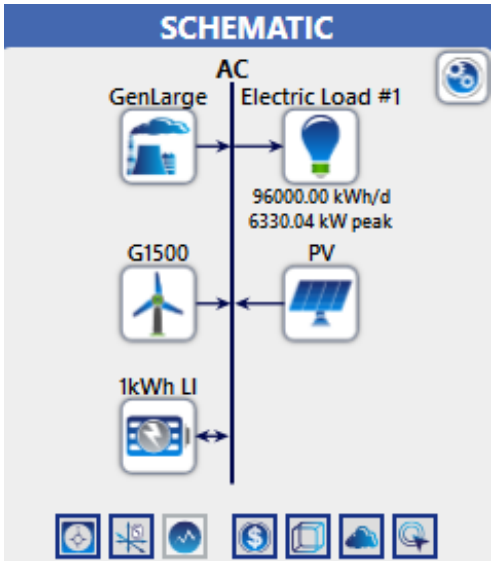
Generate Local?

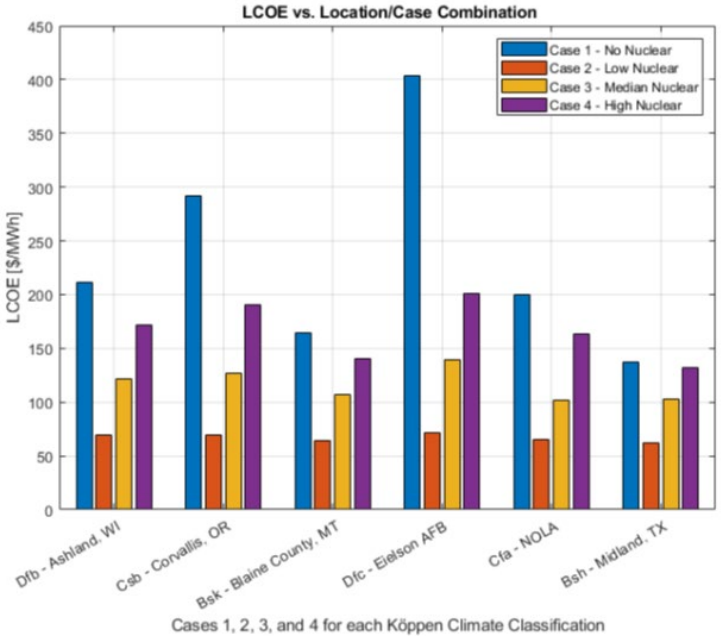
Green and still affordable ☑

Our research – nuclear on microgrids

In an islanded microgrid, what is the cost at which nuclear competes with renewables-only solutions?

- Does this change with the size of the nuclear reactor?
- How does this depend on local climate?



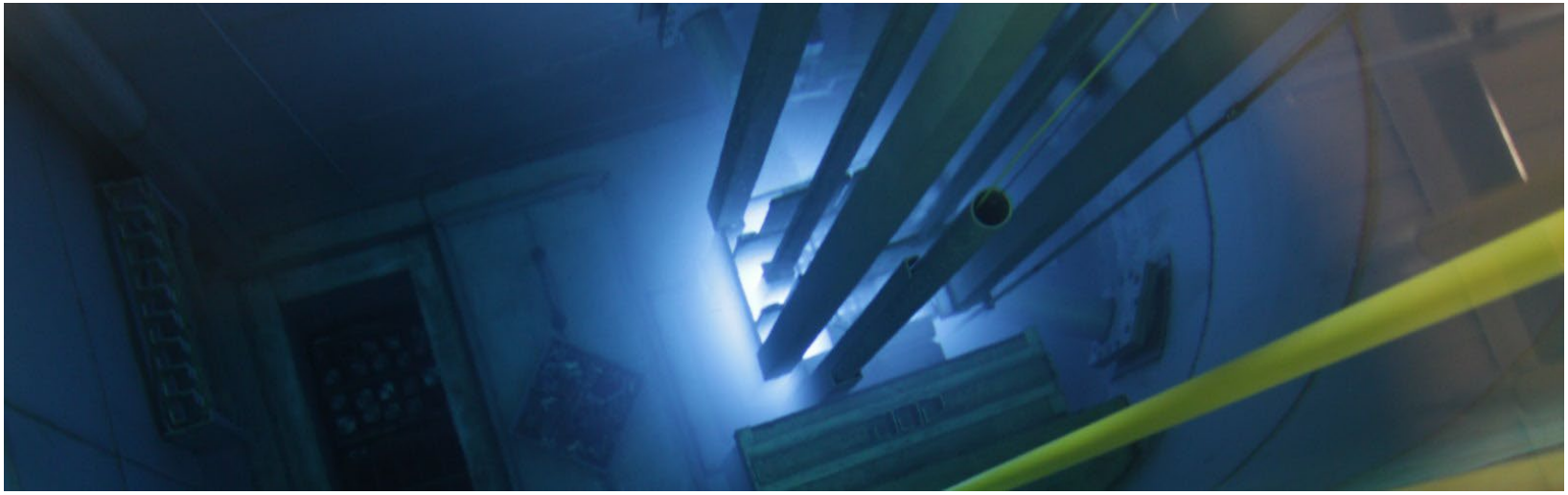


What would a microreactor mean for a community?

- **No emergency planning zone is necessary**
  - Microreactor makers will meet stringent safety requirements to demonstrate this – passive safety, very few moving parts
  - Reactor is very small – it does not have very much radioactive material in it and produces much less heat
  - **No significant accidents, no evacuations**
- **Reactor is transportable**
  - Nuclear core is removed and replaced after a few years
  - Whole reactor can be moved
  - **No decommissioning. When you stop using it, somebody takes it away.**
- **Jobs?**
  - Maybe – in the short term, they will need 1-2 staff
  - BUT in the long term they may be fully automatic.

How safe is safe?

For reference, our campus has a 1 MW nuclear reactor, in the center of Madison, operated by the students!



Conclusion

- Two ‘flavors’ of reactor for rural energy
- **Small**
  - ~50-500 MWe
  - ~$60-80/MWe targeted
  - Target being competitive with grid-scale solutions (i.e., with large plants)
  - Project size ~$100M - $1B
- **Micro**
  - Fully transportable to and from site
  - ~ 5-20 MWe
  - 0-2 staff
  - ~2-3x as expensive per MWe (will probably need to hit lower end of this at minimum to be economically viable)
  - Project size ~$50-150M

The case for microreactors

- One component of a local energy supply – own your electricity, limit transmission and distribution costs
- When used *as well as* renewables, may lead to the overall system being cost effective by providing electricity when the wind isn't blowing/sun isn't shining ***if:***
  - No fossil fuels
  - Limited reliance on external power sources
- *Resilient* – very low probability of power supply failure – electricity stays on if grid fails (think Texas…)
- **Can produce heat as well as electricity**
  - E.g., UW-Madison has a campus district heating & cooling system – there are few options for decarbonizing this
    - Note: campus district heating system is significantly larger than microreactor. May want a 'small' reactor instead.
  - Industrial heating use cases

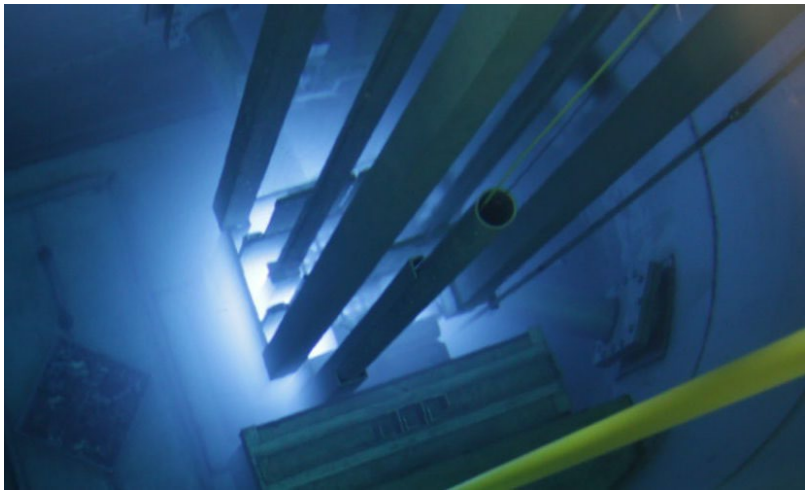
The case against microreactors

- Not yet demonstrated that they can compete with more centralized approaches on price
  - Electricity: local renewables + other power supplies somewhere else)
  - Heat: gas (or coal)

Careers…

… or what if my daughter/son wants to be a nuclear engineer?

- Many great opportunities for nuclear engineers/scientists in the U.S. at the moment:
  - Strong research and development program – national lab system, universities, industry
  - Many nuclear startups developing advanced nuclear reactors and medical isotope production facilities (e.g. SHINE in Wisconsin)
  - Nuclear medicine
  - Current nuclear plants are hiring following federal support
- UW-Madison is one of the best in the country



Thank you!

Questions?

Comments?

Acknowledgements

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